

Silicon diodes fabricated on defect-engineered material for use as radiation detectors.

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Declaration

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Herby submit for your consideration the thesis entitled “*Silicon diodes fabricated on defect-engineered material for use as radiation detectors*” The work was performed under the Supervision of Prof. S. H. Taole.

Also hereby declare that work submitted in this thesis is my own investigation and research and that it has not been submitted in part or in full for any other degree or to any other University.



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Abstract

Current-voltage and capacitance-voltage measurements have been carried out on irradiated commercially available silicon *p-i-n* photodiodes under illumination of different wavelengths. The photodiodes were irradiated by 1 MeV neutrons at different fluences. A main indication is that effects due to incident photons are more pronounced at low radiation fluence but they become negligible as the fluence increases. These results show that silicon gets quickly damaged by radiation in the initial stages of the irradiation process but as the fluence increases the material becomes resistant to further damage. The measurements were also carried out on Schottky diodes fabricated on metal-doped silicon. The metals used were gold, platinum, erbium and niobium. Using the Rutherford Backscattering Spectroscopy and X-ray Photoelectron Spectroscopy techniques, they were found to diffuse into silicon at the annealing temperature of 900 °C and a time of 18 hours. The overall results indicate that doping with metals is similar to the irradiation. Their effects on the material reduce the conductivity and change the behaviour of the diodes from the normal exponential behaviour to the Ohmic behaviour. These two features show that irradiated or metal-doped silicon is a relaxation material. This type of material is radiation-hard since the effects of radiation on it have been found to be suppressed.

List of abbreviations, constants and symbols

Symbol	Meaning	Units / Notes
A	Area	cm^2
α	Damage constant	A cm^{-1}
α_0	Absorption coefficient	cm^{-1}
A^*	Richardson constant	$\text{Am}^{-2} \text{K}^{-2}$
Al	Aluminium	
Au	Gold	
BE	Binding energy	eV
C	Capacitance	F
c	Speed of light in vacuum	$3 \times 10^8 \text{ m s}^{-1}$
CSIR	Council for Scientific and Industrial Research	
C_1	Concentration at the depth	cm^{-3}
C_0	Surface concentration	cm^{-3}
cce	Charge collection efficiency	
C_d	Full depletion capacitance	F
CdS	Cadmium Sulphide	
C_j	Junction capacitance	F
c_n	Electron capture coefficient	$\text{cm}^3 \text{s}^{-1}$
c_p	Hole capture coefficient	$\text{cm}^3 \text{s}^{-1}$
C_s	Charge storage capacitance	F
$C - V$	Capacitance-voltage	
D	Diffusion coefficient	$\text{cm}^2 \text{s}^{-1}$
d	Distance between the contacts	cm
D_n	Diffusion coefficient for electrons	$\text{cm}^2 \text{s}^{-1}$
$D_n(E)$	Electrons density of state in the conduction band	cm^{-3}
D_p	Diffusion coefficient for holes	$\text{cm}^2 \text{s}^{-1}$
D_0	Diffusion constant	$\text{cm}^2 \text{s}^{-1}$
e	Electronic charge	$1.602 \times 10^{-19} \text{ C}$
E_a	Activation energy	eV
E_c	Energy at the bottom of the conduction band	eV
E_F	Fermi energy	eV
E_{Fm}	Metal Fermi energy	eV
E_{Fs}	Semiconductor Fermi energy	eV
E_g	Energy gap	eV
E_i	Intrinsic Fermi energy	eV
E_{LED}	Photon energy of the light incident onto the diode	eV
E_{max}	Electric field at the breakdown voltage	V cm^{-1}
e_n	Electron emission coefficient	s^{-1}
e_p	Hole emission coefficient	s^{-1}

Er	Erbium	
E_v	Energy at the top of the valence band	eV
E_0	Helium energy	eV
E_1	Energy of the target atom	eV
$e - h$	Electron –hole	
f	Frequency	Hz
$F(E)$	Energy distribution function	
FWHM	Full width at half maximum	
G	Generation rate	$\text{cm}^{-3} \text{ s}^{-1}$
GaAs	Gallium Arsenide	
Ge	Germium	
g_{op}	Optical generation rate	
$g - r$	Generation-recombination	
h	Plank's constant	$6.63 \times 10^{-34} \text{ J s}$
HCl	Hydrochloric acid	
HF	Hydrofluoric	
HgCdTe	Mercury Cadmium Telluride	
HNO_3	Nitric acid	
$h\nu$	Photon energy	eV
H00	Unirradiated diode	
H13	Diode irradiated to $10^{13} \text{ n cm}^{-2}$	
H14	Diode irradiated to $10^{14} \text{ n cm}^{-2}$	
H15	Diode irradiated to $10^{15} \text{ n cm}^{-2}$	
H16	Diode irradiated to $10^{16} \text{ n cm}^{-2}$	
H17	Diode irradiated to $10^{17} \text{ n cm}^{-2}$	
InP	Indium phosphide	
I_{op}	Saturation current	A
A^*	Richardson constant	
$I - V$	Current-voltage	
J	Total current density	A cm^{-3}
J_D	Ideal diffusion current density	A cm^{-3}
J_{gen}	Generation current density	A cm^{-3}
J_n	Electron diffusion current density	A cm^{-3}
J_p	Hole diffusion current density	A cm^{-3}
J_R	Reverse current density	A cm^{-3}
J_{rec}	Recombination current density	A cm^{-3}
J_s	Saturation current density	A cm^{-3}
K	Kinematic Factor	
k_B	Boltzman constant	$1.381 \times 10^{-23} \text{ JK}^{-1}$
KE	Kinetic energy of the photoelectron	eV
l	Wafer thickness	cm
l_0	Effective thickness of the diode	cm
LCR	Inductance-Capacitance-Resistance	
LED	Light emitting diode	
Li	Lithium	

L_n	Diffusion length of electrons	cm
L_p	Diffusion length of holes	cm
M_1	Mass of helium	kg
M_2	Mass of the target atom	kg
$m-s$	Metal-semiconductor	
m_e^*	Electron effective mass	kg
m_p^*	Hole effective mass	kg
N	Bulk density of atoms in the sample	cm ⁻³
N_A	Acceptor density	cm ⁻³
N_a	Net acceptor density	cm ⁻³
Nb	Niobium	
N_c	Effective density of state in the conduction band	cm ⁻³
N_D	Donor density	cm ⁻³
N_d	Net donor density	cm ⁻³
N_{eff}	Effective doping density	cm ⁻³
n_i	Intrinsic carrier density	cm ⁻³
N_M	Metal atomic density	Atoms. cm ⁻³
n_{n0}	Majority carrier density in the n - region	cm ⁻³
n_p	Total minority carrier density in the p -region	cm ⁻³
n_{p0}	Minority carrier density in the n -region	cm ⁻³
N_v	Effective density of state in the valence band	cm ⁻³
N_0	Metal saturation solubility	Atoms. cm ⁻³
n_0	Density of electrons in the conduction band	cm ⁻³
p	Momentum	kg cm s ⁻¹
p_n	Total minority carrier density in the n -region	cm ⁻³
PC	Personal Computer	
p_{n0}	Minority carrier density in the p -region	cm ⁻³
p_{p0}	Majority carrier density in the p -region	cm ⁻³
p_0	Density of holes in the valence band	cm ⁻³
Pt	Platinum	
Q	Quantity of stored charge	C
Q_A	Activation energy	J
Q_i	Number of ions incident on the sample	
RBS	Rutherford Backscattering Spectroscopy	
RUMP	Rutherford Universal Manipulation Program	
R_s	Series resistance	Ω
SCR	Space charge region	
Si	Silicon	
SiGe	Silicon Germanium	
SiC	Silicon Carbide	
Sn	Tin	
T	Absolute temperature	K

t	Diffusion time	s
TCW	Thermoelectric cooler and warmer	
V_{BR}	Breakdown voltage	V
V_{bi}	Built-in voltage	V
V_d	Full depletion voltage	V
V_{LED}	Voltage supplied to the LED	V
V_t	Thermal voltage	eV
V_{total}	Total potential barrier	eV
W	Space charge width	cm
x_d	Depth of the concentration	cm
x_n	Space charge width into the n -region	cm
x_p	Space charge width into the p -region	cm
XPS	X-ray Photoelectron Spectroscopy	
y	Thickness of the metal film	cm
Y	Total number of the detected ions	C
Z_1	Helium atomic number	
Z_2	Atomic number of the target atom	
τ_D	Dielectric relaxation time	s
τ_0	Minority carrier lifetime	s
μ_e	Electron mobility	$\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$
μ_h	Hole mobility	$\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$
ϕ_{Fn}	Potential in n -region	eV
ϕ_{Fp}	Potential in p -region	eV
ϵ_s	Permittivity of the semiconductor	F cm^{-1}
ϕ_B	Schottky barrier height	eV
ϕ	Radiation fluence	n cm^{-2}
ϵ_0	Permittivity of free space	$8.85 \times 10^{-14} \text{ F cm}^{-1}$
ξ_{max}	Maximum electric field at full depletion voltage	V cm^{-1}
ψ_s	Spectrometer work function	eV
δn_p	Excess electron concentration	cm^{-3}
δp_n	Excess hole concentration	cm^{-3}
η	Ideality factor	
θ	Backscattered angle	deg^0
λ	Photon wavelength	nm
λ_{LED}	Peak emission wavelength of LED	nm
μ	Carrier mobility	$\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$
π	pi	3.141592654
ρ	Resistivity of semiconductor	$\Omega\text{-cm}$
σ	Conductivity	$(\Omega\text{-cm})^{-1}$
τ	Carrier lifetime	s
τ_{n0}	Excess minority carrier lifetime for electrons	s
τ_{p0}	Excess minority carrier lifetime for holes	s

Φ_0	Intensity of a photon incident on the diode	lux
Φ_m	Metal work function	eV
Φ_s	Semiconductor work function	eV
Φ_t	Light intensity transmitted through the diode	lux
χ	Electron affinity	eV
Ω	Detector solid angle	deg ⁰
σ_n	Capture cross section for electrons	cm ³ s ⁻¹
σ_p	Capture cross section for holes	cm ³ s ⁻¹
N_t^*	Concentration of the neutral donor trap	cm ⁻³
l	Distance in the depletion region	cm
E_t	Trap energy level	eV
v_{th}	Thermal velocity	cm s ⁻¹
N_t	Trap density	cm ⁻³
τ_{eff}	Effective carrier lifetime	s
$\text{\AA}$	Angstrom	1\text{\AA} = 10 ⁻¹⁰ m
E	Electric field	V cm ⁻¹

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Dedication

This work is dedicated to my mother Mrs. J. Moloi.

In loving memory of my father, who passed away during the examination process of this thesis.

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List of publications

1. Moloi S J and McPherson M 2009 “*Current-voltage behaviour of Schottky diodes fabricated on p-type silicon for radiation hard detectors*” *Physica B* **404** 2251.
2. Moloi S J and McPherson M 2009 “*The current and capacitance response of radiation-damaged silicon PIN diodes*” *Physica B* **404** 3922.

Presentation



1. Moloi S. J. and McPherson M 2008 *Electrical properties of silicon diodes determined under illumination by different wavelengths*. Quantum Electronics and Photonics (QEP) - 18 conference, Heriot-Watt University, Edinburgh, UK, 26 -29 of August 2008

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Chapter 1

Introduction

1.1 Overview

Silicon is an indirect band gap semiconductor that has been used widely to fabricate radiation detectors that are used in high energy physics experiments to detect charged particles [Martini and McMath, 1970; Van Lint, 1987; Edmonds, 1990; Holland *et al*, 1994]. These detectors are diodes that have a potential for such applications because of their conductivity which can vary either as a function of temperature or as a function of impurities added into the semiconductor [Sze, 1981]. The conductivity can also vary as a function of optical excitation to make the diodes be used as optoelectronic devices for communication [Streetman, 1990; Canham *et al*, 1996]. However, these detectors fail to operate efficiently under high radiation environments [Barthe, 2001; Eremin *et al*, 2002]. Hence, it is very important that radiation-hard detectors are fabricated where radiation-hardness essentially means long operational life. Thus, the efficiency and the lifetime of the existing silicon detectors need to be improved.

In trying to analyse the effects of radiation damage on the detectors, it has been found that the effects are due to collisions of incident high energy particles with the semiconductor lattice [Moll *et al*, 1997; Lindstrom *et al*, 1999]. The particles transfer sufficient energy to the semiconductor to move an atom within the lattice out of its normal position. This results in a creation of a large number of intrinsic point defects, vacancies and interstitials, which have active levels within the energy gap [Watkins, 2000]. The activity of these defect levels depends on their position in the energy gap.

Depending on their position, defect levels can generate charge carriers to increase the conductivity of the material or recombine charge carriers to reduce it. Some of the levels can both generate and recombine charge carriers. These levels are located near the centre of the energy gap in which position they interact equally with both bands [McPherson, 1997] and are referred to as “midgap defects”. The midgap defect maintains carrier densities at the intrinsic level and so is responsible for the semi-insulating behaviour of the material which has been attributed to the relaxation-like properties in silicon [Queisser, 1972; Haegel, 1991]. This midgap defect can, however, generate carriers to increase the conductivity or recombine carriers to reduce it.

It has been shown that the induced defects are responsible for changes in the electrical properties of the diodes [Li *et al*, 1991]. The leakage current and the breakdown voltage of diodes fabricated on *n*-type silicon increase after exposure to radiation [Lemeilleur *et al*, 1992]. It has also been observed that after radiation damage an increase in forward current with voltage changes from an exponential to a linear behaviour [Jones *et al*, 1997]. Changes due to the incident radiation also include an increase in the full depletion voltage due to an increase in the space charge density. As a result of charge removal, a conductivity-type of the *n*-type silicon also changes and it has been observed to occur at a radiation fluence of $1.4 \times 10^{13} \text{ n cm}^{-2}$ for 1 MeV neutrons [Pitzl *et al*, 1992; Anokhin *et al*, 2002].

Even though changes due to the incident radiation have been investigated for so long, a negative capacitance that is found in forward bias [Butcher *et al*, 1996; Jones *et al*, 1998; Moloi, 2005] and a low voltage-peak that is found in reverse bias [Msimanga *et al*, 2004; Gullu *et al*, 2008] have not been fully understood nor explained. It is therefore required that further studies are carried out on the defects induced in order to

explain these two features. Most of the work done has been on *n*-type silicon and so in order to obtain a complete understanding of these defects, the effects of irradiation on *p*-type silicon material need to be studied as well.

Although the radiation is known to have detrimental effects on the detector, it has been shown that initial heavy irradiation can also be used to achieve radiation-hardness of silicon diodes [Litovchenko *et al*, 2006]. The same conclusion was also reached [Moloi and McPherson, 2009] for silicon diodes irradiated with 1 MeV neutrons up to 10^{17} n cm⁻². The results obtained were explained in terms of the defect levels that turn silicon into a relaxation material. This material differs from a lifetime material in terms of the dielectric relaxation time (τ_D) and the minority carrier lifetime (τ_0). In a relaxation material $\tau_D \gg \tau_0$ while in a lifetime material $\tau_D \ll \tau_0$ [van Roosbroeck, 1961; Queisser, 1972; Ilegems and Queisser, 1975; Haegel, 1991]. It has been found that the Fermi energy of a relaxation material is not affected by further irradiation [Brudnyi *et al*, 1995] and the devices fabricated from such material are radiation-hard [Jones and McPherson, 1999].

Diodes fabricated from relaxation material show a low conductivity (or high resistivity) due to the recombination of free carriers by these levels. Another characteristic of these diodes is the Ohmic behaviour that has been shown to occur at low voltages [Jones and McPherson, 1999]. The work presented recently [Moloi and McPherson, 2009] shows that a region of the Ohmic behaviour increases with radiation fluence. However, a method of using heavy initial irradiation to develop radiation-hard detectors is expensive and the results obtained are currently difficult to explain. It is therefore important that cheaper and simpler methods that turn silicon into a relaxation material are investigated.

In order to better understand the properties of the defects induced in the silicon material further, the photo response of neutron-irradiated diodes was investigated for different light intensities [McPherson, 2005]. The results obtained then were for infra-red light and were used to explain the effects of light intensity on the diodes irradiated only up to a very low fluence of $\sim 2.5 \times 10^{14} \text{ n cm}^{-2}$. Since particle detectors will normally be operated under very high radiation environments [Eremin *et al*, 2002], it is required that the effects of light on highly irradiated diodes are studied as well. It is further necessary that other wavelengths besides infra-red are investigated. It is believed that a study of the photo response for different wavelengths is also important for the detector imaging. Since an increase in infra-red light intensity results in an increase in the measured current and capacitance of the diodes [McPherson, 2005], it is expected that both current and capacitance will also increase with an increase in the wavelength of the incident light. Therefore, a full characterization of highly irradiated diodes for different wavelengths can be used to supplement and expand on the work carried out by McPherson, [2005] for different light intensities.



In trying to develop a simple method of fabricating a radiation-hard detector, much work has been carried out on defect-engineered silicon [Moll *et al*, 1999]. This involves a deliberate addition of impurities into the silicon material before the fabrication of the detector. Depending on the amount and nature of the impurities similar defects as those that are created by exposure to radiation can be induced [Graff, 1999]. These defects tend to render the material useless while others can make the material useful for the fabrication of particle detectors. As a result, it is important that the amount and the nature of impurities introduced into the silicon are

controlled so that the desired properties are improved while the undesired ones are minimized.

It has been shown that gold turns silicon into a relaxation material [Msimanga *et al*, 2004] and also tends to suppress the effects of radiation on the material [Dixon and Ekstrand, 1986; Ali *et al*, 1995; McPherson *et al*, 1997]. This suppression effect of gold was, however, observed only on *n*-type silicon. Since gold is expensive and not easily found, it is also essential that other metals are investigated so that their effects can be compared with those of gold with the possibility of replacing it. Additionally, the effects of gold on *p*-type silicon should also be studied in order to supplement the work carried out on *n*-type silicon.

Platinum is another expensive metal that has been found to suppress the effects of irradiation [Dixon and Ekstrand, 1986]. Platinum in silicon also creates midgap defect at $E_c-0.52$ eV [Kwon *et al*, 1987], where E_c is the energy at the bottom of the conduction band. The results presented by Kwon *et al* [1987] also show that after platinum doping type-inversion occurs only on *n*-type silicon but not on *p*-type silicon. In order to understand this fact, the effects of platinum on *p*-type silicon need to be studied further as well.

In comparing the effects of gold or platinum with those of erbium, it has been found that erbium in silicon creates a midgap defect at $E_c-0.51$ eV [Benton *et al*, 1991; Coffa *et al*, 1995]. However, based on the literature reviewed, the electrical properties of diodes fabricated on erbium-doped silicon have not been published. This lack of information could be due to the low solubility erbium has in silicon such that it is difficult to use for doping [Castilho *et al*, 1991]. Additionally, the metal reacts vigorously with oxygen and this makes it difficult to study its effects in the material

without studying those of oxygen. It is then required that in introducing the metal into the material, very high vacuum conditions are required so that the amount of unwanted impurities like carbon and oxygen is minimized.

Niobium in silicon has also been found to create a midgap defect at $E_c-0.58$ eV [Pettersson *et al*, 1993]. The effect of niobium in silicon is, currently, not very well-known. Since the metal creates a midgap defect, it is hoped that it will have similar properties as irradiation, gold, platinum and erbium in silicon. Due to its properties, the effects of niobium are investigated so that they can be compared with those of irradiation and other metals (gold, platinum, and erbium) in silicon.

1.2 Aims and objectives

The ultimate aim of this work is to develop a defect-engineered silicon material to increase the radiation-hardness of particle detectors to be used in high energy physics experiments. This encompasses an enhancement of an understanding of defects induced by irradiation and metals in silicon. In particular, a change in electrical properties of silicon diodes due to irradiation and metal impurities is studied in detail. Several objectives are set in trying to achieve these aims. The first objective is to investigate the effects of light on the electrical properties of the irradiated commercial silicon *p-i-n* diodes. In this study, the results obtained from the unirradiated diodes are compared with those obtained from the irradiated diodes.

Another objective is to study the diffusion mechanisms and the depth profile of the metals (gold, platinum, erbium and niobium) into the silicon bulk using the *RBS* and *XPS* techniques. These techniques are also used to confirm that there were minimal (or none of the) unwanted impurities (contaminants) that diffused in the bulk since the deposition and the annealing processes were carried out under very high vacuum

conditions. In this study, the results obtained from the samples prior to the diffusion process were compared with those obtained from the samples after the process.

After it was established that there were very few amount of contaminants diffused into the bulk, the work was extended to the fabrication of the diodes. Schottky diodes were fabricated on undoped and on metal-doped p -silicon. The fabricated diodes were characterised by the current-voltage (I - V) and the capacitance-voltage (C - V) techniques. The latter technique is used to determine the doping profile in the material while the former one is used to determine the carrier density in the device [Senechal and Basinski, 1968; Borch *et al*, 1998]. The results obtained from the diodes fabricated on undoped p -silicon were compared with those obtained from the diodes fabricated on metal-doped p -silicon.

1.3 Thesis outline

This thesis consists of five chapters, which include this introduction as Chapter 1. Chapter 2 is a theoretical overview of semiconductors in general. The theoretical aspects of junction formed between p - and n -type semiconductors and a junction formed between a metal and a semiconductor are also dealt with in the chapter. A theoretical overview of the effects of the defects induced by irradiation and metals in silicon is also given in the chapter. The chapter details the diffusion theory and the diffusion mechanisms of the metals into the silicon bulk. The chapter ends with a theory governing the experimental techniques (RBS , XPS , I - V and C - V) that were used to characterise the samples.

Chapter 3 presents the experimental set up and analysis for the characterization techniques used in this work. In this chapter a procedure followed to characterise the commercial diodes under illumination by light of different wavelengths is explained.

The chapter also describes the preparation methods of the samples and the procedure followed to fabricate the Schottky diodes. The obtained results are discussed in Chapter 4, while the conclusion and suggestions for possible future work are presented in Chapter 5.

Chapter 2

Theoretical overview

This chapter is the theoretical overview of semiconductors in general and silicon in particular. The chapter starts with a review of semiconductors in the equilibrium and this is followed by the description of the p - n junction in Section 2.2. Section 2.3 deals with the theoretical aspect of defect-engineering while Section 2.4 describes the formation of the m - s junctions. The last section of the chapter presents the theoretical overview of the Rutherford backscattering spectroscopy (RBS), the X-ray Photoelectron Spectroscopy (XPS), the current-voltage (I - V) and the capacitance-voltage (C - V) techniques. These four techniques are used to characterise the samples in this work.

2.1 Semiconductors

Semiconductors are the materials whose electrical properties are intermediate between those of good metallic conductors and those of insulators. These materials have the electrical conductivity that is less than that of metals, but it increases with an increase in temperature. The conductivity also can vary widely as a function of optical excitation or as a function of impurities introduced in the material. This ability of varying the conductivity offers a unique application of the material in various devices such as, diodes, transistors, photocells, integrated circuits and particle detectors [Jonscher, 1960].

A semiconductor can either be a single element or a compound. The former types are called elemental semiconductors while the latter are called compound semiconductors. Elemental semiconductors are found in group IV of the periodic

table and silicon (Si) and germanium (Ge) are examples. Silicon is the semiconductor mostly used in a variety of applications and will be discussed in this work. This is due to the fact that most semiconductor devices are fabricated from silicon.

Compound semiconductors, on the other hand, are made up of a combination of group III and group V elements in the periodic table. Examples of these semiconductors are Gallium arsenide (GaAs) and Indium phosphide (InP). Compound semiconductors can also be synthesized by combining elements from column IV of the periodic table. Examples of these semiconductors are Silicon carbide (SiC) and Silicon germanium (SiGe). Cadmium sulphide (CdS) and Mercury cadmium telluride (HgCdTe) are also semiconductors made by the elements from other columns. Diamond exhibits properties of semiconductor at high temperature while tin (Sn) becomes a semiconductor at low temperature.

2.1.1. Direct and indirect semiconductors

In the semiconductor there is a forbidden energy region in which there is no allowed energy state. The upper energy band is called the conduction band while the lower band is called the valence band. The separation between the energy at the bottom of the conduction band and that at the top of the valence band is called the energy gap (E_g). At 0 K, every state in the valence band is completely occupied by electrons, while those in the conduction band are completely empty. At temperatures higher than 0 K the electrons can be thermally excited from the valence band to the conduction band. When an electron is excited to the conduction band it leaves behind an unoccupied place called hole with a positive charge. Thus, the transition of an electron across the energy gap to the conduction band results in a generation of holes in the valence band and electron in the conduction band.

The transition of the electrons from the valence band to the conduction band can either be direct or indirect. In a direct transition, the bottom of the conduction band lies directly above the top of the valence band. In this case, when an electron near the top of the valence band absorbs an energy greater than E_g , it is able to make a direct transition to a state near the bottom of the conduction band. Thus, the transition involves a change in the energy only.

In an indirect transition, the bottom of the conduction band does not lie directly above the top of the valence band. Unlike in direct transitions, in this case the transition involves absorption of energy and a phonon. The photon supplies the needed energy, while the phonon supplies the needed momentum. Thus, this type of the transition involves a change in energy as well as a change in momentum.

2.1.2. Intrinsic semiconductor

A semiconductor can either be intrinsic or extrinsic. In an intrinsic semiconductor the density of electrons in the conduction band is equal to that of holes in the valence band. Electrons and holes are the charge carriers and contribute to the conductivity of the semiconductor material. The value of the conductivity is related to the charge carrier densities and their mobilities [Sze, 1981] as

$$\sigma = e(\mu_e n_0 + \mu_h p_0) \quad (2.1)$$

where e is the electronic charge and μ_e and μ_h are the electron and hole mobilities, respectively. The density of electrons in the conduction band, n_0 , depends on the density of states and the Fermi energy distribution functions [Bar-Lev, 1984] as

$$n_0 = \int_{E_c}^{\infty} F(E) D_n(E) dE \quad (2.2)$$

where $F(E)$ is the energy distribution function given by the Fermi-Dirac distribution function [Neamen, 1997] as

$$F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{k_B T}\right)} \quad (2.3)$$

and $D_n(E)$ is the density of states for the electrons in the conduction band given [Bar-Lev, 1984] by

$$D_n(E) = \frac{\sqrt{2}}{\pi^2} \cdot \frac{(E - E_c)^{\frac{1}{2}}}{\hbar^3} \cdot (m_e^*)^{\frac{3}{2}}. \quad (2.4)$$

In the above relations, E_F is the Fermi energy, k_B ($=1.381 \times 10^{-23} \text{ JK}^{-1}$) is the Boltzman constant, T is the absolute temperature and E_c is the energy at the bottom of the conduction band (considered as 1.12 eV in this work). The electron effective mass, m_e^* is expressed [Streetman, 1990] as

$$m_e^* = \left(\frac{d^2 E_c}{dp^2} \right)^{-1} \quad (2.5)$$

where p is the momentum of the electron undergoing transition. Eq. (2.5) shows that the electron effective mass depends on the curve of the conduction band as a function of the momentum. The above relations can be substituted in the Eq. (2.2) to give the density of electron in the conduction band [Boer, 1992] as

$$n_0 = N_c \exp\left(-\frac{E_c - E_F}{k_B T}\right) \quad (2.6)$$

where N_c is the effective density of states in the conduction band defined [Boer, 1992] as

$$N_c = 2 \left(\frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}} \quad (2.7)$$

where h ($= 6.63 \times 10^{-34}$ J s) is the Plank's constant. In a similar manner, the density of holes in the valence band can be obtained [Boer, 1992] as

$$p_0 = N_v \exp\left(-\frac{E_F - E_v}{k_B T}\right) \quad (2.8)$$

where E_v is the energy at the top of the valence band (considered as 0 eV in this work) and N_v is the effective density of state in the valence band given [Neamen, 1997] as

$$N_v = 2 \left(\frac{2\pi m_p^* k_B T}{h^2} \right)^{\frac{3}{2}}. \quad (2.9)$$

It has to be noted that in the equations above n_0 and p_0 hold for intrinsic semiconductors. Since an introduction of the impurities in the material results in a change in the position of the Fermi energy, it is expected that this will lead to a change in the values of n_0 and p_0 . For an intrinsic semiconductor, the equilibrium carrier densities are equal ($n_0 = p_0 = n_i$) and their product is independent of the Fermi energy as

$$n_0 \cdot p_0 = N_c N_v \exp\left(-\frac{E_g}{k_B T}\right) = n_i^2 \quad (2.10)$$

where n_i is the intrinsic carrier density which has been evaluated as $1.15 \times 10^{10} \text{ n cm}^{-3}$ for silicon at 300 K [McPherson, 1997]. The Fermi energy can be expressed in terms of N_c and N_v as

$$E_F = \frac{E_c + E_v}{2} + \frac{k_B T}{2} \ln\left(\frac{N_v}{N_c}\right) \quad (2.11)$$

by use of Eqs. (2.6) and (2.8). By substituting for N_c and N_v in Eq. (2.11) the Fermi energy can also be defined as

$$E_F = \frac{E_c + E_v}{2} + \frac{k_B T}{2} \ln\left(\frac{m_p^*}{m_e^*}\right) \quad (2.12)$$

which shows that the Fermi energy can also be expressed in terms of the effective masses. At $T = 0$ K, the second term in Eqs. (2.11) and (2.12) vanishes to give,

$$E_F = \frac{E_c + E_v}{2} = E_i \quad (2.13)$$

where E_i is the intrinsic Fermi energy. Eq. (2.13) shows that at $T = 0$ K the Fermi energy lies exactly in the middle of the energy gap. Thus, the intrinsic Fermi energy of the silicon material is 0.56 eV.

2.1.3. Extrinsic semiconductor

In an extrinsic semiconductor the electron density in the conduction band is not equal to that of holes in the valence band. This inequality of the densities normally occurs when an intrinsic semiconductor has been doped with impurities. The semiconductor can be doped with either donor impurity atoms to be n -type or with acceptor impurity atoms to be p -type. In an n -type semiconductor the electron density in the conduction band is higher than that of holes in the valence band. Here n_0 is greater than n_i and it is given [Neamen, 1997] as

$$n_0 = n_i \exp\left(-\frac{E_i - E_F}{k_B T}\right) \quad (2.14)$$

in equilibrium. If the donor density is made large enough to create a degenerate n -type semiconductor, the Fermi energy will be situated within the conduction band. In a p -type semiconductor, on the other hand, the density of holes in the valence band is greater than that of electrons in the valence band. In this case the hole density in the equilibrium is given [Sze, 1981] as

$$p_0 = n_i \exp\left(-\frac{E_F - E_i}{k_B T}\right) \quad (2.15)$$

to show that p_0 is greater than n_i . For the p -type material the Fermi energy lies between the intrinsic position and the top of the valence band. If the concentration of

the acceptor is made large enough to create a degenerate p -type semiconductor, the Fermi energy will be situated within the valence band. A product of the electron and hole densities from Eqs. (2.14) and (2.15) is

$$n_0 p_0 = n_i^2. \quad (2.16)$$

By simply dividing Eq. (2.14) by Eq. (2.15) the Fermi energy can be expressed in terms of the charge densities as

$$E_F = E_i + \frac{kT}{2} \ln \frac{n_0}{p_0}. \quad (2.17)$$

Eq. (2.17) shows that when $n_0 < p_0$ the Fermi energy lies below E_i but when they are both equal the equation shows that the Fermi energy lies exactly at the intrinsic position.

A semiconductor can also be doped with equal densities of donor and acceptor impurities. In this case the number of positive charges is equal to the number of negative charges [Boer, 1992] as

$$p_0 + N_D = n_0 + N_A \quad (2.18)$$

where N_D and N_A are the donor and acceptor densities, respectively. In an n -type semiconductor where N_A is zero and $n_0 \gg p_0$ both p_0 and N_A in Eq. (2.18) can be neglected to yield $n_0 \approx N_D$. From Eq. (2.16), the density of holes at equilibrium can then be expressed as

$$p_0 = \frac{n_i^2}{N_D} \quad (2.19)$$

which, by substituting for p_0 in Eq. (2.17), the Fermi energy for an n -type semiconductor is given as

$$E_F = E_i + \frac{kT}{2} \ln \frac{N_D}{n_i} \quad (2.20)$$

by setting one of the n_i 's to be n_0 . In a similar manner the Fermi energy of a p -type semiconductor can be obtained as

$$E_F = E_i - \frac{kT}{2} \ln \frac{N_A}{n_i} \quad (2.21)$$

and it has to be noted that in Eq. (2.21) the negative sign arises because of the inverse of N_A/n_i . It can be noted that the preceding equations show that n_0 , p_0 , and n_i are all temperature dependent. Thus, the carrier densities in a semiconductor are affected by the temperature of the material and as a result the position of the Fermi energy changes as well.

2.1.4 Silicon

Silicon is an indirect gap semiconductor, which means that the recombination in the material requires a photon to impart energy as well as a phonon to impart momentum to a carrier that undergoes the transition. Silicon can be doped p -type or n -type and this is done in a number of ways. One of the ways of doping silicon is by the impurity diffusion. The impurity diffusion occurs when a semiconductor crystal is placed in a high temperature vacuum atmosphere containing the desired impurity atoms. At this temperature the crystal lattice expands and the impurity atoms move from a region of high concentration on the surface of the crystal to a region of lower concentration within the crystal. When the temperature decreases, the impurity atoms become permanently frozen into the substitutional lattice sites. This way of doping silicon is explained in this work.

Ion implantation doping generally occurs at lower temperatures than diffusion. A beam of the desired impurity ions is accelerated to kinetic energy in the range of 50 keV or greater and then directed to the surface of the semiconductor. The high energy

impurity ions enter the crystal and come to rest at some average depth from the surface. This method is not easily found.

Table 2.1: Some properties of silicon at 300 K (compiled from various references cited in the text).

Property	Symbol	Value	Units
Density	ρ	2.33	g cm^{-3}
Dielectric constant	ϵ_s	11.7	—
Diffusion constant			
- electrons	D_n	37.5	$\text{cm}^2 \text{s}^{-1}$
- holes	D_p	13	$\text{cm}^2 \text{s}^{-1}$
Drift mobility			
- electron	μ_n	1450	$\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$
- hole	μ_p	500	$\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$
Effective density of states			
- in the conduction band	N_c	2.9×10^{19}	cm^{-3}
- in the valence band	N_v	1.1×10^{19}	cm^{-3}
Electron affinity	χ	4	V
Electron thermal velocity	v_{th}	1.075×10^7	cm s^{-1}
Energy gap	E_g	1.12	eV
Energy of ionisation	E_{ion}	3.65	eV (ehp)^{-1}
Effective mass			
- electrons	m_n^*	$1.18 m_0$	kg
- holes	m_p^*	$0.81 m_0$	kg
Intrinsic carrier concentration	n_i	1.15×10^{10}	cm^{-3}
Intrinsic Debye Length	L_{Di}	24	μm
Maximum resistivity	ρ_{max}	3.19×10^5	$\Omega\text{-cm}$
Melting temperature	T_{melt}	1412	$^{\circ}\text{C}$
Minority carrier lifetime	τ_p	2.5×10^{-3}	s

Preparation and the atomic structure of this elemental semiconductor have been reported in the literature [Sze, 1981; Boer, 1992; Neamen, 1997]. Among the many elemental semiconductors, silicon is the most commonly used for microelectronics

and integrated circuit technology [Bar-Lev, 1984; Streetman, 1990; Boer, 1992]. Silicon devices are also used under high radiation environments for dosimetry purposes where the highest resolution is required [Martini and McMath, 1970; Van Lint, 1987]. They are also used in particle physics experiments to detect charged particles and in satellites to detect gamma and X- rays [Knoll, 2000]. For these reasons, silicon can be used in demonstrating several properties of semiconductors.

Since devices fabricated from this material normally operate at 300 K, it is necessary that properties of the material at this temperature are investigated. Some of the properties at 300 K are summarised in Table 2.1 and they have been compiled from the various references cited in the text.

2.2 The p - n junction

A typical semiconductor diode is fabricated as a p - n junction with two terminals. In this section a p - n junction in equilibrium and under bias is discussed. At equilibrium, the temperature is uniform and equal to that of the surroundings, there are no external carrier injection mechanisms and there are no external forces such as electric and magnetic fields in action.

2.2.1 Basic structure of the p - n junction

The actual p - n junction structure is formed when a p -type semiconductor is brought into contact with an n -type one. The interface separating the n - and p -regions is referred to as the space charge region or the depletion region. Schematically, a p - n junction can be represented as shown in Fig.2.1.

Because of the differing carrier densities in the immediate vicinity of the contact, majority carrier electrons in the n -region will diffuse into the p -region. A similar

situation occurs where majority carrier holes in the p -region diffuse into the n -region. A small and steady diffusion force is thus set up to induce a diffusion current across the junction [Sze, 1981].

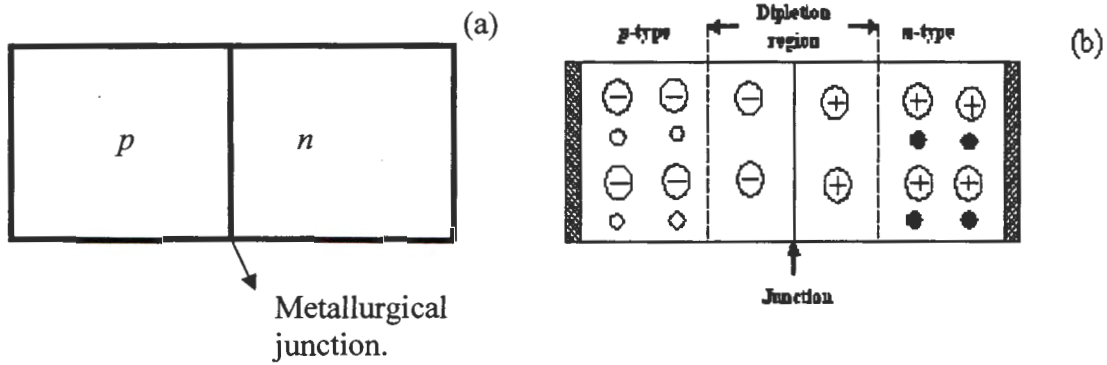


Fig.2.1: A simplified geometry of a p - n junction in (a) and the actual junction showing charges and the depletion region in (b). The $\bullet$ symbol represents an electron and the $\circ$ symbol a hole.

As electrons diffuse from the n -region, positively charged donor atoms are left behind. The opposite is true as holes diffuse from the p -region to leave fixed negative charge. This region of fixed charge is called the depletion region or the space charge region (SCR) [Streetman, 1990]. The net positive and negative charges in the n - and p -regions induce an electric field in the vicinity of the metallurgical junction that is directed from the positive charge to the negative charge or from the n -region to the p -region. Essentially, all electrons and holes are swept out of the SCR by the electric field such that the region is depleted of any mobile charge, hence the term “depletion region”. The electric field in the SCR produces another force on the electrons and holes to induce a drift current. This force is directed in the opposite direction to the diffusion force for each type of carrier [Streetman, 1990]. The result is that in thermal equilibrium, the diffusion force and the electric field force exactly balance each other, with the consequence that the diffusion current is equal to the drift current [Sze, 1981] and there is no net current flow.

2.2.2 Zero applied bias

If no voltage is applied across the p - n junction, the junction is said to be in equilibrium [Neamen, 1997]. In this condition electrons and holes diffuse as described above. The movement of charge induces an electric field and this leads to a situation where electrons and holes drift.

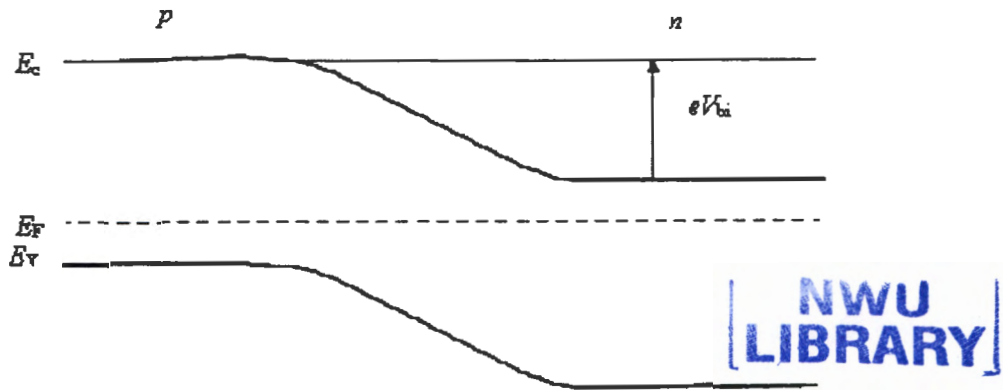


Fig.2.2: Energy band diagram of a p - n junction in thermal equilibrium showing the various energy levels (after Streetman, 1990).

At equilibrium, with zero bias, the distribution of charge is such that the Fermi energy is the same on either side of the p - n junction [Goodge, 1983]. Since the relative position of the conduction and valence bands with respect to the Fermi energy changes between the p - and n -regions, the bands will bend as the SCR is traversed. As a result, the Fermi energy is constant throughout the entire system. The energy band diagram of the p - n junction in equilibrium is shown in Fig.2.2. Electrons in the conduction band of the n -region create a potential barrier in attempting to move into the conduction band of the p -region. This potential barrier is referred to as the built-in potential and is denoted by V_{bi} .

For the n -region, the equilibrium electron density in the conduction band and for the p -region, the equilibrium hole density in the valence band are given by Eqs. (2.14)

and (2.15), respectively. The equilibrium density of majority carriers in the n -region is given [Neamen, 1997] by

$$n_{n0} = N_d \quad (2.22)$$

where N_d is the net donor density. In the p -region, the equilibrium density of minority carriers is given [Jonscher, 1960] by

$$n_{p0} = \frac{n_i^2}{N_a} \quad (2.23)$$

where N_a is the net acceptor density. As the built-in potential maintains equilibrium, the minority carrier density in the p -region and the majority carrier density in the n -region can be related by

$$n_{p0} = n_{n0} \exp\left(\frac{-eV_{bi}}{kT}\right) \quad (2.24)$$

in thermal equilibrium, where e is the electronic charge and V_{bi} is given as

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) \quad (2.25)$$

for a thermal voltage defined [Streetman, 1990] as

$$V_t = \frac{kT}{e}. \quad (2.26)$$

The built-in potential could also be given [Neamen, 1997] as

$$V_{bi} = |\varphi_{Fn}| + |\varphi_{Fp}| \quad (2.27)$$

which is just the potential between the Fermi energies in the n - and p -regions, where φ_{Fn} and φ_{Fp} are the potentials in these regions, respectively.

The electric field

In the equilibrium condition, the electric field in the p - and n -regions is zero and no net current flows in an unbiased p - n junction [Neamen, 1997]. This is due to the charge neutrality condition that exists in the regions outside the SCR. As there is no

electric field in the neutral regions, there is no change of potential in these regions and no surface charge density either.

An electric field is created in the depletion region or the SCR and this is caused by the fixed charge. The field tends to cause holes to drift towards the p -region and electrons to drift towards the n -region. These drift components, as stated earlier, are in the opposite direction to the diffusion components for the two types of carriers, and when equilibrium is established, the tendency to diffuse is balanced by the tendency to drift.

The electric field in the p -region is given [Neamen, 1997] as

$$E = \frac{-eN_a}{\epsilon_s}(x + x_p) \quad -x_p \leq x \leq 0 \quad (2.28)$$

while for the n -region, it is given [Neamen, 1997] as

$$E = \frac{-eN_d}{\epsilon_s}(x_n - x) \quad 0 \leq x \leq x_n \quad (2.29)$$

Space charge width

The distance that the depletion region or the SCR extends into the p - and n -regions from the metallurgical junction is known as the space charge width. The space charge width into the n -region for the case of zero applied voltage is given [Neamen, 1997] by

$$x_n = \left\{ \frac{2\epsilon_s V_{bi}}{e} \cdot \frac{N_a}{N_d} \cdot \frac{1}{N_a + N_d} \right\}^{\frac{1}{2}} \quad (2.30)$$

where ϵ_s is the permittivity of the semiconductor. The space charge width into the p -region for the case of zero applied voltage is similarly given by

$$x_p = \left\{ \frac{2\epsilon_s V_{bi}}{e} \cdot \frac{N_d}{N_a} \cdot \frac{1}{N_a + N_d} \right\}^{\frac{1}{2}} \quad (2.31)$$

and the sum of the two is the total space charge width given as

$$W = \left\{ \frac{2\epsilon_s V_{bi}}{e} \cdot \frac{N_a + N_d}{N_a N_d} \right\}^{\frac{1}{2}}. \quad (2.32)$$

From Eq. (2.32), it is clear that the space charge width is very strongly dependent on the donor and acceptor densities.

2.2.3 Forward applied bias

If a negative voltage is applied to the n -side of a p - n junction device, a large current will flow for a very small voltage [Streetman, 1990] and the device is said to be forward biased. The energy of the electrons on the n -side is then increased and this increases the tendency for these electrons to diffuse across the junction to the p -side. This increase in electron energy also increases the difference in surface energies between the p - and n -regions [Neamen, 1997]. That is, the potential barrier that opposes the diffusion of electrons from the n -region to the p -region is reduced from the value obtained for the unbiased case. In this situation, the equilibrium condition of Eq. (2.24) becomes

$$n_{p0} = n_{n0} \exp\left(\frac{-e(V_{bi} - V_a)}{kT}\right) \quad (2.33)$$

replacing V_{bi} with $(V_{bi} - V_a)$ to give

$$n_p = n_{n0} \exp\left(\frac{-eV_{bi}}{kT}\right) \exp\left(\frac{eV_a}{kT}\right) \quad (2.34)$$

where V_a is the applied bias. A comparison of Eqs. (2.24) and (2.34) gives

$$n_p = n_{p0} \exp\left(\frac{eV_a}{kT}\right) \quad (2.35)$$

which is the total minority carrier density in the p -region, and this is clearly greater than the thermal equilibrium value given by Eq. (2.24). Eq. (2.33) can also be used for the opposite case where

$$p_{n0} = p_{p0} \exp\left(\frac{-e(V_{bi} - V_a)}{kT}\right) \quad (2.36)$$

to give the total minority carrier density in the n - region as

$$p_n = p_{n0} \exp\left(\frac{eV_a}{kT}\right) \quad (2.37)$$

which is also greater than the equilibrium value of Eq. (2.24). In either case, the two densities that are given by Eqs. (2.35) and (2.37) are strongly dependent on the applied bias.

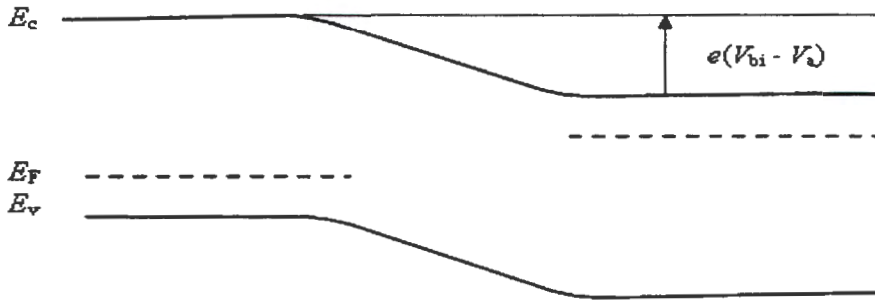


Fig.2.3: Energy band diagram of a p - n junction under forward bias showing the energy levels and the reduced potential barrier (after Streetman, 1990).

In forward bias, the applied voltage acts to lower the built-in potential barrier of a p - n junction so that electrons from the n -region are injected into the SCR to create excess minority carriers in the p -region [Boer, 1992]. The energy band diagram of a p - n junction in forward bias is shown in Fig.2.3. When electrons are injected into the p -region, excess carriers are subject to the diffusion and recombination processes. Excess electrons diffuse into the bulk p -region where they can recombine with majority carrier holes. The excess minority carrier electron density then decreases with distance from the metallurgical junction.

At forward bias, the current-voltage characteristic is given [Sze, 1981] by

$$J = J_s \left[\exp\left(\frac{eV_a}{kT}\right) - 1 \right] \quad (2.38)$$

where J is the total current density in the p - n junction and J_s is the reverse saturation current density given [Sze, 1981] as

$$J_s = \frac{eD_p n_i^2}{L_p N_D} + \frac{eD_n n_i^2}{L_n N_A} \quad (2.39)$$

where D_p is the diffusion coefficient for holes, L_p is the diffusion length of holes, D_n is the diffusion coefficient for electrons and L_n is the diffusion length of electrons. Eq. 2.38 shows that the total current is the difference between the diffusion current and generation current. This relation is known as the ideal-diode equation, and gives a good description of the I - V characteristics of a p - n junction diode over a wide range of current and voltage. The above relation also shows that the current at forward bias is a function of temperature. As the temperature increases, a lower forward voltage is required to obtain the same diode current. If the voltage is kept constant, the diode current will increase as the temperature does. The forward voltage thus increases electron diffusion from the n - to the p -side and therefore results in an increase in hole diffusion from the p - to the n -side. The result of this is an increased forward current from the p - to the n -region.

Electric field

Under a forward bias, the electric field is reduced and this is due to the reduced potential barrier. The electric field induced by the applied voltage is in the opposite direction to the electric field due to the thermal equilibrium space charge region and it is reduced below the equilibrium value [Neamen, 1997]. The electric field that prevents majority carriers from crossing the SCR is reduced and majority carrier electrons from the n -side are now injected across the depletion region into the p -type

material. At the same time majority carrier holes from the p -side are injected across the SCR into the n -type material [Boer, 1992]. In this situation there is carrier annihilation as electrons and holes tend to recombine.

Space charge width

Under forward bias, the potential barrier of the p - n junction is reduced [Schroder, 2006] and this means that less space charge is needed to produce a potential difference. That is, less of the fixed positive and negative charges in the SCR are required and this corresponds to a reduced depletion region width. In Eq. (2.32), the built-in potential barrier V_{bi} can be replaced by the total potential barrier, $(V_{bi}-V_a)$ to give

$$W = \left\{ \frac{2\epsilon_s(V_{bi}-V_a)}{e} \cdot \frac{N_a+N_d}{N_aN_d} \right\}^{\frac{1}{2}} \quad (2.40)$$

showing that the total space charge width is decreased as the applied forward bias is increased.

2.3.4 Reverse applied bias

If a negative voltage is applied to the p -side of a p - n junction device, the diffusion current decreases [Edwards-Shea, 1996]. In this case, the total potential barrier is given [Neamen, 1997] as

$$V_{total} = |\phi_{Fn}| + |\phi_{Fp}| + V_a \quad (2.41)$$

where V_a is the magnitude of the applied reverse bias.

The energy band diagram of the p - n junction in reverse bias is shown in Fig.2.4. It can be seen from the above equation that at reverse bias, the potential barrier increases as the voltage increases. The potential barrier becomes so large that virtually no electrons in the n -side conduction band or holes in p -side valence band have enough

energy to surmount it [Streetman, 1990]. The minority carrier (or injection) current is reduced and the minority carriers that diffuse to the junction are still, however, swept across by the field.

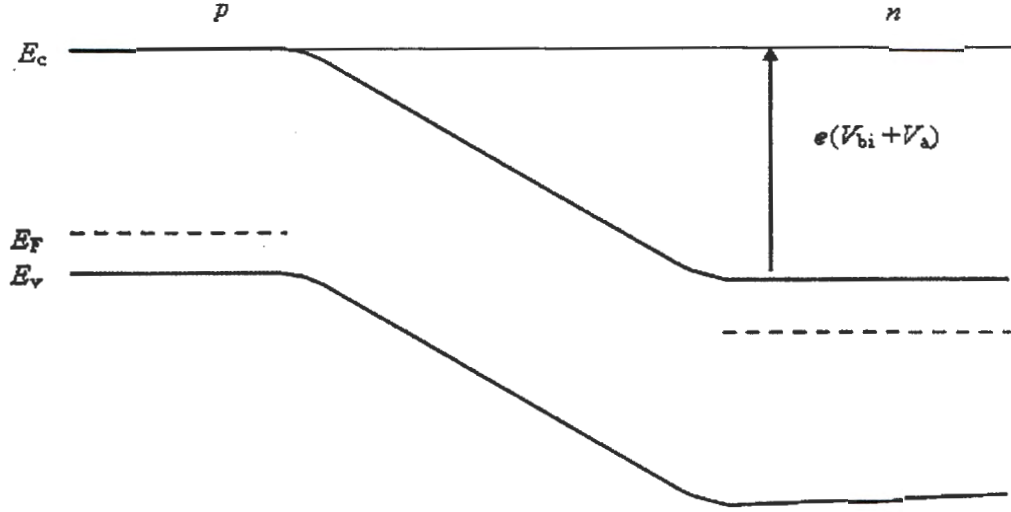


Fig.2.4: Energy band diagram of a p-n junction under reverse bias showing the respective energy levels and the increased potential barrier.

Electric field

The electric field in the neutral p - and n -regions under reverse bias is essentially zero, or at least as small as to be negligible [Neamen, 1997]. This electric field is given [Neamen, 1997] as

$$E = \frac{-2(V_{bi} + V_a)}{W}. \quad (2.42)$$

However, an increase in voltage across the SCR corresponds to an increase in the electric field acting in the region. The magnitude of the electric field acting in the SCR increases above the thermal-equilibrium value due to the applied voltage.

Space charge width

Under reverse bias, the SCR becomes wider. As the space charge width increases, the generation-recombination current also increases [Brennan, 1999]. In Eq. (2.32), the

built-in potential barrier, V_{bi} can be replaced by the total potential barrier, $(V_{bi} + V_a)$ to give

$$W = \left\{ \frac{2\epsilon_s(V_{bi} + V_a)}{e} \cdot \frac{N_a + N_d}{N_a N_d} \right\}^{\frac{1}{2}} \quad (2.43)$$

showing that the total space charge width increases with the reverse bias. As the reverse bias increases, it is expected that the depletion region width would increase to a point where the device is fully depleted [Neamen, 1997] and the depletion width is equal to the distance between the contacts [McPherson, 2002].

2.3.5 The *p-i-n* junction

In crystalline silicon, a basic structure of a *p-i-n* junction is such that one adjacent side of an intrinsic material is doped *n*-type and the other one is doped *p*-type leaving an intrinsic (undoped) layer of a finite area and thickness sandwiched between them. The presence of the intrinsic layer in the *p-i-n* junction is responsible for the unique properties of the junction. Characteristics such as lifetime and stored charge are mostly dependent on the properties of the intrinsic layer. The volume of the intrinsic region is a major factor that affects the effective lifetime of carriers [Goodge, 1983]. It has been found [Neamen, 1997] that the rate at which electrons and holes recombine is higher at the outer surface than at the centre of the intrinsic region.

When the *p-i-n* junction is forward biased, electrons and holes are injected from *p* and *n* regions into the *i*-region where they have a finite lifetime before they recombine [Goodge, 1983]. A finite quantity of charge always remains stored and this results in a lowering of the resistivity of the *i*-region. The quantity of stored charge, Q , is given [Roulston, 1999] by

$$Q = I\tau \quad (2.44)$$

where I is the current at forward bias and τ is the carrier lifetime. When the applied reverse bias is just large enough to cause avalanche breakdown, the reverse current is small. The space charge effect can be neglected and the electric field is essentially uniform across the depletion region. As the current increases, more electrons are generated near the p - i boundary and more holes are generated near the n - i boundary. These space charges will cause a reduction of the field present in the centre of the i -region. The p - i - n diode with sufficient reverse voltage to fully deplete the i -region will be depleted of mobile carriers. Thus, the avalanche region corresponds to the full intrinsic layer width. The reverse voltage across the i -layer begins to increase thus aiding the removal of the charges in the i -region.

The p - i - n junction with light

When a semiconductor with the energy gap, E_g is illuminated with light, the incident photon may be absorbed or it may pass straight through the semiconductor [Neamen, 1997], and this depends on the photon energy and on the energy gap of the semiconductor material. If the energy of the photon is less than E_g , (that is if $hf < E_g$), the photons are not absorbed. In this case, the light is transmitted right through the material and the semiconductor appears to be transparent to the light.

If the photon energy is greater than the E_g , (that is if $hf > E_g$), the energy will be absorbed by the lattice to create e - h pairs. This process is called optical generation [Edwards-Shea, 1996]. If the e - h pairs are generated within their respective diffusion length from the edges of the depletion region, minority carriers will be swept across the depletion region by the electric field. The creation of excess carriers means that there will be more electrons in the conduction band and more holes in the valence band. In this situation, a large reverse current can be produced [Navon, 1986] very

easily. The current is produced because only minority holes generated on the n -side and minority electrons generated on the p -side will be swept through the junction by the electric field. The resulting current due to optically generated carriers is [Grove, 1967]

$$I_{\text{op}} = eAg_{\text{op}}(L_n + L_p + W) \quad (2.45)$$

where A is the cross sectional area of the junction, g_{op} is the optical generation rate, L_n and L_p are the electron and hole diffusion lengths, respectively. In the relation above, the terms $AL_n g_{\text{op}}$ and $AL_p g_{\text{op}}$ are the number of electrons created per second within a diffusion length of the SCR on the p -side and the number of holes created per second within a diffusion length of the SCR on the n -side, respectively. The products AL_n and AL_p represent the volume in which the generated electrons and holes are produced and from this volume carriers can diffuse to the SCR before they recombine [Navon, 1986]. It can be seen in the above equation that the optically generated current is proportional to the optical generation rate. This is because the number of e - h pairs generated is directly proportional to the number of incident photons [McPherson, 2005].

At a temperature T , the optical generation of e - h pairs in a semiconductor occurs simultaneously as thermal generation occurs [Edwards-Shea, 1996]. This means that optically generated carriers are additional to those carriers that are thermally generated. Therefore, for optically generated carriers to have a noticeable effect on the conductivity of the semiconductor device, thermal generation must be made to be much smaller and this is achieved by cooling the semiconductor material. The optically generated carriers are called excess carriers [Edwards-Shea, 1996] and the excess carrier concentration is given [Streetman, 1990] as

$$\delta n = \tau_e g_{\text{op}} \quad (2.46)$$

for electrons and as

$$\delta p = \tau_h g_{op} \quad (2.47)$$

for holes. The quantities τ_e and τ_h are the carrier lifetimes for electrons and for holes, respectively. The conductivity due to optically generated carriers is given [Streetman, 1990] as

$$\sigma = e g_{op} (\tau_e \mu_e + \tau_h \mu_h) \quad (2.48)$$

where μ_e and μ_h are the electron and hole mobilities, respectively and the other terms are as defined previously.

2.3 Defect-engineering

The radiation tolerance of silicon can be improved by defect-engineering [Kwon *et al*, 1987; Moll *et al*, 1999; Leroy and Rancoita, 2007], which includes the deliberate addition of impurities into the material (doping). This addition of impurities is done in order to create defect levels in the energy gap thereby changing the electrical characteristics of a device made of this material. The introduction of the levels can also be achieved by radiation damage, which results in the atomic displacement. This section deals with the creation of defect levels as a result of radiation damage and metal impurities in silicon material.

2.3.1 Radiation damage

The effects of radiation damage in a semiconductor material are due to collisions between the energetic particles and the crystal lattice. The particles transfer sufficient energy to the lattice to displace an atom within the lattice out of its normal position [Moll *et al*, 1997]. The damage results from a movement of the target atom within the material such that an interstitial atom and a vacancy can be generated and this occurs as the recoiling atom comes to rest. Interstitial atoms and related vacancies have



relatively high mobility and most of them can recombine very quickly [Lindstrom *et al*, 1999]. This type of damage effect is called a displacement effect. The damage alters the electrical characteristics of semiconductor devices due to the creation of physical imperfections in the crystal lattice structure.

Ionization damage refers to the knocking-off of orbital electrons from an atom to form an ionized atom and a number of free electrons [Lindstrom *et al*, 1999]. In this type of damage, the effects can either be transient or long-term. Transient ionization damage is temporary and is caused by electron-hole pairs that are generated for example in silicon dioxide or other insulators [Johnston, 2000]. Here, the damage results in the trapping of excess carriers near the interface between the oxide (or insulator) and the semiconductor material [Dressendorfer, 1989]. Long-term ionization damage, on the other hand, is permanent since electrons and holes that are produced become fixed in their positions and charge regions are created. Here, electrons and holes are created with a certain special distribution.

Radiation damage in a semiconductor by fast neutrons creates defects in the semiconductor lattice [McPherson, 1997] that introduce additional states in the energy gap. This damage is caused by collisions of the incident neutrons with nuclei in the bulk of the semiconductor material. A large defect cluster results from neutron irradiation whereby a large amount of kinetic energy is transferred to a single atom of the lattice. As a consequence, defect levels are introduced in different numbers within the energy gap. These defects lie deep in the energy gap and as such, are known as deep levels. They may behave as carrier traps anywhere in the energy gap or as $g-r$ centres near mid-gap. When they act as traps, they can capture free carriers with the consequence that they reduce the conductivity and this leads to an increase in resistivity [McPherson, 1997].

Deep levels can also behave as recombination centres when the excess carrier density is below the equilibrium value [Schroder, 2006]. Here, the levels are situated near the centre of the energy gap and are positioned in such a way that $e-h$ pairs can easily be generated or they can easily be recombined. The process of generation and recombination of carriers is shown in the simplified band diagram of Fig. 2.5. The levels provide a path for the generation and the recombination of $e-h$ pairs across the entire energy gap. Such a path can also provide means of controlling the minority carrier lifetimes [Schroder, 2006].

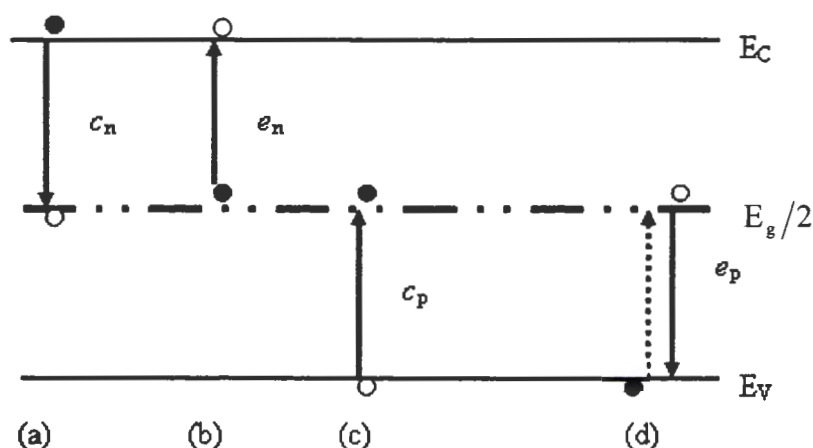


Fig.2.5: A simplified energy band diagram of a semiconductor with generation and recombination centres.

In Fig. 2.5 a centre captures an electron from the conduction band (a) and this process is characterised by the capture coefficient, c_n . After electron capture, the centre can either emit the electron back to the conduction band (b), a process called electron emission, e_n , or it can capture a hole from the valence band (c), a process shown by c_p . After either of the two events, the $g-r$ centre is occupied by a hole (d) and again has two options. Either it emits the hole back to the valence band, e_p , or it captures an electron from the conduction band (a). A deep level can be characterized by its activation energy (which is related to its position in the energy gap), its concentration

or its capture cross section (which provides a measure of the deep level as related to any trapped carrier).

Due to radiation damage, many bulk parameters of semiconductor detectors change [Li *et al*, 1991; Moll, 2003; Bruzzi, 2004]. A main effect of such irradiation is to increase the leakage current [Jones *et al*, 1997], to change the effective doping concentration of the semiconductor and to increase the charge trapping [Leroy *et al*, 1999; Bruzzi *et al*, 2005]. Deep levels can also act as compensation centres which cause a reduction in the minority carrier lifetime [Sze, 1981] or as additional impurities that change the net effective carrier density [Schroder, 2006]. The change in carrier density is induced by the removal of carriers and by carrier compensation centres and this causes the device to go through a type-inversion [Pitzl *et al*, 1992].

For silicon, the effect of radiation damage is a reduction in carrier density, which tends to make the silicon material more intrinsic [Larin, 1968]. Because of the compensation effect of radiation-induced defects, the electric field is non-uniform and so carrier motion within the detector becomes hampered. Even though the material appears to be intrinsic, it has been argued that it is actually relaxation-like [Jones and McPherson, 1999].

The relaxation material has high a very high resistivity due to the low carrier density produced by compensation of midgap defects [Jones *et al*, 1997; McPherson, 1997; Moloi and McPherson, 2009]. These midgap defects tend to interact equally with electrons and holes to act as generation-recombination centres [Jones and McPherson, 1999]. To be active such traps must be in an environment where the quasi-Fermi level is near or on the appropriate side of the trap level [Jones *et al*, 1997].

The effects of the damage cause changes in the full depletion voltage, the trapping of any drifting charge and a reduction in the detector charge collection efficiency (*cce*) [McPherson, 1997]. The level of radiation damage in a semiconductor is measured by the damage constant, α , given [McPherson, 2002] as

$$J_{\text{gen}} = \alpha\phi \quad (2.49)$$

where J_{gen} is the generation current density and ϕ is the radiation fluence. In the relation above, it is clear that an increase in the generation density is proportional to the particle fluency. The relation was found to be valid for wide fluency ranges from 10^{10} to $10^{16} \text{ n cm}^{-2}$ [Litovchenko *et al*, 2006]. However, at the fluency higher than $10^{16} \text{ n cm}^{-2}$ the relation was found to be invalid [Moloi and McPherson, 2009], since the current became independent of the radiation fluence. It was argued that the material had become a radiation-hard.

2.3.2 Metal doping

The diffusion mechanisms of impurities into silicon depend on the chemical properties and the size of the impurity atoms and the crystalline structure of the host lattice. The diffusion of impurities into silicon occurs by interstitial (or kick-out) and vacancy (substitutional) mechanisms [Graff, 1999]. Interstitial diffusion occurs when the impurity atom is lodged between the lattice sites of silicon atoms. This mechanism normally occurs when the impurity atom is small. Vacancy diffusion, on the other hand, occurs when the impurity atom substitutes for atoms on the host lattice sites and the impurity atom occupies substitutional sites.

Usually metal doping is performed by a high-temperature diffusion following vacuum deposition of a thin metal layer. The equation governing doping in the semiconductor is given [McPherson, 1997] by

$$D = D_0 \exp\left(-\frac{Q_A}{kT}\right) \quad (2.50)$$

where D is the diffusion coefficient, D_0 is the diffusion constant, Q_A is the activation enthalpy in Joules.

2.3.2.1 Gold diffusion

Doping silicon with metals was initially carried out in order to reduce the switching time of electronic devices [Wysocki *et al*, 1966]. Gold was preferred mainly because in silicon it acts as a lifetime killer [Coffa *et al*, 1988]. Since the carrier lifetime is reduced in this case, it follows that the material would be in a relaxation state. Thus, gold doping was initially carried out in order to reduce the lifetime but later it was done in order to suppress the effects of device exposure to radiation as well [Dixon and Ekstrand, 1986; Valdinoci *et al*, 1996].

The diffusion mechanisms of gold in silicon depend on the temperature [Gosele *et al*, 1980]. Gold diffuses fast on interstitial sites than on vacancy (substitutional) sites [Graff, 1999]. The solubility of gold in silicon has been found to be 10^{15} cm^{-3} at 800 °C and 10^{16} cm^{-3} at 1100 °C [Emulsitone Company, 2008], while the diffusion coefficient is $6.0 \times 10^{-9} \text{ cm}^2 \text{ s}^{-1}$ at 800 °C and increases to $8.0 \times 10^{-8} \text{ cm}^2 \text{ s}^{-1}$ at 1100 °C [Emulsitone Company, 2008]. After diffusion, the gold profile in the material has been found to be U-shaped [Coffa *et al*, 1988; Msimanga and McPherson, 2006]. It has also been shown that gold transforms the silicon material from p -type to apparent n -type [Voß *et al*, 2005].

Gold diffusion into silicon introduces defect levels at: $E_c - 0.34 \text{ eV}$, at $E_c - 0.55 \text{ eV}$ and at $E_v + 0.35 \text{ eV}$ [McPherson *et al*, 1997], where E_c is the energy level at the bottom of the conduction band and E_v is the energy level at the top of the valence

band. Since gold creates a strong recombination centre in silicon [Graff, 1999], it is expected that after gold-doping the conductivity of the material will be reduced as mobile carriers become recombined.

2.3.2.2 Platinum diffusion

Platinum in silicon has been studied because of its application as a minority carrier lifetime killer in fast-switching devices [Weng *et al*, 1987]. The diffusion properties of platinum are nearly similar to those of gold. Diffusion profiles show that platinum diffuses quickly into silicon on interstitial sites [Graff, 1999]. The solubility of platinum is found to be 10^{14} cm^{-3} at 800 °C and 10^{17} cm^{-3} at 1100 °C [Gosele *et al*, 1980]. The diffusion coefficient of platinum in silicon is $4.5 \times 10^{-8} \text{ cm}^2 \text{ s}^{-1}$ at 800 °C and this increases to $5.6 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$ at 1100 °C [Emulsitone Company, 2008]. The platinum profile is, as in the case of gold, U-shaped [Bostrom *et al*, 2000].

Platinum in silicon has also been found to create three different defect levels at $E_c - 0.23 \text{ eV}$, at $E_c - 0.52 \text{ eV}$ and at $E_v + 0.36 \text{ eV}$ [Kwon *et al*, 1987]. The donor level in the lower half of the energy gap is more active than the acceptor level in the upper half [Graff, 1999]. This is due to their values of majority capture cross sections. The majority carrier capture cross section is $3.4 \times 10^{-15} \text{ cm}^2$ for $E_c - 0.23 \text{ eV}$ and $5.4 \times 10^{-14} \text{ cm}^2$ for $E_v + 0.36 \text{ eV}$. It is thus expected that after platinum-doping the conductivity of a *p*-Si material will be reduced as the donor level compensates any majority carriers. Because of the similarities with gold, it is expected that platinum in silicon would have similar effects as gold.

2.3.2.3 Erbium diffusion

The diffusion mechanisms of erbium into silicon at 900 °C have not been reported before. Erbium has been found not on substitutional nor on interstitial sites after

annealing for 15 minutes at 600 °C [Polman *et al*, 1993]. Erbium starts to diffuse into the silicon bulk at the annealing temperature of 900 °C [Scalese *et al*, 2003]. It has been reported that the solubility of erbium in pure silicon is 10^{18} cm^{-3} at 900 °C [Eaglesham *et al*, 1991]. Shin *et al* [1995] reported the diffusion coefficient of erbium in silicon as $10^{-15} \text{ cm}^2 \text{ s}^{-1}$ at 900 °C and $10^{-12} \text{ cm}^2 \text{ s}^{-1}$ at 1300 °C.

It has been shown that erbium in silicon acts as a donor [Benton *et al*, 1991; Polman and Coffa, 1999; Shin *et al*, 1995]. The defect levels introduced are found to be at $E_c - 0.20 \text{ eV}$, at $E_c - 0.26 \text{ eV}$, at $E_c - 0.33 \text{ eV}$ and at $E_c - 0.51 \text{ eV}$ [Coffa *et al*, 1995; Shin *et al*, 1995; Polman and Coffa, 1999]. These defect levels are all donor levels in the upper part of the energy gap. It is therefore expected that the behaviour of silicon in this case will be different to the cases of gold and platinum.

2.3.2.4 Niobium diffusion

Niobium is another metal that is used to generate impurities in silicon. Based on the small amount of literature available on niobium, it is clear that the diffusion properties of the metal into silicon are currently not very well known. At this stage, the diffusion mechanisms of niobium into silicon are not known. However, niobium in silicon has been found to create defect levels at $E_c - 0.29 \text{ eV}$, at $E_c - 0.58 \text{ eV}$ and at $E_v + 0.16 \text{ eV}$ [Pettersson *et al*, 1993]. The very shallow level at $E_v + 0.16 \text{ eV}$ is expected to compensate any majority carriers. It is thus expected that after niobium-doping the conductivity of the material will be reduced as majority carriers would be compensated.

2.3.2.5 Oxygenation

Another approach that is used to improve the radiation hardness of silicon is to introduce oxygen into the material [MacEvoy *et al*, 1996]. Oxygenation decreases the

resistivity of silicon [Ruzin *et al*, 1999], thus increasing the conductivity. This effect is contrary to that of radiation damage or doping with heavy metals.

Oxygen impurities can diffuse into silicon through vacancy or interstitial sites [Ruzin *et al*, 1999]. The solubility of oxygen in silicon is $8.4 \times 10^{17} \text{ cm}^{-3}$ at 1250 °C while the diffusion coefficient is $2.3 \times 10^{-10} \text{ cm}^2 \text{ s}^{-1}$ at 1150 °C [Casse *et al*, 1999]. An oxygen concentration of $1.5 \times 10^{17} \text{ cm}^{-3}$ was found in the middle of a 300 μm thick silicon material after the annealing time of 24 hours at 1150 °C [Casse *et al*, 1999].

For devices fabricated on oxygenated silicon, the increase in the depletion voltage after type inversion was observed to be reduced by a factor of three for 1 MeV neutrons [Ruzin *et al*, 1999], for 23 GeV protons and for 192 MeV pions [Lindstrom *et al*, 2001] irradiations. The effect of oxygen at low energy (23 MeV) protons was found to be less than that at high energy (23 GeV) protons [Wyss *et al*, 2001]. Furthermore, the leakage current was found not to be influenced by the oxygen impurities in the silicon device [Lindstrom *et al*, 2001].

2.4 The *m-s* junction

An ideal metal-semiconductor (*m-s*) junction is formed when there is intimate contact between a metal and a semiconductor with no interfacial layer. Two types of the metal contacts that are formed on the material are Schottky and Ohmic contacts. A discussion of the contacts is given in the literature [Rhoderick, 1980; Sze, 1981; Streetman, 1990; Neamen, 1997; Schroder, 2006] with the recent review presented by Tung [2001]. In this section a dependence of these contacts on work function of the metal and on type of semiconductor is discussed.

2.4.1 Schottky contact

Schottky barrier is a rectifying contact that is formed when a p -type semiconductor is brought into contact with the metal work function less than that of the semiconductor. The properties of the contact are similar to those of a p - n junction. The energy band diagrams of the metal and semiconductor before and after the contact are shown in Fig.2.6. As these materials are brought into contact, charge transfer occurs until the Fermi energy in the semiconductor (E_{Fs}) is aligned with the Fermi energy in the metal (E_{Fm}) at equilibrium. In order to align the Fermi levels, the energy levels in the semiconductor are raised by an amount $e\Phi_s - e\Phi_m$ relative to the energy levels in the metal. As a result, a positive charge on the metal side and negative charge on the semiconductor side of the junction are required [Streetman, 1990]. The subsequent potential barrier that prevents further hole diffusion to the metal is formed and is given by

$$V_{bi} = \Phi_s - \Phi_m \quad (2.51)$$

and is called the built-in potential. The Schottky barrier height for holes to flow from the semiconductor to the metal is

$$e\phi_B = E_g - e(\Phi_m - \chi) \quad (2.52)$$

where Φ_s is the semiconductor work function, Φ_m is the metal work function and χ is the electron affinity of the semiconductor. Conversely, an ideal Schottky contact is also formed when an n -type semiconductor is brought into contact with the metal work function higher than that of semiconductor.

The built-in potential can be raised or lowered by the application of the voltage across the junction. If the applied voltage, V_a , is such that the semiconductor is biased positively with respect to the metal, then the potential barrier is reduced and holes

diffuse from the semiconductor to the metal. This corresponds to the forward bias.

The total current density is given [Streeman, 1990] by

$$J = J_s \left[\exp\left(\frac{eV_a}{kT}\right) - 1 \right] \quad (2.53)$$

in forward bias. Even though Eq. (2.53) is of the same form as Eq. (2.38), it has to be noted that in metal-semiconductor contact the current is due to injection of majority carriers while in $p-n$ junction it is due to the injection of the minority carriers. In the case of $m-s$ contact, the saturation current density is given [Sze, 1981] by

$$J_s = A^* T^2 \exp\left(\frac{-e\phi_B}{kT}\right) \quad (2.54)$$

where A^* is the Richardson constant for the thermionic emission.

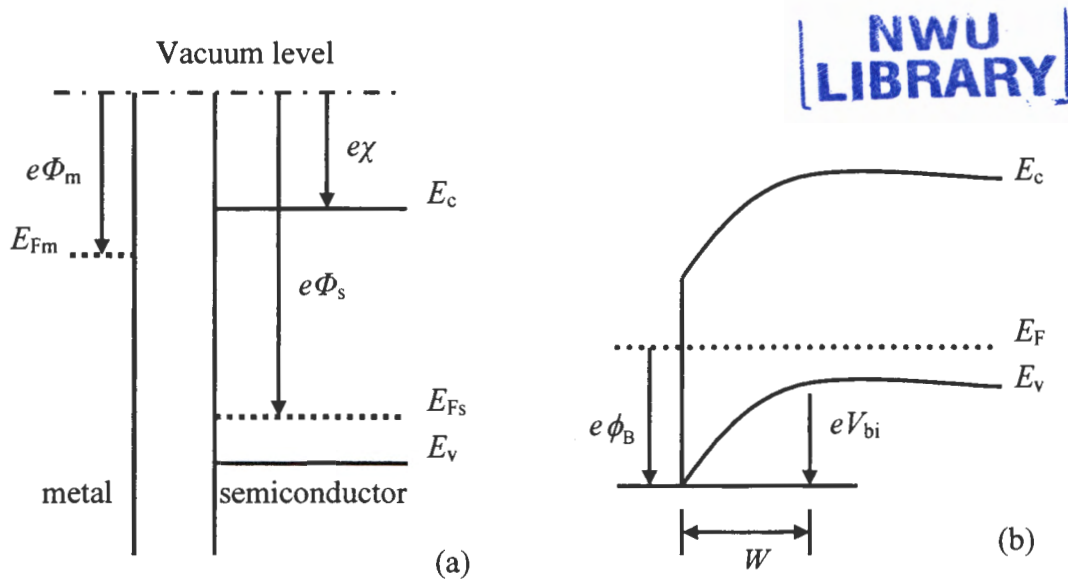


Fig.2.6: An ideal energy band diagram of a metal and a p -type semiconductor (a) before the contact and (b) after the contact at equilibrium showing the depletion width, W (after Streetman, 1990).

If the applied voltage, V_a , is such that the semiconductor is biased negatively with respect to the metal, then the potential barrier is increased. This increase of the barrier results in very few amounts of holes diffusing from the semiconductor to the metal and the current becomes negligible. This corresponds to the reverse bias.

Eq. (2.53) describes the thermionic I - V characteristics of a Schottky diode fabricated on low to moderately doped semiconductors operated at 300 K. For heavily doped semiconductor, quantum mechanical tunnelling of charges through the junction dominates and the I - V relation is modified to include both thermionic and tunnelling components. The characteristics can also be affected by charges at the metal-semiconductor interface [Streetman, 1990]. It has to be noted that the properties of the diode are not affected by the metal used to make the contact.

2.4.2 Ohmic contact

An Ohmic (or non-rectifying) contact on the other hand, is a low contact providing the conduction in both direction between the metal and the semiconductor. Thus, the contact should obey Ohm's law and the resistance of the contact is as low as possible. This contact can be achieved if the silicon work function is less than the metal work function. Fig.2.7 shows the ideal energy band diagrams of the materials before and after the contact. The Fermi level of the semiconductor is higher than that of the metal. On contact, holes flow from the semiconductor to the metal to achieve thermal equilibrium. As seen from the figure, the semiconductor energy levels are lowered by $e(\Phi_m - \Phi_s)$ across the junction. Unlike in the case of the Schottky contacts, no depletion region occurs in this case, only the accumulation of holes.

If the metal is made negative with respect to the semiconductor, there is no barrier to holes flowing from the semiconductor to the metal. If a positive voltage is applied to the metal, there is only the small potential barrier $e(\Phi_s - \chi)$ to holes flowing from the metal to the semiconductor. In either case holes can easily move across the junction and the contact is said to be non-rectifying, with a linear I - V characteristic both in the forward and reverse bias. In practice, Ohmic contact can be formed by doping the

semiconductor heavily in the contact region [Streetman, 1990]. In p -type semiconductor, a p^+ surface layer is required in contact with the metal.

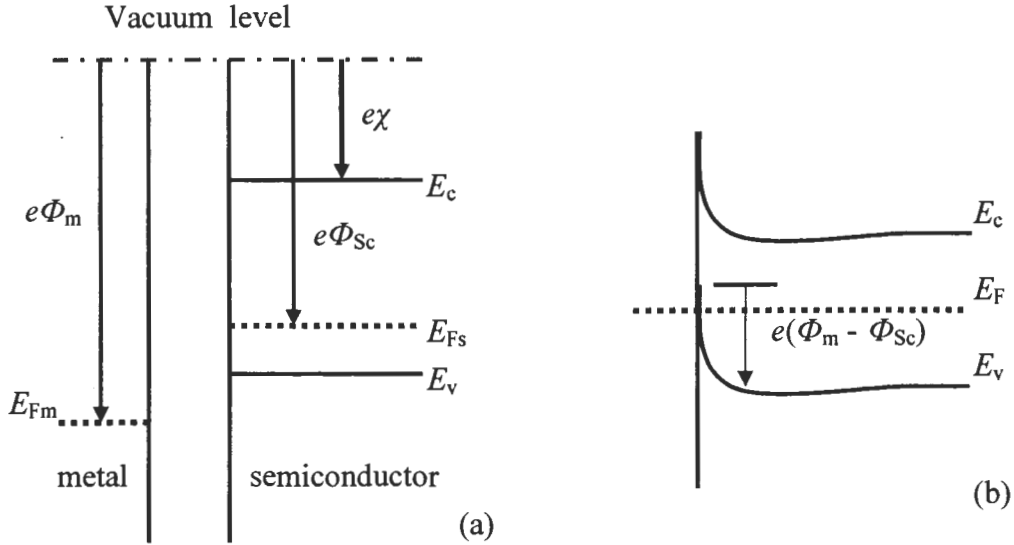


Fig.2.7: Ideal energy band diagrams of a metal and a p -type semiconductor (a) before the contact and (b) after the contact at equilibrium.

2.5 Measurement techniques

This section discusses theoretical background of the experimental techniques that were used to characterize the samples. The basic concepts of the techniques are discussed in this section. A more detailed information regarding the techniques can be found in the literature [Doolittle, 1985; Sze, 1981; Streetman, 1990; Grasserbauer and Werner 1991; Schroder, 2006]. The samples are the silicon material and the diodes fabricated on the material.

2.5.1 Material characterization

The theoretical concepts of the *RBS* and the *XPS* techniques are discussed in this section. These techniques are currently used for the surface analysis.

2.5.1.1 Rutherford Backscattering Spectroscopy (RBS)

The RBS technique is based on bombarding a sample with energetic ions and measuring the energy of the backscattering ions [Doolittle, 1985; Dev, 2001; Schroder, 2006]. The incident beam is normally of helium ions accelerated up to 3 MeV. The backscattered particles are detected by a solid state detector. The scattering is due to the Coulomb repulsion of the projectile from the nucleus of the target atom. The energy of a backscattered particle depends on the mass of the target atom and on the depth at which the scattering took place [Schroder, 2006]. A knowledge of the number and the energy of the backscattered ions make it possible to determine the atomic number and elemental concentration of the backscattered species from the surface to a few micrometers into the sample bulk.

In the RBS techniques all elements from lithium (Li) to Uranium (U) can be detected and it is best suited for the detection of heavy elements on light substrates [Schroder, 2006]. The sensitivity of the technique depends on a combination of elements and on the sequence of layers in the target. The detection threshold of the technique is in the parts per million while the accuracy of the results is of the order of 1 % [Jeynes *et al*, 1997; Boudreault *et al*, 2002].

Fig.2. 8 is a schematic diagram showing backscattering events occurring at the surface of a sample and at a given depth, Z , in the sample. When a particle of a mass M_1 and of energy E_0 collides elastically with a stationery atom of mass M_2 , energy is transferred from the high energetic particle to the stationery atom. The energy of the of the projectile after collision, E_1 , with the atom is related to the energy of the projectile before collision, E_0 , [Doolittle, 1985] as

$$E_1 = KE_0 \quad (2.55)$$

where K is the kinematic factor defined [Grasserbauer and Werner 1991; Dev, 2001] by

$$K = \left[\frac{M_1 \cos \theta + (M_2^2 - M_1^2 \sin^2 \theta)^{\frac{1}{2}}}{M_1 + M_2} \right]^2 \quad (2.56)$$

where θ is the angle between the trajectory of the incident particle before and after the scattering. The above equations show that by measuring E_1 the mass of the atoms from which the particles are scattered can be determined.

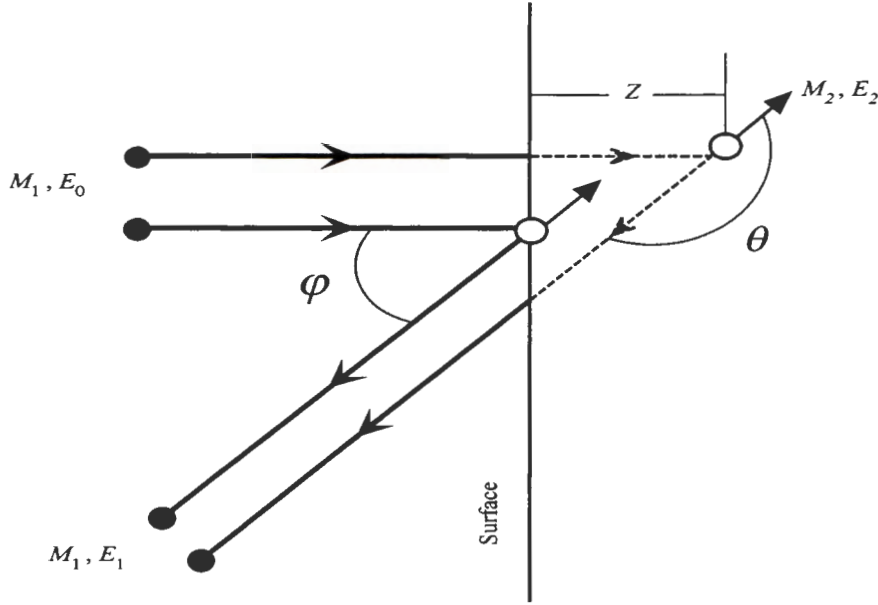


Fig.2. 8: A schematic showing the energy loss processes for backscattering from a given depth, Z , in a sample.

The total number of the detected ions is given [Dev, 2001] by

$$Y = Q_i N l \frac{d\delta}{d\Omega} \Omega \quad (2.57)$$

where Q_i is the number of ions incident on the sample, N is the bulk density of atoms in the sample, l is the sample thickness and Ω is the detector solid angle. The differential scattering cross section is given [Dev, 2001; Schroder, 2006] by

$$\frac{d\delta}{d\Omega} = \left[\frac{Z_1 Z_2 e^2}{4E_0} \right] \frac{4}{\sin^4 \theta} \frac{\left\{ \left[1 - \left(\left(\frac{M_1}{M_2} \right) \sin \theta \right)^2 \right]^{\frac{1}{2}} + \cos \theta \right\}^2}{\left\{ 1 - \left(\left(\frac{M_1}{M_2} \right) \sin \theta \right)^2 \right\}^{\frac{1}{2}}} \quad (2.58)$$

where Z_1 and Z_2 are the atomic number of the ion and the target atom, respectively.

As the ion is incident on the sample, it loses its energy onto the electrons of the target atoms by ionization and excitation as well as by nuclear collision. As it undergoes an elastic collision it can change its trajectory into an outward direction with respect to the target surface [Schroder, 2006]. During its outward path it again loses energy to the target atoms until it emerges from the target. By measuring this energy loss, the depth to which the particle has penetrated can be determined [Schroder, 2006].

2.5.1.2 X-ray Photoelectron Spectroscopy (XPS)

The XPS is a non-destructive technique used to identify the chemical species at the sample surface [Schroder, 2006]. In this technique, a sample placed in the vacuum is irradiated by photons emitted from the X-ray tube. The X-ray used is normally aluminium K_α with energy of ~ 1486.7 eV. An electron in the target atom of sample can absorb the photon energy. This results in an ejection of photoelectron from the sample. The measured kinetic energy, KE , of the ejected photoelectron at the spectrometer is given [Kerber *et al*, 1998] by

$$KE = h\nu - BE - \psi_s \quad (2.59)$$

where $h\nu$ is the photon energy, BE is the binding energy of the atomic orbital from which the emitted electron originates and ψ_s is the spectrometer work function. It has to be noted that the electrons from the atom in the sample have different kinetic

energies due to the electronic level and the type of the atom they come from. Due to this fact, *XPS* is used to identify the concentration of the elements at the surface of sample.

The *XPS* allows all elements from the periodic table except hydrogen and helium to be detected [Grasserbauer and Werner 1991]. Its sensitivity is in the range of 0.1 to 1 % while the depth resolution is in the range of 10 to 20 nm [Grasserbauer and Werner 1991].

It has to be noted that on their way through the sample, the electrons lose energy due to inelastic scattering. As a result, those electrons excited deeper within the sample may not exit the surface. In investigating the depth profile of the species using the *XPS* technique, the sample is sputtered with argon ions to remove the material from the surface [Grasserbauer and Werner 1991; Kerber *et al*, 1998].

2.5.2 Device characterization

The theoretical discussion of the *I-V* and the *C-V* techniques are presented in this section. These are the experimental techniques that were carried out on the diodes fabricated on the silicon material.

2.5.2.1 Current-voltage (*I-V*) technique

In forward bias, the potential barrier is reduced so that majority carrier electrons from the *n*-region are injected across the junction into the *p*-region, thereby increasing the minority carrier concentration. Minority carriers will recombine with majority carriers [Goodge, 1983] as they diffuse from the space charge edge, *x* into the neutral regions. The excess carrier concentrations are then found to be [Neamen, 1997]

$$\delta n_p(x) = n_p(x) - n_{p0} = n_{p0} \left[\exp\left(\frac{eV_a}{kT}\right) - 1 \right] \exp\left(\frac{x_p + x}{L_n}\right) \quad (2.60)$$

for electrons and

$$\delta p_n(x) = p_n(x) - p_{n0} = p_{n0} \left[\exp\left(\frac{eV_a}{kT}\right) - 1 \right] \exp\left(\frac{x_n - x}{L_p}\right) \quad (2.61)$$

for holes. The above relations show that the minority carrier concentrations decay exponentially with distance away from the junction. The excess minority carrier electron concentration then decreases with distance from the junction. The same discussion applies to holes injected across the SCR into the n -region. The minority carrier electron diffusion current density at the junction is given [Neamen,1997] as

$$J_n(x_p) = \frac{eD_n n_{p0}}{L_n} \left[\exp\left(\frac{eV_a}{kT}\right) - 1 \right], \quad (2.62)$$

a current density that is in a direction from the p - to the n -region. Similarly, the minority hole diffusion current density is given as

$$J_p(x_n) = \frac{eD_p p_{n0}}{L_p} \left[\exp\left(\frac{eV_a}{kT}\right) - 1 \right], \quad (2.63)$$

also in a direction from the p - to the n -region. The total current density is

$$J = J_p(x_n) + J_n(x_p) = J_s \left[\exp\left(\frac{eV_a}{kT}\right) - 1 \right] \quad (2.64)$$

which is the sum of the electron and hole current densities. The above equation is the same as Eq. (2.38) and represents the ideal current-voltage relationship for a p - n junction. The parameter J_s as defined before is

$$J_s = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n} \right] \quad (2.65)$$

and is referred to as the reverse saturation current density. This parameter is a function of the thermal equilibrium minority carrier concentrations, n_{p0} and p_{n0} . These minority carrier concentrations are proportional to n_i^2 , which is a very strong function of temperature.

The ideal current-voltage relationship is derived on the basis of the following assumptions: that the space charge regions have abrupt boundaries, that the semiconductor is neutral outside of the depletion region, that the Boltzmann approximation is valid throughout the junction region [Neamen, 1997], that the injected minority carrier densities are small compared with the majority carrier densities, that the total current is constant throughout the entire junction and that the individual electron and hole currents are constant throughout the depletion region. The last assumption ensures that there is no $g-r$ current in the junction region.

In the derivation of the ideal current-voltage relationship of Eq. (2.64), any effects that occur within the SCR were neglected. Since other current components are generated within the SCR, the actual current-voltage characteristics of a $p-n$ junction diode deviate from those generated by the ideal expression. Additional currents are generated from the recombination process. The generation current density can be written [Sze,1981] as

$$J_{\text{gen}} = \frac{1}{\tau_{\text{eff}}} (en_i W) \exp\left(\frac{eV}{2kT}\right) \quad (2.66)$$

where τ_{eff} is the effective carrier lifetime for $g-r$ process and is given [McPherson, 1997] as

$$\tau_{\text{eff}} = \left[\frac{\sigma_n \sigma_p v_{\text{th}} N_t}{\sigma_n \exp\left(\frac{E_t - E_i}{kT}\right) + \sigma_p \exp\left(\frac{E_i - E_t}{kT}\right)} \right]^{-1} \quad (2.67)$$

where σ_n is the capture cross section for electrons and σ_p is the capture cross section for holes, v_{th} is the thermal velocity, N_t is the trap density and E_t is the energy level of the trap. Then the total reverse current density is given by

$$J_R = J_s + J_{\text{gen}}, \quad (2.68)$$

which is the sum of the reverse saturation current density and the generation current density. The reverse saturation current density is independent of the reverse bias while the generation current density is a function of the depletion width. The depletion width is, in turn, a function of the reverse bias.

In forward bias the recombination current dominates. The recombination current density can be written [McPherson, 1997] as

$$J_{\text{rec}} = \sigma v_{\text{th}} N_t (e n_i W) \exp\left(\frac{eV}{2kT}\right). \quad (2.69)$$

The total forward current density is then made up of the recombination current and the diffusion current from Eq. (2.38) and Eq. (2.39) as

$$J = J_{\text{rec}} + J_D \quad (2.70)$$

where J_D is the ideal diffusion current density given [Neamen, 1997] as

$$J_D = J_s \exp\left(\frac{eV_a}{kT}\right) \quad (2.71)$$

which is dominated, at low current densities, by the recombination current. At higher current densities, the ideal diffusion current dominates. Since the recombination current and the generation current are equal at $V_a = 0$, the relations of Eq. (2.66) and Eq. (2.69) give

$$\frac{1}{\tau_{\text{eff}}} = \sigma v_{\text{th}} N_t. \quad (2.72)$$

Then, the general diode current-voltage relationship can be written [Sze, 1981] as

$$J = J_s \left[\exp\left(\frac{eV_a}{\eta kT}\right) - 1 \right] \quad (2.73)$$

where η is called the ideality factor which is a measure of departure from ideality. The ideality factor varies between 1 and 2 depending on the dominant current mechanism [Sze, 1981; Kaplan and Kaplan, 1998]. It is 1 when the diffusion current dominates (ideal diode) and 2 when the generation or recombination current is dominant.

In semiconductor device characterisation, the current-voltage (I - V) technique is used to measure the space charge density within a semiconductor material [Larabee, 1961]. These current measurements are thus expected to determine the rate of carrier creation and so the generation rate or the recombination rate. It can be noted from Eq.(2.71) that a slope of a plot of $\ln J$ versus V can be used to determine the ideality factor.

2.5.2.2 Capacitance-voltage (C - V) technique

Two types of capacitance are associated with the junction of a semiconductor diode, depending on how the junction is biased. These are the depletion region capacitance which is dominant when the device is reverse biased and the diffusion capacitance which dominates in forward bias [Sze, 1981]. Both are evaluated based on the assumption that the p - n junction is an abrupt junction between a highly doped and a low doped semiconductor [Streetman, 1990].

The depletion region (or junction) capacitance occurs in reverse bias and is due to a dipole in the SCR of the p - n junction [Streetman, 1990]. The dipole is formed when acceptor ions on the p -side provide a negative charge while donor ions on the n -side provide an equal and positive charge in the junction. The capacitance can be defined as

$$C_J = \frac{dQ}{dV_a} \quad (2.74)$$

where dQ is the differential charge and dV_a is the differential reverse voltage. The depletion region capacitance and the depletion region width are related by

$$C_J = \frac{\epsilon_s \epsilon_0 A}{W} \quad (2.75)$$

where ϵ_s is the dielectric constant of a semiconductor ($=11.7$ for Si at 300 K), ϵ_0 is the permittivity of free space ($=8.854 \times 10^{-14}$ F cm⁻¹), A is the active device area and W is the depletion region width. The above relation shows that a small depletion width has a large junction capacitance. It follows from this that a forward biased junction, which has a small width, has a larger capacitance than one that is reversed biased. To find the relationship between C_J and the applied bias Eq. (2.43) can be substituted for W in Eq. (2.2) to give

$$C_J = \frac{A}{2} \left[\frac{2e\epsilon_0\epsilon_s}{(V_{bi} + V_a)} \left(\frac{N_a N_d}{N_a + N_d} \right) \right]^{\frac{1}{2}} \quad (2.76)$$

showing that the junction capacitance varies with the inverse square root of the applied voltage. Another relation that shows that the junction capacitance is dependent on the applied reverse voltage is

$$C_J = \frac{\epsilon_s \epsilon_0 A}{\sqrt{2\mu\rho(V_a + V_{bi})}} \quad (2.77)$$

where μ is the carrier mobility and ρ is the resistivity of the semiconductor. From the equation it is clear that higher resistivity materials will have a lower depletion region capacitance. Thus, as the reverse bias increases, the depletion region width increases which results in a decrease of the depletion region capacitance.

The analysis of the variation of the junction capacitance with applied voltage is used for the determination of the net ionized doping density and its depth profile [Sze, 1981]. This doping density is related to the resistivity of the material as

$$N_d = \frac{2}{e\epsilon_s\epsilon_0} \cdot \frac{1}{A^2} \cdot \frac{dV}{dC_j^{-2}} \quad (2.78)$$

to show that it is strongly dependent on the active device area [McPherson *et al*, 1997].

The capacitance of silicon diodes which contain high concentrations of trapping centres is frequency dependent and is given [McPherson, 1997] as

$$\frac{dV}{dC_j^{-2}} = \left(\frac{1}{2} e\epsilon_s\epsilon_0 A^2 \right) \left[(N_t - N_A) + \left(1 - \frac{C_t}{\epsilon_s\epsilon_0 A} \right) N_t^* \right] \quad (2.79)$$

where N_t is the trap density and t is the distance in the depletion region where the energy level of the deep donor trap fall below the Fermi energy. At high frequencies the charge variation on the traps cannot follow the signal voltage that is applied to the junction and so cannot contribute to the measured capacitance. In the above relation, N_t^* is the concentration of the neutral donor trap.

Diffusion (or charge storage) capacitance

The diffusion (or charge storage) capacitance occurs in forward bias [Streetman, 1990]. Since current changes result from charge storage effects, the diffusion capacitance can be explained by the stored charge in the injected hole distribution [Streetman, 1990] as

$$C_s = \frac{dQ}{dV_a} \quad (2.79)$$

where C_s is the charge storage capacitance and V_a is the applied voltage. According to the above equation, the diffusion capacitance can be explained as the change in the stored minority carrier charge as a function of the change in applied bias.

At forward bias for irradiated devices, a negative capacitance has been observed [McPherson, 2002] and this has been explained as an effect caused by the built-in

charge recombining with the injected charge thereby creating a peak in reverse bias which manifests itself on a negative capacitance in forward bias.

Full depletion

The width of the depletion region associated with a $p-n$ junction increases as the reverse voltage is increased [Sze, 1981]. If the voltage could be increased enough, the depletion region would eventually extend across virtually the entire thickness of the device, resulting in a fully (or totally) depleted detector [Knoll, 2000]. When the junction is fully depleted of all carriers, the depletion region width has been widened to its maximum value, the distance between the contacts, and the junction capacitance is then referred to as the full depletion capacitance given as

$$C_d = \frac{\epsilon_s \epsilon_0 A}{d} \quad (2.80)$$

from Eq. (2.75), where d is the distance between the contacts. At full depletion, there is a maximum electric field which occurs at the point of transition between the n - and the p -type material. It has a magnitude given [Knoll, 2000] as

$$\xi_{\max} = \frac{2V_d}{d} \quad (2.81)$$

where V_d is the full depletion voltage. The distance between the contacts is also referred to as the full depletion width. Then, at full depletion it is expected that $W = d$. A value of the effective doping density at full depletion voltage, N_{eff} , is then given [Boer, 1992] as

$$N_{\text{eff}} = \frac{2\epsilon_s \epsilon_0}{ed^2} V_d \quad (2.82)$$

Chapter 3

Experimental and data analysis techniques

This chapter presents the experimental techniques that were used on the silicon material and on the diodes fabricated on the material. It also presents the methods used to analyze the data acquired from the measurements. The first section describes the experimental procedure followed by investigating the effects of light on the irradiated commercial silicon *p-i-n* diodes. The second section deals with the process undertaken to dope the silicon with metals and this is followed by a characterization of the material in Section 3.3. The process that was followed to fabricate Schottky diodes and the techniques used to characterize these diodes are discussed in Sections 3.4 and 3.5, respectively.

3.1 Silicon *p-i-n* diodes

Silicon *p-i-n* diodes were acquired from Hamamatsu S3590 industry for earlier work and characterised by *I-V* and *C-V* measurements in dark conditions prior to irradiation. The active area of the diodes was 1 cm^2 and the thickness was $300 \text{ }\mu\text{m}$. The measurements were carried out three years after the irradiation process. During this period the diodes were kept below zero in a fridge. Prior to the illumination, the measurements were carried out and similar results obtained [Moloi and McPherson, 2009] immediately after the irradiation were found. It was then assumed that the defects induced by irradiation were not annealed with time. It has to be noted that the work presented in [Moloi and McPherson, 2009] explains the effects of irradiation on the properties of the diode. The work presented here is a continuation of the MSc work [Moloi, 2005] where the effects of light on the irradiated diodes were investigated.

The light intensity transmitted through the diode, Φ_t , is related to the absorption coefficient, α_0 [Streetman, 1990] as

$$\Phi_t = \Phi_0 \exp(-\alpha_0 l_0) \quad (3.1)$$

where Φ_0 is the intensity of a photon incident on the diode and l_0 is the active thickness of the diode. The above relation shows that at a constant l_0 , the light intensity increases exponentially with a decrease in the absorption coefficient. The absorption coefficient varies with the photon wavelength, λ and the energy gap, E_g [Sapoval and Hermann, 1993] as

$$\alpha_0 \propto \left(\frac{hc}{\lambda} - E_g \right)^\gamma \quad (3.2)$$

where h and c are as defined before and $\gamma = 1/2, 3/2$ and 2 for the direct transition, for the vertical forbidden transition and for the indirect transition between extreme situated at different points in the zone, respectively. Equation (3.2) holds only for $hc/\lambda > E_g$. The opposite case occurs if the wavelength of the incident photons is greater than 1700 nm, in which case the absorption coefficient of the silicon becomes negligible [Bar-Lev, 1993]. This dependence of the absorption coefficient on the wavelength shows that the intensity of photons that have a shorter wavelength is reduced with the depth of penetration into the silicon such that they are absorbed over a short distance. These photons could also be absorbed very close to the surface of the silicon. In either case the result is a lower amount of photo-generated carriers contributing to the measured current. Photons with a long wavelength, on the other hand, are absorbed over a long distance into the silicon and this results into a higher amount of photo-generated carriers contributing to the measured current. Thus, at the same applied electric field, short wavelengths will show low current while long

wavelengths will show high current. The total current is then given [Navon, 1986] by

$$I = I_s \left[\exp\left(\frac{eV_a}{kT}\right) - 1 \right] - (eAL_p g_{op} + eAL_n g_{op}) \quad (3.3)$$

where the first term on the right hand side refers to the ordinary dark current in the *p-i-n* junction and the second term corresponds to the photocurrent due to generated minority carriers. If V_a is zero, the first term on the right vanishes, and the current is negative and is given only by optically generated carriers.

The measured reverse current is expected to increase with an increase in light intensity. This is due to the fact that the carriers that are optically generated within the space charge region increase with the intensity. This increase of the current with an increase in the intensity has been presented by McPherson [2005] on the results obtained from the silicon *p-i-n* diodes. Since the intensity is related to the wavelength according to Eqs. (3.1) and (3.2), it is expected that the current will also increase with wavelength. This is shown in the next chapter.

3.1.1 Current-voltage measurements

Current-voltage measurements were carried out on the commercial silicon *p-i-n* diodes in the dark and under illumination by different wavelengths. The measurements were carried out using a Keithley 6487 picoammeter with a voltage source. The picoammeter was used to measure the current of the diodes and to supply the required biasing voltage across the diode. The instrument was operated in the remote mode by connecting it to a personal computer (PC) through an RS-232 cable. An add-in utility for Microsoft Excel was installed in the computer for control of the picoammeter. Using this software, data can be acquired using Excel, after which the

analysis can be carried out using the ORIGIN package followed by a generation of graphics for display and comparison.

The ORIGIN software is a Microcal package that is used for data analysis and plotting. The package has the advantage that data can be analysed in various ways and simultaneously plotted on several windows. Furthermore, several layers of the plots can be displayed on a single page or together in one plot. This feature makes easy the comparison of various types of the plots and so is the comparison of samples and their characteristics.

The diodes were irradiated by 1 MeV neutrons of different fluences of $\sim 10^{13}$, to $\sim 10^{14}$, to $\sim 10^{15}$, to $\sim 10^{16}$ and to $\sim 10^{17}$ n cm⁻². The diodes were named H13, H14, H15, H16 and H17, respectively. The measurements were carried out at 302 K. The temperature was monitored for every diode prior to, during and after carrying out the measurements.

The diode was placed in an in-house, custom-made, high resistance test fixture (sample holder) for the voltage sweep run. The test fixture was designed based on the commercial high resistance test fixture acquired with the Keithley Picoammeter. The design was adopted for the samples and to eliminate any light incident into the holder. The sample holder was placed 200 cm away from the computer and the Picoammeter. It was then possible to assume that the sample was completely isolated from the surroundings electronics.

The illumination was achieved by use of LEDs of different wavelengths. After several investigations, the LEDs were each placed at a distance of 10 mm in front of the devices to ensure full illumination. The LEDs were positioned in such a manner that the maximum light was incident onto the centre of the device. In this way it was

possible to assume that the illumination was, as much as possible, over the whole active area of the diode. Thus, any differences in the results would only be due to changes in the wavelength of the LEDs.

The LEDs were powered from a Goodwill GSP-3030 d.c. voltage source which can supply up to 30 V. The current through the LEDs was kept constant at 20 mA throughout each measurement to ensure constant illumination. The properties of the LEDs used are summarized in Table 3.1 where some of the values have been extracted from the manufacturer's data sheet [RS Components, 2007].

Table 3.1: Properties of the LEDs that were used to illuminate the diodes. Some of the values were extracted from the manufacturer's data sheet [RS Components, 2007].

LED	λ_{LED} (nm)	E_{LED} (eV)	V_{LED} (V)
Red	660	1.88182	5
Orange	610	2.03607	5
Yellow	590	2.10509	5
Green	565	2.19823	5

The colours of the LEDs used are presented in the first column of the table corresponding to their peak emission wavelengths, λ_{LED} , as quoted in the manufacturer's data sheet. In the third column is the energy value calculated by using the relation $E_{\text{LED}}\lambda_{\text{LED}} = hc$, which is presumed to be the photon energy of the light incident onto the diode. It can be seen from the table that the photon energy emitted by the LEDs is higher than the energy gap of silicon ($= 1.12$ eV at 300 K). In this situation where $E_{\text{LED}} > E_g$, it is expected that the incident light will be absorbed throughout the depth of the silicon material to generate electron-hole ($e-h$) pairs. These will be separated and drawn to opposite electrodes by the applied voltage (field) to contribute to the measured current.

The measurements were carried out at reverse bias up to 100 V in voltage steps of 0.01 V up to 0.10 V, of 0.10 V up to 1.00 V and finally of 1.00 V up to 100 V. The current limit was set to 2.5 mA. The time between the measurements was set at 1 s, a time determined after many trials [Moloi, 2005] and was intended to allow the current to settle so that a more realistic value is acquired. For all measurements, each device and LED were placed in the sample holder. Between measurements, the diodes were stored at sub-zero temperatures in a refrigerator.

3.1.2 Capacitance-voltage measurements

The C - V measurements were carried out manually using an Agilent 4263B Inductance-Capacitance-Resistance (LCR) meter. The data were acquired up to 30 volts using an external voltage supplied by a Goodwill GSP-3030 d.c. voltage source. The measurements were carried out on the six diodes at a frequency of 1 kHz. After several trial measurements [Moloi, 2005], a time of 8 s was chosen between readings. This was found to be the most suitable time to allow for the capacitance to settle and thus to allow acquisition of a more realistic value.

The samples were mounted onto an external Agilent 16065A test fixture. The illumination conditions similar to those described above (device and LED) were maintained. The LCR meter was zeroed, first as an open circuit and then as a short circuit prior to taking readings. This was done in order to correct for the capacitance of the leads and for any stray capacitance.

3.2 Material preparation

A procedure used to prepare the samples is described briefly in the following sections. The samples were prepared in vacuum by electron beam deposition of the metals onto

the silicon. Thereafter, the samples were annealed in vacuum conditions to diffuse the metals into the silicon bulk.

3.2.1 Wafer preparation

The substrates used in this study are *p*-type silicon polished on one side. The resistivity of the material ranges from 1 to 20 Ω cm and the thickness from 350 to 400 μm . The substrates were obtained by dicing a 75 mm diameter silicon wafer into squares of 0.9 cm x 0.9 cm pieces using a diamond tip cutter. The wafer was placed on a finely perforated stage mounting and held during the cutting process through vacuum suction. After the cutting process, the square pieces were cleaned using an ultrasonic cleaner. The cleaner consists of a water tank of about 8×10^5 - $10 \times 10^5 \text{ m}^3$ and a beaker tray able to hold six beakers suspended in the tank. In each of the cleaning steps, each substrate was immersed in a beaker containing a certain solution as shown in Fig. 3.1 and the beaker was placed in the water tank for five minutes.

Since the properties of silicon are sensitive to contaminations, the cleaning process of the substrates was done with thorough care. Fig. 3.1 shows the steps taken to clean the substrates. This is a standard chemical cleaning procedure [Hanselaer *et al*, 1986; Singh *et al*, 2000; Rahab *et al*, 2001; Cimilli *et al*, 2007]. The substrates were first dipped in methanol to remove any grease, after which they were put in acetone to wash away the methanol residue. This was followed by immersion in trichloroethylene, again to remove grease and dirt, and dipping in acetone to wash away the trichloroethylene remaining on the substrates. The final dirt and grease removal step was done by immersion in methanol after which the substrates were rinsed in de-ionized water. The substrates were then dipped in a 20% solution of hydrofluoric (HF) acid to remove any oxide layer. Finally, the cleaned substrates

were dipped in de-ionized water for five minutes. Before the substrates could be loaded into the high vacuum chamber for metal deposition, they were blow-dried using nitrogen gas.

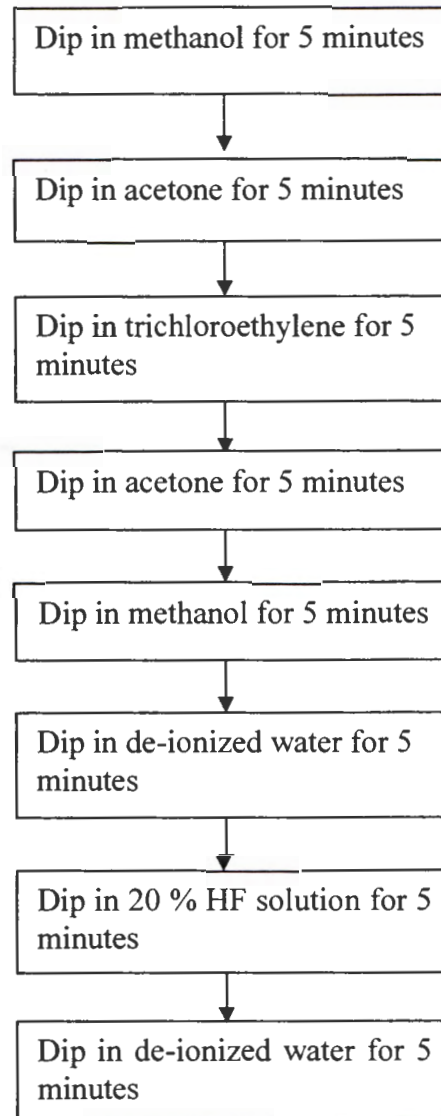


Fig. 3.1: *Wet cleaning of silicon substrates.*

3.2.2 Metal deposition

For the metal deposition process, eight of the substrates were mounted onto aluminium sample holders and then loaded into an evaporation chamber at pressures below 10^{-6} mbar. Two out of the eight substrates were deposited with gold, platinum, erbium and niobium and then mounted onto sample holders labelled A, B, C and D,

respectively. Two substrates were deposited and kept to fabricate the undoped diodes. The deposition was achieved by electron beam evaporation of the metal onto the polished surface of each of the substrates.

Extreme care was taken to prevent the introduction of any undesired impurities into the silicon substrates. This was done by maintaining the pressure in the chamber lower than 5×10^{-8} mbar before the evaporation process. This pressure was achieved by using a rotary roughing pump and a turbo-molecular pump. The rotary pump was able to reduce the pressure in the chamber to 10^{-2} mbar while the turbo-molecular pump reduced it to 10^{-6} mbar. Before the evaporation process, liquid nitrogen was introduced to reduce the pressure further to about 2×10^{-8} mbar.

During the evaporation process, the thickness of the deposited layer was also monitored using a crystal monitor mounted in the chamber. The vibration frequency of the monitor was proportional to the mass of material deposited onto its surface. Calibrating this change in frequency due to the atomic weight of the metal gives a measure of the thickness of the deposited film. However, if the monitor has been used for long times, the calibration becomes non-linear and this affects its accuracy. It is therefore required that the exact thickness deposited is determined after each metal deposition. In this work, the *RBS* technique was used to determine the exact thickness of the metal deposited. The rate of the evaporation ranged from 2.3 to $4.6 \text{ \AA s}^{-1}$.

According to previous calculations [Msimanga, 2004] the amount of metal to be deposited depends on the saturation solubility and the diffusion coefficient of the metal into the silicon bulk. The thickness of the metal film to be uniformly deposited onto the substrate is given [Msimanga, 2004] as

$$y = l \frac{N_0}{N_M} \quad (3.4)$$

where l was the wafer thickness ($= 390 \mu\text{m}$), N_0 is the metal saturation solubility and N_M is the metal atomic density. The atomic densities of gold, platinum, erbium and niobium are 0.59×10^{-23} , 0.66×10^{-23} , 0.33×10^{-23} and $0.56 \times 10^{-23} \text{ atoms.cm}^{-3}$, respectively. The saturation solubility of gold is $1 \times 10^{15} \text{ atoms.cm}^{-3}$ at 800°C and $8 \times 10^{15} \text{ atoms.cm}^{-3}$ at 1000°C , that of platinum is $8 \times 10^{14} \text{ atoms.cm}^{-3}$ at 900°C and that of erbium is $8 \times 10^{19} \text{ atoms.cm}^{-3}$ at 900°C . Using its saturation solubility at the annealing temperatures of 800 and 1000°C the amount of gold to be deposited is $0.068 \text{ \AA}$ and $0.542 \text{ \AA}$ thick, respectively. Based on the same calculations using the saturation solubility of platinum at 900°C , the thickness of the metal required on the substrates was evaluated as $0.048 \text{ \AA}$ while that required for erbium using its saturation solubility at 900°C is $122.2 \text{ \AA}$. It can be noted that very thin layers of metals are required to saturate silicon at temperatures higher than 800°C .

At this stage the saturation solubility of niobium is not known. However, the amount of metal deposited was of the order of $1000 \text{ \AA}$ thick for all cases to minimize any effects of possible evaporation of metal atoms and to ensure that there were a sufficient number of atoms to saturate the bulk. After the evaporation process the substrates were kept in the chamber for 2 hour to cool them down. The *RBS* results show that the thickness of gold, platinum, erbium and niobium deposited on the silicon surface were $1510 \text{ \AA}$, $1100 \text{ \AA}$, $1050 \text{ \AA}$ and $1150 \text{ \AA}$, respectively.

3.2.3 Vacuum annealing

After the samples were removed from the evaporation chamber, they were placed in U-shaped porcelain boats with the coated side facing upwards. Only the two opposite edges of each substrate were in contact with the inner walls of the boat. The boats

were then placed in a vacuum furnace and the substrates were annealed at 900 °C for 18 hours in order to induce diffusion of the metals into the silicon bulk. The reason for choosing these times is given later. The boats were at the centre of the heating elements of the furnace. The vacuum was obtained by using a mechanical forepump together with a turbo-molecular pump. The furnace was operated at a pressure of 10^{-6} mbar.

It has to be noted that the annealing process depends on the depth from the surface and the time of annealing. An important function in the diffusion theory is the error function given [Boer, 1992] as

$$C_1 = C_0 \operatorname{erfc}\left(\frac{s}{2\sqrt{Dt}}\right) \quad (3.5)$$

where C_1 is the concentration at a depth s from the surface, C_0 is the surface concentration, which is assumed to be constant, D is the diffusion coefficient and t is the diffusion time. Using Eq. (3.5) the annealing time required for the metal to diffuse right through the sample can be determined [Msimanga, 2004]. At 800 °C and 1000 °C the annealing times required for gold to diffuse through the sample were calculated as 18 hours and as 3 hours, respectively. The diffusion coefficient of gold is $6 \times 10^{-9} \text{ cm}^2\text{s}^{-1}$ at 800 °C and $4 \times 10^{-8} \text{ cm}^2\text{s}^{-1}$ at 1000 °C. It can be seen from the calculations that a very thin layer of gold is required to saturate silicon with gold atoms at temperatures higher than 800 °C and at annealing times less than 18 hours. Thus, it was decided to anneal at 900 °C for 18 hours.

Based on the same calculations as above using the saturation solubility and the diffusion coefficient of platinum at 900 °C the annealing time required to diffuse platinum through the sample was evaluated as 7 hours. Similar to gold, a very thin layer of platinum is enough to saturate silicon at 900 °C, for times less than 18 hours.

This is because of the high saturation solubility or the low diffusion coefficient of both metals have in silicon. The diffusion coefficient of platinum at 900°C is $3.0 \times 10^{-7} \text{ cm}^2\text{s}^{-1}$ [Emulsitone Company, 2008]. It was thus decided to anneal platinum at 900 °C for 18 hours.

The annealing time required for erbium to diffuse right through at 900 °C was calculated using the saturation solubility as 6×10^5 hours. The very large annealing time shows that erbium has a very low saturation solubility or a very high diffusion coefficient in silicon. It has to be noted that this unrealistic annealing time could not be adopted in this work. However, it is expected that with a thickness of 1000 Å deposited, the metal would be able to diffuse into the silicon at 900 °C for the annealing time of 18 hours. Thus these figures were adopted for erbium. The annealing time for niobium was not evaluated since its diffusion coefficient is currently not known. The temperature evolution of the annealing process of the samples is shown in Fig. 3.2.

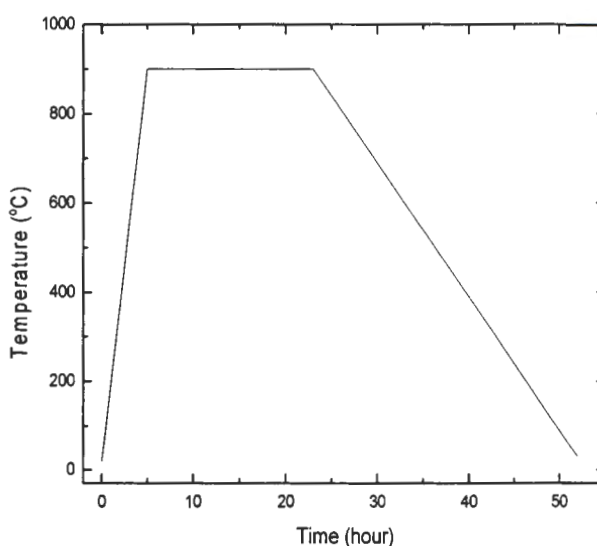


Fig. 3.2: *Temperature evolution of the annealing process of the samples at 900 °C for 18 hours.*

3.3 Material characterization

The primary analytical techniques used to characterize the silicon material are the Rutherford Backscattering Spectroscopy (*RBS*) and the X-ray Photoelectron Spectroscopy (*XPS*) techniques. The *RBS* technique is used to determine the layer thickness, the concentration and the depth distribution of the deposited metals. However, due to its high detection threshold, the *RBS* is not adequate for measurements of metal concentration in the silicon bulk [Schroder, 2006]. The *XPS* technique, on the other hand, is used to investigate the depth profile of the diffused metals. The theory governing these techniques has been explained in the literature [Grasserbauer and Werner, 1991; Schroder, 2006] as was summarized in Chapter 2. This section only explains how the samples were characterised and analysed using the techniques.

3.3.1 Rutherford backscattering spectroscopy

The *RBS* measurements were carried out on the samples prior to and after the diffusion process. The *RBS* system at iThemba LABS used some time ago [Msimanga and McPherson, 2006] on *n*-type silicon was used in this study. The measurements were carried out with 2 MV Van der Graff accelerator using 2 MeV helium ions at a scattering angle of -10° with a beam current of 2.5 nA. The scattered ions were collected through a surface barrier detector placed at an angle of 160° to the incident beam with a system resolution of 20 keV full width at half maximum (FWHM). The beam was ~ 1 mm thick and approximately 10 μC was collected.

The computer program used to analyse the *RBS* spectra is Rutherford Universal Manipulation Program (RUMP) [Doolittle, 1985; Mohanty and Kasiviswanathan, 2006]. The programme enables a comparison of the simulated and the experimental

spectra. A sample result is shown in Fig. 3.3. The spectrum shows the normalized yield (ion intensity) of backscattered helium particles plotted against the channel number. The ion energy corresponding to each channel number is given by the top horizontal axis. The signal edges resulting from the silicon substrate and the gold are marked in the figure. The height of the peak is related to the concentration of backscattered ions detected while the width is an indication of the layer thickness. The input parameters for simulation are the energy, the charge and the current of the incident beam. The parameters also include the experimental geometry and the detector resolution.

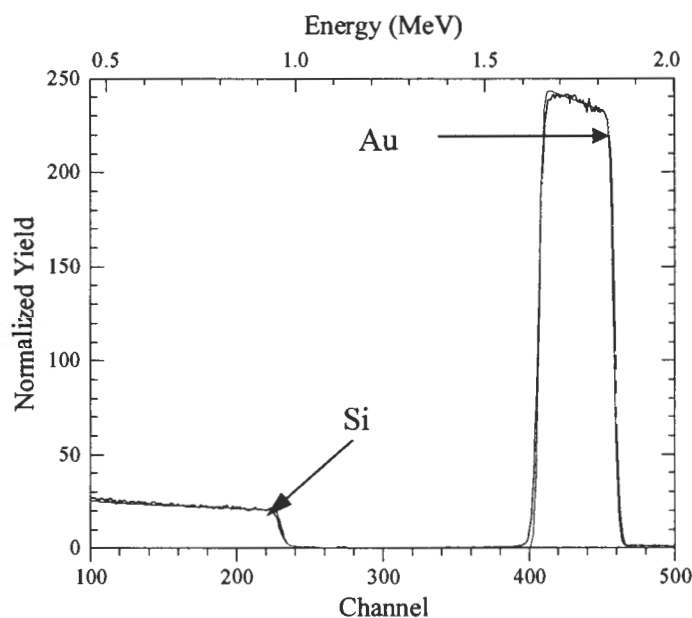


Fig. 3.3: *RBS spectra of a gold-deposited unannealed sample. The dashed line is the experiment (black) line continuous (red) line is the simulation.*

3.3.2 X-ray Photoelectron Spectroscopy

To supplement the *RBS* data, *XPS* measurements were carried out using the Physical Electronics Quantum 2000 instrument at Council for Scientific and Industrial Research (CSIR). An Al K_{α} radiation with energy of 1486.6 eV was used to excite photoelectrons from the sample. The measurements were carried out at 300 K and at the pressures below 10^{-9} mbar. The photoelectrons were separated by an analyzer

with a pass energy of 58.7 eV. The diameter of the X-ray beam was 100 μm . The detection angle was 45° from a surface that is normal to the sample. For depth profiling, the sample surfaces were sputtered with argon ions for three minutes while the binding energy regions of the specific element were being monitored.

Depth profiling analyses were performed from the top surface of the sample to the silicon bulk. An example of the *XPS* spectra is shown in Fig. 3.4 for the gold-deposited sample prior to the annealing process. The spectra for carbon and oxygen are also shown, elements that are found to be the main contaminants in the samples. Contamination is expected since the *XPS* measurements were carried out two years after annealing. The spectra are presented with the relative atomic concentration as a function of the sputter depth. During the measurements, the pressure in the chamber was always in the range of 10^{-10} mbar.

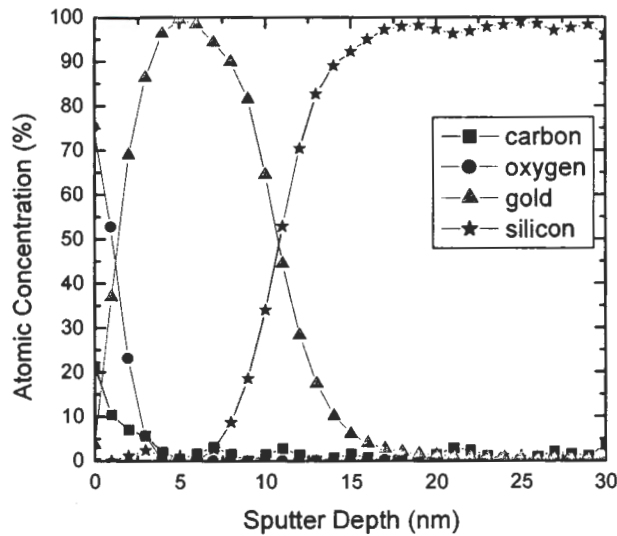


Fig. 3.4: *XPS* depth profile of a gold-deposited unannealed sample. Four elements are detected.

3.4 Device fabrication

The first set of devices consisted of six *p-i-n* diodes acquired from industry. These devices were described in Section 3.1. The second set of the devices comprised

Schottky diodes fabricated in-house at iThemba LABS. Prior to device fabrication, it was realised that there were still metal residues on the surface of the substrates. It was thus necessary to follow the diffusion process with a chemical process. The process involves dipping the substrates into a solution intended to dissolve away (or etch) the metal residue only without reacting with the silicon. In this way, it is expected that any possible surface conduction after device fabrication is minimized as much as possible. This conjecture was tested by repeatedly measuring the surface resistance of the sample by a probe multimeter, which read very low compared to uncoated silicon.

The gold- and platinum-doped substrates were dipped in warm aqua regia solution (HCl: HNO₃ in the ratio 3:1) for 50 minutes. Since platinum residues were found not to be completely etched away from the surface after this time, the substrates were dipped again in aqua regia solution but with an HCl: HNO₃ ratio of 3:2 and for 60 minutes. The erbium- and niobium-doped substrates, on the other hand, were dipped in HCl for 30 minutes. The etching methods are different because gold and platinum are dissolved in aqua regia solution while erbium and niobium are dissolved in HCl. The substrates were then cleaned using a similar procedure as described in Section 3.2. After this etching process the substrates were loaded into the evaporation chamber to form Ohmic contacts.

In making Ohmic contacts on the *p*-type silicon samples, a procedure that was followed by Lee *et al*, [2001] using *p*-type silicon carbide was adopted as this method was purported to work well. The contact was realized by vacuum evaporation of nickel where a layer of 1500 Å thick was deposited onto the unpolished side of the samples. This contact was fabricated over the whole surface. The substrates were then annealed at 980 °C for 30 minutes in vacuum in order to allow for the diffusion of the nickel into the surface layers of the silicon. It is expected that after this short

annealing time a certain amount of nickel would diffuse slightly into the samples to form a shallow p^+ region. The nickel remaining on the surface is then used for the contact.

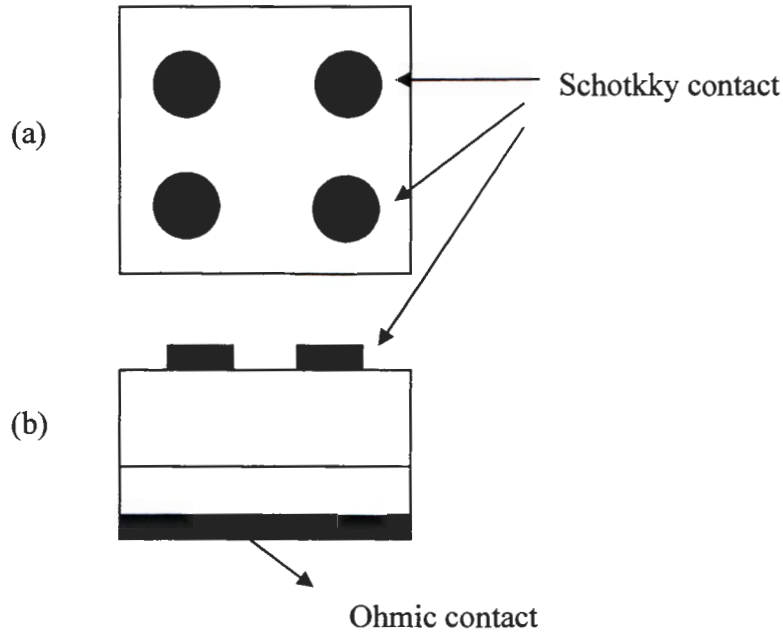


Fig. 3.5: A schematic representation of the plan view (a) and the side view (b) of a complete device.

The Schottky contact was formed by vacuum evaporation of 1500 Å of gold onto the polished side of the substrates. This contact was fabricated in this way on the undoped p -silicon substrates and on those doped with gold, erbium and niobium. The Schottky contact on the platinum-doped samples was achieved by evaporation of 1500 Å of titanium mainly because our gold supplies had been expended. In all cases the Schottky contacts were patterned through a 1 cm x 1 cm brass mask with four holes of 2 mm diameter. In forming this contact any interactions between the depositing metal and the holes of the mask on the material were neglected mainly because the energy at which the metals were deposited was expected not to be high enough to eject any atoms from the brass. The finished devices each consists of four Schottky diodes on a

single substrate with one common Ohmic contact. A schematic diagram of the plan view (a) and the side view (b) of a finished device is shown in Fig. 3.5.

3.5 Schottky diodes

The Schottky diodes fabricated in-house at iThemba LABS were also characterised with the current-voltage (I - V) and the capacitance-voltage (C - V) techniques. In reverse bias the I - V technique is used to determine the leakage current and the breakdown voltage [Sze,1981] while in forward bias it is used to determine the saturation current, the ideality factor and the Schottky barrier height of the diode [Streetman, 1990]. The C - V technique in reverse bias is used to determine the effective carrier density and the Schottky barrier height [Neamen, 1997], while in forward bias it is used to determine the rate at which charge is injected in the space charge region.

3.5.1 Current-voltage measurements

The set up similar to the one used to characterise the silicon p - i - n diodes was also used for these set of the diodes. In this case the data were taken from -10 V to 10 V with a voltage step of 0.01 V. It is only for voltages within these limits that the maximum current limit of 25 mA can be set on the programme. An option of a lower current limit (of 20 mA) that our equipment can reach is not available on the programme. The measurements were carried out at 303 K. The temperature was monitored for every diode prior to, during and after carrying out the measurements. Even though the measurements were performed at 303 K, it is considered that they are a fair estimate to those that would be carried out at 300 K. Most constants used here were derived for 300 K.

The I - V measurements were also carried out in the dark and at different temperatures. For these temperature measurements the sample was loaded in a thermoelectric cooler and warmer (TCW) with their leads connected from the electrode of the test fixture. The leads were wrapped with insulation tape to prevent any possible short circuiting. The cooling capacity of the TCW is 20 °C below ambient temperature and it has a heating capacity of 65 °C above. A Honey-well connected in series with the thermostat is used to control the temperature inside TCW. The controller has two relay switches to regulate the temperature of the TCW. The temperature of the sample is monitored by a J-type thermocouple connected from the temperature controller to the inside of the TCW and placed close to the sample.

The temperature was swept either upwards or downwards manually in step of 10°C for each measurement. The measurements were carried out at the temperature ranging from 10 to 60 °C. A temperature was set on the controller which maintains the set value with only small departure of ± 1 °C. To maintain the set temperature constant, both heating and cooling were done simultaneously to attain the equilibrium temperature in the TCW.

Fig. 3.6 shows logarithmic plots of the I - V characteristics both in reverse bias and in forward bias for two of the diodes that were fabricated on undoped p -silicon. The data are presented in logarithmic format in order to clarify whether the devices are fabricated on lifetime or on relaxation material. Three linear regions (i, ii, iii) are observed in forward bias. These regions are discussed in Chapter 4. The analysis is also based on the forward $\ln(I)$ versus V graph. The slope obtained from the linear region of the graph can be used to determine important parameters such as the ideality factor, the saturation current and the Schottky barrier height.

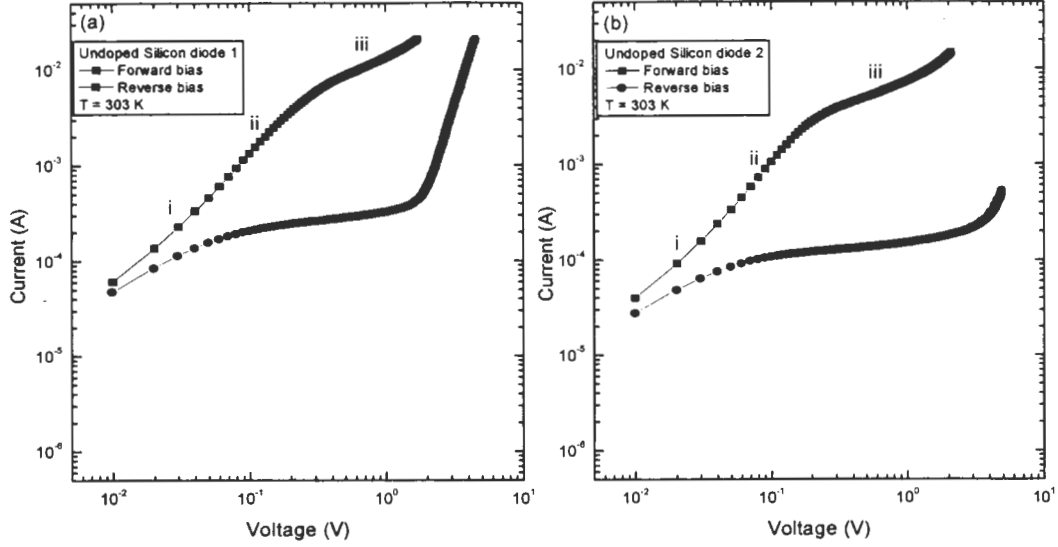


Fig. 3.6: The I - V characteristics of the diodes fabricated on undoped p -silicon. Three linear regions(i, ii, iii) are observed in forward bias.

3.5.2 Capacitance-voltage measurements

The capacitance-voltage measurements at high frequency (1 MHz) were carried out on the Schottky diodes fabricated in-house at iThemba LABS using an HP4192A LF impedance analyzer [Legodi *et al*, 1999]. The measurements were carried out in the dark at 300 K. In this case, the data were acquired up to 12 V. It is expected that at this frequency the diodes would not show the low-voltage peak that was observed before [McPherson, 2002; Msimanga and McPherson, 2006; Gullu *et al*, 2008(a)]. This peak is due to charges at the interface [Gullu *et al*, 2008(a)] that follow the AC signal and contribute to the measured capacitance at low frequency.

The main analysis in C - V measurements is based on a linear plot of capacitance against voltage at room temperature and at a frequency of 1 MHz. An example of this type of analysis is shown in the plots of Fig. 3.7 for the diodes that were fabricated on undoped p -silicon. Even though gold is known to be used on n -type semiconductors for the Schottky contacts [Msimanga *et al*, 2004; Kumar *et al*, 2006], the results

obtained in this work show that the metal can also be used on *p*-type silicon material as well. This is also shown in Fig. 3.6 where the fabricated diodes exhibit typical *I-V* characteristics of the diode.

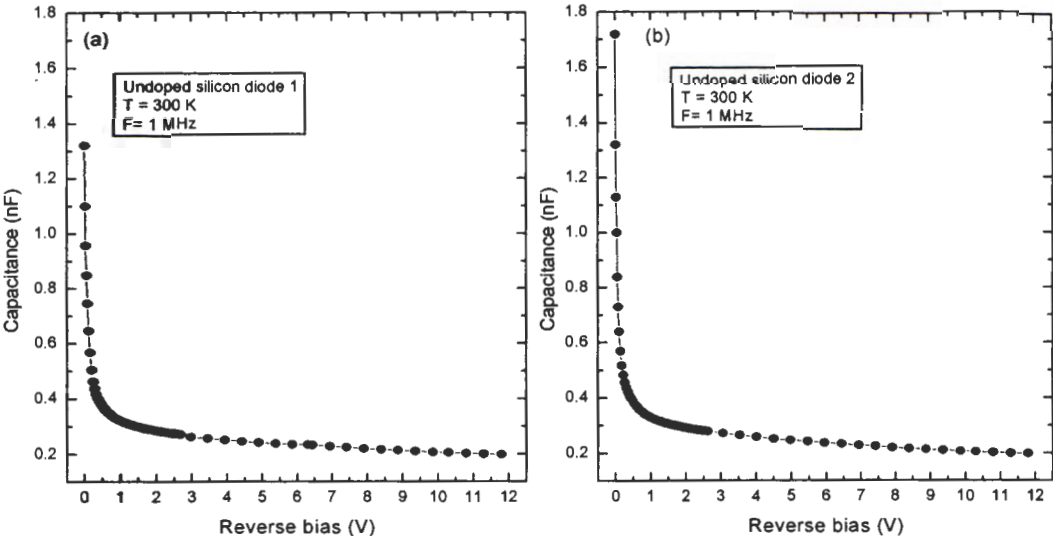


Fig. 3.7: *The C-V characteristics of the diodes fabricated on undoped p-silicon measured at 300 K and at 1 MHz.*

Another method of analysis is based on the plot of C^{-2} against reverse bias. This type of analysis is used to investigate the doping density within the material. The linear region of the plot shows that the doping profile within the material is uniform and the doping density can be evaluated.

Chapter 4

Results and discussion

This chapter presents the results obtained from the measurements carried out on the silicon and the diodes fabricated on it. The chapter consists of three sections. The first section presents and discusses the results obtained from the electrical characterization (I - V and C - V measurements) that were carried out on the irradiated commercial silicon p - i - n diodes under illumination. The second section presents the results obtained from the RBS and XPS measurements. These material characterizations (RBS and XPS) were carried out on the samples prior to and after the diffusion process. The last section deals with discussions of the results obtained from the electrical characterization of the Schottky diodes fabricated on the undoped and metal-doped p -Si.

4.1 Silicon p - i - n diodes

Silicon p - i - n diodes were acquired from Hamamatsu for earlier work and characterised by I - V and C - V measurements in dark conditions prior to irradiation. The typical characteristics similar to those shown in Fig. 3.6 and Fig. 3.7 were obtained [Moloi, 2005]. The photo response of the unirradiated diode under illumination of different wavelengths has been investigated and presented before [Moloi, 2005]. The results obtained from the diodes after radiation damage in the dark conditions have been presented recently [Moloi and McPherson, 2009]. A change of the electrical properties of the diodes was explained in terms of the defect levels induced by irradiation in the energy gap. The work presented in this instance is the characterisation of the same diodes under the illumination but after radiation damage by 1 MeV neutrons. The results obtained on the unirradiated diodes are

compared with those obtained on the irradiated diodes and the effect of light is investigated as the fluence increases.

4.1.1 Current-voltage measurements

The I - V characteristics of the unirradiated diode under the illumination of different wavelengths are shown in Fig. 4.1 (a) with an arbitrary reference line drawn from 1 μ A at 4 mV to 1 mA at 0.15 kV. The same results were obtained and presented in [Moloi, 2005]. The measured current increases by more than two orders of magnitude when the diode is illuminated. The current measured in the dark is much lower than that measured with the red LED, which is also much higher than that measured with the orange, the yellow and the green LEDs. These results show that light from the red LED is absorbed over a longer distance to generate more e - h pairs that contribute to the measured current than that from the other LEDs.

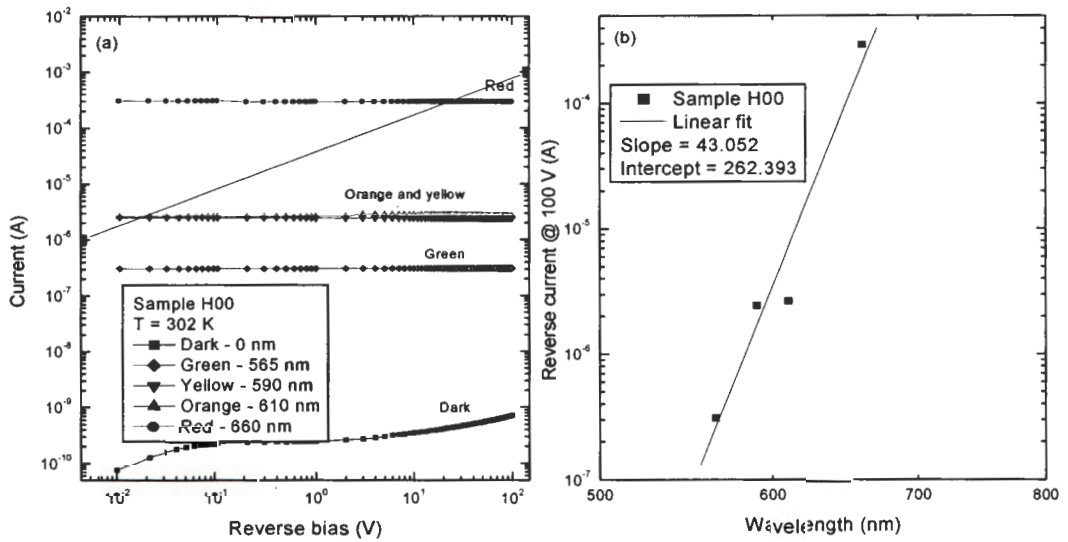


Fig. 4.1: A variation of the reverse I - V characteristic under illumination with light of different wavelengths at 302 K for H00 (a) and a plot of the reverse current measured at 100 V as a function of the wavelength (b).

Another observation from Fig. 4.1 (a) is that the photocurrent shows saturation up to 1×10^2 V for all the LEDs indicating that the photocurrent is independent of the

voltage. This lack of dependence shows that the electric field is not high enough to draw the charges to opposite electrodes to contribute to the measured current. The profile of the dark current at low voltages differs from that at high voltages. The current increases linearly up to 4×10^{-2} V, after which some form of saturation is observed up to 1×10^1 V. The initial increase of the current could be due to thermal generation of carriers when the voltage is low or due to the built-in charge of the material. At voltages higher than 1×10^1 V an increase in the current shows that the diode is attempting to approach breakdown, which means that at this high voltage the electric field is able to separate the $e-h$ pairs to draw them to opposite electrodes to contribute to the measured current.

The profile of Fig. 4.1 (a) was used to generate a plot of the current measured at 100 V as a function of wavelength. This analysis is shown in the logarithmic plot of Fig. 4.1 (b) and was done in order to investigate the variation of the current with a wavelength of the incident light. A linear relation is noted with a slope much greater than unity (at 43.1). The magnitude of the slope shows that the current varies exponentially with the wavelength. It has to be noted that the slope of unity would be showing that the relationship is linear.

The effects of light on the current can be explained by the relation:

$$I = I_s \left[\exp\left(\frac{eV_a}{kT}\right) - 1 \right] - (eAL_p g_{op} + eAL_n g_{op}). \quad (4.1)$$

As stated before the second term in the equation corresponds to the photocurrent due to generated minority carriers. The current has been found to increase with an increase in light intensity [McPherson, 2005]. This indicates that as the intensity of light incident on the device increases, the density of the generated minority carriers increases, hence, the measured current increases. The results that are presented here

show that an increase in intensity is similar to an increase in wavelength of light incident on the device. This relation of the intensity and wavelength is explained by Eqs. (3.1) and (3.2).

Fig. 4.2 shows the I - V results for H13, the diode irradiated to a fluence of $\sim 10^{13}$ n cm⁻², with arbitrary reference line as in Fig. 4.1. The dark current is higher than that of H00 and its profile is found to be positioned closer to the profile of the green light at high voltages. This increase of the dark current is due to an increase in the number of e - h pairs after radiation damage in the material. The increase in e - h pairs is due to the defect levels induced in the energy gap of the silicon [Jones *et al*, 1998]. In this case the current is the sum of the saturation current and generation current as in Eq. (2.68). As it can be seen from the equation that the trap density is proportional to the generation current.

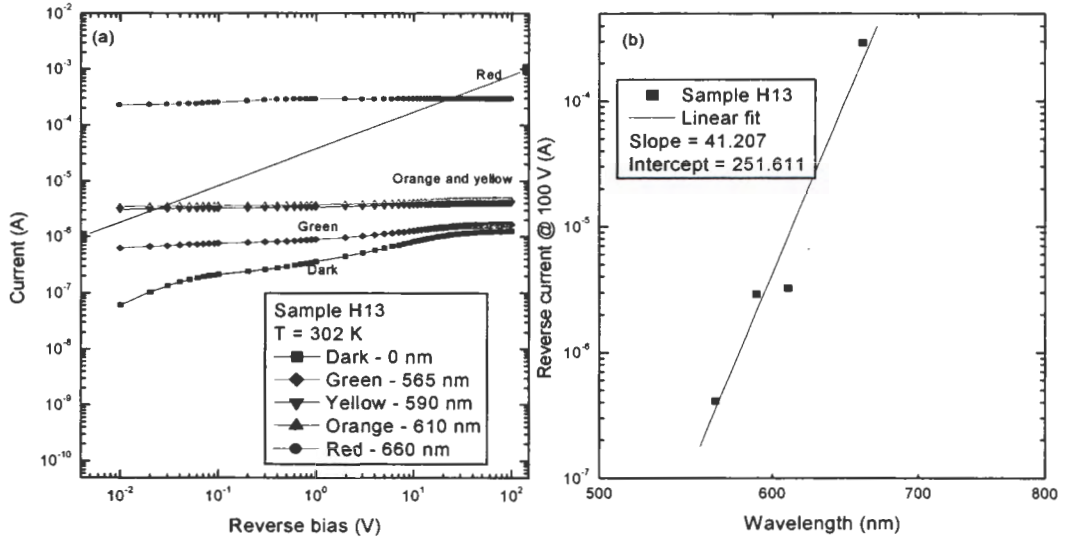


Fig. 4.2: A variation of the reverse I - V characteristic under illumination with light of different wavelengths at 302 K for H13 (a) and a plot of the reverse current measured at 100 V as a function of the wavelength (b).

The photocurrent for all wavelengths, on the other hand, still shows saturation up to 10^2 V. It can be noted that only the current generated by the green LED has increased

slightly in this diode and that it is no longer completely independent of the voltage. The significance of this is that in this diode the density of the defects generated by the radiation is not high enough to be able to recombine those carriers generated by the green light. Thus, some current is measured so that the trend is both due to those carriers generated by the radiation defects as well as those generated by the incident photons.

A plot of the current measured at 100 V as a function of the wavelength for H13 is shown in Fig. 4.2 (b). A linear relation is obtained. The slope is found to be 41.2, slightly lower than the 43.1 obtained for H00. This reduction of the slope shows that carrier generation is less. This is due to the defect levels that are induced by the irradiation in the energy gap. These defects recombine the photo-generated carriers to reduce the amount of carriers that are drawn to the electrodes. This results in a decrease in the measured photocurrent. Since these defects increase with an increase in the radiation fluence [McPherson, 2004], it is expected that the measured photocurrent will decrease as the radiation fluence increases further.

Fig. 4.3 shows the I - V characteristics of the diodes irradiated to $\sim 10^{14}$ (a), $\sim 10^{15}$ (b), $\sim 10^{16}$ (c) and $\sim 10^{17}$ (d) n cm^{-2} all with the arbitrary reference line as in previous graphs. A main observation from plot (a) for diode H14 is that the current generated by shorter wavelengths is equal to the dark current. These results show that the properties of this diode are independent of the incident light of the shorter wavelengths. Even though the current generated by the red LED is higher than that generated by the other LEDs, it can be seen that the trend has come closer to that of the dark current (or that the red LED current has decreased) for low voltages. This is due to the fact that the photo-generated carriers are recombined by the radiation-induced defect levels to reduce the photocurrent. In comparison with H13, however,

the dark current in H14 has increased to show that the defect levels can also generate carriers to contribute to the measured current. Thus, these levels can recombine photo-generated carriers to reduce the photocurrent or generate carriers to increase the dark current.

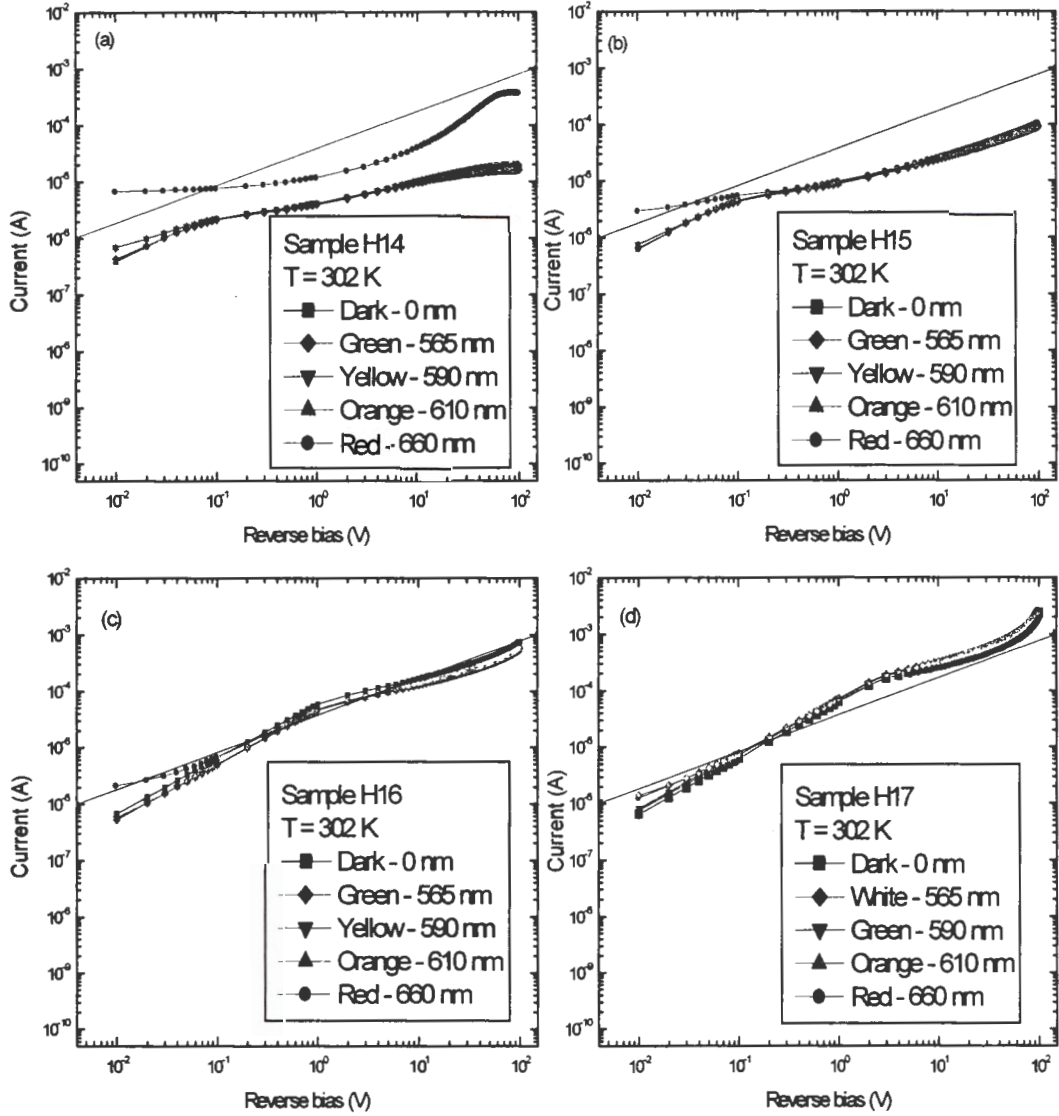


Fig. 4.3: A variation of the reverse I-V characteristic under illumination with light of different wavelengths at 302 K for diodes H14 (a), H15 (b), H16 (c) and H17 (d).

Another observation from plot (a) is that the trend for the red LED is different from all the other trends, showing saturation up to 10^0 V from where the current increases linearly with voltage up to 7×10^1 V. At voltages higher than 7×10^1 V the current

becomes constant (or is saturated). The trends of the shorter wavelengths, in contrast, show a linear increase of current with voltage up to 7×10^{-2} V from where the saturation (constant current) is observed up to 10^2 V. Since the number of defect levels increases with an increase in radiation fluence, it is expected that the properties of the diodes irradiated to fluences higher than 10^{14} n cm⁻² will be independent for all wavelengths of the incident light.

The results for H15, the diode irradiated to a fluence of $\sim 10^{15}$ n cm⁻² are shown in plot (b). The trends have come closer together and the photocurrent has decreased for all voltages. A significant observation is that for all wavelengths, the current continues increasing at 100 V. The trend for the red LED at low voltages, however, is independent of the applied voltage to show saturation of the current. Two linear regions with different slopes are observed in the plot for the trends of the shorter wavelengths and dark current. It can be noted that the slope of the linear region at voltages lower than 1×10^{-1} V is higher than the slope of the linear region at high voltages. A high slope at low voltages shows that in H15 the current is due to carriers that are generated by the incident light, by the temperature and by the radiation induced defect levels.

Unlike the current measured for H00, H13 and H14, the current measured for H15 does not show saturation at high voltages for all wavelengths which might indicate the onset of breakdown. This implies that there are more charges drawn to the electrodes. This in turn shows that at high voltage it is becoming easier to separate the $e-h$ pairs such that any mobile charge gets drawn to the electrodes to contribute to the measured current.

The results for H16, the diode irradiated to a fluence of $\sim 10^{16} \text{ n cm}^{-2}$ are shown in plot (c). At low voltages the trend for the red LED shows a slight independence of voltage. At high voltages, however, the current generated at all wavelengths is nearly equal to the dark current. The current increases linearly up to $7 \times 10^0 \text{ V}$, after which a gentle increase is observed up to $5 \times 10^1 \text{ V}$. At voltages higher than $5 \times 10^1 \text{ V}$, the current varies as $V^{1/2}$ to show that the diode is attempting to approach breakdown. Unlike in the case of diode H00 where breakdown is observed for dark current only, in H16 and H15 breakdown is observed for all currents. This means that any mobile charge is being drawn to the respective electrodes to contribute to the current. It is interesting to note that the profiles are all situated on the arbitrary reference line drawn from $1\mu\text{A}$ to 1 mA .

The current for diode H17, as shown in plot (d), increases linearly with voltage up to $3 \times 10^0 \text{ V}$ after which a gentle increase is observed up to $7 \times 10^1 \text{ V}$. At voltages higher than $7 \times 10^1 \text{ V}$ the current increases quickly with voltage up to 10^2 V to signify the onset of breakdown. Similar to H16 and H15, the onset of breakdown in H17 is also observed for all currents. Since the trends for photocurrent are not horizontal as it was observed in H00 and H13, and are found to be grouped together with the trend of the dark current, it can be argued that the effects of light are reduced as the fluence increases. This is due to the defect levels induced in the energy gap of the material by the irradiation. They recombine photo-generated carriers and make the measured current independent of the incident photons. It is worth noting that the profiles at high voltages are above the reference line in all cases.

From the obtained results it can be seen that the linear region of the trend at low voltages increases with an increase in radiation fluence. As a result, the diodes become more Ohmic as the fluence increases. This Ohmic behaviour of the diodes

has been explained elsewhere [Jones and McPherson, 1999; Moloi and McPherson, 2009] in terms of the defects that turn silicon into a relaxation material. The behaviour is caused by the generation-recombination ($g-r$) centres that are induced in the energy gap of the material [Jones *et al*, 1997]. These levels are situated close to the midgap where they interact equally with both bands to maintain the Fermi energy at the intrinsic level [Brudnyi *et al*, 1995]. This type of material is known to be resistant to radiation damage. Thus, the results presented here also show that the material becomes radiation-hard after the initial heavy damage by radiation.

At high electric fields, however, the Ohmic behaviour is not that well-pronounced to show that the field is able to quickly sweep out carriers. Thus, a large number of carriers are collected at opposite electrodes to induce breakdown. It must be noted here that the charge in the device is due to photo-generated carriers as well as to $e-h$ pairs generated from $g-r$ centres. However, at this fluence the measured current becomes limited by the $g-r$ centre activity such that the photo-generation activity is irrelevant. This is also shown by the photocurrent being equal to the dark current at all voltages.

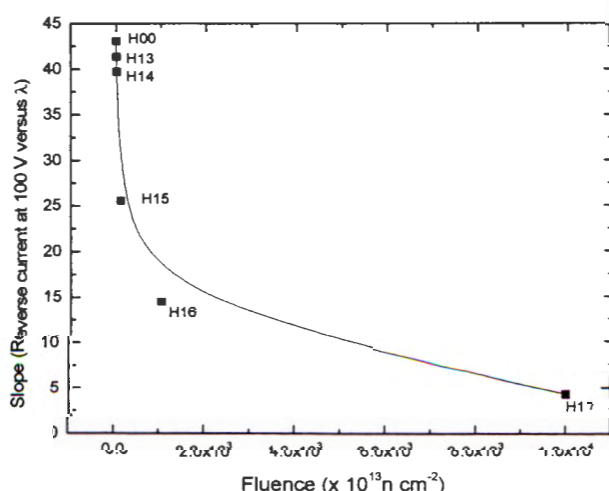


Fig. 4.4: A variation of the slopes (obtained from a current versus wavelength plot) with fluence. The slope decreases as the fluence increases.

A linear relationship of the reverse current measured at 100 V with wavelength was also obtained for the diodes H14, H15, H16 and H17 as in Fig. 4.1 (b) and Fig. 4.2 (b). The slopes obtained were used to generate the plot of Fig. 4.4. These values of the slopes are shown in Table 4.1 for all the diodes tested. At low fluences a considerable dependence of the slope on the fluence is observed but from H15 the slope decreases gently with fluence to show that the measured current becomes independent of the incident light. These results show that the effects of light are reduced as the material becomes radiation-hard (or relaxation-like) after heavy irradiation.

Table 4.1: Slopes obtained from the plots of the reverse current measured at 100 V as a function of the wavelength for unirradiated and irradiated devices.

Diode	H00	H13	H14	H15	H16	H17
Slope	43.052	41.307	39.701	25.598	14.502	4.285

4.1.2 Capacitance-voltage measurements

In capacitance measurements, the donor density can be related to the full depletion capacitance as

$$N_d = \frac{2C_d^2}{e\epsilon_s\epsilon_0 A^2} (V_d). \quad (4.2)$$

The above relation shows that for a constant donor density in the depletion region, $V_d \propto C_d^{-2}$ which is the case for uniform doping and is often assumed for devices made from lifetime material. Also, because any a.c. changes in the charge are produced at the edges of the depletion region [Blood and Orton 1992], the capacitance is controlled mainly by the width such that $C \propto W^{-1}$. As a result, the effective carrier density is not constant, and is given as

$$N_{\text{eff}} = \frac{2C_d^2}{e\epsilon_s\epsilon_0 A^2} (V_d) \quad (4.3)$$

for a relaxation semiconductor by substitution of N_d with N_{eff} . This means that $C_d \propto \sqrt{N_{\text{eff}}}$ for a constant V_d . Hence, any increase in radiation fluency is expected to increase N_{eff} . This point has already been made and confirmed by I - V data. In this section we present the C - V data in support of the I - V data presented above.

Fig. 4.5 shows reverse C - V characteristics of the unirradiated diode, H00, in the dark and under illumination by light of different wavelengths. A main observation from plot (a) is that the capacitance measured at short wavelengths (610 nm, 590 nm and 565 nm) is equal to that measured in the dark for all voltages (not for 1 V). Another striking feature is that the profiles of the capacitance measured at these wavelengths differ from that of the red LED (660 nm). The profiles for low wavelengths show a steep fall at low voltages which becomes a gradual fall at higher voltages. The profile for the red LED, on the other hand, is horizontal (or constant capacitance) at voltages lower than 1×10^1 V to show that the capacitance is nearly independent of the voltage. This lack of dependence is due to the fact that the e - h pairs generated by the red LED are not being drawn out to the electrodes such that there is a large electrical neutral bulk (enb) as fixed charge is neutralised. However, as the voltage increases, these e - h pairs are reduced in the depletion region as they become drawn out and this results in a decrease in the measured capacitance of the diode (or an increase in the depletion width). These results show that a high voltage is required to fully deplete the diode when it is under illumination by the red LED, and this is shown where the capacitance suddenly falls at about 25 V.

The profiles of plot (a) were used to generate a graph of the capacitance measured at 3×10^1 V as a function of wavelength and this is shown in plot (b). It can be noted that

linear fit adopted does not correspond to a realistic description of the data. The slope, however, is found to be much greater than unity (63.8) to confirm that carrier generation is exponentially related to the incident wavelength. Thus, the C - V data presented in this section is consistent with the I - V data presented earlier.

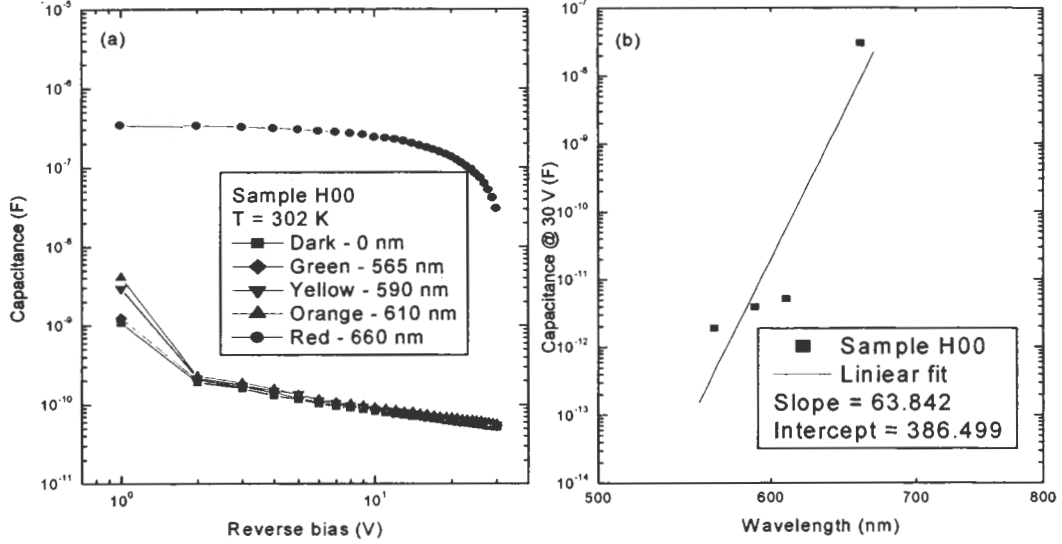


Fig. 4.5: A variation of the C - V characteristic under illumination with light of different wavelengths at 302 K for H00 (a) and a plot of the capacitance measured at 30 V as a function of the wavelength (b).

Fig. 4.6 shows the C - V results for H13, the diode irradiated to a fluence of 10^{13} n cm^{-2} . As for H00, the capacitance measured at shorter wavelengths is equal to that measured in the dark as shown in plot (a). The capacitance measured under illumination by the red LED has increased and at low voltages it is independent of the voltage as in the case for H00. The sudden fall in capacitance occurs at a lower voltage of 2×10^1 V.

A plot of the capacitance measured at 3×10^1 V as a function of the wavelength for H13 is shown in plot (b). A linear relation is obtained with a slope of 43.2. This slope is lower than the one evaluated for H00 (63.8) to show that the rate at which the capacitance, due to incident photons increases has been reduced for H13. As

explained before, this reduction is due to recombination of photo-generated carriers with radiation-induced defect levels to increase the enb and so to increase the depletion width.

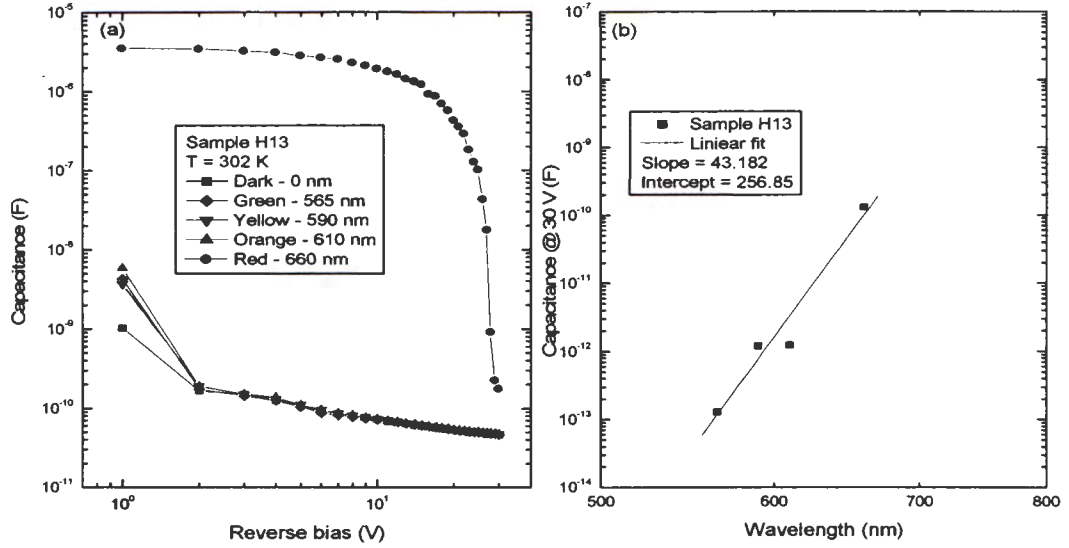


Fig. 4.6: A variation of the C - V characteristic under illumination with light of different wavelengths at 302 K for H13 (a) and a plot of the capacitance measured at 30 V as a function of the wavelength (b).

Fig. 4.7 shows the C - V characteristics of the diodes that were irradiated to $\sim 10^{14}$ (a), to $\sim 10^{15}$ (b), to $\sim 10^{16}$ (c) and to $\sim 10^{17}$ (d) n cm^{-2} . It can be seen from plot (a) for diode H14 that the capacitance measured at shorter wavelengths is still comparable to that measured in the dark. The trends are similar to those of diodes H00 and H13. However, there is an increase in dark capacitance due to an increase in the number of e - h pairs after radiation damage. Unlike for diodes H00 and H13, at voltages lower than 3×10^0 V a trend of the red LED resembles those of the other LEDs, after which it becomes independent of the applied voltage up to 1×10^1 V. The trend for the red LED has shifted closer to that of the dark capacitance showing that the capacitance measured with the red LED has decreased. The reduction in photocapacitance is due to the recombination of photo-generated carriers by radiation-induced defect levels. At voltages higher than 1×10^1 V the capacitance increases gradually with the applied

voltage. The reason for this slight increase of the capacitance at high voltages is currently not known. It might be an indication of the effects of the incident light on the diodes just before type inversion of the material [Pitzl *et al*, 1992].

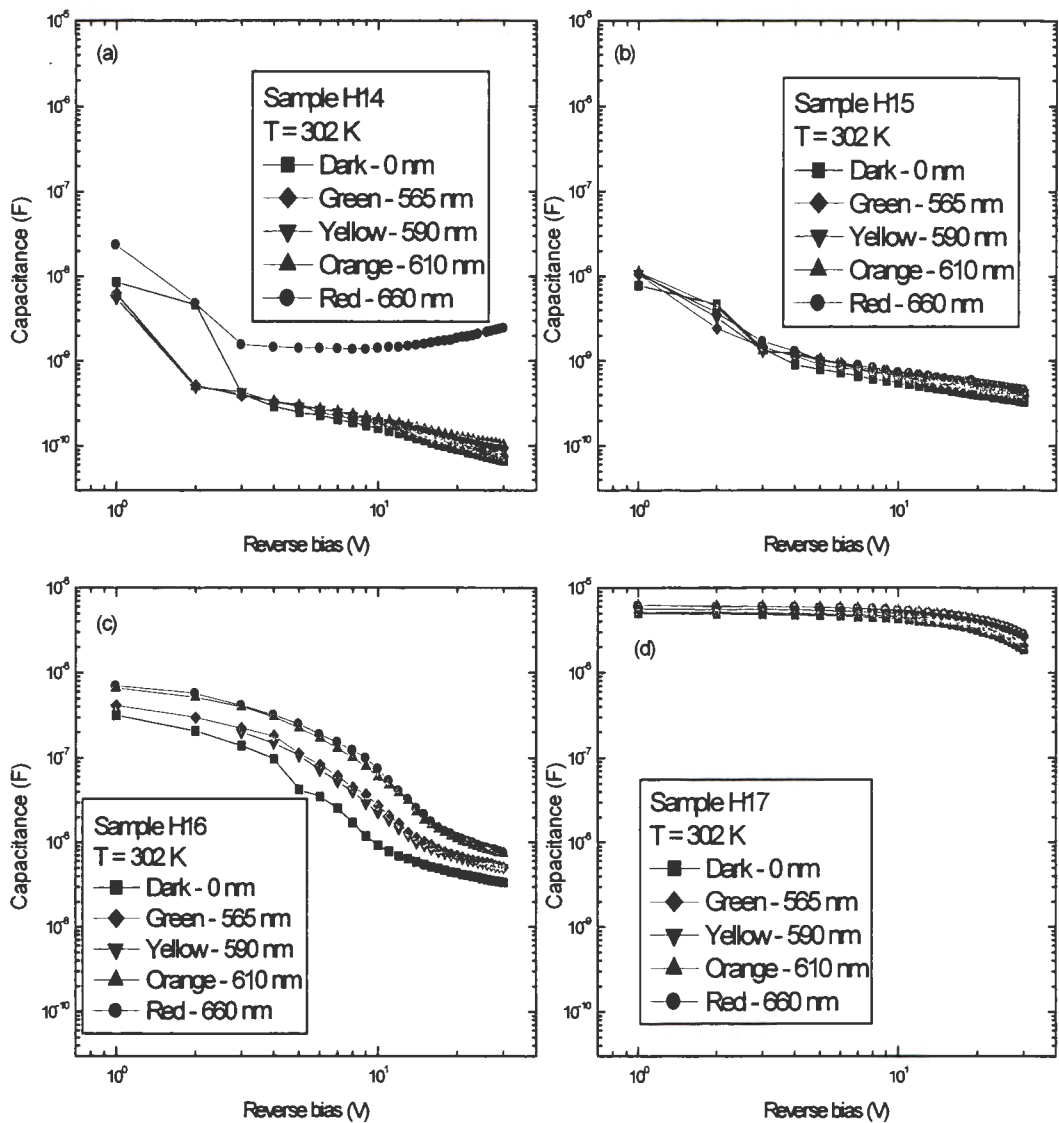


Fig. 4.7: A variation of the C-V characteristic under illumination with light of different wavelengths at 302 K for diodes H14 (a), H15 (b), H16 (c) and H17 (d).

The results for H15, the diode irradiated to $\sim 10^{15}$ n cm⁻² are shown in plot (b). The trends have come closer together and the capacitance measured under illumination is equal to that measured in the dark. In comparing the capacitance measured for diode H14 with that measured for diode H15, one notices that the capacitance measured in

the dark is increased by 10 % while that measured by the red LED has decreased by the same percentage. This result shows that the rate of generation of carriers by defect levels equal to that of recombination. This process where the generation rate is equal to the recombination rate can only occur if the defect levels are positioned at the midgap where they interact equally with both the valence and the conduction bands. Properties and effects of these levels on the material have been explained elsewhere [Jones *et al*, 1997] and they were found to contribute to the relaxation behaviour of the material.

The diodes fabricated from the relaxation material have been found to perform better as radiation-hard detectors [Jones and McPherson, 1999]. Thus, light can be used to investigate the radiation-hardness of the semiconductor onto which the diode has been fabricated. As the material becomes radiation-hard (or relaxation-like) due to the initial heavy radiation damage, properties of the diode become independent of the incident light.

The results for H16, the diode irradiated to $\sim 10^{16} \text{ n cm}^{-2}$ are shown in plot (c). It was expected that the capacitance would be independent of the light incident onto the diode as was shown for the current in Fig. 4.3 (c). However, the results show that the capacitance varies with the wavelength. Unlike for diodes H00, H13, H14 and H15, in the case of H16 a variation of the capacitance is observed for all wavelengths. The trends, on the other hand, are following each other and the capacitance decreases steadily up to a voltage of $2 \times 10^1 \text{ V}$. At voltages higher than $2 \times 10^1 \text{ V}$ the fall in capacitance is reduced to show that the diode is becoming fully depleted. A significance of the dependence of the capacitance on the wavelength is that the capacitance is increasing to resemble a trend of the red LED shown for H00 and H13. This occurs as the device attempts to attain a level of full damage. This is the level at

which the light has no effect and the material is governed only by the $g-r$ centre activity which is a limiting factor.

The results for H17, the diode irradiated to $\sim 10^{17} \text{ n cm}^{-2}$ are shown in plot (d). The trends have come closer together to show that the capacitance measured in the dark is equal to that measured under illumination. The dark capacitance has increased and is found to be constant at voltages lower than $1 \times 10^1 \text{ V}$. At voltages higher than $1 \times 10^1 \text{ V}$ the capacitance decreases gently. Unlike for diodes H00 and H13 where only a trend of the red LED shows that the capacitance is constant, for diode H17 the capacitance is constant for all wavelengths. Of most importance is that the trend for all wavelengths is different to all the other diodes, and is much similar to the trend for the red LED for diodes H00 and H13. As stated, this trend indicates that carrier transport in the device is governed only by the $g-r$ centres which contribute to the cause of the relaxation-behaviour in the material [Jones *et al*, 1997].

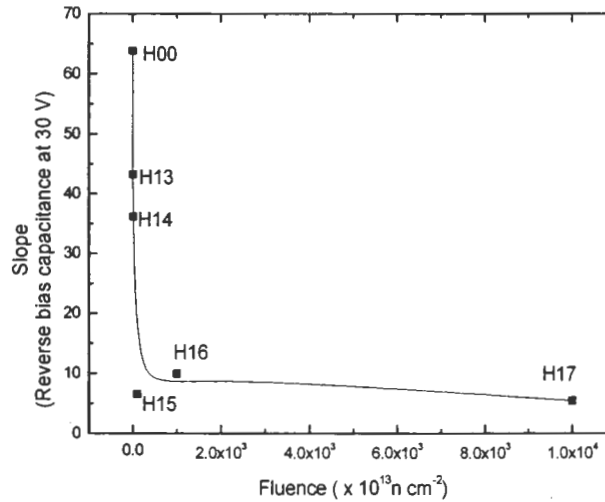


Fig. 4.8: A variation of the slopes (obtained from a capacitance versus wavelength plot) with fluence. The slope decreases as the fluence increases.

A linear relationship of the capacitance measured at $3 \times 10^1 \text{ V}$ with wavelength was obtained for diodes H14, H15, H16 and H17 as in Fig. 4.5 (b) and Fig. 4.6 (b). The

slopes obtained were used to generate Fig. 4.8 and are shown in Table 4.2 for all the diodes tested. This trend for the capacitance is similar to the one shown in Fig. 4.4 for the current. A considerable dependence of the slope on fluence is observed at low fluence to show that the incident light has an effect on the measured capacitance. At high fluence the trend becomes horizontal to show that the slope is becoming independent of the fluence. This independence of the slope shows that at high fluence the effects of light on the measured capacitance are reduced.

Since at high fluence the relaxation behaviour of the diodes is clearly observed, where the Ohmic behaviour is more pronounced [Moloi and McPherson, 2009], the results show that as the material becomes radiation-hard, the diode capacitance is not influenced by the incident light. The radiation hardness of silicon due to initial heavy damage has been explained before for a diode irradiated to 10^{16} n cm⁻² [Litovchenko *et al*, 2006]. Device behaviour at high fluence or after radiation damage is governed solely by *g-r* activity.

Table 4.2: Slopes obtained from the plots of the capacitance measured at 100 V as a function of the wavelength for unirradiated and irradiated devices

Diode	H00	H13	H14	H15	H16	H17
Slope	63.842	43.182	36.139	6.557	9.929	5.54

4.2. Material characterization

The discussion on the results obtained from the *RBS* and *XPS* measurements is mainly based on the comparison of the metal-deposited samples prior to and after the annealing process. The *RBS* measurements were carried out on the samples immediately after the deposition and the annealing processes while the *XPS* measurements were carried out two years after the processes. During this period the samples were stored at subzero temperature in the fridge. The results show that the

samples were contaminated with carbon and oxygen. These contaminants are more on the surface of the samples than in the bulk. It is possible that changes observed in silicon properties were due to the metals intentionally diffused into the bulk.

4.2.1 *RBS* measurements

Gold-deposited samples

Fig. 4.9 shows the *RBS* spectra of the gold-deposited samples prior to and after the annealing process. The front edges of gold and silicon are marked by arrows in plot (a). Also in the figure the dashed (black) line denotes the experimental data and the continuous (red) line shows the RUMP simulated curve. The simulation fits very well to the spectrum of the unannealed sample. The simulation for the annealed sample could not be done since it was difficult to match with the experimental data. It has to be noted that the simulation of the data obtained from the annealed samples is difficult since some of the metals produced isotopes as they diffuse into the silicon bulk. The simulation of the curves is not of concern at this stage. Of concern is a change of shape in the spectrum and the reduction and the sloping of the metal peak after the annealing process.

The *RBS* spectrum of the unannealed sample shows the gold peak which fall off sharply at the low energy edge. This fall shows the abrupt silicide-silicon interface and smooth silicide surface [Prabhakar *et al*, 1983; Iaiche *et al*, 2005]. The spectrum does not show evidence of contamination or a formation of the oxide layer on the silicon surface. If there was an oxide layer formed, the yield due to the oxygen would have superimposed on the silicon plateau [Grasserbauer and Werner, 1991]. Thus, the thickness of the layer, if any, formed must be below 30 nm, the depth resolution of the *RBS* technique [Londergan *et al*, 2001].

Using the RUMP software, the simulated data show that the thickness of gold deposited on the silicon surface is 1510 Å, which translates to the atomic concentration of 891.64 cm⁻². This value is higher than 1000 Å, which was recorded during the deposition process of the metal. This difference of the measured thickness could be due to the incorrect reading of the crystal monitor in the vacuum chamber. The efficiency of the monitor reduces if it has been used for a long time.

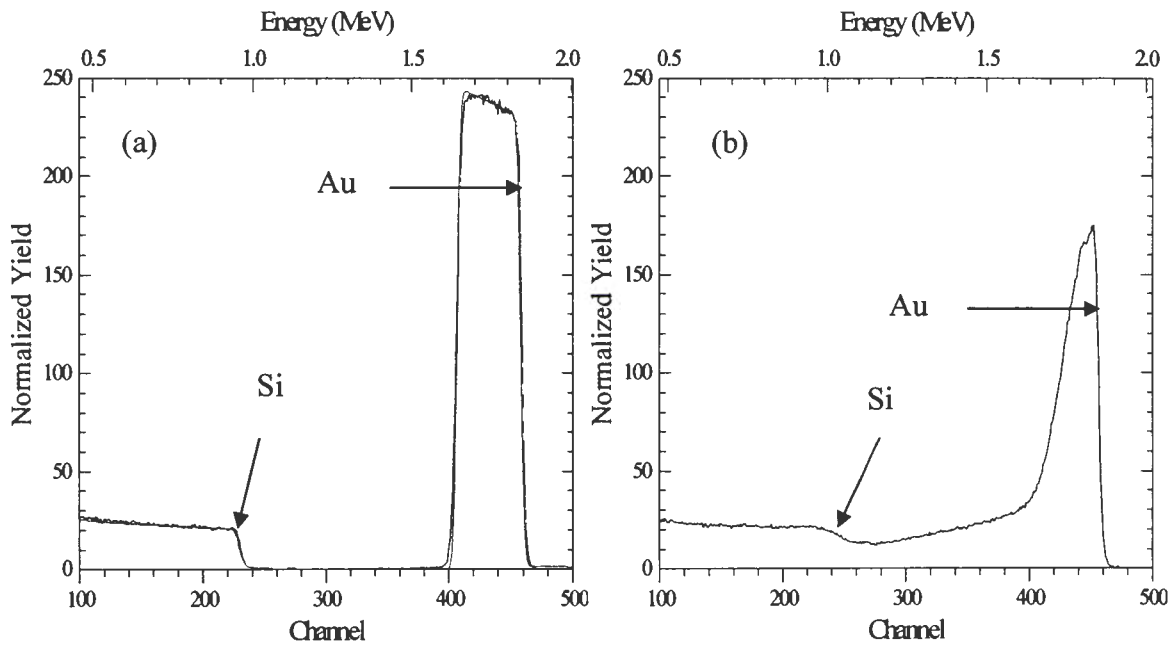


Fig. 4.9: RBS spectra from the gold-deposited samples (a) prior to and (b) after the annealing process.

In plot (b), for the annealed sample, the gold peak height and width at half maximum from the front surface indicate that there is still a considerable amount of gold on the silicon surface. It can be noted that the gold peak height in the figure is less than the one in plot (a). This shows that the gold concentration remaining on the silicon surface after the annealing process is 29 % less than in the unannealed sample. Another observation from plot (b) is the sloping of the gold peak height at the lower energy edge. This sloping shows that a metal-silicide has been formed as a large amount of gold was incorporated in silicon during the diffusion process [Dev, 2001; Tan *et al*, 2002]. The non-zero yield observed between channel 400 and 280 is

currently not understood. This non-zero yield could be showing a considerable amount of gold into silicon.

It has to be noted that the results obtained here do not show the diffusion mechanism of gold into silicon. The spectrum observed in plot (b) is, however, similar in shape to those presented for the samples that were annealed at the temperature of 1000 °C for 12 hours [Msimanga and McPherson, 2006]. The results in that case were thought to be due the substitutional or the kick-out mechanism of gold into silicon. The kicking-out mechanism, however, dominates in the annealing temperature ranging from 800 to 1200 °C [Gosele *et al*, 1980]. At this annealing temperature range, the diffusion profile of gold in silicon is U-shaped [Coffa *et al*, 1988]. Since the samples in this work were annealed at 900 °C, the result obtained can be interpreted in a similar way. The *RBS* spectra obtained by Msimanga and McPherson [2006], however, presents the non-zero yield only up to channel 360 while the spectrum presented in plot (b) shows the non-zero yield up to the silicon peak. This disparity could be due to the initial amount of gold deposited on the substrates. In the case of Msimanga and McPherson, [2006] the initial amount of gold deposited was low ($\sim 280 \text{ \AA}$).

Platinum-deposited samples

Fig. 4.10 shows the *RBS* spectra of the platinum-deposited sample prior to and after the annealing process. The platinum peak in plot (a) falls off sharply at the low energy edge to show the abrupt silicide-silicon interface and smooth silicide surface before the diffusion process. The spectrum, however, shows the small peak at channel 400 which cannot be accounted for at this stage. Since metals form isotopes as they are deposited on silicon [Mohanty and Kasiviswanathan, 2006], it is possible that the peak is due to one of the platinum isotopes. However, the *XPS* results presented later in this chapter suggest that the peak may be due to the bonding of carbon to platinum.

The thickness of platinum deposited is found to be 1100 Å, which translates to the atomic concentration of 728.05 cm⁻². This value is higher than (1000 Å) the one determined by the crystal monitor. In this case the crystal monitor used was better than the one used for the deposition of gold.

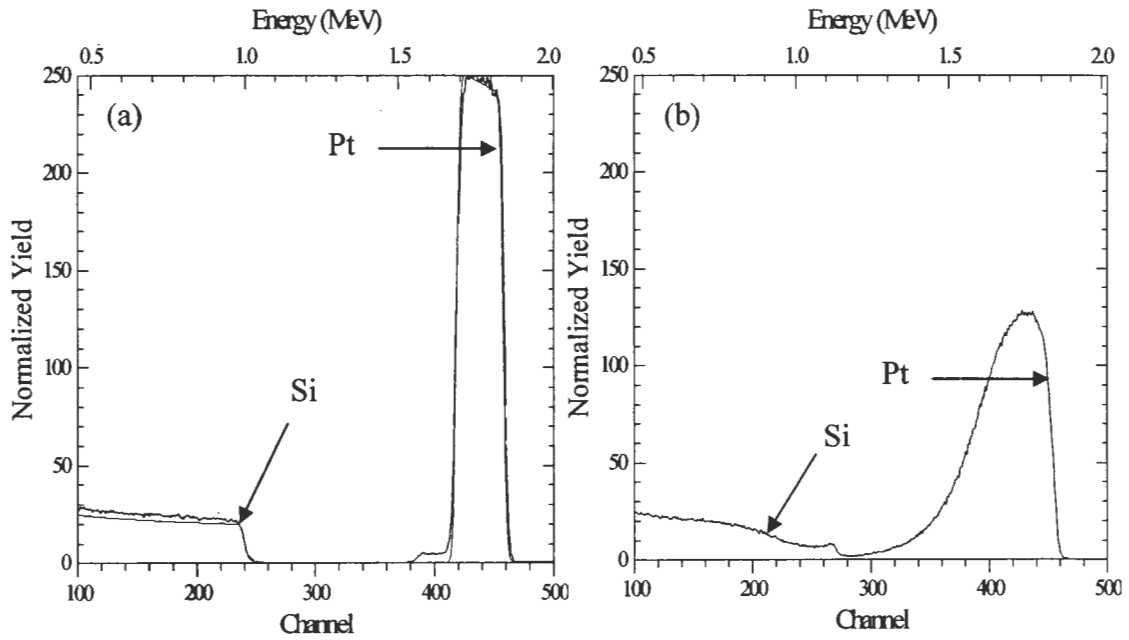


Fig. 4.10: RBS spectra from the platinum-deposited samples prior to (a) and after the annealing process (b).

In plot (b), the spectrum indicates that there is still a considerable amount of platinum on the silicon surface. The peak height is less than the one in plot (a) to show that the platinum concentration remained on the silicon surface after the annealing process is 52 % less than in the unannealed sample. The spectrum shows the sloping of the platinum peak at the low energy edge to indicate that platinum silicide was formed as platinum was incorporated in silicon during the diffusion process. These results are similar to those presented in Fig. 4.9 (b) for the gold-deposited samples. Another observation from the figure is that the small step has shifted towards the front edge of silicon (280). This shifting may be showing that platinum has diffused into the silicon bulk with a very low amount of carbon bonding on it. The no-zero yield is, however, not as pronounced as in the case of gold-deposited sample.

The spectrum presented in plot (b) is similar to the one presented for the platinum-deposited sample that were annealed at 900 °C for 3 hours [Prabhakar *et al*, 1983]. At this annealing temperature the diffusion mechanism of platinum in silicon is kick-out mechanisms [Schmidt *et al*, 1999; Bostrom *et al*, 2000]. The defect level that was found to be more active was a donor level at the lower half on the energy gap [Prabhakar *et al*, 1983], which is known to be the recombination centre. It is expected that the resistivity of silicon will increase after doping with platinum since the mobile carrier would be recombined.

Erbium-deposited samples

Fig. 4.11 shows the *RBS* spectra of the erbium-deposited samples prior to and after the annealing process. As it was observed in Fig. 4.9 and Fig. 4.10 for gold and platinum samples, respectively, the erbium peak also falls off sharply at the low energy edge to show the abrupt silicide-silicon interface and smooth silicide surface before the diffusion process. The spectrum does not show an evident of the contamination on the sample. Unlike in the case of platinum samples where the small step was observed, the spectrum does not show any formation of the isotope. The thickness of the erbium deposited is found to be 1150.00 Å, which translates to the atomic concentration of 376.44 cm⁻². This value is higher than (1000 Å) the one determined by the crystal monitor.

In plot (b), the erbium peak height is less than the one in plot (a). The erbium concentration remaining on the silicon surface after the annealing process is 39 % less than in the unannealed sample. The spectrum shows the sloping of the erbium peak at the lower energy edge to indicate that erbium-silicide was formed as erbium was incorporated in silicon during the diffusion process. This sloping is, however, not slanted as those observed in Fig. 4.9 (b) and Fig. 4.10 (b). Unlike in the case of gold

and platinum, the spectrum shows a peak on the silicon plateau at channel 150. This small peak shows that the sample was contaminated by either oxygen or carbon during the annealing process. This peak was expected to be slightly higher since erbium reacts vigorously with oxygen. However, it is found to be very low due to the very high vacuum in which the annealing process was carried out. It can be noted that the non-zero yield between the erbium and silicon peaks is not observed in the case of the erbium-deposited sample.

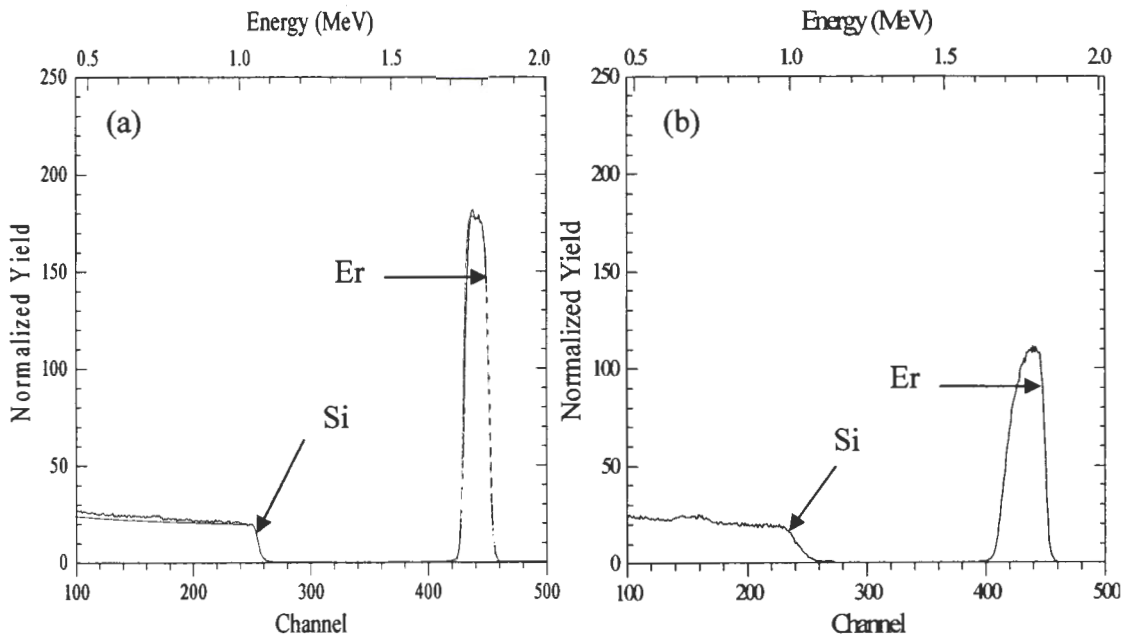


Fig. 4.11: RBS spectra from the erbium-deposited samples prior to (a) and after the annealing process (b).

Niobium-deposited samples

Fig. 4.12 shows that the niobium peak also falls off sharply at the low energy edge to show the abrupt silicide-silicon interface and smooth silicide surface before the diffusion process. The thickness of the niobium deposited is found to be 1050 Å, which translates to the atomic concentration of 585.57 cm^{-2} . The spectrum shows the oxygen peak on the silicon plateau at channel 150. This peak makes the best fit of the simulation not to be achieved for the silicon data. It can be noted from the figure

that the height of the silicon plateau has increased slightly because of the oxygen peak.

In plot (b), the niobium peak height is less than the one in plot (a). The niobium concentration remaining on the silicon surface after the annealing process is 56 % less than in the unannealed sample. The sloping of the peak is also observed at the lower energy edge. This sloping is more slanted than the one observed in Fig. 4.11 (b), for the erbium-deposited sample, but less than those observed in Fig. 4.9 (b) and Fig. 4.10 (b), for the gold-deposited and platinum-deposited samples, respectively. The step observed in channel 270 points to the formation of the impurity compound [Msimanga, 2004]. This compound could be due to the reaction of silicon and either with oxygen or carbon. Carbon and oxygen are elements known to contaminate the substrates during the growth of the silicon wafer [Neamen, 1997].

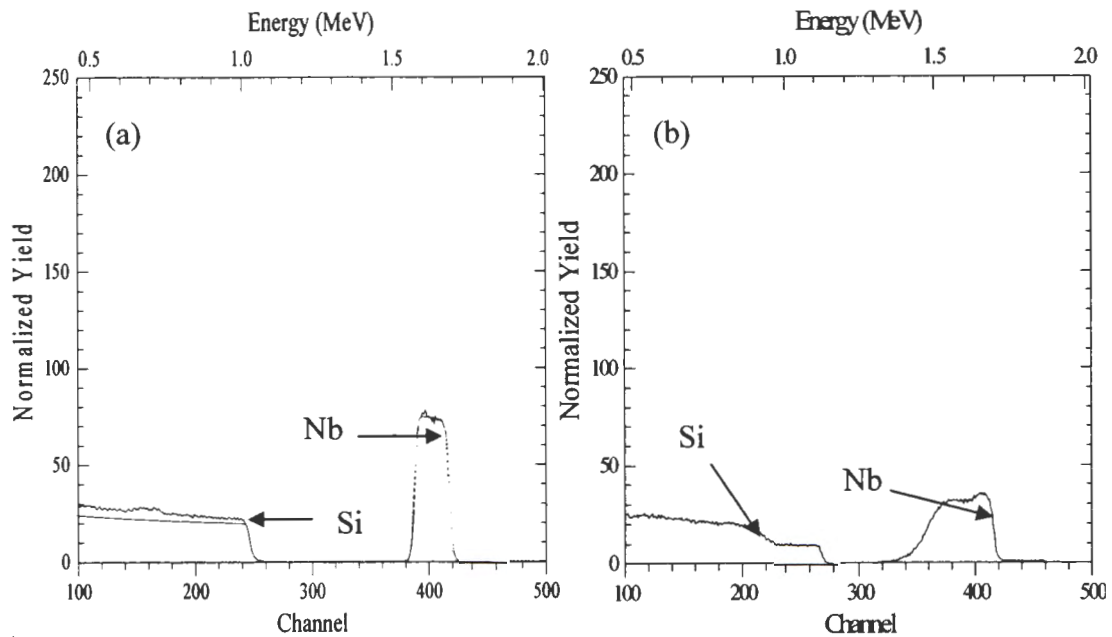


Fig. 4.12: RBS spectra from the niobium-deposited samples prior to (a) and after the annealing process (b).

The RBS measurements show that prior to the annealing process, the metal-silicide is not formed and there is no interface layer formed between the silicon and the metal layer. A good simulation curve was fitted well on the spectra to determine the exact

amount of metal deposited on the samples. The *RBS* spectra obtained from the samples after the annealing process show a reduction of the metal peak. Apart from the spectra obtained from the erbium-coated sample, the spectra for other samples indicate the sloping of the metal peak at the lower energy edge to indicate that the metal-silicide was formed when the metal was diffusing into the bulk. The non-zero yield is more pronounced on the gold-coated and platinum-coated samples to indicate that there are considerable amount of metal diffused into the bulk. On the erbium-coated sample, however, the non-zero yield is not observed to indicate that the diffused amount of erbium might be below the detection limit of the technique.

The *RBS* results presented here do not explain the depth profiling of the metal from the surface to the silicon bulk. They do not also indicate the profiling of the sample contaminants. It has to be noted that the slanting of the metal peaks at the lower energy edge and the non-zero yield that is observed mainly in Fig 4.9 (b) and Fig. 4.10 (b) cannot be thoroughly explained by the results obtained from the *RBS* measurements. These features are not explained because it is difficult to simulate the *RBS* spectrum that has these features. Since the contaminants affect the properties of silicon and the diodes fabricated on it, the information regarding these contaminants should be acquired so that they can be minimized in the silicon bulk. Thus, another surface sensitive technique is required to supplement the results obtained from the *RBS* technique.

4.2.2 XPS measurements

To supplement the *RBS* results, the *XPS* measurements were carried out on the samples. The *XPS* spectra of interest in this work are for silicon, gold, platinum,

erbium and niobium. Carbon and oxygen are the main contaminants of the samples and their spectra are also analysed.

Gold-deposited samples

Fig. 4.13 shows the *XPS* depth profile for gold-deposited samples (a) prior to and (b) after the diffusion process. The spectra for carbon and oxygen are also presented in the figure. In plot (a) the spectra show that carbon with 22 % atomic concentration and oxygen with 75 % atomic concentration dominate on the surface. The sudden fall of the spectra is observed and they disappear completely after 2.5 nm. These elements are the main contaminants and are found only on top of the surface with very thin layers. This is expected since the measurements were carried out two years after the deposition process and during this period the samples were enclosed in the desiccators.

The *XPS* spectrum shows 100% atomic concentration of gold at the depth of 5 nm. After 6 nm the concentration of gold decreased to 2 % and then disappears completely at 16 nm. The atomic concentration of silicon increases sharply until it saturates at 16 nm. It was noted that the sharp increase of the silicon spectrum corresponds to the sharp decrease of the gold spectrum to show that there is no interface layer between gold and silicon [Pankow, 2003]. It is evident from the results that after 16 nm only the silicon spectrum dominates. This shows that there are no contaminants and gold has not diffused into the bulk. These results agree very well with those that are presented in Fig. 4.9 (a) for the *RBS* measurements.

In plot (b) the spectra show that carbon with 40 % atomic concentration and oxygen with 28 % atomic concentration still dominate on the surface. The spectra for these contaminants disappear completely after sputter depth of 10 nm to show that they are

very thin on the surface and do not diffuse into the bulk. Gold is also found on the surface with 10 % atomic concentration. For the further sputter depth, the concentration increases to 60 % at 18 nm. After 18 nm the spectrum falls quickly and disappears completely at 50 nm.

Silicon is also observed with 24 % atomic concentration on the surface after the diffusion process. The concentration decreases slightly before the depth of 7 nm and then increases sharply to 90 % atomic concentration at 25nm. After 26 nm the spectrum shows a tendency of saturation. As explained earlier, a sharp decrease of gold that corresponds to a sharp increase of silicon indicates that there is no interface layer formed between gold and silicon after the diffusion process. The presence of silicon on the surface shows that it was exposed when gold was diffusing into the bulk.

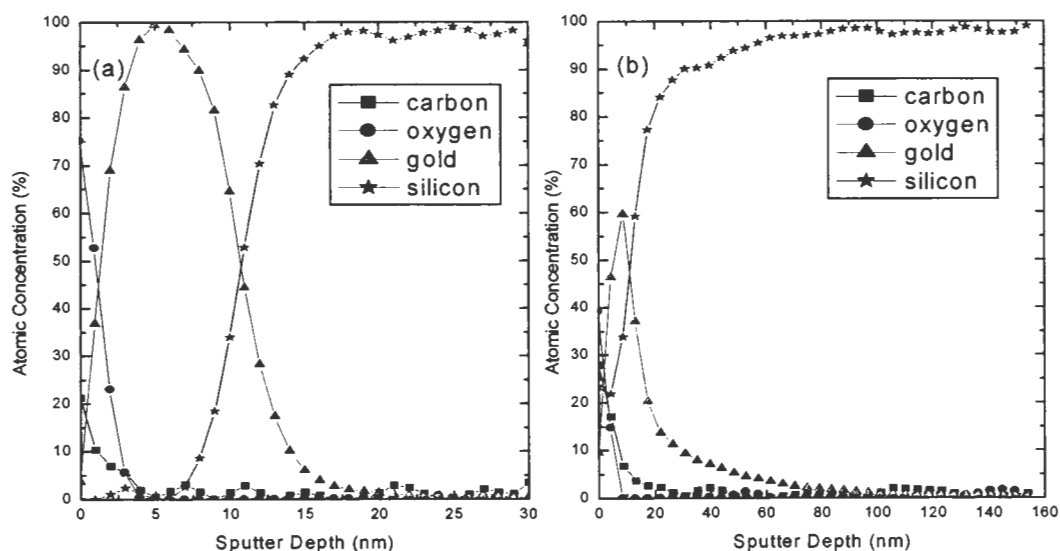


Fig. 4.13: XPS depth profile for gold-deposited samples prior to (a) and after the annealing process (b) showing carbon and oxygen.

It is worth noting that the gold peak is found in the silicon spectrum with a higher atomic concentration at the sputter depth less than 18 nm. The shifting of the gold peak to the higher sputter depth confirms the diffusion of gold into the silicon. This is

evident from the *RBS* results in Fig. 4.9 (b) where the spectra show the sloping of gold peak at the lower energy. The *XPS* results show that the sloping observed in Fig. 4.9 might be indicating the gold-silicide with a high concentration of gold. With the aid of *XPS* results, it might be said that the non-zero yield observed in Fig. 4.9 is associated with gold in silicon.

Platinum-deposited samples

Fig. 4.14 shows the *XPS* depth profile for the platinum-deposited samples (a) prior to and (a) after the annealing process. The depth profile of carbon and oxygen are also presented in the figure to show that the sample was contaminated. The spectra presented in plot (a) show that carbon with 55 % atomic concentration and oxygen with 14 % atomic concentration dominate on the surface. A sudden fall of the carbon spectra to 47 % is observed after 1 nm and then it almost saturates at 45 % atomic concentration up to the depth of 8.5 nm. At the depth of 9 nm the concentration decreases sharply and disappears completely after the sputter depth of 15 nm. Since the spectrum is not decreasing sharply at the lower sputter depth as observed in Fig. 4.13, for gold-deposited sample, these results show that there is a thick layer of carbon on the sample. The oxygen spectrum, on the other hand, disappears completely after the depth of 2 nm to show that it is very thin on the surface.

The 22 % atomic concentration of platinum is also found on the surface. The platinum spectrum increases sharply to 55 % at the sputter depth of 1.5 nm and then saturates at 8.5 nm. After 9 nm the spectrum follows the one of carbon and decreases sharply to 16 nm. After the depth of 17 nm the spectra disappears completely. Since the carbon and platinum spectra reach the saturation and decrease sharply at the same depth, it can be said that carbon is bonded to platinum. These results explain the small peak observed in Fig. 4.10 (b) for the platinum-deposited sample. The peak has a very low

yield to show that the atomic concentration of carbon is lower than that of platinum. This is shown in Fig. 4.14 where the carbon spectrum is found to be lower than that of platinum at the saturation levels. It has to be noted that either the sample was contaminated by carbon during the deposition process or during the cleaning process since it is also observed in Fig. 4.10, for the results obtained immediately after the deposition. Thus, the XPS measurements can be used to explain features that are observed in the RBS spectra.

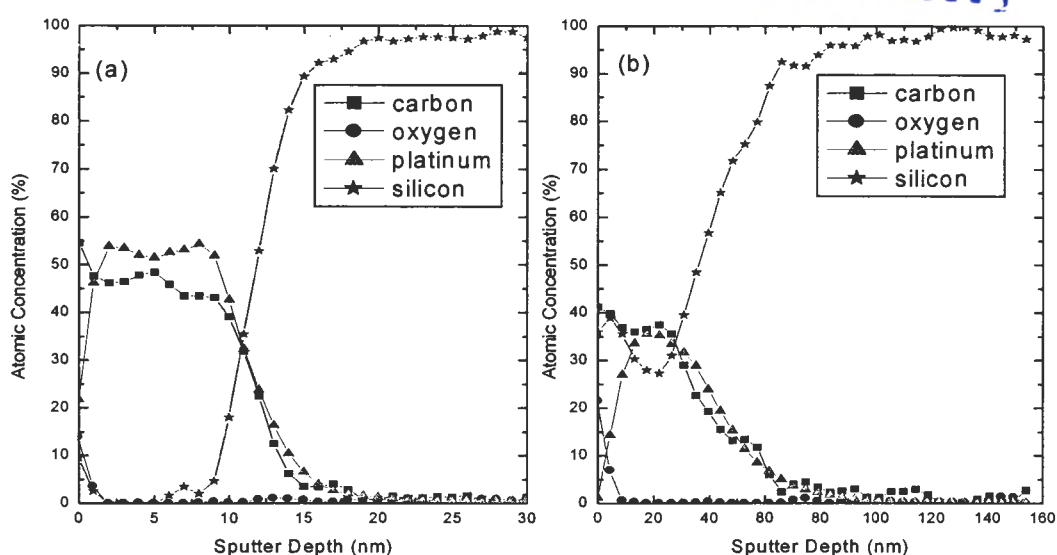


Fig. 4.14: XPS depth profile for platinum-deposited samples prior to (a) and after the diffusion process (b) showing carbon and oxygen.

The silicon spectrum shows the 9 % atomic concentration on the surface which decreases rapidly after 1 nm. After the sputter depth of 2 nm the spectrum disappears. After 7.5 nm the spectrum increases sharply up to 92 % at 17.5 nm and then the saturation is observed. The sharp increase of silicon spectrum corresponds to the sharp decrease of carbon and platinum spectra to show that there is no interface layer formed between platinum and silicon. Even though they are bonded, carbon and platinum are not found in the silicon bulk. This is shown in plot (a) where the silicon

spectrum completely dominates after 18 nm. This point was also explained in Fig. 4.10 (a) for the *RBS* results where the silicon plateau is observed to be smooth.

In plot (b) the spectra show carbon with 42 % atomic concentration on the surface and it remains almost constant up to the sputter depth of 30 nm. After 31 nm, the carbon concentration decreases with sputtering depth. In comparing the carbon spectra for both plots (a) and (b), it can be noted that in plot (b) the concentration has decreased at the higher sputter depth. This is an indication that carbon has decreased on the surface and diffused into the silicon bulk. As it is observed in Fig. 4.10, where the small peak is shifted towards the (silicon) lower channel to indicate that it has gone into the silicon bulk after the diffusion process. The oxygen spectrum, on the other hand, shows 22 % atomic concentration on the surface. Since the layer is very thin on the surface, the spectrum disappears completely at low sputter depth (4 nm).

Platinum is found on the surface with 2 % atomic concentration. For the further sputter depth, the spectrum increases to 50 % at 20 nm. After 21 nm the spectrum falls quickly and then disappears completely at 70 nm. Silicon is also observed with 35 % atomic concentration on the surface. The spectrum decreases slightly as sputter depth increases to 30 nm and then increases sharply to 92 % at 40 nm. After 41 nm the spectrum shows a tendency of saturation. As was explained earlier, a sharp decrease of carbon and platinum that corresponds to a sharp increase of silicon indicates that there is no interface layer formed between platinum and silicon. A presence of silicon on the surface shows that it was exposed when platinum was diffusing into the bulk.

It is worth noting that the platinum peak was found in the silicon spectrum with a higher atomic concentration at the sputter depth of 20 nm. The shifting of the

platinum peak to the higher sputter depth confirms the direct diffusion of platinum into the silicon bulk. It is shown by the *RBS* results in Fig. 4.10 that platinum-silicide is formed as platinum diffuses into the bulk. This is evident from the *RBS* results where the spectra show the sloping of platinum peak at the lower energy. The non-zero yield observed in Fig. 4.10 indicates that there is a considerable amount of platinum in silicon. It has to be noted that the non-zero yield found on the *RBS* spectrum of platinum-deposited sample is, however, not more pronounced as that of gold-coated sample. This is due to the difference between the relative atomic concentrations of silicon and the metals. In the platinum-deposited sample the difference between platinum atomic concentration and silicon atomic concentration at the depth of 19 nm is low. This results in low non-zero yield observed in Fig. 4.10.

Erbium-deposited samples

Fig.4.15 shows the *XPS* depth profile for erbium-deposited samples prior to (a) and after the diffusion process (b). The depth profile of carbon and oxygen are also presented in the figure to show that the sample was contaminated. In plot (a) the spectra show that carbon with 47 % atomic concentration and oxygen with 40 % atomic concentration dominate on the surface. The carbon concentration decreases sharply to 6 % at the sputter depth lower than 2 nm to show that it is very thin on the surface. After 2.5 nm, the spectrum oscillates between 0 and 5 % atomic concentration until it disappears completely at 20 nm. The oscillation could be due to fluctuation in the system. Unlike in the case of gold-deposited and platinum-deposited samples, where the oxygen spectrum in this case decreases to 25 % and then remains almost constant up to the sputter depth of 12.5 nm. After 13 nm the concentration decreases to 5 % at 15.5 nm and then to 0 %. This behaviour suggests that there is a thick layer of oxygen on the surface. Even though the *XPS* results show

the high relative concentration of oxygen on the surface, it has to be noted that the sample was contaminated after the deposition since the oxygen peak is not observed in Fig. 4.11. These results show that erbium can react with oxygen at low temperature.

The erbium spectrum increases sharply from 11 % on the surface to 65 % at the sputter depth less than 2 nm. After 2.5 nm the spectrum oscillates between 74 and 65 % atomic concentration up to the depth of 12 nm. After 12.5 nm the concentration decreases sharply to 5 % at 20 nm and then disappears completely.

The silicon spectrum shows the 0% atomic concentration on the surface showing that silicon has not been exposed to the surface. At the depth of less than 11.5 nm the spectrum oscillates between 0 and 3 %. This oscillation of the spectra at low atomic concentration could be due to fluctuation in the system. At the depth higher than 12 nm the sharp increase of the spectrum corresponds to the sharp decrease of erbium to show that there is no interface formed between erbium and silicon.

In plot (b) the spectra show carbon with 15 % atomic concentration and oxygen with 53 % atomic concentration on the surface. The carbon spectrum falls steadily to 3% at 25 nm. After 30 nm the spectrum increases to 11 % at 40 nm and then decreases steadily until it disappears at 70 nm. At the depth less than 7 nm the oxygen spectra decreases to 4.5 % and then increases to 20 % at 20 nm. After 21 nm the spectrum oscillates between 15 % and 18 % up to 48 nm and then decreases to 4 % at 78 nm. At the depth higher than 80 nm the spectrum disappears completely. Spectra for carbon and oxygen disappear after the longer sputter depth to show that carbon and oxygen are thick on the sample.

Erbium is found on the surface with the concentration of 3.5 %. The erbium spectrum increases to 37 % at the depth of less than 7 nm and then decreases to 28 % at the depth of 18 nm where it remains almost constant up to 33 nm. After 34 nm the spectra decreases rapidly to 2.5 % at the depth of 80 nm and then it disappears completely. The silicon spectrum, on the other hand, shows 30 % atomic concentration on the surface. At the depth less than 7 nm the spectrum increases to 49 % and then oscillates between 50 % and 45 % up to 40 nm. After 41 nm the concentration increases sharply to 95 % and then saturates. The sharp increase of silicon spectrum corresponds to the sharp increase of the erbium spectrum to show that there is no interface layer formed between.

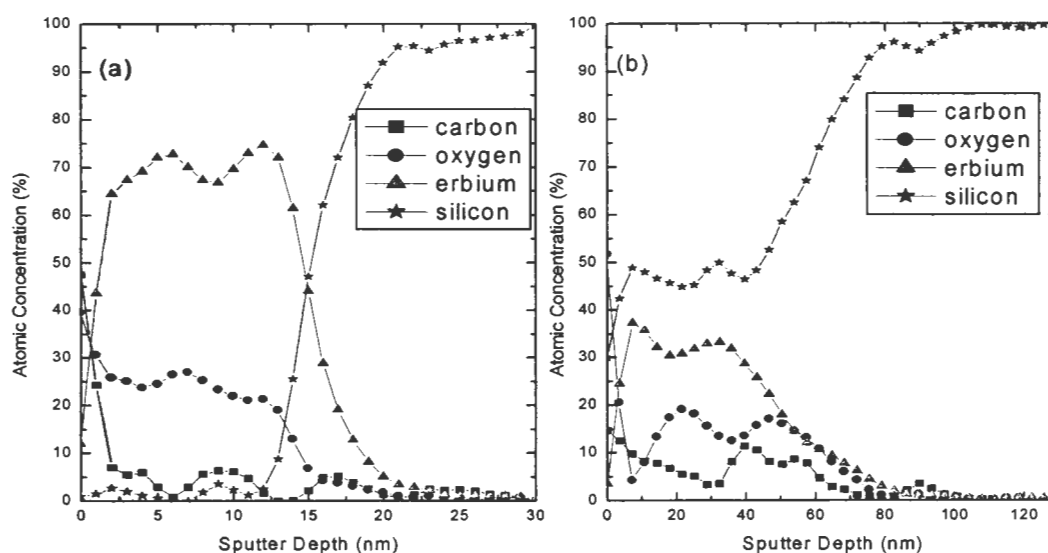


Fig.4.15: XPS depth profile for erbium-deposited silicon samples prior to (a) and after the diffusion process (b) showing carbon and oxygen.

Unlike in the case of gold and platinum, erbium spectrum is, however, found below the silicon spectrum at all depths. It can also be noted that the spectrum is not found in the silicon spectrum like in the other cases. These results suggest that erbium did not diffuse into the bulk. It can also be noted in Fig. 4.11 for RBS results that the sloping of the erbium peak at low energy edge is not pronounced to show that not

much of the silicide formed during the diffusion process. However, the *RBS* results also show a decrease in the erbium peak to indicate that erbium diffused into the bulk. The *XPS* result also show erbium atoms exposes silicon atoms as they diffuse into the bulk. These results could be showing that the relative atomic concentration of the erbium diffused in the bulk is below the detection limit (0.1 %) of the technique [Grasserbauer and Werner, 1991; Londergan *et al*, 2001]. As the sputter depth increases the sensitivity of the technique is also reduced [Schroder, 2006].

It is expected that few concentration of erbium will diffuse into the bulk at the annealing temperature of 900 °C for 18 hours. In order to have the considerable concentration of erbium into the silicon bulk the annealing time of 6×10^5 hours is required. This unreliable time was not adopted in this work since the intention is to investigate the effects of metals on the properties of the diodes fabricated on the silicon. The main concern is to create defects in silicon. The amount of metals diffused into the bulk is not of concern at this stage. This diffused atomic concentration of erbium that can not be detected by both techniques, however, is found to have huge effects on silicon. These effects of erbium are shown later in the chapter.

Niobium-deposited samples

Fig. 4.16 shows the *XPS* depth profile of niobium-deposited samples prior to (a) and after the diffusion process (b). In plot (a) the spectra show carbon with 71 % atomic concentration and oxygen with 25 % atomic concentration dominate on the surface. The carbon spectrum decreases sharply to 5 % at the depth lower than 2.5 nm to show that it is very thin on the surface. After 2.5 nm, the spectrum increases to 8 % and then it remains almost constant up to 10 nm. After 11 nm the spectrum disappears completely. The oxygen spectrum increases to 55 % at the depth lower than 2.5 nm.

At the depth higher than 2.5 the spectrum decreases to 2 % then it disappears at the depth higher than 8 nm. Both spectra show that they are thick on the surface.

A very low relative atomic concentration of niobium is observed on the surface. The spectrum increases to 48 % at the depth lower than 7 nm and then decreases to 3 % at the depth of 13 nm. After 13 nm the spectrum remains constant up to 30 nm. It can be noted in plot (a) that there is a very low atomic concentration of silicon on the surface. After 2.5nm the spectrum increases to 5.5 % and then remains constant up to 6 nm. At the depth higher than 6 nm the spectrum increases sharply to 86 % at 13 nm and then increases sharply to 93 % at 17.5 nm. The rapid increase corresponds to the sharp decrease of niobium to show that there is no interface layer. After 17.5 nm the silicon spectrum remains constant at 95 % up to 30 nm.

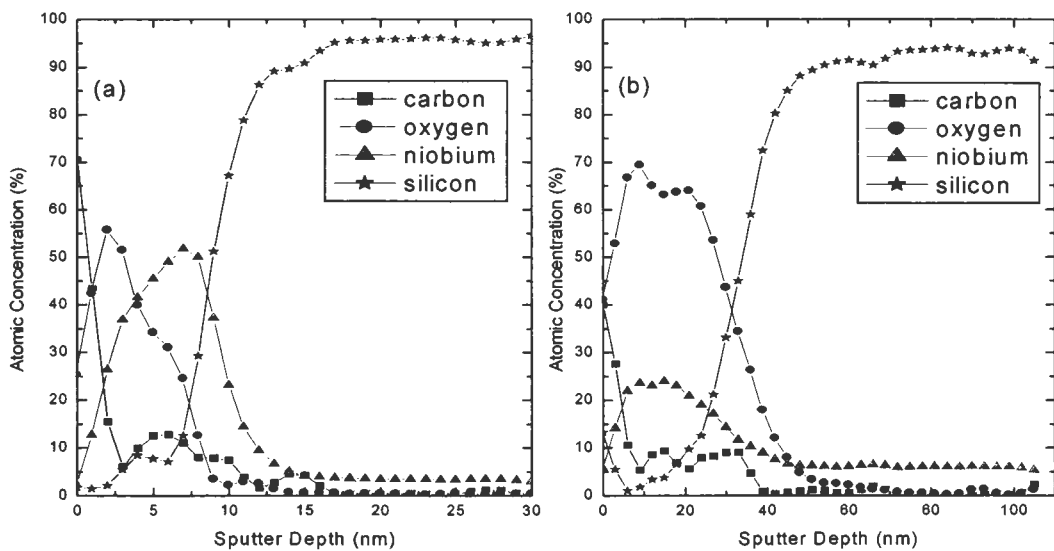


Fig. 4.16: XPS depth profile for niobium-deposited samples prior to (a) and after the diffusion process (b) showing carbon and oxygen.

It has to be noted that the carbon spectrum disappears at 10 nm after the rapid increase of the silicon spectrum to show that carbon is found in the bulk. Thus, superimpose found in the silicon plateau for RBS measurements in Fig. 4.12 is associated with carbon not oxygen as stated. A very low atomic concentration of niobium is also

found in silicon bulk up to the depth of 30 nm. The *RBS* measurements presented above do not show niobium in silicon. Since the *XPS* measurements were carried out two years after the deposition process, the results may indicate that niobium has diffused into the bulk at room temperature.

In plot (b) the spectra show carbon with 40 % atomic concentration and oxygen with 41 % atomic concentration on the surface. The carbon spectrum falls rapidly to 5 % at 9 nm and then remains almost constant up to 32 nm. After 32 nm the spectrum disappears completely. At a depth of less than 10 nm the oxygen spectra increases sharply to 70 % and then decreases to 64 % at 22.5 nm. After 23 nm the spectrum decreases sharply to 3 % at 50 nm and then disappears completely.

Niobium is found on the surface with the relative concentration of 5 %. The niobium spectrum increases to 24 % at the depth less than 10 nm and then remains almost constant up to 18 nm. After 19 nm the spectrum decreases gently to 8 % at 40 nm and then it remains constant up to 110 nm. The silicon spectrum, on the other hand, shows 14 % atomic concentration on the surface. A presence of silicon on the surface shows that it was exposed when niobium was diffusing into the bulk. At the depth less than 6 nm the silicon spectrum decreases sharply to 0 % and then increases gently up to 15 % at 18 nm. After 20 nm the spectrum increases sharply to 92 % at 50 nm and then saturates. The sharp increase corresponds to the sharp decrease of oxygen to show that there is no interface between niobium and silicon.

It can be noted that the silicon spectrum is below the niobium spectra at the depth of between 9 nm and 16 nm to show that niobium-silicide is formed with high niobium atomic concentration. These results agree with those obtained from *RBS* measurement in Fig. 4.12 where the sloping of the niobium peak is observed at the

lower energy edge after the diffusion process. The non-zero yield is, however, not observed in Fig. 4.12. The *RBS* results could be showing that the niobium atomic concentration diffused is below the detection limit of the technique (10^{16} atoms.cm⁻³).

4.3 Schottky diodes

Schottky diodes were fabricated on the undoped and on the metal-doped *p*-silicon. The metals used are gold, platinum, erbium and niobium. The discussion presented here is based on the comparison of the results obtained on the Schottky diodes that were fabricated on the undoped samples with those that were fabricated on the metal-doped *p*-silicon. The investigations were carried out on all the diodes but only two of the diodes from each sample are presented. Two of the diodes are presented because all four diodes from one sample exhibit similar characteristics.

4.3.1 Current measurements

The current measurements in reverse bias are used to determine the leakage current and the breakdown voltage [Lampert, 1956; Larrabee, 1961]. In forward bias the measurements are used to determine the saturation current, the ideality factor and the Schottky barrier height [Sze, 1981]. The logarithmic format of the data can be used to classify whether the diode is fabricated on the relaxation or on the lifetime material.

4.3.1.1 Undoped diodes

Fig. 4.17 shows the logarithmic *I-V* characteristics both in reverse bias and in forward bias for two of the diodes that were fabricated on the undoped *p*-silicon. In reverse bias, a breakdown voltage is observed at 3×10^0 V. A similar behaviour of the leakage current has been observed in earlier work using commercial silicon *p-i-n* diodes [Jones and McPherson, 1999]. The breakdown voltage is given [Sze, 1981] as

$$V_{BR} = \frac{\epsilon_s E_{max}^2}{2eN_A} \quad (4.4)$$

where E_{max} is the electric field at the breakdown voltage. The above equation shows that a decrease in the majority carrier density results in an increase in the breakdown voltage. A decrease in the density can be due to the recombination of the charge carriers in the depletion region by defect levels induced by impurities or irradiation. As a result, a conductivity of the diode is reduced.

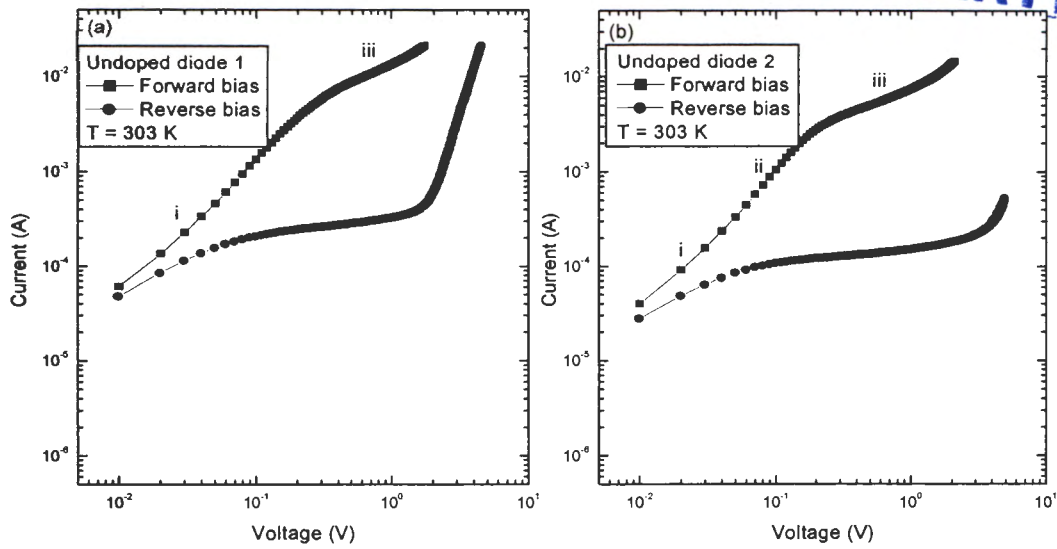


Fig. 4.17: The I - V characteristics of the diodes fabricated on undoped p -silicon.

In forward bias three linear regions (i, ii and iii) with slopes of 1.1, 1.8 and 1.5 are observed. The slope of 1.1 (~ 1.0) shows that the current increases linearly with voltage while the one of 1.8 (~ 2.0) shows that it starts to increase exponentially at 4×10^{-2} V up to 2×10^{-1} V. Due to the effects of the series resistance when the applied voltage is large, the slope is found to decrease to 1.5 to show a slow increase of the current.

Similar regions that are found in forward bias have been observed [Larrabee, 1961] on germanium p - i - n diodes. Since the diodes of this work exhibit similar behaviour as

the ones studied by [Larrabee, 1961; Jones and McPherson 1999], it can safely be concluded that the diodes were properly fabricated. Thus, any change in diode properties will be due to the metals introduced into the bulk of the material.

Gold is known to make the Schottky contact only on the *n*-type semiconductor [Msimanga *et al*, 2004]. In this work it is shown that the metal can also be used on *p*-type semiconductor for the contact as well. This rectifying (Schottky) behaviour of the metal on the material is due to the fact that, in silicon gold is a donor. As it is deposited on the material the *p-n* junction is formed [Monch, 1990]. As a result, the rectifying behaviour of the metal on the material is observed. The rectifying behaviour of gold on *p*-Si was also observed on the work carried out by [Kaniowska and Misiuk, 2003]

The effect of the series resistance is shown clearly in Fig. 4.18. In the figure the tangent lines show the linear region of the plots where the effect of the series resistance is negligible. These linear regions are clearly shown as the insets of both plots. The current-voltage behaviour of the diodes with series resistance, R_s is given [Schroder, 2006] by

$$J = J_s \left[\exp \left(\frac{e(V_a - IR_s)}{\eta kT} \right) - 1 \right] \quad (4.5)$$

where η is the ideality factor. In practice the slope of the linear region is used to evaluate the ideality factor by re-arranging Eq. (2.73) as

$$\eta = \frac{e}{kT} \frac{dV}{d \ln(I)} \quad (4.6)$$

to show that η decreases with an increase in temperature for constant slope. This effect of temperature on the ideality factor was also observed [Danielsson *et al*, 2001] on the work carried out on the diodes fabricated on the silicon carbide. The saturation

current, on the other hand, is calculated from the Y-intercept of the linear region of a forward $\ln(I)$ versus V plot.

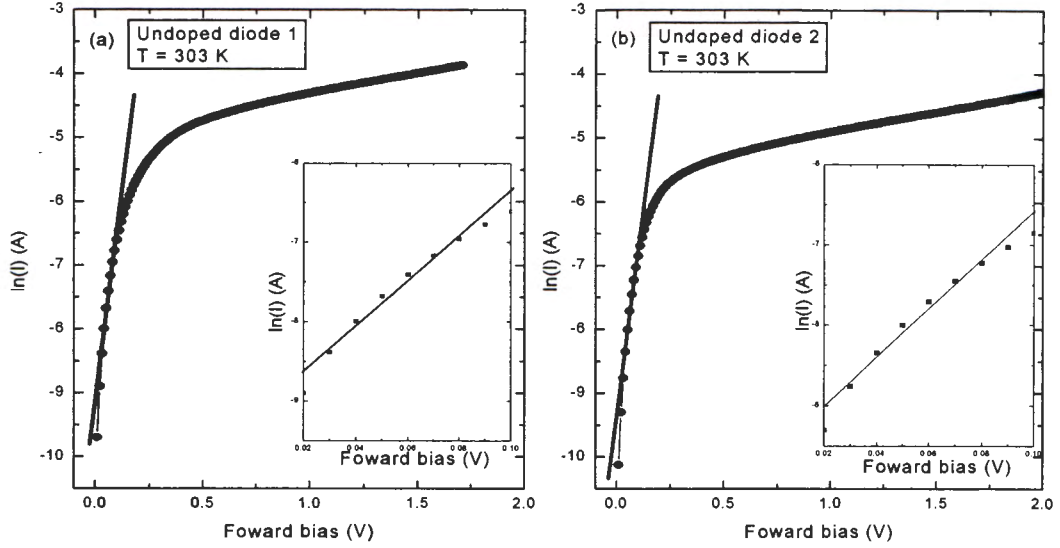


Fig. 4.18: $\ln(I)$ versus voltage for the undoped diodes. An enlargement view of the linear regions is shown as insets for the both plots.

The Schottky barrier height is determined from Eq. 2.54 according to

$$\phi_B = \frac{kT}{e} \ln \left(\frac{AA^*T^2}{I_s} \right) \quad (4.7)$$

and is strongly influenced by the deposition method of the metal used in fabricating the Schottky contact. In the above relation A represents the area of the diode (a circle of 2mm diameter for the devices) and A^* is the Richardson constant given as $32 \text{ A cm}^{-2} \text{ K}^{-2}$ for p -type silicon [Schroder 2006]. The parameter is evaluated by substituting a value of the saturation current (or an exponential of the Y-intercept) in Eq. (4.7).

Parameters for the diodes that were fabricated on the undoped p -silicon are given in Table 4.3. The parameters are different even though the diodes were fabricated on the same substrate and this could be due to the inhomogeneous deposition of gold during the fabrication of the Schottky contact. It can be seen from the table that the high value of the ideality factor (1.35) in diode 1 corresponds to a high value of the

saturation current (106 μA). The low value of the ideality factor (1.26) in diode 2 corresponds to a high value of the Schottky barrier height (0.63 V). This type of variation of the ideality factor and the Schottky barrier height has been reported by other authors before [Cetin *et al*, 2005]. It is expected that parameters obtained from diodes fabricated on metal-doped substrates will vary similarly as the ones obtained from diodes fabricated on the undoped *p*-silicon. This is because the Schottky contacts were fabricated under the same conditions for all diodes in this work.

Table 4.3: A summary of device parameters evaluated from *I-V* plots for diodes fabricated on undoped *p*-silicon.

Parameter	Diode 1	Diode 2	Average
I_s (μA)	106	68.2	87.1
η	1.35	1.26	1.31
ϕ_B (V)	0.62	0.63	0.63

The *I-V* measurements on the undoped diodes were also carried out for temperatures ranging from 280 to 330 K. In reverse bias the measurements were used to extract the activation energy of the material. A variation of the reverse *I-V* characteristic with temperature for the undoped diodes is shown in Fig. 4.19.

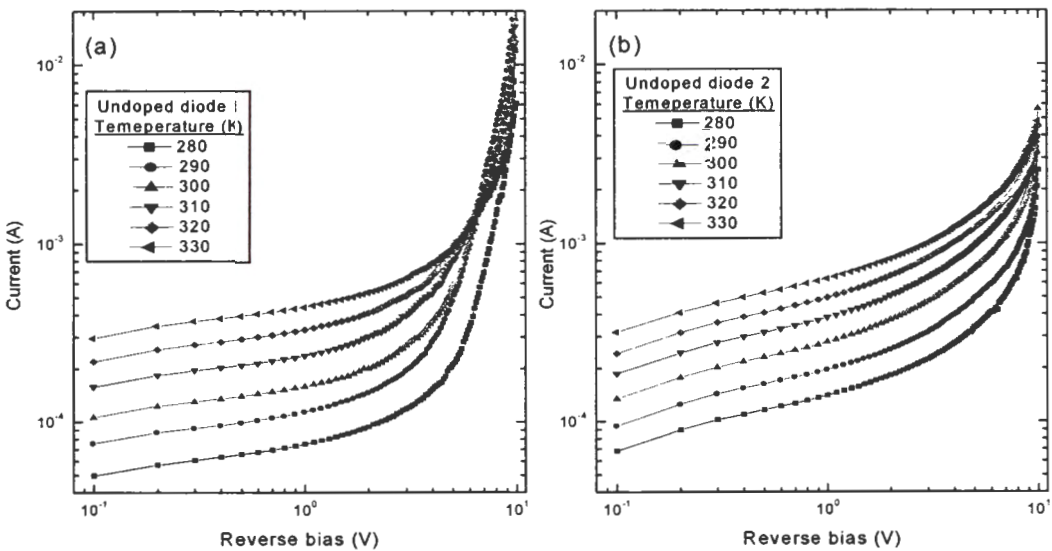


Fig. 4.19: A variation of the reverse *I-V* characteristic with temperature for the undoped diodes.

It can be seen from the figure that the current increases with temperature at voltages lower than the break down voltage. The current increases by a factor of 5 from that of 280 K to the one of 330 K. After the breakdown voltage the current is independent of temperature. These results show that as the temperature increases more carriers with sufficient energy are collected to the opposite electrodes to contribute to the measured current.

The reverse current (I) varies with temperature [Pattabi *et al*, 2007] as

$$I \propto \exp\left(\frac{-E_a}{kT}\right) \quad (4.8)$$

where E_a is the activation energy of the material. Eq. 4.8 shows that a plot of $\ln(I)$ against T^{-1} is a linear relation from which the slope can be used to determine E_a . The data from the temperature variation of the reverse I - V characteristic were used to determine the activation energy of the material at 0.5 V, at the voltage where an increase in current due to temperature is more pronounced.

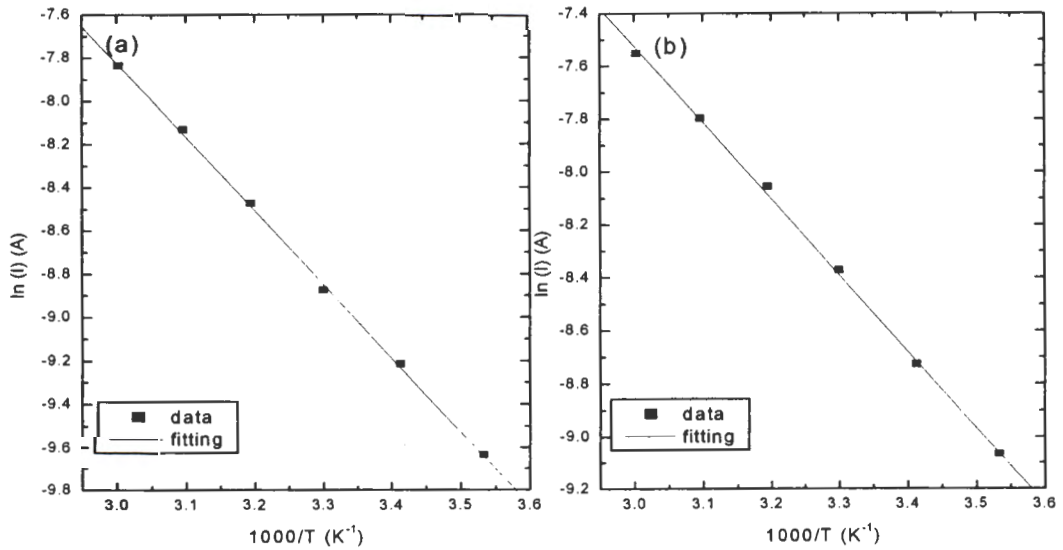


Fig. 4.20: The plots of $\ln(I)$ versus T^{-1} at a constant reverse bias of 0.5 V for the undoped diodes.

Fig. 4.20 shows the plots of $\ln(I)$ against T^{-1} for the undoped diodes. The linear relations are found from both plots. The activation energy for diodes 1 is found to be 0.29 eV and 0.24 eV for diode 2. As explained earlier, the difference in quantities is due to the inhomogeneous deposition of gold during the formation of Schottky contact.

Fig. 4.21 shows the forward I - V characteristic of the undoped diodes as a function of temperature. It can be noticed that the forward current increases with temperature for the same voltage. This increase of the current due to the temperature is not pronounced as observed in Fig. 4.19, for the reverse current. This is because the reverse current is due to the carrier generation while the forward current is due to the diffusion mechanism [Boer, 1992; Streetman, 1990]. The trends are found to be parallel to each other, especially at low voltages, to show that they are not affected by temperature.

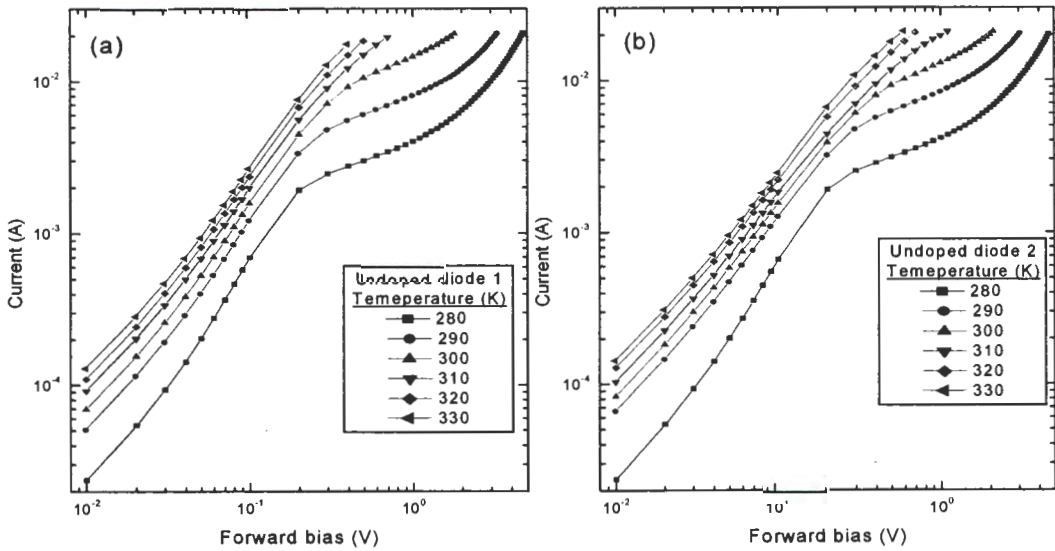


Fig. 4.21: A variation of the forward I - V characteristic with temperature for the undoped diodes.

Using the forward bias profile, the measurements were used to investigate the variation of the saturation current, ideality factor and the Schottky barrier height with

temperature. The temperature measurements were taken on the four diodes and the variation of the parameters with temperature was investigated. The average values of the parameters for all diodes were taken and are presented in Table 4.4 for the undoped diode.

Table 4.4: A variation of the parameters obtained from the undoped diodes with temperature.

Temperature (K)	280	290	300	310	320	330
I_s (μ A)	32.1	65.8	86.7	115	145	175
η	1.36	1.29	1.24	1.18	1.13	1.04
Φ (V)	0.63	0.63	0.62	0.63	0.62	0.62

The saturation current is a function of temperature [Boer, 1992; Sze, 1981; Streetman, 1990; Neamen, 1997; Singh *et al*, 2000] and the results obtained show that it increases with temperature. This variation has been observed before [Tataroglu and Altindal, 2009] and it shows that the amount of carriers withdrawn to the opposite electrodes to contribute to the measured current increases with temperature. Thus the saturation current is directly proportional to the square of carrier concentration as it can be seen in Eq. (2.39).

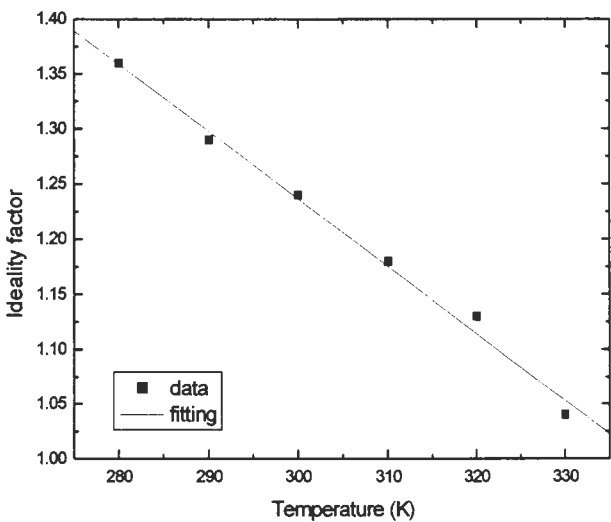


Fig.4.22: Temperature dependence of the ideality factor for the undoped diode.

The ideality factor decreases with an increase in temperature. This variation of the ideality factor with temperature is not due to the slope obtained from the plot of $\ln(I)$ versus V . Since the trends are all parallel to each other the slopes are almost constant. It can be noted from Eq. (4.6) that the ideality factor decreases with an increase in temperature at the constant slope. This temperature dependence of the ideality factor for the undoped diode can be seen in Fig.4.22.

The linear relation with the slope of -0.006 K^{-1} is observed in the figure. The extrapolation of the data to the ideality factor close to unity gives the temperature of 340 K. These results show that at temperatures ranging from 280 to 330 K, there are charge carriers that are not collected to the opposite electrodes to contribute to the measured current to show that the silicon is not completely “defect-free”. This means that there are defect levels that recombine charge carriers. As a result, the diode does not exhibit, completely, the non-ideal behaviour. However, at 340 K the diode will exhibit an ideal behaviour since all charge carriers would have enough energy to be emitted from these levels.

According to Eq. (4.7), the Schottky barrier height is expected to increase with an increase in temperature for the constant saturation current or to increase with a decrease in the saturation current for the constant temperature. However, this condition cannot hold since the saturation current varies with temperature. This variation of the saturation current due to temperature makes the Schottky barrier height depend on both quantities. The results obtained in this work show that the Schottky barrier height is independent of temperature. This independence disagrees with the results presented in the literature [Karatas *et al*, 2007; Krishnan *et al*, 2008; Gupta *et al*, 2009; Yuksel, 2009] based on the result that were obtained on the diodes

fabricated on p -Si. The results in that case were interpreted in terms of the metal-semiconductor interface charges.

The obtained results, however, agree with those presented by [Aboelfotoh, 1991] where tungsten was used for the Schottky contacts on p -Si. This independence could be due to the fact that the rate at which the temperature increases is the same as the rate at which the saturation current increases in the logarithmic scale. As it can be seen in Eq. (4.7), these rates cancel each other and make the Schottky barrier to be independent of the temperature and the saturation current. These results also show that the measured current is due to the space charge region not the interface charges since the Schottky barrier height is independent of the temperature.

4.3.1.2 Gold-doped diodes

I - V measurements were also carried out on the diodes that were fabricated on the gold-doped p -silicon. The results for these measurements are shown in Fig. 4.23. The plots show a marked difference from those in Fig. 4.17, particularly the reverse bias characteristics. The current increases linearly with voltage and does not show any trend for saturation or breakdown. It is expected that for higher voltages this trend would not change. In forward bias the current increases linearly with voltage up to 10^1 V. These trends of the current have been observed [Msimanga *et al*, 2004] on diodes fabricated on gold-doped n -type silicon. Another observation from the figure is that both trends have come closer to each other especially at low voltages. These are typical characteristics of diodes fabricated on relaxation material [Jones *et al*, 1998]. Thus, gold turns p -type silicon into a relaxation material just as it does n -type silicon.

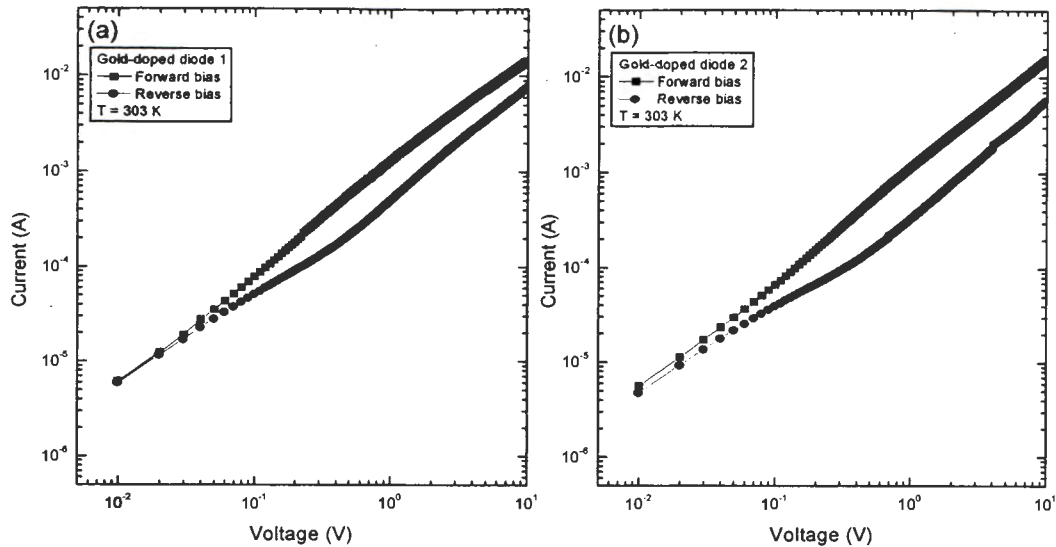


Fig. 4.23: The I - V characteristics of diodes fabricated on gold-doped p -silicon. The currents have come closer to each other especially at low voltages and are more Ohmic than in the previous case.

The same analyses presented in Fig. 4.18 were also carried out on the gold-doped diodes. The linear regions at low voltage were also observed on gold-doped diodes and the slope was used to evaluate the parameters shown in Table 4.5. The parameters are different even though the diodes were fabricated from the same substrate. They are, however, related to each other in the same manner as the parameters obtained from the diodes fabricated on undoped p -silicon. That is, a high ideality factor corresponds to a high saturation current while a low ideality factor corresponds to a high Schottky barrier height.

Table 4.5: A summary of device parameters evaluated from I - V plots for diodes fabricated on gold-doped p -silicon.

Parameter	Diode 1	Diode 2	Average
I_s (μ A)	13.2	9.85	11.5
η	1.99	1.80	1.90
ϕ_B (V)	0.68	0.69	0.69

Fig. 4.24 shows a variation of the reverse I - V characteristic with temperature for the gold-doped diodes. The current increases with temperature for the same voltage. Unlike in Fig. 4.19, for undoped p -silicon diodes, the trends for gold-doped diodes

have come closer together to show that effects of temperature are reduced. This is due to the defect levels induced by gold in silicon. These levels recombine charge carriers and this leads in a reduction of the measured current. As a result, the resistivity of the material increases.

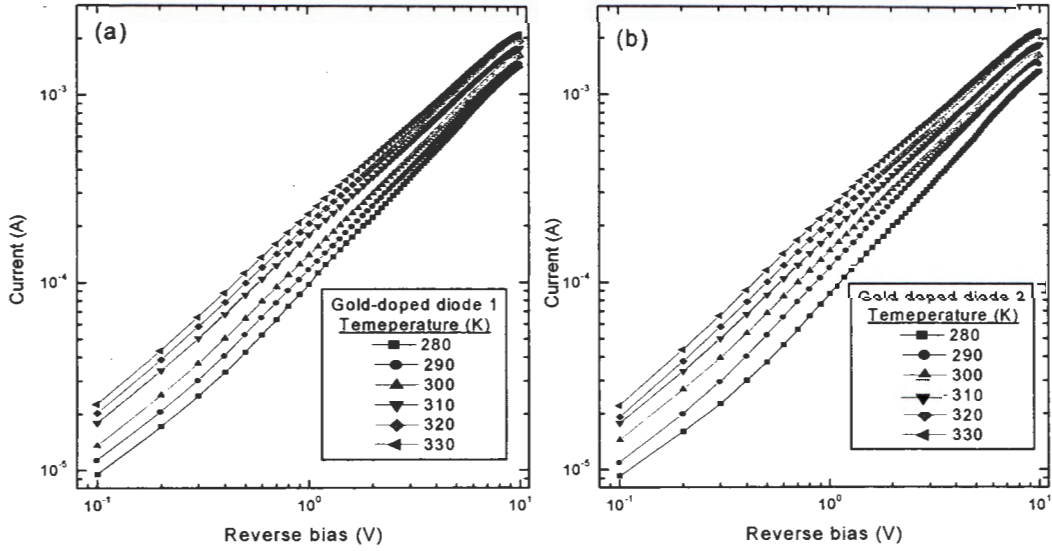


Fig. 4.24: A variation of the reverse I - V characteristic with temperature for the gold-doped diodes.

Fig. 4.25 shows the plots of $\ln(I)$ against T^{-1} for gold-doped diodes. The linear relations are found from both plots. The activation energy for diode 1 is found to be 0.16 eV and 0.18 eV for diode 2. Both activation energies are lower than those obtained from the undoped diodes. It is usual to get the activation of the control sample to be higher than the one of the defect induced samples [McPherson, 2002; Yaroslavski and Ruzin, 2006; Pattabi *et al*, 2007]. These defects can be induced by irradiation or by doping the material with metals. In the work presented by Yaroslavski and Ruzin [2006] the activation of the control sample (silicon-germanium detector) was found to be 0.43 eV and 0.27 eV for the irradiated detector. In the case of Pattabi *et al* [2007], the activation energy found on the unirradiated n^+p diode was found to be 0.54 eV and 0.50 eV on the irradiated diode while in the case of

McPherson [2002] the activation energy of the unirradiated silicon *p-i-n* diodes was found to be 0.87 eV and 0.54 eV for the irradiated diode. A decrease of the activation energy shows that the rate at which the carriers are generated by temperature is reduced by the defect levels induced in the material. These levels recombine the thermal generated carriers as a result, the effects of temperature on the characteristics of the diode are reduced. This is evident in Fig. 4.24 where the trends of current are found to be closer to each other after doping silicon with gold.

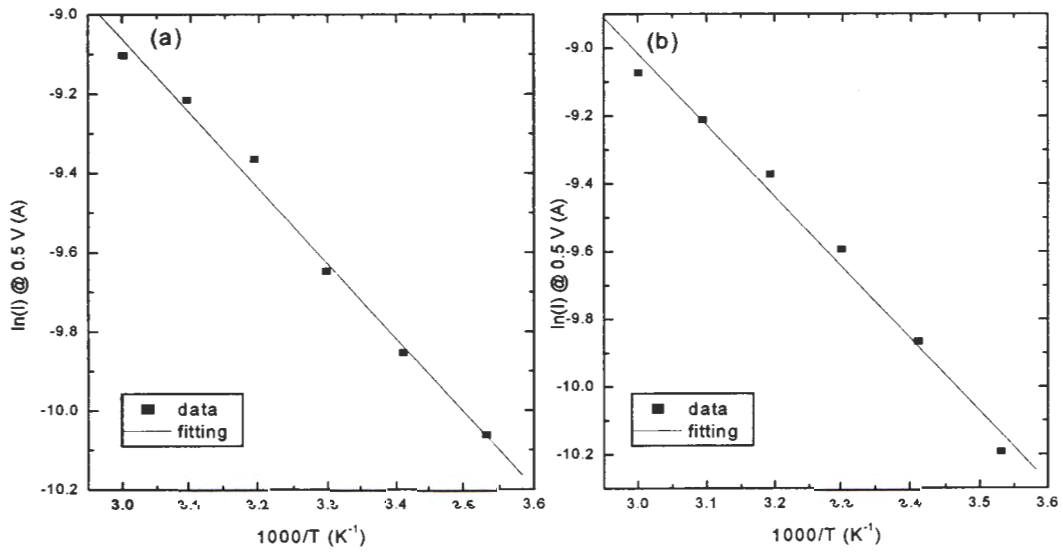


Fig. 4.25: The plots of $\ln(I)$ versus T^{-1} at a constant reverse bias of 0.5 V for the gold-doped diodes.

Fig. 4.26 shows the forward *I-V* characteristic of gold-doped diodes as a function of temperature. Unlike in the case of the undoped diodes, it can be noticed that the forward current of gold-doped diodes is independent of the temperature. The independence is more pronounced at high voltages. At the voltages lower than 1×10^{-1} V the trends are parallel to each other to show that they are not affected by the temperature.

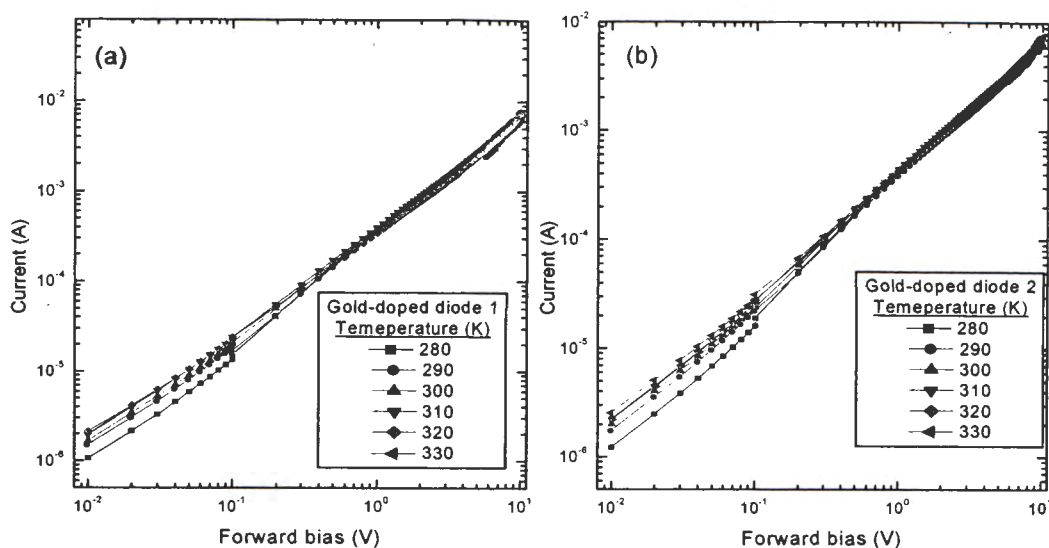


Fig. 4.26: A variation of the forward I - V characteristic with temperature for the gold-doped diodes.

Table 4.6 shows a variation of the saturation current, the ideality factor and the Schottky barrier height with temperature. Similar to the undoped p -silicon diodes, the saturation current for gold-doped diodes increases to show that the amount of carriers withdrawn to the opposite electrodes to contribute to the measured current increases with temperature. The saturation current has increased by the factor of 1.4 from that of 280 K to the one of 330 K. The Schottky barrier height, on the other hand, is still found to be independent of the temperature.

Table 4.6: A variation of the parameters obtained from the gold-doped diodes with temperature.

Temperature (K)	280	290	300	310	320	330
I_s (μ A)	10.2	11.1	11.9	12.6	13.1	13.9
η	1.90	1.87	1.84	1.80	1.76	1.73
ϕ_B (V)	0.68	0.7	0.69	0.68	0.68	0.69

The ideality factor of the gold-doped diode decreases with an increase of temperature. This temperature dependence of the ideality factor for the gold-doped diode can be seen from Fig. 4.27. The linear relation is observed with the slope of -0.003 K^{-1} . The

magnitude of the slope is lower than the one obtained from undoped diodes (-0.006 K^{-1}) to show that the rate in which the carriers are thermally generated have reduced after doping with gold. The extrapolation of the data to the ideality factor close to unity gives the temperature of 537 K. This high temperature required for the ideal behaviour shows that there are carriers that are not collected to the opposite electrodes to contribute to the measured current within this temperature range. These carriers are recombined with the induced defects levels in the energy gap of silicon to increase the resistivity of the material. At 537 K these carriers will be emitted from the levels and the diode would exhibit the ideal behaviour.

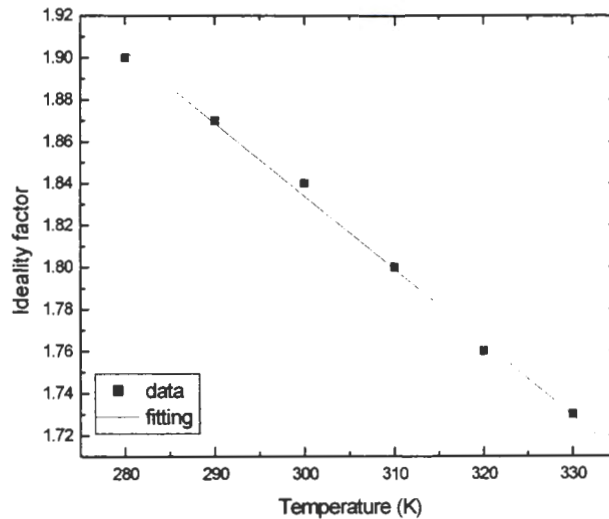


Fig. 4.27: *Temperature dependence of the ideality factor for the gold-doped diode.*

4.3.1.3 Platinum-doped diodes

Fig. 4.28 shows I - V characteristics for the diodes fabricated on platinum-doped p -silicon. The trends for both diodes are similar except for a large gap shown between the reverse and the forward currents of diode 1 in plot (a). The existence of this gap could be associated with surface damage that would have occurred during the process

of etching away the remaining platinum from the surface of the substrate. However, this effect is not of concern at this stage.

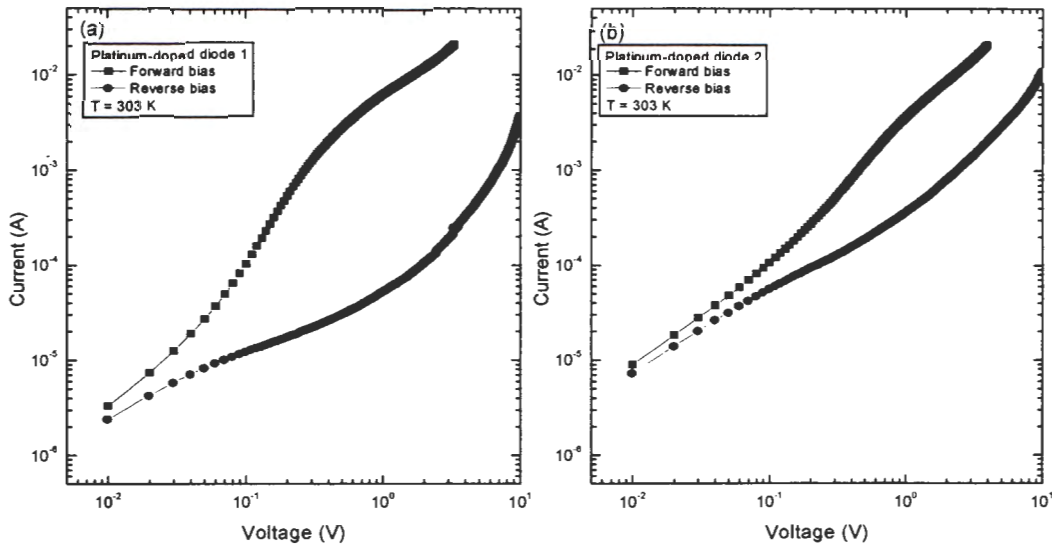


Fig. 4.28: *The I-V characteristics of diodes fabricated on platinum-doped p-silicon. A large gap is noticeable between the two currents in diode 1.*

What is of concern is the reverse current which is observed to increase sharply at high voltages. This increase is not as sharp as the one observed in Fig. 4.17 (a) and the trend is observed to bend towards the voltage-axis or to flatten. A trend of the forward current is, however, similar to the one observed in Fig. 4.17 but it also bends towards the voltage-axis. These results show that platinum in silicon suppresses early breakdown and also makes the device current become Ohmic. In Fig. 4.28 (b) a gap between the two trends at low voltages is almost equal to the gaps observed in Fig. 4.23 for gold-doped diodes. These results show that platinum in silicon has similar effects as gold. Even though the effects of platinum in silicon have been studied, according to the gathered information, these results have never been observed or published before.

The parameters evaluated for platinum-doped diodes are presented in Table 4.7 where a high ideality factor in diode 2 corresponds to a high saturation current, while

a low ideality factor in diode 1 corresponds to a high Schottky barrier height. The variation of parameters is similar to that of diodes fabricated on undoped and on gold-doped p -silicon even though the Schottky contacts were fabricated using a different metal (titanium) for this set of diodes. These results show that the parameters do not depend on the type of metal used to fabricate the Schottky contacts. Therefore, a change in the diode properties is due to the metals introduced into the material not the contacts used.

Table 4.7: A summary of device parameters evaluated from I - V plots for diodes fabricated on platinum-doped p -silicon.

Parameter	Diode 1	Diode 2	Average
I_s (μ A)	5.12	6.77	5.95
η	1.54	1.64	1.59
ϕ_B (V)	0.71	0.70	0.71

Fig. 4.29 shows a variation of the reverse I - V characteristic with temperature for the platinum-doped diodes.

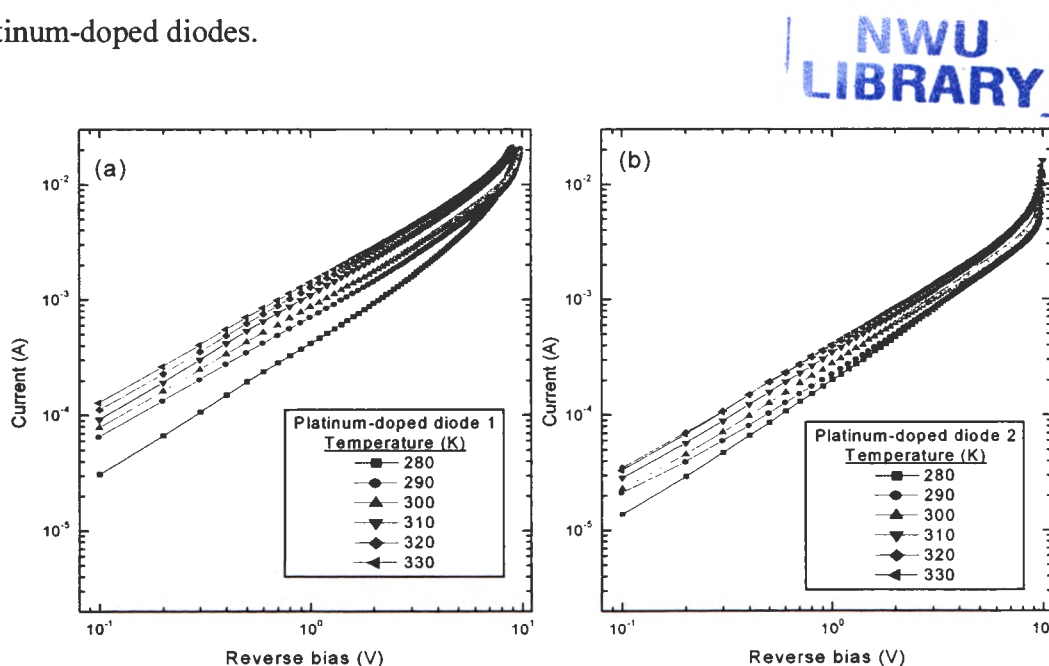


Fig. 4.29: A variation of the reverse I - V characteristic with temperature for the platinum-doped diodes.

The current in Fig. 4.29 increases with temperature for the same voltage. Similar to gold, the trends have come closer together to show that effects of temperature are

reduced due to the defect levels induced by platinum in silicon. These levels recombine the thermal generated carriers to increase the resistivity of the material.

Fig. 4.30 shows the plots of $\ln(I)$ against T^{-1} for platinum-doped diodes. Similar to undoped and gold-doped diodes, the linear relations are found from both plots. The activation energy for diode 1 is found to be 0.18 eV and 0.15 eV for diode 2. These activation energies are found to be lower than those obtained from the undoped diodes (0.29 eV and 0.24 eV). As it was explained in the case of gold-doped diodes, the reduction of the activation energy shows that the rate in which the current increases with temperature is reduced due to the defect levels induced in the energy gap. As the temperature generates charge carriers, the defect levels recombine and the amount of the carriers collected to the opposite electrodes is reduced. As a result the resistivity increases.

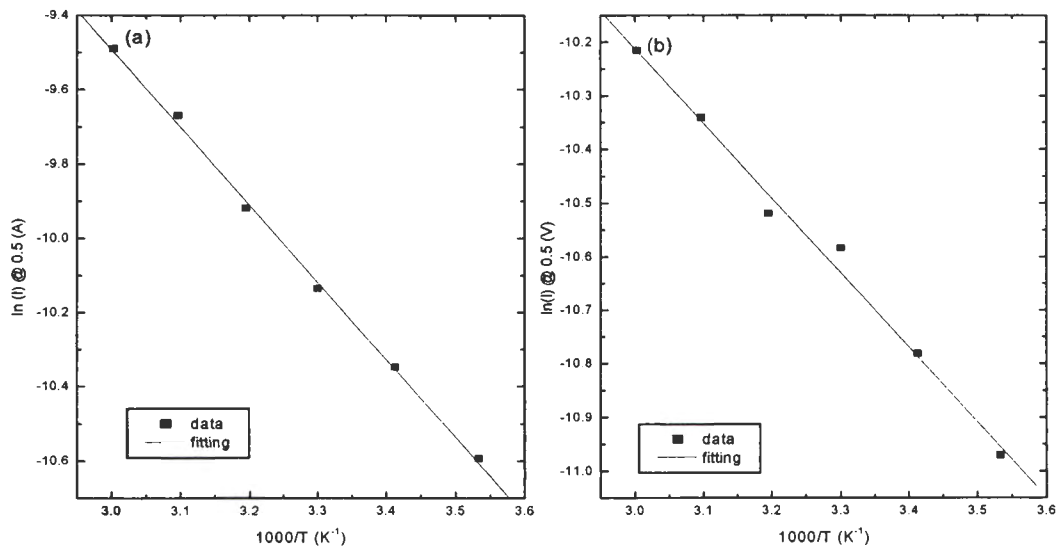


Fig. 4.30: The plots of $\ln(I)$ versus T^{-1} at a constant reverse bias of 0.5 V for the platinum-doped diodes.

Fig. 4.31 shows the forward I - V characteristic of the platinum-doped diodes as a function of temperature. The current increases slightly with temperature at the same

voltage. The trends are, however, similar to show that they are not affected by the temperature.

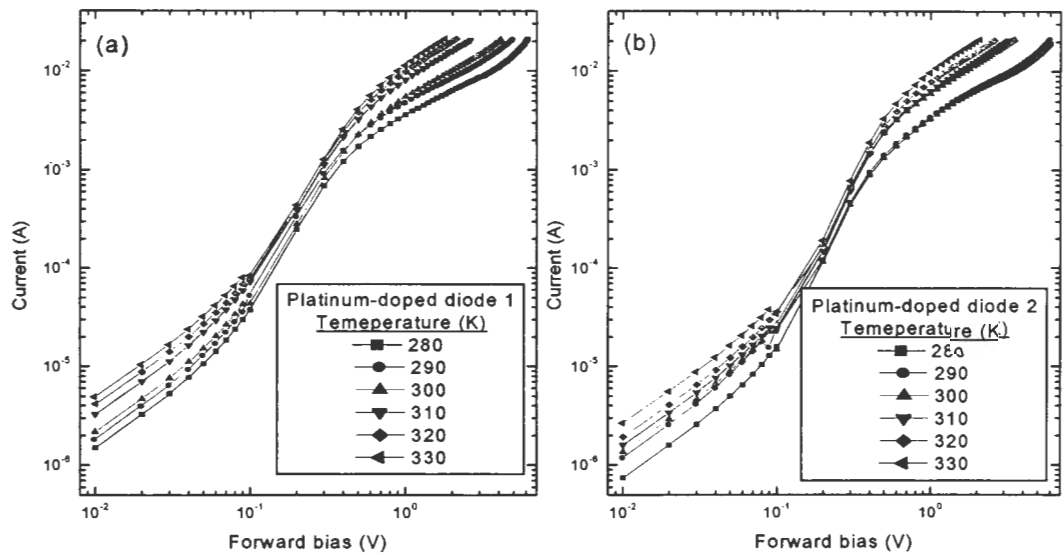


Fig. 4.31: A variation of the forward I - V characteristic with temperature for the platinum-doped diodes.

The variation of the parameters with temperature for the platinum-doped diodes is shown in Table 4.8 where they are found to vary in a similar manner with those obtained from other diodes (undoped and gold-doped diodes). That is, an increase with temperature results an increase with the saturation current while the Schottky barrier height remains almost constant.

Table 4.8: A variation of the parameters obtained from the platinum-doped diodes with temperature.

Temperature (K)	280	290	300	310	320	330
I_s (μ A)	4.50	5.90	7.30	9.70	9.80	12.0
η	1.47	1.44	1.42	1.41	1.40	1.38
ϕ_B (V)	0.72	0.72	0.72	0.71	0.70	0.71

The linear decrease of the ideality factor with temperature is observed in Fig. 4.32 with the slope (-0.002 K^{-1}) lower than those obtained from the undoped diodes (-0.006 K^{-1}) in magnitude. The extrapolation of the data to the ideality factor close to unity gives the temperature of 544 K which is higher than that of gold-doped diodes. This

temperature difference can be explained in terms of the majority-carrier capture cross-sections of the donor levels created by both metals below the half energy gap. These donor levels are known to be the strong recombination centres in *p*-type silicon [Kwon *et al*, 1987; Watanabe and Munakata, 1993]. The capture-cross section of the donor level created by gold is ($2.5 \times 10^{-15} \text{ cm}^2$) lower than that created by platinum ($8.4 \times 10^{-15} \text{ cm}^2$) [Graff, 1999]. Thus, the amount of the carriers collected to the opposite electrodes in platinum-doped diodes is less than the amount of the carriers collected in gold-doped diodes at the temperature ranging from 280 K to 330 K.

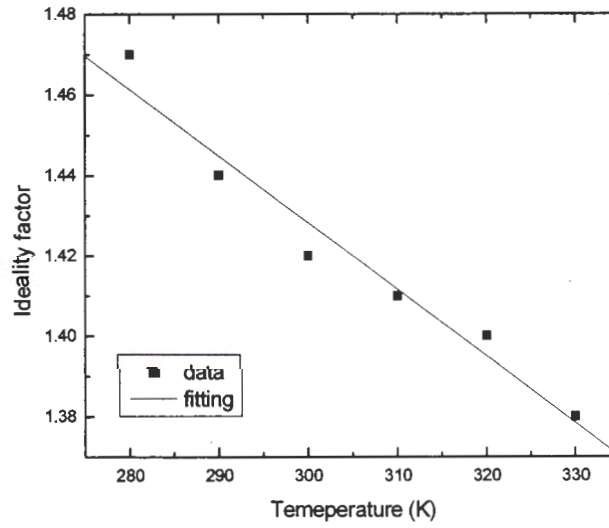


Fig. 4.32: *Temperature dependence of the ideality factor for the platinum-doped diode.*

4.3.1.4 Erbium-doped diodes

Fig. 4.33 shows *I-V* characteristics for the diodes fabricated on erbium-doped silicon. The reverse current is equal to the forward current up to $6 \times 10^{-2} \text{ V}$ from where it deviates slightly up to the current limit. The forward current also increases linearly with voltage up to the current limit. The two observations clearly indicate that erbium creates defect levels in the material that make the device current Ohmic. Very similar trends were observed [Moloi and McPherson 2009] on the devices irradiated up to $10^{17} \text{ n cm}^{-2}$ by 1 MeV neutrons. In that case the results were interpreted in terms of

the defects induced by the irradiation in the silicon. Thus, erbium in silicon behaves as gold and platinum. It also induces very similar effects as irradiation with 1 MeV neutrons.

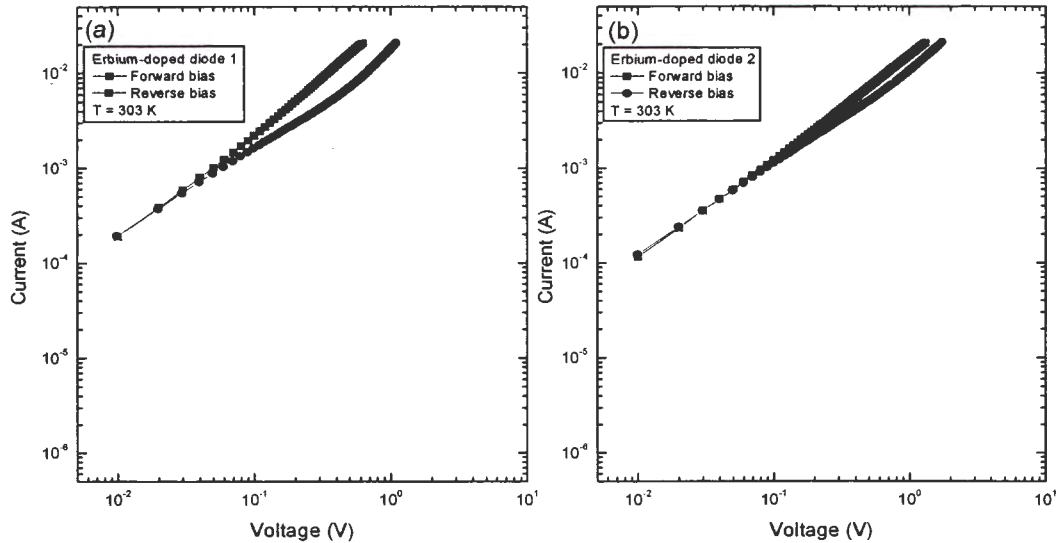


Fig. 4.33: *The I - V characteristics of diodes fabricated on erbium-doped p -silicon. At low voltages the currents are equal and both increase linearly with voltage. The current here is much more Ohmic than in the previous cases.*

The parameters evaluated from the I - V plots of erbium-doped diodes are shown in Table 4.9 where diode 1 shows a high ideality factor and a high saturation current while diode 2 shows a low ideality factor and a high Schottky barrier height. The variation of the parameters thus still resembles the variation observed in the diodes fabricated on undoped, on gold-doped and on platinum-doped p -silicon.

Table 4.9: A summary of device parameters evaluated from I - V plots for diodes fabricated on erbium-doped p -silicon.

Parameter	Diode 1	Diode 2	Average
I_s (μ A)	338	207	273
η	1.92	1.82	1.87
ϕ_B (V)	0.58	0.60	0.59

A variation of the reverse I - V characteristic with temperature for the erbium-doped diodes is shown in Fig. 4.34 where the current increases with the temperature at the same voltage. This increase of the current due to the temperature is more pronounced

at low voltages. At the voltages higher than 2 V the current is independent of the temperature.

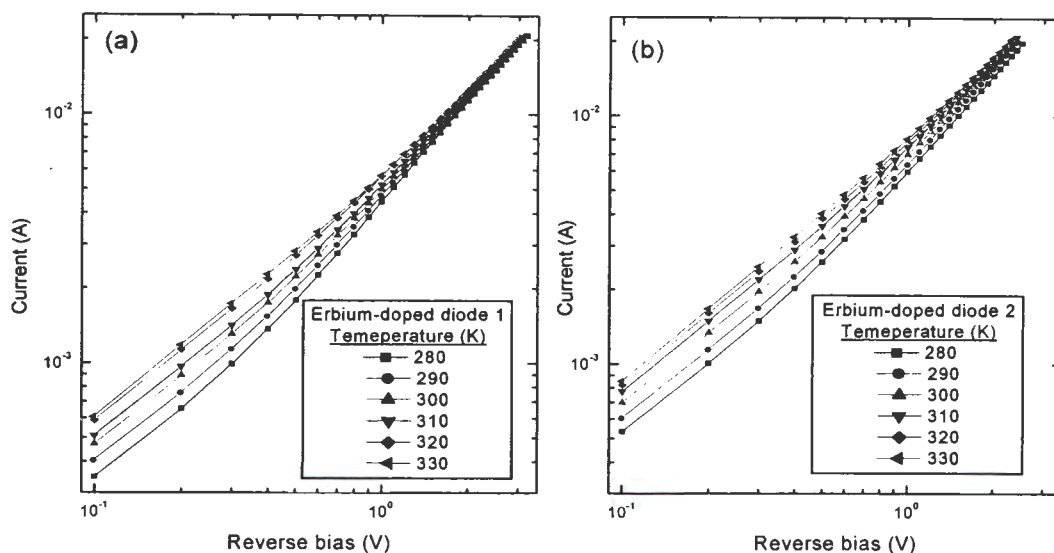


Fig. 4.34: A variation of the reverse I - V characteristic with temperature for the erbium-doped diodes.

The linear relationship of $\ln(I)$ against T^{-1} for erbium-doped diodes is shown in Fig. 4.35. The activation energy for diode 1 is found to be 0.12 eV and 0.10 eV for diode 2. These activation energies are found to be lower than those obtained from the other diodes. In contrast, it is explained above that the defects induced by erbium generate carriers to increase the diode current, however, the low values of the activation energies obtained imply that the defects also recombine the thermal generated carriers to reduce the effects of temperature.

These results obtained from the erbium-doped diodes can be interpreted in a similar way to those that were obtained on the diodes that were irradiated up to $3.4 \times 10^{13} \text{ n cm}^{-2}$ [McPherson, 2004]. In that case the current was found to increase while the activation energy decreases after the irradiation. They are also similar to those that are presented in Section 4.1 for the irradiated silicon p - i - n diodes. It is observed that the diode current increases after the irradiation while the effects of light are found to

be reduced as radiation fluence increases. The results in both cases are interpreted in terms of the defect levels that are situated at the centre of the energy gap. These levels are known to be the cause of the relaxation-behaviour of silicon [Jones and McPherson, 1999]. They can generate or recombine to maintain the charge carrier density at the intrinsic level. Thus, if the density is higher than $1.15 \times 10^{10} \text{ cm}^{-3}$ at 300 K these levels recombine charge carriers to reduce the amount of carriers that contribute to the measured current. If the density is low the levels generate carriers up to the intrinsic carrier concentration.

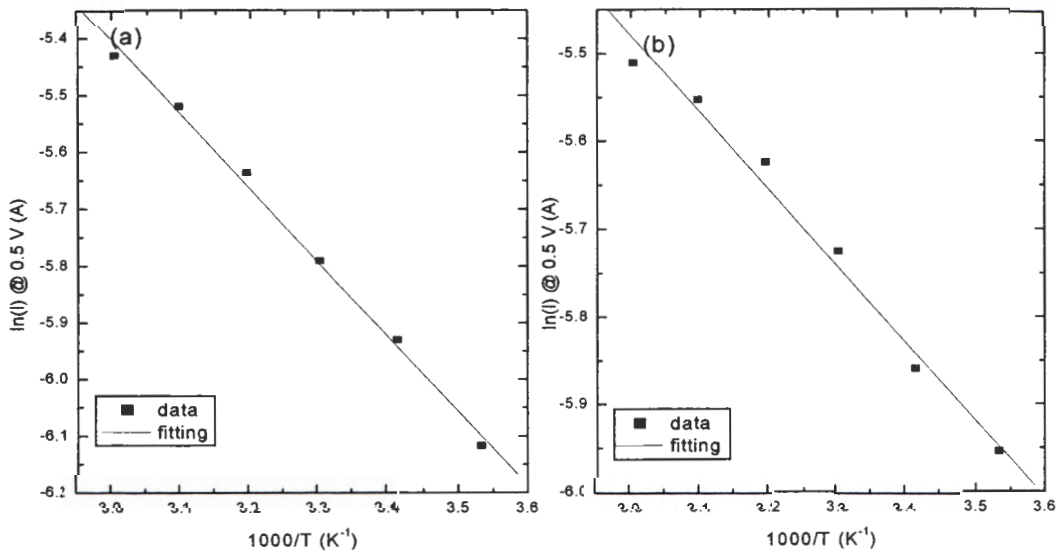


Fig. 4.35: The plots of $\ln(I)$ versus T^{-1} at a constant reverse bias of 0.5 V for the erbium-doped diodes.

It has to be noted that the RBS and the XPS measurements suggest a very low atomic concentration of erbium diffused into the bulk due to the solubility the metal has into silicon. As a result, the density of the defects induced by erbium in silicon is very low. It is expected that at the annealing temperature higher than 900°C and the annealing time higher than 18 hours the defect density will be high and the diodes properties will be completely independent of the temperature.

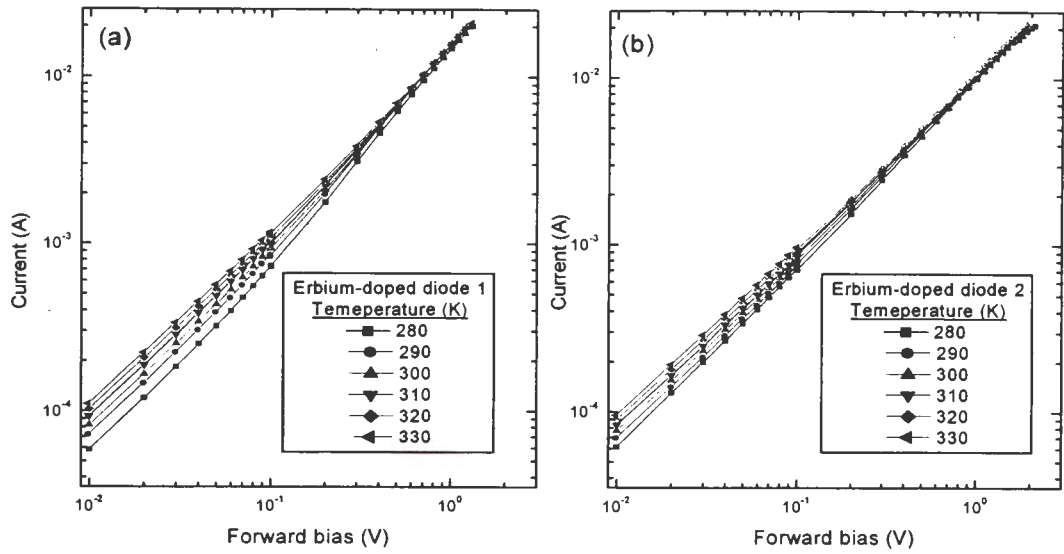


Fig. 4.36: A variation of the forward I - V characteristic with temperature for the erbium-doped diodes.

Fig. 4.36 shows the forward I - V characteristic of the erbium-doped diodes as a function of temperature. The forward current of erbium-doped diodes is independent of the temperature at high voltages. At the voltages lower than 5×10^{-1} V the current is found to increase slightly with temperature for the same voltage. The trends at low voltages are parallel to each other to show that they are independent of temperature.

Table 4.10: A variation of the parameters obtained from the erbium-doped diodes with temperature.

Temperature (K)	280	290	300	310	320	330
I_s (μ A)	210	230	245	255	260	267
η	1.89	1.88	1.88	1.87	1.87	1.86
ϕ_B (V)	0.57	0.57	0.56	0.56	0.57	0.57

The variation of the parameters obtained from the erbium-doped diodes with temperature is presented in Table 4.10. The parameters vary with temperature as those obtained from other diodes (undoped, gold-doped and platinum-doped diodes). The linear relation of the ideality factor with temperature is shown in Fig. 4.37. The slope is found to be $(-5.4 \times 10^{-4} \text{ K}^{-1})$ lower than the slopes obtained from other diodes in magnitude. The extrapolation of the data to the ideality factor close to unity gives

the temperature of 192×10^1 K which is also higher than the melting temperature of silicon (168×10^1 K). These results show that the rate at which the thermal carriers are generated at the erbium-doped diodes is very low due to the defect levels induced by erbium in the energy gap.

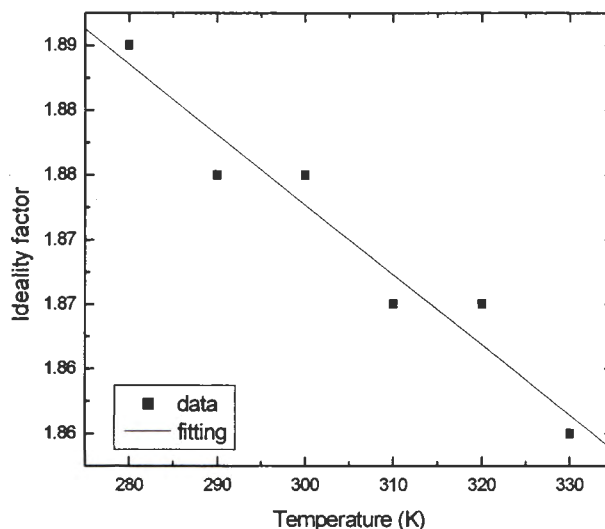


Fig. 4.37: *Temperature dependence of the ideality factor for the erbium-doped diode.*

4.3.1.1 Niobium-doped diodes

Fig. 4.38 shows I - V characteristics for diodes fabricated on niobium-doped p -silicon. The reverse current increases linearly with voltage up to the current limit. The trend of the forward current is similar to that presented in Fig. 4.17 for undoped diodes except that in this case the trend has bent towards the X-axis. These results show that niobium in silicon behaves in a similar manner as gold, platinum and erbium do. These metals suppress the effects of breakdown and make the device current Ohmic. They also make the reverse current to be equal the forward current, particularly at low voltages. These effects are similar to those induced by irradiation with 1 MeV neutrons [Moloi and McPherson, 2009]. Thus, metals in silicon have similar effects as irradiation.

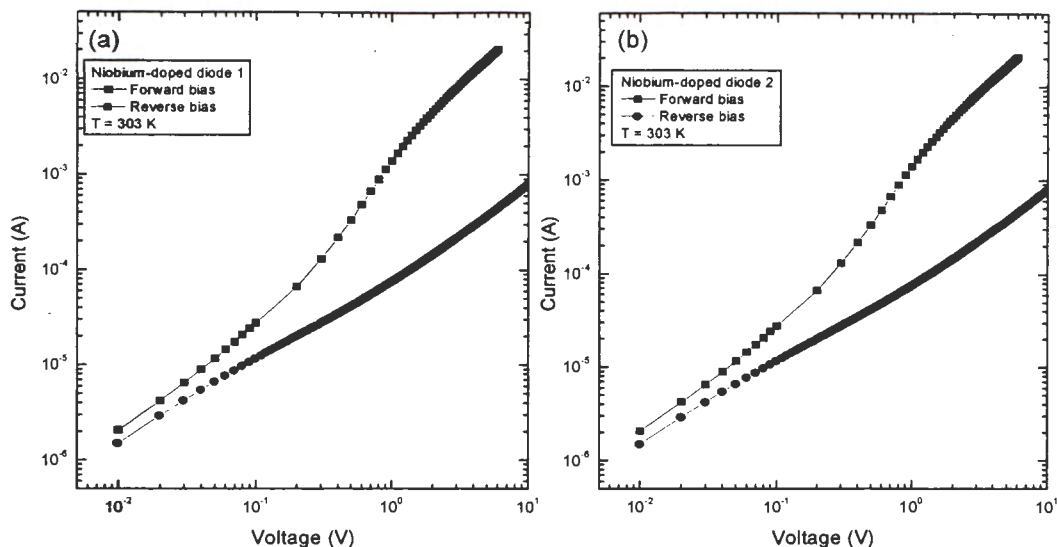


Fig. 4.38: *The I - V characteristics of diodes fabricated on niobium-doped p -silicon. The Ohmic behaviour of the current is more pronounced at reverse bias.*

The parameters for niobium-doped diodes are shown in Table 4.11. The saturation current of both diodes is found to be lower (at $3.53 \mu\text{A}$ and $3.52 \mu\text{A}$) than that of the other diodes (undoped at $87.1 \mu\text{A}$, gold-doped at $11.5 \mu\text{A}$, platinum-doped at $5.95 \mu\text{A}$ and erbium-doped at $273 \mu\text{A}$). Since the parameters are related to each other as explained earlier, this low current implies that the Schottky barrier height is large in this case. A point to note here is that all parameters are similar for the two diodes, as opposed to the other cases. It can be noted that the deposition of gold in this case was homogeneous.

Table 4.11: A summary of device parameters evaluated from I - V plots for diodes fabricated on niobium-doped p -silicon.

Parameter	Diode 1	Diode 2	Average
I_s (μA)	3.53	3.52	3.53
η	1.68	1.68	1.68
ϕ_B (V)	0.72	0.72	0.72

A variation of the reverse I - V characteristics with temperature for the niobium-doped diodes is shown in Fig. 4.39 where the trends are observed to be closer at high voltages. At the voltages lower than $3 \times 10^0 \text{ V}$ a dependence of the current on the

temperature is more pronounced and the trends are observed to be parallel to each other.

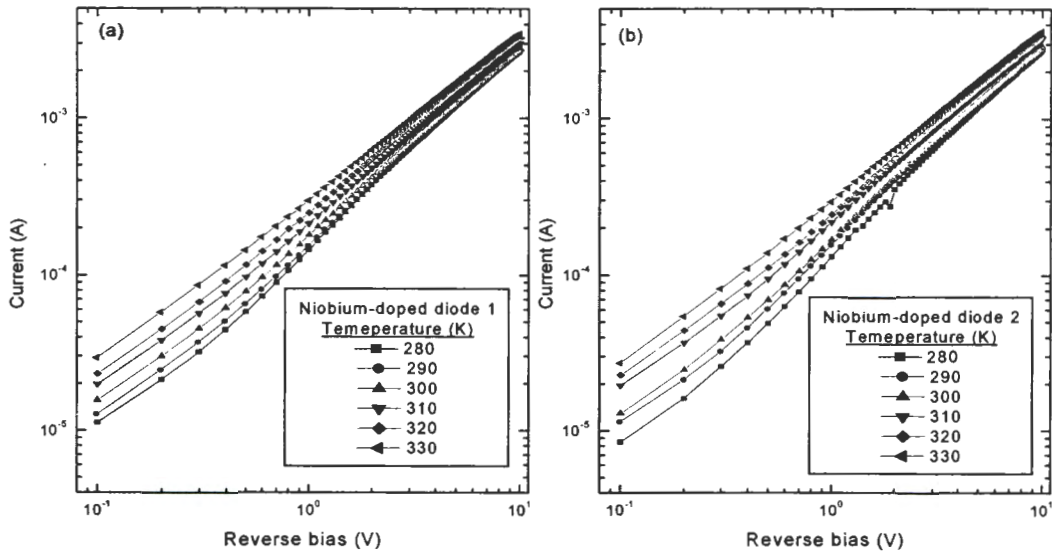


Fig. 4.39: A variation of the reverse I - V characteristic with temperature for the niobium-doped diodes.

The linear relationship of $\ln(I)$ against T^{-1} for niobium-doped diodes is shown in Fig. 4.40 where the activation energy for diode1 is found to be 0.16 eV and 0.17 eV for diode 2. Both energies are in the same range with those obtained from gold-doped and platinum-doped diodes but higher than those obtained from erbium-doped diodes. The energies are, however, lower than those obtained from the undoped diodes to show that the rate in which the carriers are generated by temperature is low due to the defect levels induced by niobium in silicon. As explained earlier, these levels recombine and reduce the amount of the charge carriers that are withdrawn to the opposite electrodes. As a result the effects of temperature on the diode properties are reduced.

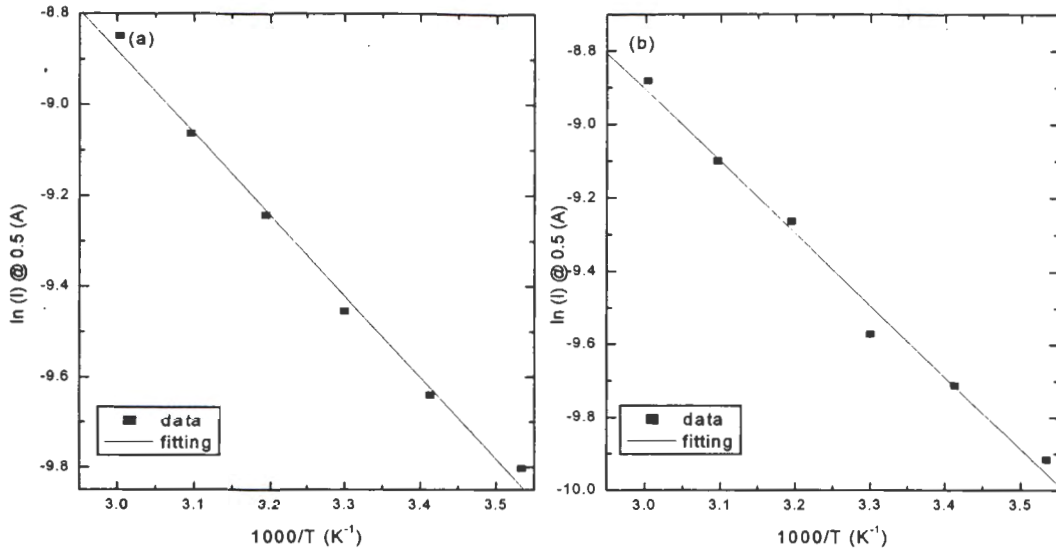


Fig. 4.40: The plots of $\ln(I)$ versus T^{-1} at a constant reverse bias of 0.5 V for niobium-doped diodes.

Fig. 4.41 shows the forward I - V characteristic of the niobium-doped diodes as a function of temperature. The reason for the discontinuity at 0.1 V is currently not known. However, it could be due to the voltage difference between 0.1 and 1.0 V. Unlike in the case of the other diodes it can be noted that the forward current of niobium-doped diodes is independent of temperature. This independence is more pronounced at voltages higher than 1×10^0 V.

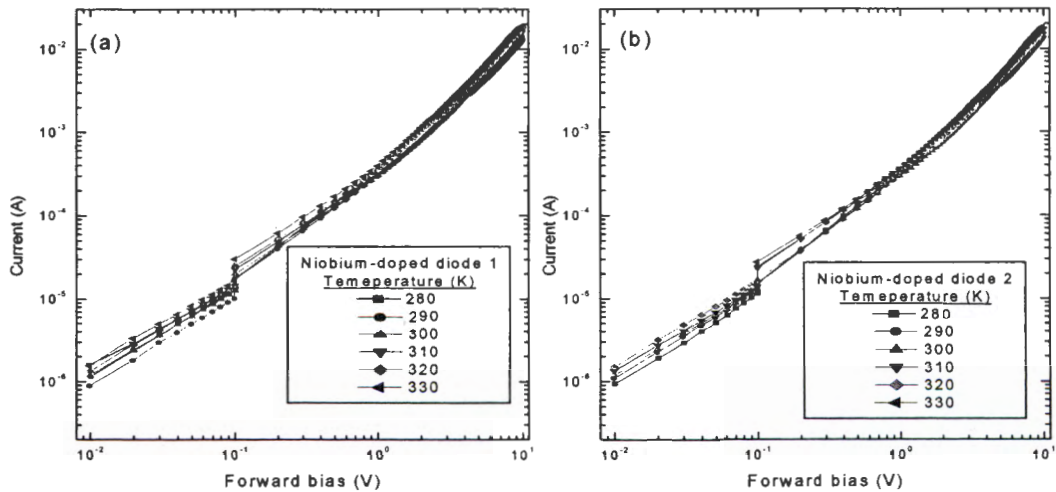


Fig. 4.41: A variation of the forward I - V characteristic with temperature for the niobium-doped diodes.

A variation of the parameters obtained from the niobium-doped diodes with temperature is presented in Table 4.12 where the saturation current is found to increase with the temperature. Unlike in the case of the other diodes, the ideality factor is independent of temperature. A relationship between the temperature and ideality factor is not linear and it is horizontal at high temperature (not presented here). The results obtained show that the forward current is completely independent of the temperature. As observed on the other diodes (undoped, gold-doped, platinum-doped and erbium-doped diodes), the Schottky barrier height is independent of the temperature to show that it is not bulk property.

Table 4.12: A variation of the parameters obtained from the niobium-doped diodes with temperature.

Temperature (K)	280	290	300	310	320	330
I_s (μ A)	2.69	2.73	2.78	2.80	2.81	2.83
η	1.70	1.69	1.69	1.68	1.68	1.68
ϕ_B (V)	0.71	0.72	0.71	0.71	0.73	0.71



The I - V characteristics of the diodes at 303 K show that gold, platinum and niobium decrease the conductivity while erbium increases it. The metal-doped diodes exhibit the Ohmic behaviour which is a property of a device fabricated on a relaxation-like material [Jones and McPherson, 1999]. In comparing the effects of these metals on silicon, the parameters evaluated from all devices are presented in Table 4.13. These are average values obtained from two of the diodes fabricated from each sample.

The saturation current of the diode fabricated on undoped silicon is 87.1 μ A. This current is higher than 8.4 μ A evaluated by Msimanga *et al.* [2004] on n -type silicon diodes. The high value suggests that here the current is not entirely diffusion but includes other mechanisms such as generation and recombination [Sze, 1981]. The presence of these mechanisms results in non-ideal behaviour of the lifetime diodes and this implies the presence of impurities. This is confirmed by the ideality factor of

1.31 which is greater than unity. The non-ideal behaviour could also be due to the interface layer present between the metal and the silicon [Cetin *et al*, 2005] or due to the fact that the material is not as pure as stated. In the first case, it is possible that an interface layer was formed during material preparation or during the fabrication of Schottky contacts. In the second case, it is possible that there were impurities in the silicon that became active at any stage to contribute to the generation current. This case is more probable since absolute purity can never be achieved in an ingot formation [Neamen, 1997].

Table 4.13: A summary of the device parameters evaluated from I - V plots for all the diodes.

Parameter	Undoped	Au-doped	Pt-doped	Er-doped	Nb-doped
I_s (μA)	87.1	11.5	5.95	273	3.53
η	1.31	1.9	1.59	1.87	1.68
ϕ_B (V)	0.63	0.69	0.71	0.59	0.72

The Schottky barrier height evaluated on the undoped diode is 0.63 V. The sum of the Schottky barrier heights evaluated from n -type and p -type silicon should give the energy gap of silicon [Lee *et al*, 2001]. The Schottky barrier height obtained [Msimanga *et al*, 2004] on n -type silicon was found to be 0.64 V. The sum of these heights is higher than the energy gap. This discrepancy is due to the different methods used in making the Schottky contacts during the fabrication process of the diodes. Even though gold was used in fabricating the Schottky contact on n -type silicon, nickel was used as glue between gold and silicon. Since the Schottky barrier height is a surface property, the charge interface could be formed and affect the value of the Schottky barrier height.

The saturation current of the gold-doped diode is lower (at 11.5 μA) than that of the diode fabricated on undoped silicon (87.1 μA). The lower current is due to the defects

that are created by gold in the energy gap of the material [Watanabe and Munakata, 1993]. Since the current is reduced, the defects present are acting more as recombination centres and they trap all available mobile carriers to reduce the conductivity. This means that the recombination mechanism is dominant in the device and this is confirmed by the high value of the ideality factor (of 1.90). It has also recently been reported [Asubay *et al*, 2008] that in *p*-type semiconductors, donor levels present in the energy gap are responsible for the high value of the Schottky barrier height. The high value evaluated (of 0.69 V) shows that donor levels have been created by the gold. These donor levels compensate majority carriers (holes) in the material to reduce the conductivity and so to increase the resistivity. In this way then, gold creates levels that recombine [Graff, 1999] as well as compensate [Asubay *et al*, 2008].

The saturation current of the platinum-doped diode is reduced by a factor of 15 (to 5.95 μ A) from that of the diodes fabricated on undoped *p*-silicon and by a factor of 2 from that of the gold-doped diode. The ideality factor of the diode (at 1.59) is greater than the one of the diode fabricated on undoped *p*-silicon (at 1.31) but lower than the one of the gold-doped diode (at 1.90). The Schottky barrier height of the diode (at 0.71 V) is higher than the ones of the diodes fabricated on undoped (0.63 V) and on gold-doped *p*-silicon (0.69 V). This high value of the Schottky barrier height shows that platinum in silicon creates donor levels in the energy gap that compensate holes to reduce the conductivity of the material. This reduction of the conductivity, as it has been said before for gold, shows that both gold and platinum create strong recombination centres. This implies that donor levels in the lower half are more active than acceptor levels in the upper half of the energy gap.

The saturation current of the erbium-doped diode has increased by a factor of 3 (to 273 μA) from that of the diode fabricated on undoped *p*-silicon. This shows that defects created by erbium in silicon are responsible for the generation of carriers to increase the conductivity of the material. However, the ideality factor of the diode at 1.87 is higher than that of the diodes fabricated on undoped (1.31) and on platinum-doped (1.59) silicon but lower than that of the diode fabricated on gold-doped (1.90) *p*-silicon. The Schottky barrier height (of 0.59 V) is lower than that of the other diodes. Since the erbium-doped diode also exhibits Ohmic behaviour as the gold-doped and platinum-doped diodes, it is expected that some of the levels created by erbium will have similar activity as those created by gold and platinum.

The saturation current of the niobium-doped diode (at 3.53 μA) is lower than that of the other diodes. In a similar manner as the defects created by gold and platinum, those that are created by niobium also compensate majority carriers in the energy gap to reduce the conductivity. The ideality factor of 1.68 is lower than that of the gold-doped (1.90) and erbium-doped (1.87) diodes, but higher than that of the diodes fabricated on undoped (1.31) and on platinum-doped (1.59) silicon. The Schottky barrier height of the diode is higher at 0.72 V than that of the other diodes. This shows that niobium creates donor levels in the energy gap of silicon that compensate holes to reduce the conductivity.

The ideality factor and the Schottky barrier height are related to each other only for diodes fabricated on the same material. This is expected since the ideality factor depends more on the defect levels created in the energy gap than on the contacts [Msimanga and McPherson, 2006]. It is thus argued that an increase in the value of the ideality factor is due to metals introduced into the material rather than to the methods used to fabricate the contacts.

A comparison of the metals shows that gold, platinum and niobium create recombination centres that cause the conductivity to decrease. Erbium has an opposite effect in that the conductivity increases. However, in all cases the current is Ohmic and all the metals generate the midgap defect, which is common in all cases. It is clear therefore that the Ohmic behaviour of the current is caused by the midgap defect. The current profile of the erbium-doped diode is, however, very similar to that of diodes irradiated by 1 MeV neutrons [Moloi and McPherson, 2009]. This is expected since in both cases the midgap defect acts as a generation centre. Further to this, the behaviour of erbium is expected to be different from that of the other metals since it generates defects only in the upper half of the energy gap. These defects are responsible for the high saturation current (or the low barrier height) and the high ideality factor. Thus, the midgap defect created by metals in silicon is responsible for the relaxation-like behaviour of the material.

At temperatures ranging from 280 K to 330 K the effects of temperature on the I - V characteristics of the metal-doped diodes is found to be reduced. The reduction of these effects can be explained in terms of the low activation energy obtained from these diodes. The defects induced by metals recombine the charge carriers that are generated by temperature. This recombination of the carriers results in a reduction of the activation energy. These results are similar to those presented for the irradiated diodes under illumination. Similarly, the effects of temperature are reduced on the metal-doped diodes. Thus, the doping of silicon with the metals is similar to the radiation-damage.

4.3.2 Capacitance measurements

To supplement the I - V results presented above, C - V measurements were also carried out on the fabricated diodes to investigate the doping profile and the doping density of the material. The measurements were carried out at 300 K and at 1 MHz.

4.3.2.1 Undoped diodes

Fig. 4.42 shows the linear plot of C - V at 300 K and at 1 MHz for the diodes fabricated on undoped p -silicon. The C - V profile of diode 1 shown in plot (a) is similar to that of diode 2 shown in plot (b). Both plots indicate a steep fall in the capacitance at low voltages which changes to a gradual fall. At high voltages the fall in capacitance is almost negligible. The initial fall of the capacitance is due to an increase of the depletion width as the voltage increases. At high reverse voltages the fall is negligible as the capacitance saturates to show that the diodes become fully depleted. These well known trends of the capacitance have been observed [Msimanga *et al*, 2004] on the diodes fabricated on n -type silicon. They have also been observed on the commercial silicon p - i - n diodes [McPherson, 1997; Moloi, 2005].

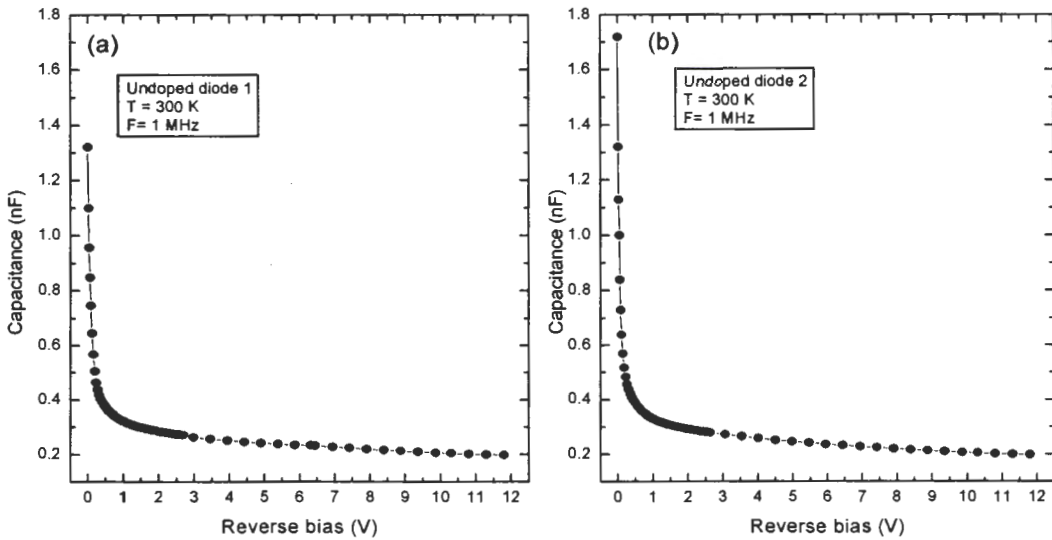


Fig. 4.42: The C - V characteristics of diodes fabricated on undoped p -silicon measured at 300 K and at 1 MHz.

Even though the diodes are fabricated on p -silicon using gold for Schottky contacts, the results show that they were properly fabricated. As stated earlier, gold can be used to make Schottky contacts on p -silicon as well. This point is stated here because gold is known to make Schottky contacts only on n -type silicon.

A second method of analysis is based on the plot of C^{-2} - V at 300 K and 1 MHz. This type of analysis is shown in Fig. 4.43 for diodes fabricated on undoped p -silicon. Two different linear regions are observed in both plots to show that the doping profile is not uniform. The linear region at voltages lower than 1 V is smaller than that at voltages between 1.5 and 12 V showing the uniformity over large voltage ranges. This shows that the doping profile in diodes fabricated on undoped p -silicon is uniform over a large depletion width.

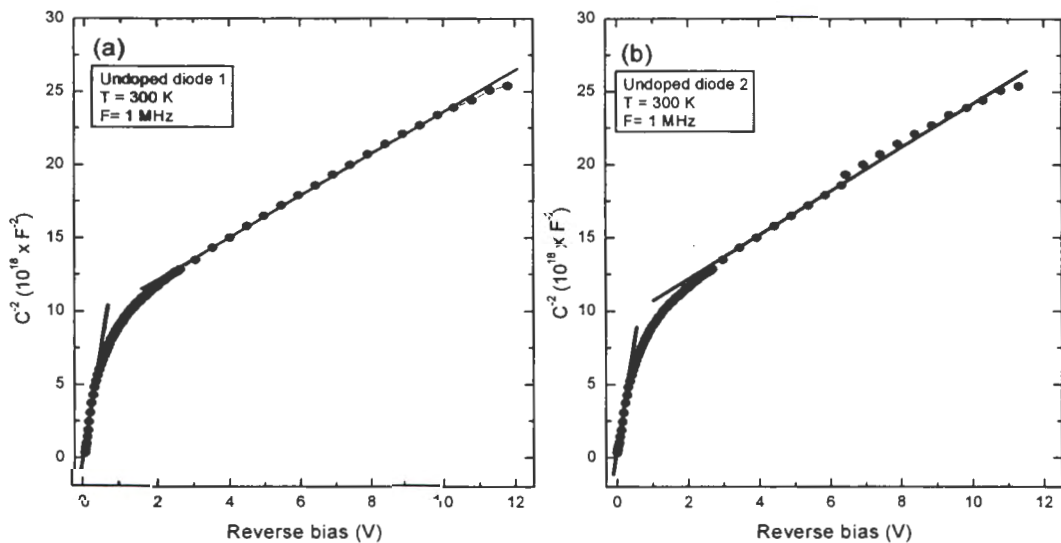


Fig. 4.43: The C^{-2} - V characteristics of diodes fabricated on undoped p -silicon generated from the data of Fig. 4.42.

The evaluated values of the doping density and the Schottky barrier height for the undoped diodes are given in Table 4.14. These parameters were evaluated using the slopes obtained from linear region between 1.5 V and 12 V. The Schottky barrier height can be expressed [Sze, 1981] as

$$\phi_B = V_{bi} + \frac{kT}{e} \ln \left(\frac{N_v}{N_A} \right) \quad (4.9)$$

where V_{bi} is the built-in voltage obtained from the intercept on the voltage axis of C^{-2} against V graph.

The parameters presented in Table 4.14 are slightly different even though the diodes were fabricated on the same substrate. As stated earlier, this could be due to the inhomogeneous deposition of gold during the fabrication of the Schottky contact. It can be seen from the table that a low doping density ($7.60 \times 10^{15} \text{ cm}^{-3}$) in diode 1 corresponds to a high Schottky barrier height (0.53 V).

Table 4.14: A summary of diode parameters evaluated from C^{-2} - V plots for diodes fabricated on undoped p -silicon.

Parameter	Diode1	Diode 2	Average
$N_A (\times 10^{15} \text{ cm}^{-3})$	7.60	7.70	7.65
$\phi_B (\text{V})$	0.53	0.50	0.52

The doping densities and the Schottky barrier heights at low voltage linear regions were also evaluated but these are not presented in the table. The doping density was found to be $6.59 \times 10^{14} \text{ cm}^{-3}$ in diode 1 and $8.58 \times 10^{14} \text{ cm}^{-3}$ in diode 2, while the Schottky barrier heights were found to be 0.294 V and 0.287 V in diode 1 and diode 2, respectively. It can be noted that these doping densities and Schottky barrier heights are lower than those evaluated from the wider linear regions.

4.3.2.2. Gold-doped diodes

Fig. 4.44 shows the C - V characteristics for the diodes fabricated on gold-doped p -silicon. The profiles for both diodes are similar apart from the fact that the capacitance measured for diode 1 is $\sim 0.6 \text{ nF}$ at 0 V while the one for diode 2 is $\sim 1.7 \text{ nF}$. However, at voltages higher than 0.5 V the capacitance for both diodes shows a

tendency to saturate. Unlike in the case of the undoped diodes, the capacitance measured for gold-doped diodes tends to slope at low voltages.

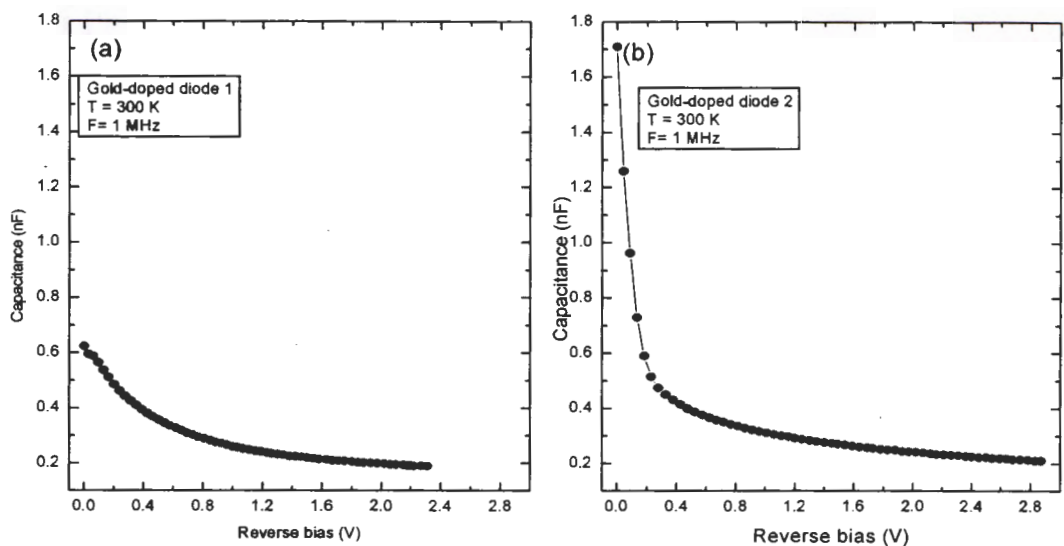


Fig. 4.44: The C - V characteristics of diodes fabricated on gold-doped p -silicon measured at 300 K and at of 1 MHz.

Fig. 4.45 shows the C^{-2} - V characteristics of the diodes fabricated on gold-doped p -silicon.

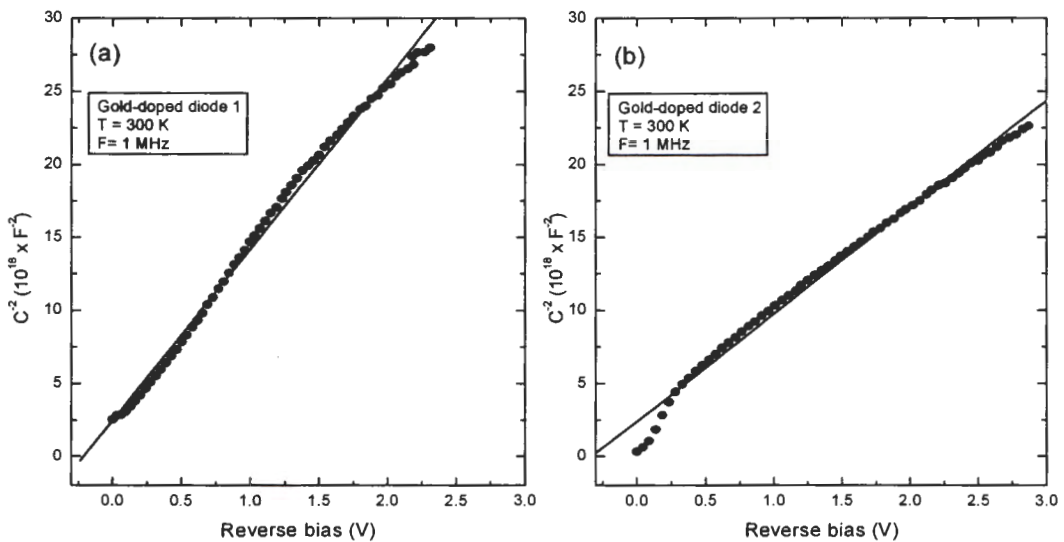


Fig. 4.45: The C^{-2} - V characteristics of diodes fabricated on gold-doped p -silicon generated from the data of Fig. 4.44.

A linear region is observed for all voltages in plot (a) to show that the doping profile in this diode is uniform over the whole depletion width. In plot (b), however, two linear regions are observed to show that the doping profile is not uniform over the whole depletion width. However, at the range between 0.25 V and 2.8 V the plot shows that the doping profile is uniform over a large depletion region.

Table 4.15

Table 4.15 shows parameters evaluated from the reverse C^{-2} - V of the gold-doped diodes. The parameters are different even though the diodes are fabricated from the same substrate to show an inhomogeneous deposition of gold during the fabrication of the Schottky contacts. They are not related to each other in the same manner as the parameters obtained for the diode fabricated on undoped p -silicon. In gold-doped diodes the low value of the doping density ($1.05 \times 10^{15} \text{ cm}^{-3}$) in diode 1 corresponds to a low Schottky barrier height (0.47 V) while the high doping density ($1.67 \times 10^{15} \text{ cm}^{-3}$) in diode 2 corresponds to a high Schottky barrier height (0.58 V). The doping density and the Schottky barrier height obtained from the low voltage range of diode 2 were found to be $0.50 \times 10^{15} \text{ cm}^{-3}$ and 0.30 V, respectively.

Table 4.15: A summary of diode parameters evaluated from C^{-2} - V plots for diodes fabricated on gold-doped p -silicon.

Parameter	Diode1	Diode 2	Average
$N_A (\times 10^{15} \text{ cm}^{-3})$	1.05	1.67	1.36
$\phi_B (\text{V})$	0.47	0.58	0.53

4.3.2.3 Platinum-doped diodes

Fig. 4.46 shows C - V characteristics of the diodes fabricated on platinum-doped p -silicon and it can be seen that the trends for both diodes are similar. Even though titanium was used to fabricate the Schottky contacts on the platinum-doped substrates, the results presented in Fig. 4.46 show similar characteristics as those presented for undoped and gold-doped substrates where gold was used to fabricate the contacts. As

has been found on other semiconductors such as p -SiC [Lee *et al*, 2001] and p -InGaP [Gombia *et al*, 2003], it is found in this work that gold can also be used to form Schottky contacts on p -Si material in a similar way as titanium is used.

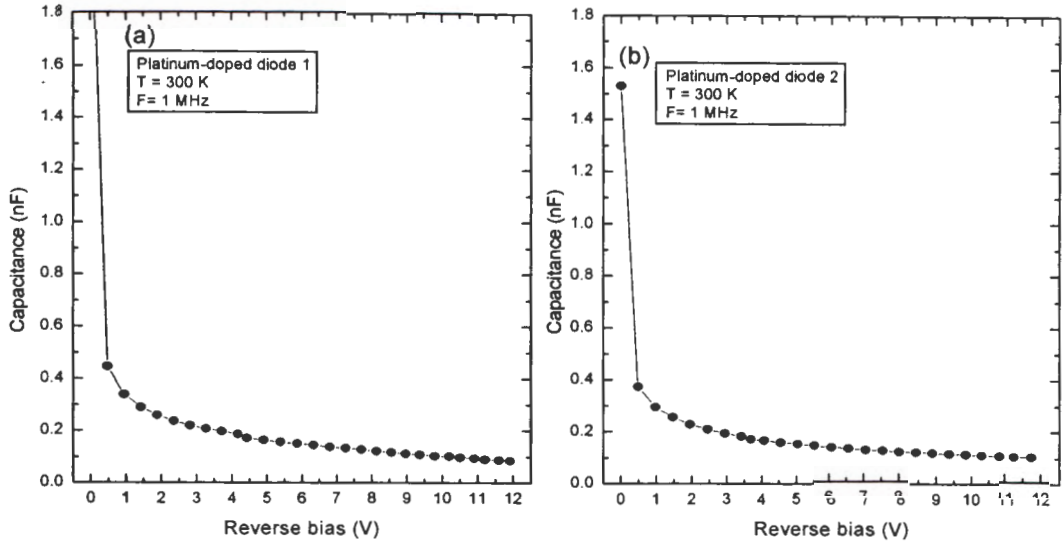


Fig. 4.46: The C - V characteristics of diodes fabricated on platinum-doped p -silicon measured at 300 K and at 1 MHz.

Fig. 4.47 illustrates the doping profiles of the diodes fabricated on platinum-doped p -silicon in the form of C^{-2} - V graphs.

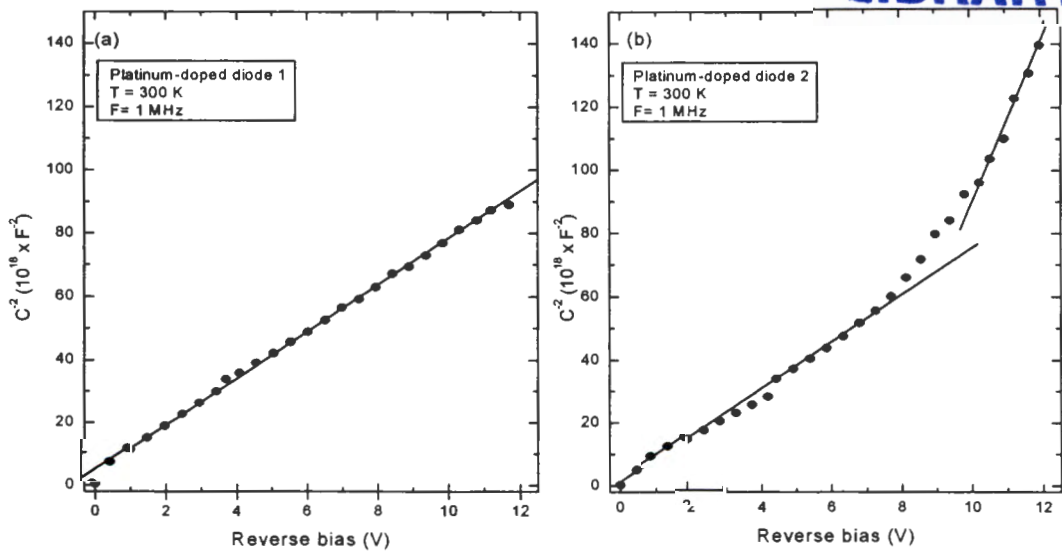


Fig. 4.47: The C^{-2} - V characteristics of diodes fabricated on platinum-doped p -silicon generated from the data of Fig. 4.46.

It can be seen in plot (a) that the doping profile is uniform over the whole depletion region. In plot (b) two linear regions are observed to show that the doping profile in this diode is not uniform over the whole depletion region. The plot, however, shows that the doping profile is uniform over a large depletion region of the voltage range of 0 V and 8 V.

The parameters evaluated for platinum-doped diodes are presented in Table 4.16 where a low doping density in diode 1 ($1.65 \times 10^{15} \text{ cm}^{-3}$) corresponds to a high Schottky barrier height (0.83). The variation of parameters is similar to that of diodes fabricated on undoped silicon even though the Schottky contacts were fabricated using a different metal (titanium) for this set of diodes. These results show that the parameters do not depend on the type of the metal that is used to fabricate the Schottky contacts.

Table 4.16: A summary of diode parameters evaluated from C^2 - V plots for diodes fabricated on platinum-doped silicon.

Parameter	Diode1	Diode 2	Average
$N_A (\times 10^{15} \text{ cm}^{-3})$	1.65	1.67	1.66
$\phi_B (\text{V})$	0.83	0.33	0.58

As it is found in the I - V results presented in Section (4.2), a change in the diode properties is due to the metals introduced into the material not the metals used to fabricate the contacts. The doping density at the voltage range of 10 V and 12 V is found to be $0.62 \times 10^{15} \text{ cm}^{-3}$ which is lower than the one obtained from the larger linear region. The Schottky barrier height at this voltage range was evaluated as -16 V. The reason for this unusual value of the Schottky barrier height is currently not known.

4.3.2.4 Erbium-doped diodes

Fig. 4.48 shows C - V characteristics for the diodes fabricated on erbium-doped p -silicon.

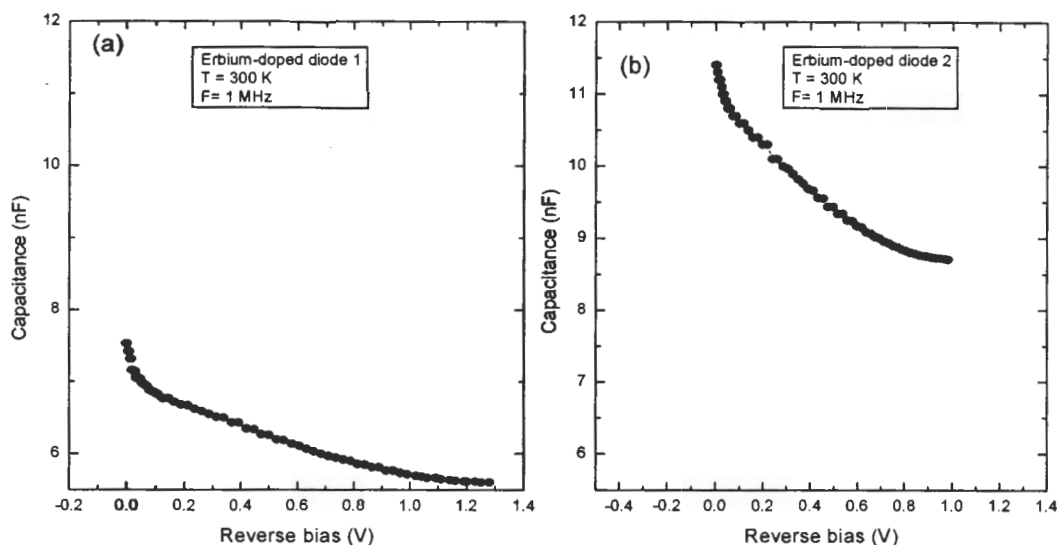


Fig. 4.48: *The C - V characteristics of diodes fabricated on erbium-doped p -silicon measured at 300 K and at 1 MHz.*

Unlike in the case of the other diodes (undoped, gold-doped and platinum-doped) where the capacitance decreases sharply at low voltages, in this case of erbium-doped diodes the capacitance decreases gently with voltage and there is no indication of saturation. These results can be interpreted in terms of the defect levels that are induced by erbium in the energy gap of silicon. The induced levels generate a very high number of charge carriers. Since at low voltages the electric field is not high enough to draw the generated carriers out of the depletion region to the opposite electrodes, the capacitance decreases gradually with an increase in applied voltage. Thus, the rate at which the generated carriers are drawn out is low and this shows that a very high voltage is required to fully deplete the diodes. Similar results have been presented [Moloi and McPherson, 2009] on a diode that was irradiated by 1 MeV neutrons to a fluence of 10^{17} n cm⁻². The results in that case were interpreted in terms

of the defect levels that turn silicon into a relaxation material. Thus, some of the defects induced by erbium in silicon have similar effects as those induced by irradiation and they are all responsible for the relaxation behaviour of the material.

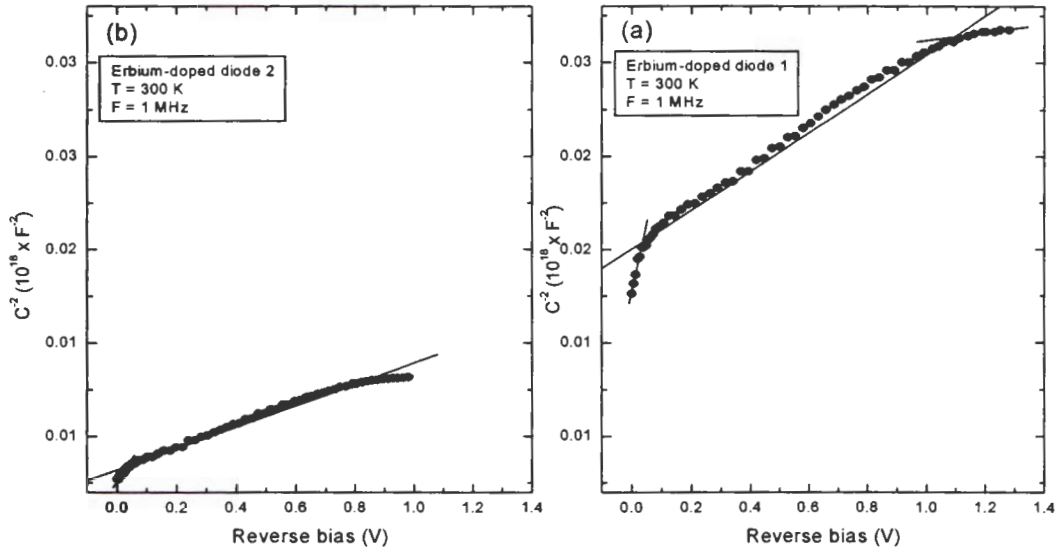


Fig. 4.49: The C^{-2} - V characteristics of diodes fabricated on erbium-doped p -silicon generated from the data of Fig. 4.48.

Fig. 4.49 illustrates the doping profiles of the diodes fabricated on erbium-doped p -silicon in the form of C^{-2} - V graphs. Even though the profile of diode 1 shown in plot (a) gives a higher C^{-2} value than that of diode 2 shown in plot (b), it can be seen that the trends for both diodes are similar. The doping profile in both diodes is not uniform but the C^{-2} - V variation is linear over a wide voltage range of 0.1 V - 1 V and of 0.1 V – 0.9 V for diode 1 and diode 2, respectively.

The parameters evaluated from the C^{-2} - V plots of erbium-doped diodes are shown in Table 4.17 where a low doping density from diode 1 ($1160 \times 10^{15} \text{ cm}^{-3}$) corresponds to a high Schottky barrier height (2.05) and a high doping density in diode 2 ($2100 \times 10^{15} \text{ cm}^{-3}$) corresponds to a low Schottky barrier height (1.50 V). This variation of the parameters resembles the variation in the diodes fabricated on undoped and on platinum-doped p -silicon. It can be noted that the doping density evaluated from the

diodes are very high. These values correspond to the almost degenerate semiconductor.

The parameters were also evaluated at low bias and at high bias regions for both diodes. In diode 1, the doping density was found to be $369 \times 10^{15} \text{ cm}^{-3}$ at low voltage and $873 \times 10^{15} \text{ cm}^{-3}$ at high voltage. These doping densities correspond to the Schottky barrier heights of 0.34 V and 8.45 V, respectively. In diode 2, on the other hand, the doping density is $172 \times 10^{15} \text{ cm}^{-3}$ and $286 \times 10^{15} \text{ cm}^{-3}$ at high voltage. These values of the doping density correspond to the Schottky barrier heights of 0.38 and 6.28 V, respectively. The significance of these high barrier heights is currently not understood, however, the doping density values are lower than those obtained from the larger linear regions but higher than the doping densities obtained from other diodes.

Table 4.17: A summary of diode parameters evaluated from C^{-2} - V plots for diodes fabricated on erbium-doped p -silicon.

Parameter	Diode 1	Diode 2	Average
$N_A (\times 10^{15} \text{ cm}^{-3})$	1160	2100	1630
$\phi_B (\text{V})$	2.05	1.50	1.78

4.3.2.5 Niobium-doped diodes

Fig. 4.50 shows the C - V characteristics for diodes fabricated on niobium-doped p -silicon. These diodes show unusual characteristics, that is, a gentle decrease of the capacitance up to 2 V, after which a steep fall is observed up to 4.5 V. At voltages higher than 4.5 V the capacitance decreases gently. It can be noted that both diodes do not show any saturation of the capacitance, indicating that a high voltage is required to fully deplete these diodes.

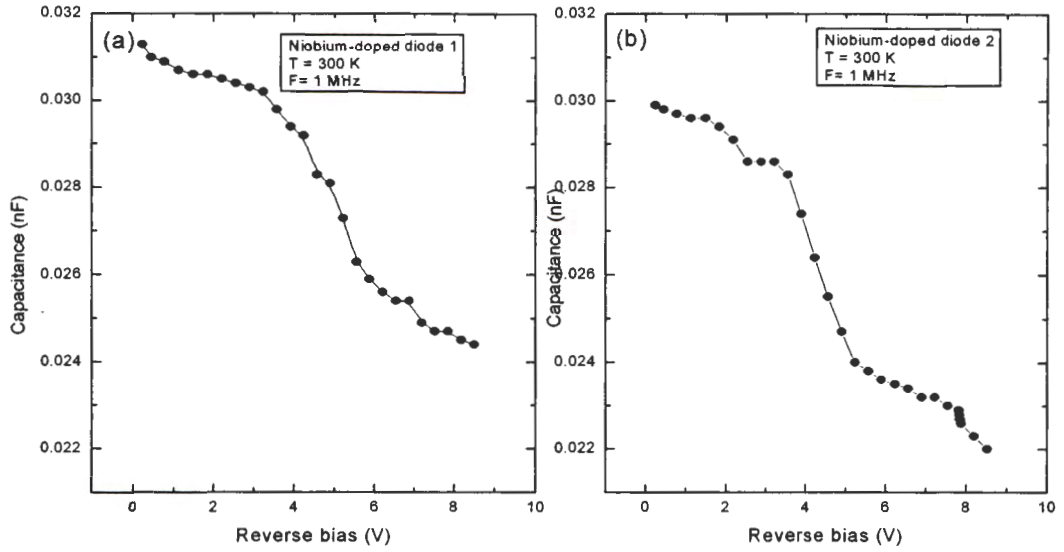


Fig. 4.50: The C - V characteristics of diodes fabricated on niobium-doped p -silicon measured at 300 K and at 1 MHz.

Fig. 4.51 illustrates the doping profiles of the diodes fabricated on niobium-doped p -silicon in the form C^{-2} - V graphs. Three linear regions are observed in both diodes to show that the doping profile is not uniform. A rapid increase of C^{-2} is observed at about 3 V in both diodes. These trends of C^{-2} have been observed [Siddiqui, 1998] on the P^+ - N diodes. According to Siddiqui, [1998], this behaviour of C^{-2} shows that the doping density varies with distance from the junction.

The values of the doping density and the Schottky barrier height evaluated on the regions where the variation is linear over wider voltage range are given in Table 4.18. It can be noted that parameters are not related to each other in the same manner as the parameters obtained from the diodes fabricated on undoped, platinum-doped and erbium-doped p -silicon. In niobium-doped diodes the high doping density ($0.08 \times 10^{15} \text{ cm}^{-3}$) in diode 1 corresponds to a high Schottky barrier height (3.64 V) while the low doping density ($0.04 \times 10^{15} \text{ cm}^{-3}$) in diode 2 corresponds to a low Schottky barrier height (1.01 V). This variation of the parameters is similar to the one for gold-doped diodes.

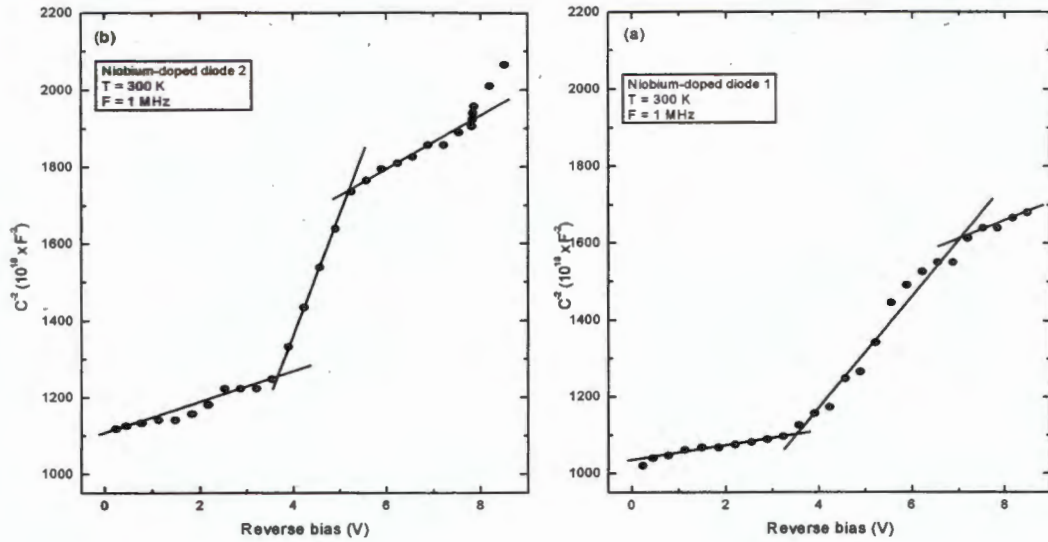


Fig. 4.51: The C^2 - V characteristics of diodes fabricated on niobium p -silicon generated from the data of Fig. 4.50.

The parameters were also evaluated at low and at high voltage linear regions for both diodes. In diode 1, the doping density is $0.65 \times 10^{15} \text{ cm}^{-3}$ at the low voltage region and $0.17 \times 10^{15} \text{ cm}^{-3}$ at the high voltage region. These doping densities correspond to the Schottky barrier heights of 55 V and 15 V, respectively. In diode 2, on the other hand, the doping density is $0.3 \times 10^{15} \text{ cm}^{-3}$ at the low voltage region and $0.2 \times 10^{15} \text{ cm}^{-3}$ at the high voltage region. These doping densities correspond to the Schottky barrier heights of 27 V and 24 V, respectively. The significance of these high barrier heights is currently not understood. Even though these doping densities are found to be higher than those obtained from the wider linear region in these diodes, it can be noted that they are lower than those obtained from undoped, gold-doped, platinum-doped and erbium-doped diodes.

Table 4.18: A summary of diode parameters evaluated from C^2 - V plots for diodes fabricated on niobium-doped p -silicon.

Parameter	Diode 1	Diode 2	Average
$N_A (\times 10^{15} \text{ cm}^{-3})$	0.08	0.04	0.06
$\phi_B (\text{V})$	3.64	1.01	2.33

A summary of device parameters evaluated from C^{-2} - V plots for all five diodes is presented in Table 5. The doping density of the diode fabricated on undoped p -silicon is $7.65 \times 10^{15} \text{ cm}^{-3}$ slightly higher than ($2.20 \times 10^{15} \text{ cm}^{-3}$) the one obtained [Cetin *et al*, 2005] for Ti/ p -Si and lower than ($17.0 \times 10^{15} \text{ cm}^{-3}$) the one obtained [Hanselaer *et al*, 1986] on the Au/ p -Si using the C - V measurements at 1 MHz. The high value of the doping density is due to the interface between gold and silicon [Hanselaer *et al*, 1986].

Table 4.19: A summary of device parameters evaluated from C^{-2} - V plots for all the diodes.

Parameter	Undoped	Au-doped	Pt-doped	Er-doped	Nb-doped
$N_A (\times 10^{15} \text{ cm}^{-3})$	7.65	1.36	1.66	1630	0.06
$\phi_B (\text{V})$	0.52	0.53	0.58	1.78	2.33

It can be seen from the table that the doping densities obtained from the gold-doped, platinum-doped and niobium-doped diodes are lower than that of the undoped diode. A decrease in the doping density on the p -Si has been observed [Karats and Turut, 2006; Gullu *et al*, 2008; Gullu *et al*, 2008(a)] on the gamma irradiated diodes. This decrease in the doping density was explained in terms of the defect induced by irradiation in the energy gap to increase the resistivity of the material. The doping density obtained from erbium-doped diode is, however, quite different from the others. The doping density evaluated from the erbium-doped diodes may indicate the degenerate semiconductor. It is higher than that of undoped diode since the defects induced by erbium are only found in the upper half of the energy gap. The C - V profile of the erbium-doped diodes is similar to the one observed on the irradiated silicon p - i - n diodes [Moloi and McPherson, 2009]. Thus, the effects of erbium are similar to those of radiation-damaged in silicon.

Chapter 5

Summary and Conclusions

The conclusions of this work are drawn from the results obtained from measurements carried out on the silicon material and the diodes fabricated on the material. The material was characterised with *RBS* and *XPS* techniques, while the diodes were characterised with *I-V* and *C-V* techniques. There are conclusions from this work that are considered as contributions to basic of knowledge while others support the results that have been obtained by other workers in the field of semiconductor detectors.

5.1 Silicon *p-i-n* diodes

The commercial silicon *p-i-n* diodes were irradiated by 1 MeV neutrons to different fluences. The *I-V* and *C-V* measurements were carried out on the diodes at 302 K prior to and after irradiation. The measurements were carried out in the dark and under illumination of different wavelengths. The results obtained show that the measured current and capacitance of radiation-damaged diodes increase with an increase in the wavelength of light incident on the diodes. This increase of the quantities was also observed [McPherson, 2005] on the results obtained from the diodes irradiated to a very low fluence. The effects tend to be reduced as the fluence increases due to the defect levels induced by the radiation in the energy gap. These levels recombine photo-generated carriers to reduce the photocurrent and the photocapacitance of the diode. They also act as generation centres since the dark current and the dark capacitance increase after irradiation.

The defect levels that can generate and recombine charge carriers are responsible for the relaxation behaviour of silicon. They stabilize the Fermi level at the intrinsic

position where it is not affected by further irradiation [Brudnyi *et al*, 1995]. The diodes fabricated from this material have been found to be resistant to radiation damage [Jones and McPherson, 1999]. Thus, light of different wavelengths can be used to investigate the properties of diodes fabricated on radiation-hard material. It is for the first time to report that after a diode has become a radiation-hard (or relaxation) device, the effects of light on its properties are reduced. A conclusion regarding the radiation-hardness of silicon after initial heavy damage was also reached [Litovchenko *et al*, 2006; Moloi and McPherson, 2009] based on results obtained from the diodes irradiated up to $10^{17} \text{ n cm}^{-2}$.

5.2. Material characterization

The *RBS* and *XPS* measurements were carried out on the samples prior to and after the annealing process. The measurements indicate that considerable amounts of gold and platinum diffuse into silicon at the annealing temperature of 900 °C for 18 hours. The kicking-out diffusion mechanisms dominate and the diffusion profile of the metals in silicon is U-shaped at this temperature. Due to a very low solubility it has in silicon, the amount of erbium diffused is below the detection limit of the techniques used. The measurements also show that there are very small amounts of contaminants (carbon and oxygen) diffused into the silicon after the annealing process.

5.3 Schottky diodes

The Schottky diodes were successfully fabricated on the undoped and metal-doped *p*-silicon. The metals used are gold, platinum, erbium and niobium. The Schottky contact on the material was achieved by deposition of gold on *p*-silicon wafer. The *I-V* and *C-V* measurements were carried out on the diodes to investigate a change in electrical properties of the diodes due to the metals introduced into the material.

Changes of the various parameters such as the saturation current, the ideality factor, the Schottky barrier height and the doping density have been investigated.

The I - V measurements show that the diodes fabricated on the metal-doped p -silicon deviate from the ideal to the non-ideal behaviour. The measured current of the diodes is Ohmic and the breakdown voltage is not observed. Furthermore, the reverse and forward bias current profiles converged. These properties of the diodes current are caused by the midgap defect created by the metals in the energy gap. This defect causes the relaxation behaviour of the material. Thus, the diodes are fabricated on relaxation silicon. The same conclusion was also reached [Msimanga *et al*, 2004] based on the results obtained from the diodes fabricated on the gold-doped n -silicon.

Due to the defect levels, the saturation current of gold-doped, platinum-doped and niobium-doped diodes is found to be lower than that of the undoped diodes. This reduction of the saturation indicates that the defect levels that are created by gold, platinum and niobium recombine charge carriers to increase the resistivity of the material. The saturation current of the erbium-doped diode is, however, found to be higher than that of undoped diode to show that the defect levels induced by erbium generate charge carriers to increase the conductivity of the material.

The I - V measurements were also carried out on the diodes in the temperature range of 280-330 K. The current was found to increase with temperature for the same voltage, while the breakdown voltage was independent of the temperature. A trend of the forward current was found to be independent of the temperature. These effects of temperature were found to be reduced on metal-doped diodes due to the defect levels induced by metals in the energy gap. This reduction of the effects of temperature on the properties of the diodes was confirmed by low values of the activation energies

obtained from the metal-doped diodes. Even though the levels induced by erbium generate charge carriers to increase the conductivity, they are also found to recombine the thermal carriers to decrease the conductivity as well. These results show that the defect levels induced by erbium can generate or recombine charge carriers. These are properties of the midgap defect.

A variation of the parameters (the saturation current, the ideality factor and the Schottky barrier height) with temperature was investigated. The saturation current was found to increase, while the ideality factor decreases with temperature. This dependence of the ideality factor is more pronounced on the gold-doped and platinum-doped diodes. The Schottky barrier height is, however, independent of the temperature to show that it is a surface property not a bulk property.

The C - V measurements show that the doping profile of the Schottky diodes is uniform over the whole depletion region. The doping densities evaluated from the gold-doped, platinum-doped and niobium-doped diodes are lower than that evaluated from undoped diode. The reduction of the doping density shows that the amount of the charge carriers withdrawn to the opposite electrodes is reduced. This is due to the defect levels induced by the metals in the energy gap. As explained, these defect levels recombine charge carriers and decrease the conductivity of the material. The doping density evaluated from the erbium-doped is, however, higher than that of undoped diode to show that the defect levels induced by erbium generate charge carrier to increase the conductivity.

It has been shown that the Schottky barrier heights obtained from the I - V and C - V measurements are not the same. This is mainly due to the presence of the thin layer, at

the interface [Cetin *et al*, 2005; Karatas and Turut, 2006; Gullu *et al*, 2008] to show that the parameter is not a bulk property.

In summary, it has been shown that irradiation is similar to doping with any of the metals. The measured current of the irradiated and metal-doped diodes is Ohmic. The resistivity of the diodes also increases due to the recombination of the charge carriers by defect levels induced in the energy gap. These two properties of the diode are caused by the midgap defect that is created by irradiation or metal in the energy gap. This defect is the cause of the relaxation behaviour of the material. Thus, the diodes are fabricated on relaxation material.

The effects of platinum, erbium and niobium are presented for the first time and are responsible for the relaxation behaviour of *p*-silicon. It is expected that detectors fabricated from platinum-doped, erbium-doped or niobium-doped silicon would be resistant to any kind of radiation environment as gold-doped [Dixon and Ekstrand, 1986; McPherson *et al*, 1997] or as radiation-damaged [Moloi and McPherson, 2009] material has been found to be. These diodes are also expected to exhibit negative capacitance [McPherson, 2004] in forward bias.

5.4 Possible future work

The work carried out here serves only as an investigation of the effects of defects induced by irradiation and metal on properties of the diodes. To extend a study of the defects induced, the effects of temperature on the irradiated diodes and those of light on the metal-doped diodes should be investigated. In addition, the *C-V* measurements in forward bias should be carried out on the metal-doped diodes.

It must be noted that exact properties of the defect levels created by the irradiation and the metals in silicon are not investigated in this work. The deep level transient spectroscopy (*DLTS*) measurements should be performed on the diodes to investigate trap densities, capture cross sections and exact trap positions in the energy gap. Other measurements like Hall Effect, Secondary Ion Mass Spectrometry (*SIMS*) should be carried out on the material. It is hoped that information regarding the diffusion mechanism of the metals (gold, platinum, erbium and niobium) in silicon would be enhanced.

The platinum-doped, erbium-doped and niobium-doped diodes need to be irradiated with neutrons to determine any suppression of radiation effects as has been done with gold-doped diodes [McPherson *et al*, 1997]. With these results it is hoped that a holistic picture to assist in understanding the Ohmic behaviour of the devices and the relaxation behaviour of the material would be found. This would assist in the fabrication of the ultimate radiation detector.

It is also important, however, to understand the mechanisms involved when different particles with different energies interact with the silicon material. Thus, studies must also be performed with other fundamental particles such as protons, gamma rays, pions and electrons. This knowledge could then provide some guidance for the study of devices exposed to other fundamental particles in comparison to 1 MeV neutrons.

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