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Analysis of the carrier conduction mechanism in 100 MeV O^{7+} ion irradiated Ti/*n*-Si Schottky barrier structures

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ABSTRACT

The electrical transport properties of Ti/*n*-Si Schottky barrier structure irradiated by 100 MeV O^{7+} ion has been studied between 120 K and 320 K and compared with unirradiated Ti/n-Si structure to gain the understanding of carrier transport mechanism in irradiated devices. The barrier parameters have been extracted using the current-voltage (*I–V*) characteristics in forwarding bias. It is found that Schottky barrier height (zero bias) increases while the value of ideality factor becomes smaller with increasing temperature. Recent models consisting of inhomogeneous barrier potential at the metal-semiconductor (MS) interface have been used to explain the behavior of barrier parameters. The role played by the high energy ions at MS interface during irradiation is considered to understand the observed behavior.

1. Introduction

The Schottky barrier contacts formed by metal-semiconductor (MS) junctions are generally used as rectifying contacts in integrated circuits. Besides their useful applications in electronic devices and particle detectors, they are also used as a research tool for characterization of materials [1,2]. Since the potential barrier at junction influences the carrier transport through the MS interface, so it is necessary to understand the process of Schottky barrier creation and modification for successful device operation. Any process that can alter the MS interface, modifies the transport properties of the Schottky barrier structure as well. The irradiation with energetic ions can alter the MS interface, which leads to modification in Schottky barrier and carrier transport properties [3–5]. In radiation ambience like space and nuclear reactors, semiconductor devices are under the shower of energetic ions continuously. To simulate the performance of these devices in a radiation environment, the studies of high energy ion irradiation are very helpful. It is essential to study the effect of irradiation by high energy ions on the transport properties of Schottky barriers in the field of particle detector development, which are used in nuclear and particle physics experiments [1] and in aerospace [6]. The irradiation by heavy ions is already used in silicon power devices for the minority carrier's lifetime reduction and to introduce the defects in a controlled manner [7,8]. Although, studies on high energy ion irradiation effect at MS interface have been reported [4,9,10] but the deeper understanding of the basic transport mechanism in irradiated Schottky barrier device still remains incomplete. The influence of irradiation by high energy ions on the carrier transport mechanism can be explored by studying their electrical transport behavior. The study of *I–V* characteristics of MS interface is normally used to understand the mechanism of barrier formation and carrier conduction. Most of the ion irradiation studies on metal/Si structure have been examined as a function of ion fluence at room temperature. The study of *I–V* characteristics at room temperature alone cannot provide detail information about the mechanism of potential barrier formation and carrier transport at MS interface. However, a temperature dependent study of *I–V* characteristics permits one to understand the nature of the carrier transport mechanism in detail. In this work, we have studied the *I–V* characteristics of 100 MeV O^{7+} irradiated Ti/*n*-Si Schottky barrier structure with varying temperature. The extracted barrier parameters showed a strong dependence on temperature. The recent models of barrier inhomogeneity at MS interface are used to interpret the obtained results. The role played by the energetic ion irradiation in this process is also discussed.

2. Experimental details

In the present study, Ti/*n*-Si Schottky barrier diode structures were made on *n*-type Si (1 0 0) wafer having resistivity 1 Ω-cm (doping concentration ~ 10^{15} cm^{-3}). The Ohmic contacts of low resistivity were fabricated by Al deposition on backside (RCA cleaned) surface

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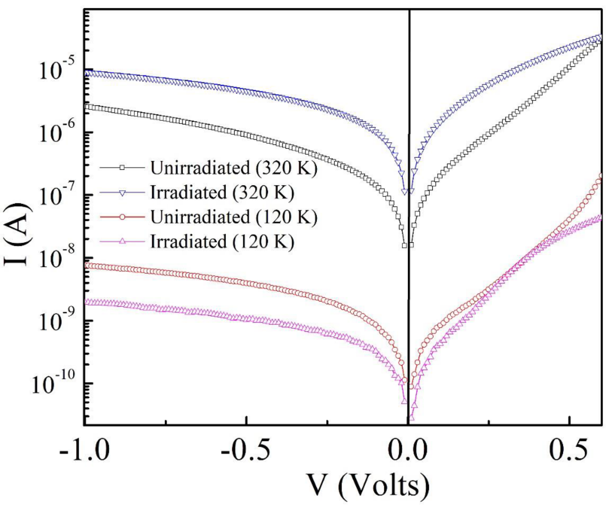

Fig. 1. I–V characteristics of Ti/*n*-Si Schottky barrier structures before and after irradiation at different temperatures.

using thermal evaporation technique which was followed by the annealing at 525 °C (25 min) in flowing argon gas atmosphere [11]. The Schottky contacts having circular geometry (diameter 2 mm) were created on RCA cleaned samples by deposition of 100 nm Ti layer by thermal evaporation. The ion irradiation of the samples was done by 100 MeV $^{16}O^{7+}$ ion beam at room temperature using the 15UD Pelletron accelerator available at Inter-University Accelerator Centre, New Delhi [12]. The mean projected range of 100 MeV O^{7+} ions inside the silicon is 95.2 µm having ($S_e/S_n \sim 1800$) at the Ti/*n*-Si interface. The fluence chosen for irradiation was 1×10^{12} ions cm^{-2} and the ion current was 1.0 nA to avoid the sample heating. A programmable source meter (Keithley 2400) was used for the *I–V* measurements at different temperatures between 120 K and 320 K.

3. Results and discussion

To understand the transport mechanism in detail temperature dependent electrical measurements of Ti/*n*-Si Schottky structures were made in the temperature range varying from 120 to 320 K. The experimental *I–V* characteristics of Ti/*n*-Si structure before and after 100 MeV O^{7+} ion irradiation at different temperatures are shown in Fig. 1. A strong temperature dependence of *I–V* curves is observed, which have a linear region at low forward biases. It is observed that series resistance dominates the behavior at higher bias voltages after ion irradiation. It is expected that ion irradiation will produce the defects having their energy levels deep inside the semiconductor band gap. These defects can trap the free carriers and act as the scattering centers leading to a decrease in carrier concentration and mobility, which results in an increase in series resistance. The *I–V* characteristics shown here represent an average behavior which was measured for few samples having identical electrical properties. The measured current at a particular bias increases as temperature increases. Usually, nonideal *I–V* characteristics of MS interface are explained using the standard model of thermionic emission [13]. According to this model, the current across the MS interface is written as

$$I = I_s\left[exp\left(\frac{q(V - IR_S)}{nkT}\right) - 1\right] \tag{1}$$

where V represents the voltage applied across the interface, n is the ideality factor, R_s is series resistance and other symbols k and T have usual meanings. The saturation current I_s is expressed as

$$I_s = AA^{*}T^2 exp\left(-\frac{q\phi_B}{kT}\right) \tag{2}$$

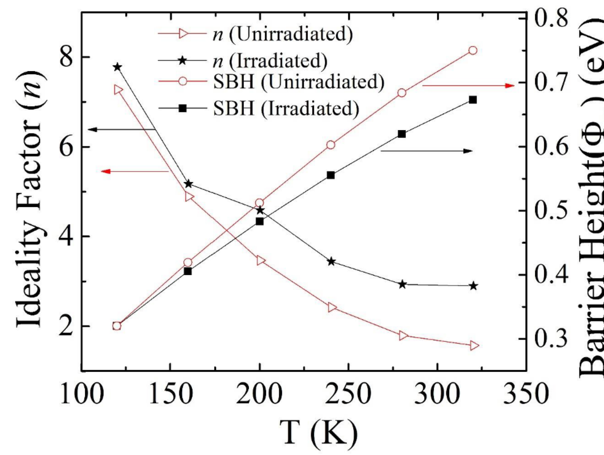

Fig. 2. Variation of SBH and ideality factor of Ti/*n*-Si(1 0 0) junction as the function of temperature. Solid lines represent a guide to the eye.

In the above equation, A is the effective device area (3.14×10^{-2} cm^2), and A^* the Richardson's constant of semiconductor (in this case 112 A cm^{-2} K^{-2} for *n*-Si) [13] and ϕ_B is the Schottky barrier height (SBH) at zero bias.

The slope of the linear region of semilogarithmic ln(*I*)–*V* curves, where the series resistance is negligible ($IR_s \ll V$), is used to calculate the ideality factor (n) and the intercept is used to calculate I_s. Further, the Schottky barrier parameters n and ϕ_B are calculated by the expressions

$$n = \frac{q/kT}{d(lnI)/dV} \tag{3}$$

and

$$\phi_B = \frac{kT}{q} ln\left(\frac{AA^{*}T^2}{I_s}\right) \tag{4}$$

Fig. 2 shows the zero bias SBH calculated by using Eq. (4) at different temperatures for Ti/*n*-Si Schottky barrier structure before and after irradiation. In unirradiated (as prepared) structure, SBH increases from a value of 0.32–0.76 eV between 120 and 320 K while for 100 MeV O^{7+} ion irradiated Ti/*n*-Si structures SBH varies from 0.32 eV to 0.67 eV. The n is a dimensionless parameter and its value decreases from 7.4 to 1.6 for unirradiated Ti/*n*-Si structure and 7.9 to 2.4 for irradiated structure. The greater value of n (> 1) indicates the deviation of carrier transport from thermionic emission to other transport mechanisms across the interface. The decrease of SBH after irradiation can be related to an increase of leakage current as shown in Fig. 1. The 100 MeV ion irradiation induced defects will result in an increase of interface states density. The high value of interface states will result in a high value of ideality factor indicating that other transport mechanisms dominate over the thermionic emission. These current mechanisms lead to an increase in leakage current value and a decreased value of SBH. Other current transport mechanisms such as generation-recombination of the carriers in the depletion region and tunneling of carriers across the barrier also lead to non-ideal behavior [14,15].

The ideal thermionic emission model consisting the image force lowering and tunneling can be used to explain the temperature dependence of barrier parameters. The barrier lowering by image force is $\Delta\phi \propto (N_d)^{1/4}$, where N_d denotes the donor concentration [13]. The magnitude of $\Delta\phi$ is of the order of 0.01 eV and in our case can be ignored. At low temperatures, the tunneling of carriers across the Schottky barrier is given by a characteristic tunneling parameter E_{00} [13]

$$E_{00} = \frac{\hbar}{2}\sqrt{\frac{N_d}{\epsilon_s\ m^*}} \tag{5}$$

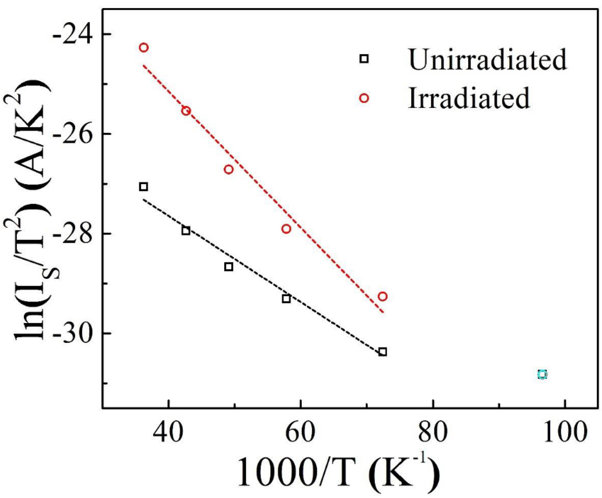

Fig. 3. Richardson plot, $\ln(I_s/T^2)$ vs $1/T$ for Ti/*n*-Si(1 0 0) Schottky barrier in the temperature range 120–320 K.

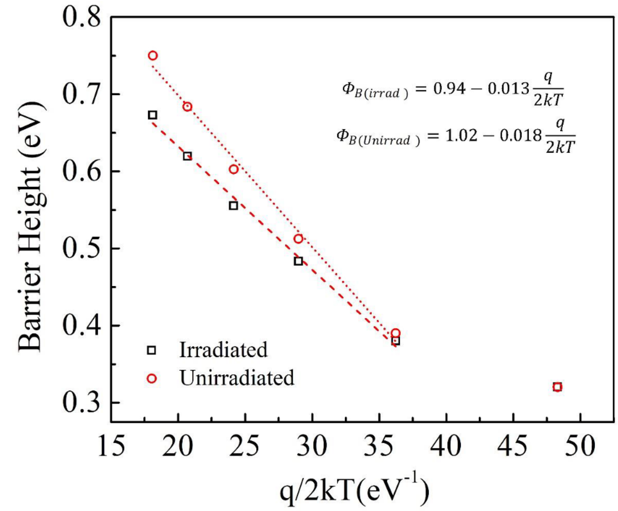

Fig. 4. Apparent barrier height versus $q/2kT$ plot as a function of temperature. The dotted line represents a linear fitting of the data.

where ϵ_s and m^* are the relative permittivity and effective mass of electron in *n*-Si, respectively. The comparison of the characteristic parameter E_{00} with kT inferred the transport phenomena across the Schottky barrier junction. The thermionic emission will be deduced if $kT \gg qE_{00}$, $kT \approx qE_{00}$ will give thermionic-field emission and $kT \ll qE_{00}$ will deduce field emission. In this case, for irradiated Ti/*n*-Si structure by using the values of $N_d \sim 10^{15}$ cm^{-3}, $m^* = 0.3\,m_0$ (for *n*-Si) [13] and $\epsilon_s = 11.7$ in Eq. (5) results in the value of E_{00} to be ~0.25 meV, which is much smaller compared to the thermal activation energy of 26 meV at 300 K and 11 meV at 80 K. Since $kT \gg qE_{00}$ in this case, so the tunneling current is negligible and current conduction is mainly through the thermionic emission.

The Richardson plot, (ln (I_s/T^2) versus $(1/T)$ can be used to understand the non-ideal behavior of Ti/*n*-Si Schottky barrier structure before and after irradiation. For the activation energy plot, Eq. (2) is rearranged as

$$ln\left(\frac{I_s}{T^2}\right) = ln(AA^*) - \frac{q\phi_B}{kT} \tag{7}$$

Fig. 3 depicts the plot of $\ln(I_s/T^2)$ with $(1/T)$ between 120 and 320 K for Ti/*n*-Si Schottky barrier structure before and after ion irradiation. The Richardson plots are not linear in the measured temperature range indicating that the activation energy is changing with varying temperature. It is not possible to linear fit the curves in the whole temperature range, so the curve can be divided into different activation energy regions having different slopes. In Fig. 3, Richardson plots give a linear region between 160 K and 320 K and below this temperature, there are not sufficient data points to fit the linear region. From the slope of linear fitting, an SBH value of 0.10 eV for the unirradiated diode and a value of 0.14 eV for irradiated Ti/*n*-Si Schottky structures were calculated. The values of SBH extracted by Richardson plot are quite lower than those determined by the forward *I–V* characteristics. We get the Richardson constant (A^*) 9.8×10^{-10} A cm^{-2} K^{-2} and 8.9×10^{-8} A cm^{-2} K^{-2} for unirradiated and ion irradiated structures respectively. A very small value of Richardson constant shows the possibility of the presence of laterally inhomogeneous barrier at Ti/*n*-Si interface [16,17]. The deviation from ideal thermionic emission can be described with barrier heights having the Gaussian distribution at the interface using the potential fluctuation model [18]. According to this model, the barrier is treated as inhomogeneous, which consists of nanoscale regions with varying barrier heights. The transport behavior of carriers across the Schottky barrier is the thermally activated process and is led by the current flowing via lower barrier height regions at low temperatures. The number of electrons crossing the barrier starts to enhance at relatively higher temperatures. As a result, the value of *n* approaches towards unity and the value of SBH also increases upon temperature enhancement.

The Gaussian distribution of SBH at MS interface can be expressed by the equation [18]

$$P(\phi_B) = \frac{1}{\sigma\sqrt{2\pi}}exp\left[-\frac{(\phi_B - \bar{\phi}_B)^2}{2\sigma^2}\right] \tag{8}$$

where σ and $\bar{\Phi}_B$ are the standard deviation of barrier height distribution the mean barrier height (at $T = 0$ K) respectively. The apparent SBH (Φ_B) extracted from the *I–V* measurements, is correlated to mean SBH $(\bar{\Phi}_B)$ by the following equation [18],

$$\Phi_B = \bar{\Phi}_B - \frac{q\sigma^2}{2kT} \tag{9}$$

Assuming that σ is temperature independent, the above equation proposes that a plot between ϕ_B and $q/2kT$ will produce an evaluation for SBH distribution. Fig. 4 shows the ϕ_B versus $q/2kT$ plot, in which σ and $\bar{\Phi}_B$ are extracted from the slope and intercept of the linearly fitted data, respectively. Before irradiation, the values obtained for $\bar{\Phi}_B$ and standard deviation (σ^2) are 1.02 eV and 0.018 respectively, which become 0.94 eV and 0.013 respectively after high energy ion irradiation. A high value of σ indicates the more inhomogeneous barrier. The 100 MeV O^{7+} ion irradiation results in a lower value of standard deviation σ showing that the inhomogeneity in the Schottky barrier height is changed after ion irradiation.

The Richardson plot Eq. (7) can be modified by putting the value of ϕ_B from Eq. (9) as follows,

$$ln\left(\frac{I_s}{T^2}\right) - \left(\frac{q^2\sigma^2}{2k^2T^2}\right) = ln(AA^*) - \frac{q\bar{\phi}_B}{kT} \tag{10}$$

Fig. 5 exhibits the plot of $\left[ln\left(\frac{I_s}{T^2}\right) - \left(\frac{q^2\sigma^2}{2k^2T^2}\right)\right]$ versus q/kT in the temperature range from 160 K to 320 K, where the slope of the linear plot gives the value of $\bar{\Phi}_B$ and the Richardson constant may be calculated from the intercept $(ln(AA^*)$. For the Ti/*n*-Si structures, using the value of σ (from Fig. 4), the calculated values of A^* and $\bar{\Phi}_B$ are 105 A cm^{-2} K^{-2} and 0.93 eV for irradiated structure and 62 A cm^{-2} K^{-2} and 1.02 eV respectively. The value of extracted mean barrier height agrees well with the value calculated from the Gaussian distribution of SBH. The obtained value of Richardson constant for irradiated Ti/n-Si structures is also in excellent accordance to the

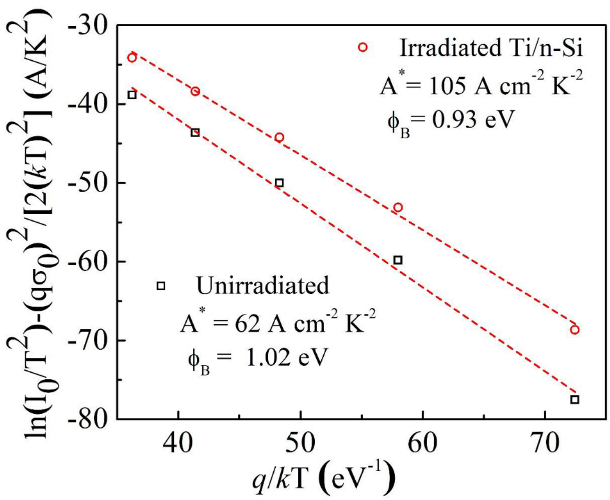

Fig. 5. Modified Richardson plot for Ti/*n*-Si Schottky barrier diode consisting of a Gaussian distribution of the barrier heights in the temperature range160K-320 K.

calculated Richardson constant for *n*-type silicon. So, barrier inhomogeneities consideration at ion irradiated Ti/*n*-Si interface gives the more accurate value of Richardson constant. This indicates that the current across the irradiated Ti/*n*-Si Schottky barrier junction can be described by thermionic emission consisting of a Gaussian distribution of SBH. Various parameters may be responsible for barrier inhomogeneity at the Ti/*n*-Si interface. The dopant clustering and different phases having different barrier heights at the interface can also lead to barrier inhomogeneities. It is really important to know the changes at MS interface induced by the energetic ions in order to understand the observed *I–V* characteristics of irradiated Ti/*n*-Si Schottky barrier junctions.

In the case of highly energetic ions, ion after modifying the MS interface goes far inside the semiconductor having a range of few tens of micrometer. These ions lose energy in the material through the electronic S_e (inelastic collisions near the entrance) and nuclear energy loss S_n (elastic collisions at the end of ion range) [19]. The S_e and S_n affect the interface in a different manner. In general, S_n creates the point defects (vacancies, interstitials) while S_e causes the excitation or ionization of the atoms leading to produce defect complexes near the MS interface [20,21]. In our case, 100 MeV O^{7+} ions have S_e three orders of magnitude larger than the S_n value ($S_e/S_n \sim 1800$). So, an apparent influence of S_e in the development of the irradiated region including the process of defect creation and impurity dispersal is expected. In high energy ion irradiation, due to high S_e rapid energy transfer takes place via electron-phonon coupling leading to an abnormally excited system and the temperature around the ion track area becomes very high [22]. The evolution of this high temperature along the ion track creates the high density of defects having a diffusion length of around 25 nm [23,24]. So, this large S_e can modify the microscopic inhomogeneities in MS interface. If the defect density at MS interface is not enough to pin the Fermi level at a single energy level in bandgap then local pinning of the Fermi level can take place, which may result in inhomogeneous SBH [25]. In this case, irradiation of Ti/*n*-Si structure with 100 MeV O^{7+} ions can also result in variation in nanoscale interface reactions in ion track region having variation in barrier height. The low barrier height phases having the size large compared to the silicon Debye length will affect significantly the apparent barrier height extracted by *I–V* characterization.

4. Conclusion

In summary, 100 MeV O^{7+} ion irradiated Ti/*n*-Si Schottky barrier structure is investigated using temperature dependent *I–V* characterization. Variations in ideality factor and SBH with varying temperature clearly show the deviation from ideal thermionic emission model, which can be explained assuming a Gaussian distribution of SBH with a mean value of 0.92 ± 0.11 eV. A different temperature behavior of electrical characteristics indicated that high energy ion irradiation modified the inhomogeneity in the Ti/*n*-Si Schottky barrier. Further, the value of Richardson's constant calculated by the modified activation energy plot is in close agreement with the known value for *n*-type Si. These results show the critical role of spatial potential fluctuations at MS interface in irradiated Ti/*n*-Si Schottky structures, which may be useful in detail understanding of carrier transport mechanism in ion irradiated Ti/*n*-Si Schottky barrier structure.

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