CHAPTER 5

Effect of Swift Heavy Ion Irradiation on Si Schottky Barrier Diodes

5.1 Preamble

The electrical characteristics of a metal-semiconductor contact are extremely sensitive to contaminants and any form of damage introduced at the interface. Ion irradiation at the interface causes modification of the interface and affects the electrical characteristics of the Schottky diode formed on the semiconductor. There have been many studies on the effect of low energy ion implantation on the electrical characteristics of Si based Schottky barrier diodes [1-7]. These studies established that low energy ion implantation generally decreased the Schottky barrier heights on n-type Si and increased the barrier heights on p-type Si. But the studies on the modifications of electrical characteristics of Schottky barrier diodes by swift heavy ion irradiation (having energies of a few tens to hundreds of MeV) are rather scarce in the literature [8-10]. An important difference in this case with respect to low energy ion implantation is the high electronic energy loss due to inelastic collisions of swift heavy ions (SHI) at the metal-semiconductor (MS) interface of Schottky barrier diode (SBD). In case of low energy ion implantation, nuclear energy loss is the dominant energy loss mechanism whereas for swift heavy ion
Effect of Swift Heavy Ion Irradiation on Si Schottky Barrier Diodes

irradiation, electronic energy loss due to inelastic collision is two to three orders of magnitude larger than nuclear energy loss. In case of SHI the range of ion in the semiconductor is a few tens of micrometer (\( \mu \)m) and so ion goes deep into the substrate after modifying the interface unlike the case of low energy implantation where ions get implanted close to the interface.

The Schottky barrier height (SBH) of a metal on silicon is determined primarily by the metal-semiconductor interface states and is nearly independent of the doping concentration [11]. Swift heavy ion irradiation of the Schottky barrier diode is expected to produce defect centers at the MS interface leading to the enhancement in density of interface states. These interface states controls the SBH and are responsible for the observed modifications in the barrier height of SBD. But here the role of intense electronic energy loss has to be given proper consideration. The large electronic energy loss may induce effects like, mixing at the interface, modification of the microscopic inhomogeneities at the interface and annealing of the interface defects, which can alter the electronic structure of the MS interface. Although the above explanation is relatively easy to comprehend, but the issue of modification of interface by swift heavy ion irradiation in silicon involves quite complex phenomena comprising of many competing processes.

Apart from its importance in understanding the fundamental physics issues of the problem, the study of the effect of swift heavy ion irradiation on Si based Schottky barrier diodes is having practical applications also. The irradiation work on Si Schottky diodes is very much important for understanding the behavior of Si based devices which are used in radiation environments like space, nuclear reactors, and particle detectors [12-14]. Moreover, the swift heavy ion irradiation is useful in some applications like controlled reduction of the minority carrier lifetime in silicon power devices [15], formation of deep buried layers [16], and introduction of controlled amount of defects in semiconductors [17].

In this chapter, results of in situ current-voltage (I-V) and capacitance-voltage (C-V) measurements performed on various n-Si based Schottky barrier diodes during swift
Effect of Swift Heavy Ion Irradiation on Si Schottky Barrier Diodes

Heavy ion irradiation have been presented and discussed. In Section 5.2 we have described the results of in situ I-V and C-V measurements on 100 MeV $^{16}$O$^{7+}$ ion irradiated Au/n-Si Schottky diode. Section 5.3 deals with in situ I-V and C-V measurements performed on 180 MeV $^{107}$Ag$^{14+}$ ion irradiated Ag/n-Si Schottky diode. In Section 5.4 the results of in situ I-V measurements performed on 200 MeV $^{107}$Ag$^{14+}$ ion irradiated Pt/n-Si Schottky diode have been described. In the same section the results of interface state density calculations performed on Pt/n-Si diode employing capacitance based technique, which is described in Sub-section 4.9.1 of Chapter 4, have been presented.

5.2 In situ C-V and I-V studies on 100 MeV $^{16}$O$^{7+}$ irradiated Au/n-Si Schottky barrier diode

The Schottky diode was fabricated on phosphorus-doped n-type [0.2-0.3 $\Omega$-cm resistivity] Si wafers of (111) orientation. The Au Schottky contact was deposited on the polished side of the wafer. The diameter of the Schottky contact was 2 mm and thickness was 100 nm. Aluminum ohmic contact was deposited on the back side of the wafer. The detail of the complete Schottky diode fabrication process has been given in Sub-section 2.2.3 of Chapter 2. The irradiation was performed by 100 MeV $^{16}$O$^{7+}$ ion beam. Current-voltage (I-V) and capacitance-voltage (C-V) measurements of the Schottky diode were carried out in situ by stopping the beam after irradiation at various fluences. The fluence was varied from $1 \times 10^{12}$ to $1 \times 10^{13}$ ions cm$^{-2}$ and the ion beam current was kept constant at 1 nA throughout the whole experiment. The complete description of in situ I-V and C-V measurement method has been given in Sub-section 2.7.4 of Chapter 2. The C-V measurements give change in carrier concentration and Schottky barrier height as a function of fluence. From I-V measurements changes in various parameters of the Schottky diode with respect to fluence have been calculated. The results of these measurements are described in detail.
5.2.1 In situ C-V measurements

From C-V measurements, the ionized-donor/carrier concentration, \( N_D \), and Schottky barrier height, \( q\Phi_B \), are calculated using Equations (4.23) and (4.24) of Chapter 4. Figure (5.1) shows the \( 1/C^2 \) versus \( V \) plots for pristine and irradiated Au/n-Si Schottky diode. It is observed that the capacitance decreases with increase in fluence. For pristine SBD the value of capacitance at zero bias is 1776 pF, while for the final fluence of \( 1\times10^{13} \) ions cm\(^{-2} \), it decreases to 1233 pF. The donor concentration in n-Si for pristine diode is \((2.7\pm0.1)\times10^{16} \) cm\(^{-3} \). It then decreases with increase in fluence and at a final fluence of \( 1\times10^{13} \) ions cm\(^{-2} \), its value comes down to \((6.8\pm0.3)\times10^{15} \) cm\(^{-3} \). The value of Schottky barrier height for the pristine diode is \(0.93\pm0.03\) eV and then it decrease with the increase in fluence. For a fluence of \( 1\times10^{13} \) ions cm\(^{-2} \), the value of SBH drops down to \(0.57\pm0.03\) eV. The values of donor concentration and SBH at various fluences have been given in Table (5.1).

![Figure 5.1 C-V characteristics of unirradiated as well as irradiated (fluence ranging from \( 1\times10^{12} \) to \( 1\times10^{13} \) ions cm\(^{-2} \)) Au/n-Si(111) Schottky barrier diode.](image-url)
**Table 5.1** The ionized-donor concentration, $N_D$, Schottky barrier height, $q\Phi_B$, ideality factor, $n$, reverse saturation current, $I_S$, and reverse leakage current, $I_R$, of unirradiated as well as irradiated (fluence ranging from $1\times10^{12}$ to $1\times10^{13}$ ions cm$^{-2}$) Au/n-Si(111) Schottky barrier diode.

<table>
<thead>
<tr>
<th>Fluence (ions cm$^{-2}$)</th>
<th>$N_D$ (cm$^{-3}$)</th>
<th>$q\Phi_B$(C-V) (eV)</th>
<th>$n$</th>
<th>$q\Phi_B$(I-V) (eV)</th>
<th>$I_S$ (µA)</th>
<th>$I_R$ (at 2V) (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$2.7\times10^{16}$</td>
<td>0.93</td>
<td>2.3</td>
<td>0.83</td>
<td>0.003</td>
<td>6.8</td>
</tr>
<tr>
<td>$1\times10^{12}$</td>
<td>$9.7\times10^{15}$</td>
<td>0.69</td>
<td>3.9</td>
<td>0.66</td>
<td>1.9</td>
<td>46.3</td>
</tr>
<tr>
<td>$3\times10^{12}$</td>
<td>$8.8\times10^{15}$</td>
<td>0.63</td>
<td>3.9</td>
<td>0.66</td>
<td>2.1</td>
<td>51.3</td>
</tr>
<tr>
<td>$7\times10^{12}$</td>
<td>$7.5\times10^{15}$</td>
<td>0.56</td>
<td>3.7</td>
<td>0.66</td>
<td>2.5</td>
<td>54.5</td>
</tr>
<tr>
<td>$1\times10^{13}$</td>
<td>$6.8\times10^{15}$</td>
<td>0.57</td>
<td>3.8</td>
<td>0.66</td>
<td>2.7</td>
<td>59.0</td>
</tr>
</tbody>
</table>

In order to understand the observed modifications in the C-V characteristics, it is important to understand the implications of swift heavy ion irradiation at the MS interface. It is known that when a swift heavy ion penetrates inside a solid target, it transfers its energy to the solid mainly through two mechanisms: 1) electronic energy loss, $S_e$, due to inelastic collisions causing excitation/ionization of the target atoms, and 2) nuclear energy loss, $S_n$, due to elastic collisions causing displacements of the atoms from their regular lattice sites [18]. The elastic collisions are known to create defects in the semiconductor material like vacancies, interstitials and combination/agglomeration of these defects leading to the formation of complex and stable defect structures [2,3,5,10]. From the earlier studies on swift heavy ion irradiation of Si [9], it has been reported that the most prominent defects created in silicon are singly and doubly negative charge states of divacancy, and vacancy-oxygen (VO) center. These defects have associated deep levels present inside the band-gap of n-Si and they act as traps for the free carriers.
resulting in reduction of their concentration. The deep level at $E_C-0.23$ eV has been identified as associated with doubly negative charge state of divacancy. The singly negative charge state of divacancy introduces a deep level situated at $E_C-0.43$ eV. The deep level positioned at $E_C-0.18$ eV is associated with the VO center. In many studies the signatures of these deep defects in n-Si after irradiation have been found employing deep level transient spectroscopy (DLTS) measurements [3,4,9]. The decrease in capacitance of the Schottky diode after irradiation implies a widening in the semiconductor depletion width. Since the charge-neutrality condition at the MS interface should be satisfied, widening of the depletion width results from a reduction of the ionized-donor or free carrier concentration after swift heavy ion irradiation. This is confirmed from the C-V measurements. In fact the ionized donor concentration decreases from $2.7 \times 10^{16}$ cm$^{-3}$ for the pristine diode to $6.8 \times 10^{15}$ cm$^{-3}$ for same diode when irradiated at a fluence of $1 \times 10^{13}$ ions cm$^{-2}$. A schematic diagram depicting a possible model to explain the observed behavior is shown in Figure (5.2). One of the mechanisms causing a decrease in the net ionized donor concentration is the existence of negatively charged deep defect centers as has been shown by many authors using DLTS measurements [3,4,9]. Because of the presence of these centers, some of the positive shallow donors in the depletion region are compensated so that the effective net ionized-donor concentration is decreased. The donor compensation causes widening of the depletion width so that the charge-neutrality condition is maintained at the MS interface. The increase in the depletion width results in decrease in the Schottky diode capacitance as can be seen from Equation (4.22) of Chapter 4.

### 5.2.2 In situ I-V measurements

**In situ** I-V measurements have been performed on Au/n-Si(111) Schottky diode and the I-V curves at various fluences have been analyzed within the framework of thermionic emission theory. These curves have been fitted with Equation (4.1) of Chapter 4 and various Schottky diode parameters have been extracted out. Figure (5.3) shows the I-V characteristics for pristine as well as irradiated Schottky diode at various fluences.
Figure 5.2 The effect of donor-charge compensation by negative charge centers on the depletion width has been shown schematically. (a) The band diagram of a Schottky barrier diode when charged defects are not present at the interface. (b) The increase in the depletion width due to donor charge compensation.
Effect of Swift Heavy Ion Irradiation on Si Schottky Barrier Diodes

ranging from $1 \times 10^{12}$ to $1 \times 10^{13}$ ions cm$^{-2}$. For pristine Schottky diode the ideality factor, $n$, is equal to 2.3±0.1. After irradiation with a fluence of $1 \times 10^{12}$ ions cm$^{-2}$, the value of ideality factor increases to 3.9±0.1. After that it remains almost constant at this value up to a fluence of $1 \times 10^{13}$ ions cm$^{-2}$. The reverse saturation current, $I_{Sr}$ for the pristine SBD is $3 \times 10^{3}$ μA. It then increases with fluence and for a final fluence of $1 \times 10^{13}$ ions cm$^{-2}$ it acquires a value of 2.7 μA. Similarly, the reverse leakage current, $I_{Rr}$ (at 2 V) also increases from a value of 6.8 μA for the pristine SBD to a value of 59.0 μA for the final fluence of $1 \times 10^{13}$ ions cm$^{-2}$. The reverse I-V characteristics for pristine as well as irradiated SBD are shown in Figure 5.4. It is clear from Figure 5.4 that as the fluence increases the reverse characteristics of the Schottky diode deteriorates with regard to its rectifying behavior. The increase in reverse leakage current is due to the introduction of defects in the MS interface as well as depletion region of SBD. The defects produced at the MS interface region cause an increase in defect assisted tunneling of the free electrons [19]. The defects introduced in the depletion region leads to enhancement of generation-recombination current [20]. The variations of ideality factor, reverse saturation current and reverse leakage current with the fluence are summarized in Table (5.1).

The behavior of Schottky barrier height with fluence of 100 MeV $^{16}$O$^{7+}$ ion beam may be explained as follows. When the swift heavy ion penetrates through the MS interface, it loses the energy through nuclear and electronic energy loss mechanisms. The variation of nuclear, $S_n$, and electronic, $S_e$, energy losses as a function of depth inside the Au/n-Si Schottky diode is shown in Figure (5.5). It is clear from the figure that near the MS interface $S_e$ is the dominant energy loss mechanism being about 1600 times larger than $S_n$. At the MS interface, the average values of $S_e$ and $S_n$ are 1.74 keV/nm and 0.11×10$^{-2}$ keV/nm, respectively. In the top 100 nm Au layer, the values of $S_e$ and $S_n$ are 2.78 keV/nm and 0.17×10$^{-2}$ keV/nm while in silicon near the MS interface the values of $S_e$ and $S_n$ are 0.69 keV/nm and 0.04×10$^{-2}$ keV/nm, respectively. All these energy loss calculations have been performed using SRIM-98 [21] simulation program. It is known that nuclear energy loss causes production of various types of
Effect of Swift Heavy Ion Irradiation on Si Schottky Barrier Diodes

Figure 5.3 Forward I-V characteristics of unirradiated as well as irradiated (fluence ranging from $1 \times 10^{12}$ to $1 \times 10^{13}$ ions cm$^{-2}$) Au/n-Si(111) Schottky barrier diode.

Figure 5.4 Reverse I-V characteristics of unirradiated as well as irradiated Au/n-Si(111) Schottky barrier diode.
defects in the semiconductors \([2,3,5,10]\) like vacancies, interstitials, and complex defects formed out of combination of primary defects. This leads to the introduction of interface states at MS interface, which influences the Schottky barrier height \([22,23]\). According to the Fermi level pinning model of Bardeen \([24]\), when the interface state density, \(D_S\), is very high, the Schottky barrier height of SBD on an n-type semiconductor in the so-called Bardeen-limit is given by

\[
\Phi_{BB} = \left( E_g / q - \phi_0 \right) - \Delta \Phi
\]

where \(E_g\) is the band-gap of the semiconductor, \(q\phi_0\) is the energy level in coincidence with the Fermi level before the metal-semiconductor contact was formed (also called the neutrality level), and \(q\Delta \Phi\) is the lowering of the Schottky barrier due to image force (it being of the order of 0.01 eV may be neglected). On the other hand, when \(D_S\) is zero, then the barrier height of SBD on an n-type semiconductor in the so-called Schottky-limit \([25]\) is given by
Effect of Swift Heavy Ion Irradiation on Si Schottky Barrier Diodes

\[ \Phi_{BS} = \Phi_M - \chi - \Delta \Phi \]  

(5.2)

where \( \Phi_M \) is the work function of the metal and \( \chi \) is the electron affinity of the semiconductor. According to Sze [26], \( q\Phi_0 = 0.30 \pm 0.36 \text{ eV} \), \( q\chi = 4.05 \text{ eV} \), \( E_g = 1.12 \text{ eV} \) for Si at \( T=300\text{K} \), and \( q\Phi_M = 5.1 \text{ eV} \) for Au. Using these values the estimated values \( q\phi_{BB} \) and \( q\phi_{BS} \) are 0.82 \pm 0.36 eV and 1.05 eV respectively. This means that when the interface state density, \( D_S \), increases from the Schottky-limit to the Bardeen-limit, the SBH should decrease from 1.05 eV to 0.82 \pm 0.36 eV. From the I-V characteristics for pristine diode we have calculated the Schottky barrier height as 0.83 \pm 0.01 eV. This means that there is a finite density of interface states existing at the Au/n-Si(111) interface for the unirradiated sample. The SBH decreases to a value of 0.66 \pm 0.01 eV at an irradiation fluence of \( 1 \times 10^{12} \text{ ions cm}^{-2} \). After this fluence it remains constant at 0.66 \pm 0.01 eV up to a fluence of \( 1 \times 10^{13} \text{ ions cm}^{-2} \) as shown in Table (5.1). The observed decrease in SBH of Au/n-Si Schottky diode after swift heavy ion irradiation correlates well with the increase in interface state density and the resultant orientation of the Schottky barrier towards the Bardeen-limit. As the swift heavy ion passes through the SBD it produces strong ionization of the target atoms near the MS interface due to large electronic energy loss (\( S_e = 1.74 \text{ keV/nm} \), \( S_e/S_{Te} \approx 1600 \)) at the MS interface. Since the electronic energy loss mainly determines the energy dissipation of fast ions, so it is natural to expect a noticeable influence of lattice ionization in the evolution of the irradiated area including mechanisms of defect production and impurity distribution [10,27]. In a recent study [28], Motooka et al. observed annealing of the point defects due to electronic energy loss when a single crystalline silicon wafer was irradiated with 5 MeV Si ion beam. In the present investigation it is seen that after a fluence of \( 1 \times 10^{12} \text{ ions cm}^{-2} \) the rate of creation of defects gets balanced by the rate of annealing of defects at the MS interface by electronic excitation/ionization of the target atoms up to a fluence of \( 1 \times 10^{13} \text{ ions cm}^{-2} \). Thus the irradiation initially causes an increase in interface state density leading to decrease in the SBH at an irradiation fluence of \( 1 \times 10^{12} \text{ ions cm}^{-2} \). After this fluence the effect of annealing of the defects causes the interface state density
to remain rather constant and hence the SBH also remains unaltered up to a fluence of $1 \times 10^{13}$ ions cm$^{-2}$, which is an order of magnitude higher.

5.3 In situ C-V and I-V studies on 180 MeV $^{107}$Ag$^{14+}$ irradiated Ag/n-Si Schottky barrier diode

The modifications in capacitance-voltage (C-V) and current-voltage (I-V) characteristics of Ag/n-Si Schottky diode induced by 180 MeV $^{107}$Ag$^{14+}$ ion irradiation at low temperature (80 K) have been studied. The C-V and I-V characteristics were recorded in situ at various irradiation fluences ranging from $5 \times 10^{10}$ to $1 \times 10^{13}$ ions cm$^{-2}$. During irradiation the ion beam current was having a steady value of 2 nA ($\sim 9 \times 10^8$ ions per sec.). The Schottky diode was fabricated on n-Si(100) substrate having a resistivity of 80 m$\Omega$ cm. The diameter of the Ag Schottky contact was 2 mm and its thickness was 100 nm. Now we present the detail results of in situ C-V and I-V measurements on swift heavy ion irradiated Ag/n-Si Schottky barrier diode.

5.3.1 In situ C-V measurements

Using C-V measurements, the carrier concentration or ionized donor concentration, $N_D$, has been calculated at various fluences using Equation (4.23) of Chapter 4. Figure (5.6) displays the value of zero-bias capacitance of SBD as a function of fluence. Before irradiation, the capacitance of the diode is 778 pF and its value decreases sharply to 286 pF at an irradiation fluence of $5 \times 10^{10}$ ions cm$^{-2}$. After this fluence there is a relatively slow decrease in capacitance and its value at fluence of $1 \times 10^{13}$ ions cm$^{-2}$ reduces to 242 pF. The C-V characteristics of Ag/n-Si Schottky diode at various fluences are shown in Figure (5.7). The carrier concentration for the pristine sample, as derived from $1/C^2$ versus $V$ curve of Figure (5.7), comes out to be $1.50 \times 10^{17}$ cm$^{-3}$. At a fluence of $5 \times 10^{10}$ ions cm$^{-2}$, it decreases to $3.50 \times 10^{16}$ cm$^{-3}$. After that there is a slow decrease in carrier concentration with fluence and its value becomes $2.50 \times 10^{16}$ cm$^{-3}$ after a fluence of $1 \times 10^{13}$ ions cm$^{-2}$. It is to be mentioned that the carrier concentration in
Figure 5.6 The variation of zero-bias capacitance of Ag/n-Si Schottky diode with respect to fluence of $^{107}$Ag$^{14+}$ ion beam.

Figure 5.7 $1/C^2$ versus $V$ plots for Ag/n-Si Schottky diode before and after irradiation with various fluences of 180 MeV $^{107}$Ag$^{14+}$ ion beam.
n-Si wafer is profiled maximum up to a depth of about 0.5 μm as calculated from Equation (4.22) of Chapter 4. The variation of carrier concentration or ionized donor concentration, \( N_D \), with fluence is displayed in Table (5.2).

A swift heavy ion impinging upon a solid loses its energy through two processes

a) nuclear energy loss, \( S_n \), through elastic collisions with the lattice atoms causing their displacements and

b) electronic energy loss, \( S_e \), through inelastic collisions which causes excitation/ionization of the electrons of the target atoms. For 180 MeV \( ^{107}\text{Ag}^{14+} \) ions falling on Ag/n-Si Schottky diode, the dominant energy loss mechanism near the surface is \( S_e \), while \( S_n \) becomes prominent only near the projected range, \( R_p \), of \( ^{107}\text{Ag}^{14+} \) ion. The \( R_p \) of 180 MeV \( ^{107}\text{Ag}^{14+} \) ion in Ag/n-Si is 20.8 μm. The variation of \( S_e \) and \( S_n \) of 180 MeV \( ^{107}\text{Ag}^{14+} \) ion in Si with respect to depth is shown in Figure (5.8). These calculations have been done utilizing the Monte Carlo simulation program for Stopping and Ranges of Ions in Matter, SRIM98 [21]. The average value of \( S_e \) near the metal-semiconductor (MS) interface region is 22.3 keV/μm while that of \( S_n \) is 0.08 keV/μm. (For 180 MeV \( ^{107}\text{Ag} \) ions, \( S_e = 12.6 \) keV/μm and \( S_n = 0.04 \) keV/μm in Si, and \( S_e = 32.3 \) keV/μm and \( S_n = 0.12 \) keV/μm in Ag). The \( S_n \) causes production of defects in n-Si [2,3,5,10] like vacancies and interstitials or complex defects formed by a combination of the primary defects and/or dopant and impurity atoms. The energy levels corresponding to these defects exist inside the band-gap of the semiconductor and thus they act as traps for the free carriers resulting in a decrease in their concentration in n-Si.

5.3.2 In situ I-V measurements

The current transport in a Schottky barrier diode occurs through various mechanisms like thermionic emission (TE), generation-recombination, thermionic field emission (TFE) and field emission (FE) [29]. At low temperature and high dopant concentration in the semiconductor, the thermionic field emission or field emission becomes the dominant current transport process. In the present case the dopant concentration is \( 1.5 \times 10^{17} \) cm\(^{-3} \) and the sample temperature is 80 K and hence the current
transport is dominated by thermionic field emission process. In the case of TFE the current-voltage relationship is given by Equation (4.4) of Chapter 4. In Sub-section 4.2.2 of Chapter 4, this current transport process has been described in detail. There we talked about the tunneling parameter, $E_0$, that is determined using Equations (4.5) and (4.6). Now we will discuss about the variations in various Schottky diode parameters after swift heavy ion irradiation.

In the present case, for pristine sample the ionized donor concentration, $N_D = 1.5 \times 10^{17}$ cm$^{-3}$ and $T = 80$ K. Hence $kT = 6.89$ meV, $E_{00} = 3.79$ meV and $E_0 = 7.57$ meV. In this case $kT/qE_{00} = 1.8 < 4$, and hence TFE will be the dominant current transport process in Ag/n-Si Schottky diode [29]. The experimental value of $E_0$ can be determined from the slope of log$I$ versus $V$ curve. From the interception on the current axis, the value of $I_S$ may be known. Figure (5.9) shows in situ I-V characteristics measured at 80 K for pristine as well as irradiated Ag/n-Si Schottky diode at various fluences. These curves are linearly fitted using Equation (4.4) and the values of parameters $E_0$ and $I_S$ are extracted out. The tunneling parameter $E_0$ is related to the ideality factor $n$ as: $n = E_0/kT$. The theoretical value of $E_0$, as determined using Equation (4.5) and (4.6), is 7.57 meV for the pristine SBD. The experimental value that is found by linear fitting of the log$I$ versus $V$ curve comes out to be 82.08 meV. At a fluence of $5 \times 10^{10}$ ions cm$^{-2}$ it increases to 102.65 meV. After that there is not much change in the value of $E_0$ and at a fluence of $1 \times 10^{13}$ ions cm$^{-2}$ its value is 96.18 meV.

The reverse saturation current, $I_S$, for the pristine SBD is $1.30 \times 10^{-4}$ $\mu$A. At a fluence of $5 \times 10^{10}$ ions cm$^{-2}$ it increases to $1.20 \times 10^{-2}$ $\mu$A and after that does not change much with fluence and remains close to $1.10 \times 10^{-2}$ $\mu$A. Likewise the reverse leakage current, $I_R$, is also not much affected by the irradiation and its value (at 3 V) remains close to 52 $\mu$A. The values of various parameters of the diode like $E_0$, $n$, $I_S$, $I_R$, and $N_D$ with respect to irradiation fluence are summarized in Table (5.2).

The parameter $E_0$ is connected with the transmission probability of electrons across the Schottky barrier [19,30]. It characterizes the electric field at the MS interface at a given bias through the carrier concentration and the dielectric constant. It also
Figure 5.8 The variation of electronic, $S_e$, and nuclear, $S_n$, energy losses of $^{107}\text{Ag}^{14+}$ ion in Ag/n-Si with respect to depth.

Figure 5.9 I-V characteristics of Ag/n-Si Schottky diode before and after irradiation with various fluences of 180 MeV $^{107}\text{Ag}^{14+}$ ion beam.
Table 5.2 Values of Schottky diode parameters of Ag/n-Si diode at various fluences of 180 MeV $^{107}$Ag$^{14+}$ ion beam. The diode is kept at a temperature of 80 K.

<table>
<thead>
<tr>
<th>Fluence (ions cm$^{-2}$)</th>
<th>$E_0$ (meV)</th>
<th>$n$</th>
<th>$I_S$ (μA)</th>
<th>$I_R$ (at 3V) (μA)</th>
<th>$N_D$ (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pristine</td>
<td>82.08</td>
<td>11.9</td>
<td>1.30×10$^{-4}$</td>
<td>52</td>
<td>1.50×10$^{17}$</td>
</tr>
<tr>
<td>$5\times10^{10}$</td>
<td>102.65</td>
<td>14.9</td>
<td>1.20×10$^{-2}$</td>
<td>30</td>
<td>3.50×10$^{16}$</td>
</tr>
<tr>
<td>$1\times10^{11}$</td>
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<td>15.1</td>
<td>1.50×10$^{-2}$</td>
<td>34</td>
<td>3.00×10$^{16}$</td>
</tr>
<tr>
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<td>10.6</td>
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<td>72</td>
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</tbody>
</table>

characterizes the density of states through the effective mass. Therefore any mechanism which enhances the electric field or the density of states at the MS interface, or affects the energy bands in the near interface region, may increase the TFE and so the value of $E_0$. Mechanisms increasing the electric field at the MS interface may be geometrical inhomogeneities as crystal defects, interface roughness, local pile up of dopant atoms (e.g. around crystal defects), the interface charge including the fixed one and that of interface states. Furthermore, multi-step tunneling via interface states also yields high apparent $E_0$ [31]. In Ag/n-Si diode the theoretical value of $E_0$ is 7.57 meV while the experimental value comes out to be 82.08 meV. This apparent high value of $E_0$ is possibly due to the presence of defects at the MS interface which are produced during cleaning and etching process of the n-Si wafer and during deposition of the Ag Schottky
Effect of Swift Heavy Ion Irradiation on Si Schottky Barrier Diodes

contact. During cleaning and etching process of the n-Si wafer, a finite thickness of oxide layer will remain on the surface of the semiconductor and interface defects exist at the oxide/semiconductor boundary which assist in tunneling of the carriers through the Schottky barrier. Also during the deposition process some defects/impurities may be created/introduced at the MS interface causing enhancement in the tunneling of carriers through the barrier. Some authors, like Horvath et al. [30,32,33], have reported in their works that the experimental value of $E_0$ comes out to be many times more than the theoretical value. They found that in case of CrSi$_2$/Si Schottky diodes the ratio of experimental and theoretical values of $E_0$ was about 6 – 45, in GaAs Schottky junctions this ratio was about 4, and in InP Schottky barriers it was close to 16. They explained these anomalously large experimental values of $E_0$ based upon the above-mentioned model. Fabrication of a Schottky contact having experimental value of $E_0$ close to theoretical value depends mostly upon the conditions under which one performs the cleaning, etching, annealing and deposition. Precise control and optimization of all these parameters is extremely involved process.

In the present study, the effect of 180 MeV $^{107}$Ag$^{14+}$ irradiation on the I-V characteristics of Ag/n-Si Schottky diode has been highlighted. It is shown that in Ag/n-Si Schottky diode there is already high defect density/other imperfections existing at the MS interface as mentioned above. The main aim is to understand how the swift heavy ion irradiation modifies the electrical behavior of this diode. This investigation will shed light on the basic ion-solid interaction processes at the MS interface causing the modification of the I-V behavior of the diode. It has already been discussed that the swift heavy ion irradiation causes defect production at the MS interface through the nuclear energy deposition. These defects at the MS interface are responsible for the increase of $E_0$ at a fluence of 5x10$^{10}$ ions cm$^{-2}$ where its value is 102.65 meV. After this fluence there is not much change in the value of $E_0$. This may be due to the huge electronic energy deposition ($S_e/S_n \approx 300$) which leads to partial annealing of the already existing defects and hence as the irradiation fluence increases the value of $E_0$ remains unaltered.
5.4 Electrical characteristics of Pt/n-Si Schottky barrier diode

The Pt Schottky contact was deposited on the n-Si(100) substrate having initial carrier concentration of about $4 \times 10^{16}$ cm$^{-3}$. The dopant concentration was measured using C-V technique. The diameter of the Schottky contact was 2 mm. The current-voltage (I-V) and capacitance-voltage (C-V) measurements were performed on these diodes. Using I-V and C-V measurements, interface state density has been calculated in Pt/n-Si Schottky diode. For calculation of interface state density, a recent model proposed by Chattopadhayay et al [34] has been used. Utilizing this model the interface state density is calculated for Pt/n-Si Schottky diode and results are described in Sub-section 5.4.1.

5.4.1 Determination of interface state density in Pt/n-Si Schottky diode

The interfacial layer model given in Sub-section 4.9.1 of Chapter 4 has been used to calculate the interface state density in Pt/n-Si Schottky barrier diode. The salient results of these calculations are presented. Figure (5.10) shows the I-V characteristics of Pt/n-Si Schottky diode. The surface potential, $\psi_s$, is calculated from the experimental I-V characteristics using Equation (4.38) of Chapter 4, and is shown in Figure (5.11) as a function of forward bias. It is observed from Figure (5.11) that the surface potential decreases in a non-linear manner with forward voltage, which is due to the fact that the voltage drop across the series resistance is comparable with the forward voltage. Figure (5.12) shows the plots of measured C-V data at 1 MHz and 1 kHz. It is seen that the capacitance at high frequency (1 MHz), $C_{HF}$, remains constant with respect to forward voltage. The capacitance at low frequency (1 kHz), $C_{LF}$, shows a continuous increase with forward voltage. The energy distribution of interface state density, $D_{it}$, with respect to distance from the conduction band edge, $E_{C-E_{it}}$, has been displayed in Figure (5.13).
Effect of Swift Heavy Ion Irradiation on Si Schottky Barrier Diodes

Figure 5.10 Forward I-V characteristics of Pt/n-Si Schottky diode. The diameter of the Schottky contact is 2 mm.

Figure 5.11 Variation of surface potential, $\psi_s$, with forward voltage for Pt/n-Si Schottky diode.
Effect of Swift Heavy Ion Irradiation on Si Schottky Barrier Diodes

Figure 5.12 Experimental low and high frequency capacitance as a function of forward voltage for Pt/n-Si Schottky diode.

Figure 5.13 Energy distribution of interface state density, $D_{it}$, of Pt/n-Si Schottky diode.
The interface state density has been calculated using Equation (4.44) of Chapter 4. At an energy distance of 0.50 eV from the conduction band edge, the value of $D_{it}$ is $5.3 \times 10^{12}$ cm$^{-2}$ eV$^{-1}$. Then it starts decreasing with increase in distance and at a distance of 0.70 eV from the conduction band edge it possesses a minimum value of $1.3 \times 10^{11}$ cm$^{-2}$ eV$^{-1}$. After that $D_{it}$ remains constant at this value.

5.4.2 In situ current-voltage characterization of 200 MeV $^{107}$Ag$^{15+}$ ion irradiated Pt/n-Si Schottky diode

The Pt/n-Si Schottky diode was irradiated with 200 MeV $^{107}$Ag$^{15+}$ ion beam and its current-voltage (I-V) characteristics were recorded in situ during irradiation. The diameter of the Schottky contact was 2 mm. The I-V characteristics were recorded at various fluences ranging from $1 \times 10^9$ to $1 \times 10^{12}$ ions cm$^{-2}$. The ion beam current was kept constant at 0.6 nA during the whole irradiation experiment. The I-V characteristics for the pristine diode is shown in Figure (5.14). The ideality factor, $n$, of the pristine diode is $1.80 \pm 0.05$ and the Schottky barrier height, $q\Phi_B$, is $0.75 \pm 0.01$ eV. The reverse saturation current, $I_S$, is having a value of $4.68 \times 10^{-8}$ A, while the reverse leakage current, $I_R$, at a reverse voltage of 1 V is equal to $7.73 \times 10^{-7}$ A. The I-V characteristics of the Schottky diode at various fluences after irradiation have been displayed in Figure (5.15). The Schottky diode parameters have been calculated for various fluences using the slope-and-intercept method described in Section 4.4 of Chapter 4. The values of these parameters at various fluences are given in Table (5.3). It is observed that the Schottky diode parameters remain almost up to a fluence of $1 \times 10^{10}$ ions cm$^{-2}$. After this fluence value, the parameters $n$, $I_S$ and $I_R$ starts increasing with increase in fluence, while $q\Phi_B$ begins to decrease. At the final fluence value of $1 \times 10^{12}$ ions cm$^{-2}$, the values of $n$, $I_S$, $I_R$ and $q\Phi_B$ become $4.32$, $5.75 \times 10^{-7}$ A, $5.76 \times 10^{-6}$ A and 0.68 eV, respectively.

The swift heavy ion irradiation results in increase in interface state density at the Pt/n-Si interface since it leads to creation of various kinds of defects at the interface and depletion region. This causes increase in recombination current [20] and also in tunneling current through the interface states [33]. This leads to an increase in ideality...
Figure 5.14 Current-voltage characteristics of pristine Pt/n-Si(100) Schottky diode.

Figure 5.15 Current–voltage characteristics of 200 MeV $^{107}$Ag$^{14+}$ ion irradiated Pt/n-Si(100) Schottky diode at various fluences.
Effect of Swift Heavy Ion Irradiation on Si Schottky Barrier Diodes

Table 5.3 Values of ideality factor, $n$, saturation current, $I_S$, reverse leakage current, $I_R$ and Schottky barrier height, $q\Phi_B$, for Pt/n-Si Schottky diode at various fluences of 200 MeV $^{107}\text{Ag}^{15+}$ ion beam.

<table>
<thead>
<tr>
<th>Fluence (ions cm$^{-2}$)</th>
<th>Ideality factor, $n$</th>
<th>Saturation current, $I_S$ (A)</th>
<th>Reverse leakage current (1V) $I_R$ (A)</th>
<th>Schottky barrier height, $q\Phi_B$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.80</td>
<td>4.68x10$^{-8}$</td>
<td>7.73x10$^{-7}$</td>
<td>0.75</td>
</tr>
<tr>
<td>$1\times10^9$</td>
<td>1.70</td>
<td>3.72x10$^{-8}$</td>
<td>7.73x10$^{-7}$</td>
<td>0.76</td>
</tr>
<tr>
<td>$7\times10^9$</td>
<td>1.64</td>
<td>4.47x10$^{-8}$</td>
<td>7.77x10$^{-7}$</td>
<td>0.75</td>
</tr>
<tr>
<td>$1\times10^{10}$</td>
<td>1.71</td>
<td>5.25x10$^{-8}$</td>
<td>7.76x10$^{-7}$</td>
<td>0.75</td>
</tr>
<tr>
<td>$7\times10^{10}$</td>
<td>2.04</td>
<td>1.58x10$^{-7}$</td>
<td>1.44x10$^{-6}$</td>
<td>0.72</td>
</tr>
<tr>
<td>$1\times10^{11}$</td>
<td>2.74</td>
<td>3.39x10$^{-7}$</td>
<td>1.82x10$^{-6}$</td>
<td>0.70</td>
</tr>
<tr>
<td>$7\times10^{11}$</td>
<td>4.23</td>
<td>6.50x10$^{-7}$</td>
<td>4.63x10$^{-6}$</td>
<td>0.68</td>
</tr>
<tr>
<td>$1\times10^{12}$</td>
<td>4.32</td>
<td>5.75x10$^{-7}$</td>
<td>5.76x10$^{-6}$</td>
<td>0.68</td>
</tr>
</tbody>
</table>

The ideality factor with fluence. The increase in recombination current results in the enhancement of reverse leakage current. The Schottky barrier height is influenced significantly by the increase in interface state density after irradiation and it decreases with increase in fluence. A possible model to explain this decrease after irradiation has already been discussed in detail in Sub-section 5.2.2.

5.5 Conclusions

In this chapter the results pertaining to the effect of swift heavy ion irradiation on electrical transport properties of various n-Si based Schottky barrier diodes have been
presented and discussed. In Section 5.2 the detail results of \textit{in situ} I-V and C-V measurements performed on Au/n-Si Schottky diode irradiated by 100 MeV $^{16}$O$^{7+}$ ions have been reported. After irradiation the degradation in rectifying properties of the Schottky diode has been observed. The Schottky barrier height after irradiation is assumed to be influenced by the increase in interface state density. The decrease in its value is explained within the framework of Schottky and Bardeen models. The Section 5.3 deals with study of modification in I-V and C-V characteristics of Ag/n-Si Schottky diode at low temperature (80 K) irradiated by 180 MeV $^{107}$Ag$^{14+}$ ions. The I-V characteristics have been analyzed within the framework of thermionic-field emission model due to high dopant concentration ($N_D=1.5\times10^{17}$ cm$^{-3}$) in n-Si and low temperature conditions. The \textit{in situ} I-V and C-V measurements reveals that there is a gradual degradation in various Schottky diode parameters up to a fluence of $5\times10^{10}$ ions cm$^{-2}$ and after that these parameters do not change much with increase in fluence. The possible role of huge electronic energy loss in annealing of defects at the metal-semiconductor (MS) interface has been invoked to explain this constancy of barrier parameters. In Section 5.4 the calculation of interface state density in Pt/n-Si Schottky diode has been performed based upon an interfacial layer model using experimental forward I-V and C-V characteristics. The effect of 200 MeV $^{107}$Ag$^{14+}$ ion irradiation on I-V characteristics of Pt/n-Si Schottky diode has also been given in this section. It is observed that after a fluence of $1\times10^{10}$ ions cm$^{-2}$ the Schottky diode parameters starts degrading due to irradiation-induced defects at the MS interface as well as in the depletion region.
Effect of Swift Heavy Ion Irradiation on Si Schottky Barrier Diodes

References

Effect of Swift Heavy Ion Irradiation on Si Schottky Barrier Diodes


Effect of Swift Heavy Ion Irradiation on Si Schottky Barrier Diodes


