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Influence of swift heavy ion irradiation on electrical characteristics of Au/n-Si (1 0 0) Schottky barrier structure

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Abstract
The influence of swift heavy (180 MeV $^{107}Ag^{14+}$) ion irradiation on Au/n-Si Schottky diode characteristics has been analysed using *in situ* current–voltage (I–V) characterization. The values of the Schottky barrier height (SBH), the ideality factor and series resistance R_s for each irradiation fluence have been obtained from the forward bias I–V characteristics. For an unirradiated diode, the SBH and ideality factor were 0.74 ± 0.01 eV and 1.71, respectively. The barrier height decreases to 0.69 ± 0.01 eV as the fluence increases to a value of 1×10^{11} ions cm^{-2}. It is found that after an irradiation fluence of 1×10^{11} ions cm^{-2} the SBH remains immune to further irradiation up to a fluence of 5×10^{12} ions cm^{-2}. The observed behaviour is interpreted on the basis of energy loss mechanisms of energetic ions at the metal–semiconductor interface and irradiation-induced defects.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The Schottky barrier diode (SBD) is one of the fundamental semiconductor devices. In current research, the formation of a potential barrier at the metal–semiconductor (MS) interface is of prime interest. The interface states control the position of the Fermi level in the semiconductor band gap and are responsible for the modification in the Schottky diode parameters. Any mechanism that affects the MS interface also influences the performance of these Schottky barrier devices. Swift heavy ion (SHI) irradiation is one of the mechanisms which is able to modify the MS interface and the transport properties [1, 2]. In SHI irradiation, the electronic energy loss S_e due to inelastic collisions is two to three orders of magnitude larger compared with nuclear energy loss S_n due to elastic collisions. This large electronic energy loss may lead to phenomena such as mixing at interface, modification or introduction of microscopic inhomogeneties at the interface and annealing of the interface defects that can alter the electronic structure of the MS interface. The studies on the effect of SHI irradiation on the SBD are important for fundamental understanding of the phenomenon of ion–solid interaction at the interface as well as application. In some fields such as the testing of radiation hardness for the aerospace industry [3] and the development of particle detectors [4], it is extremely important to correlate the effects of ion irradiation on the material properties with the modification of the electrical characteristics of Schottky barriers. Moreover, SHI irradiation is useful in some applications like controlled reduction of the minority carrier lifetime in silicon power devices, formation of deep buried layers, and introduction of controlled amount of defects in semiconductors [5–7]. These studies shed light on the basic ion–solid interaction processes, and their influence on various properties of semiconductors.

The modifications induced by SHI irradiation at the MS interface can be investigated by studying the electrical behaviour of a Schottky diode. There are reports in the literature [8–10] on the effect of ion implantation on the electrical characteristics of Au/n-Si(1 0 0) SBD but modifications of Au/n-Si(1 0 0) Schottky barriers induced by SHI irradiation have not been studied extensively.

Singh *et al* (2001) studied the effect of 100 MeV $^{16}O^{7+}$ ions on Au/n-Si in the fluence range 1×10^{12} to 1×10^{13} ions cm^{-2} and found that Schottky barrier height (SBH) remains constant

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irrespective of irradiation fluence [2]. This behaviour was attributed to high S_e value ($S_e/S_n \sim 1500$) at the MS interface.

In this work, we present the results of the detailed investigation of I–V characteristics of Au/n-Si SBD irradiated with 180 MeV $^{107}Ag^{14+}$ ion beam at various irradiation fluences ranging from 5×10^9 to 5×10^{12} ions cm^{-2}. The ion fluences were chosen in order to rule out the possibility of ion beam mixing at the interface. Irradiation with higher fluences may result in ion beam mixing at the interface or phase formation [11], which drastically affects the barrier properties. As 180 MeV $^{107}Ag^{14+}$ ions have much higher S_n value (0.03 keV nm^{-1}) than 100 MeV $^{16}O^{7+}$ ions (0.0001 keV nm^{-1}), the role of S_n should also be given proper consideration in this case for further improvement of the understanding of the effect of SHI irradiation on SBDs. A systematic I–V characterization of the SHI irradiated Au/n-Si SBD is carried out *in situ* in a wide fluence range on the same SBD keeping all other physical conditions such as sample, ion flux, temperature and vacuum environment identical. To study the true effect of ion irradiation it is necessary that the fluence dependence study should be done on the same sample because the effect of irradiation depends on the initial conditions of the samples. After each fluence, we present the changes in electrical characteristics evaluated using forward bias I–V measurements.

2. Experimental details

The substrate used to fabricate the Schottky diodes in this experiment was mirror-polished n-type Si(1 0 0) substrate of resistivity 0.5–1.0 Ω cm (doping concentration 1×10^{15} cm^{-3}) that has an area of 5 mm × 5 mm and thickness 275 μm. The fabrication process of Schottky diodes is described in detail elsewhere [1].

The ion irradiation was performed at room temperature by 180 MeV $^{107}Ag^{14+}$ ion beam using the 15UD Pelletron accelerator facility at Inter-University Accelerator Centre, New Delhi [12]. The irradiation fluence was varied from 5×10^9 to 5×10^{12} ions cm^{-2}. During irradiation the beam current was 4.0 nA corresponding to 3.1×10^9 ions cm^{-2} s^{-1} to avoid excessive sample heating. The current–voltage (I–V) measurements were carried out with a programmable Keithley 2400 source meter. The capacitance–voltage (C–V) measurements were carried out at 1 MHz by using a Boonton 7200 capacitance meter. All of the measurements were carried out in a vacuum of 10^{-7} mbar.

3. Experimental results and discussion

The current–voltage (I–V) characteristics of Au/n-Si(1 0 0) Schottky contact in the fluence range 5×10^9 to 5×10^{12} ions cm^{-2} are shown in figure 1. Current transport in Schottky contacts is due to majority carriers and it may be described by thermionic emission over the interface barrier. The experimental data are fitted by the conventional thermionic emission equation, which is given by [13]

$$I = I_0 \exp\left(\frac{q(V - IR_s)}{nkT}\right)\left[1 - \exp\left(-\frac{q(V - IR_s)}{kT}\right)\right], \tag{1}$$

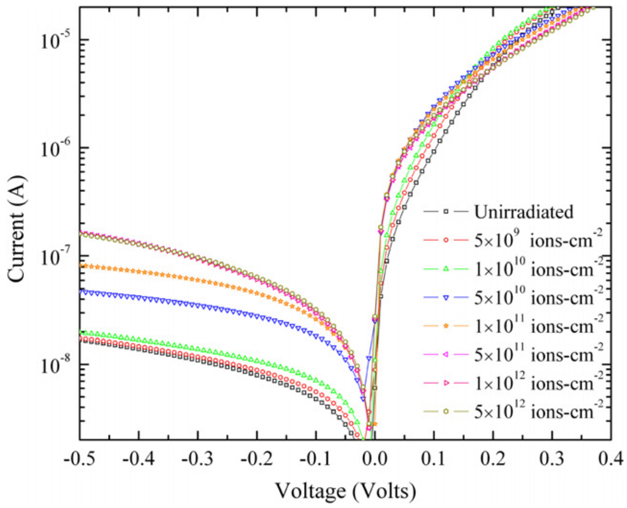

Figure 1. Experimental current–voltage characteristics of the Au/n-Si(1 0 0) Schottky diode at different irradiation fluences.

where I_0 is the saturation current and n is the ideality factor. The saturation current I_0 is given by

$$I_0 = AA^*T^2 \exp\left(-\frac{q\Phi_{B0}}{kT}\right), \tag{2}$$

where A^*, A and Φ_{B0} represent the Richardson constant, the contact area (0.0314 cm^2) and zero-bias SBH, respectively. Other symbols in the above equations have their usual meaning. SBH for the as prepared sample is 0.74 ± 0.01 eV. This low value of barrier height may be due to the presence of a non-uniform thin oxide layer at the interface (related to device fabrication process) [14,15]. The barrier height decreases with increasing irradiation fluence and becomes 0.69 ± 0.01 eV at an irradiation fluence of 1×10^{11} ions cm^{-2}. After this fluence SBH remains insensitive to irradiation upto the fluence value of 5×10^{12} ions cm^{-2}. From the slope of $\ln(I)$ versus V curve, the value of the ideality factor is calculated using the relation

$$n = \frac{q}{kT}\left(\frac{d(V - IR_s)}{d\ln(I)}\right). \tag{3}$$

The experimental value of ideality factor n derived from I–V data varies from 1.71 for unirradiated sample to 3.09 at irradiation fluence of 1×10^{12} ions cm^{-2}. The variation of ideality factor and SBH as a function of irradiation fluence is shown in figure 2.

The series resistance effect on the electrical characteristics of Au/n-Si Schottky structures and its dependence on irradiation fluence were investigated in the fluence range 5×10^9 to 5×10^{12} ions cm^{-2}. The series resistance is a very important parameter of Schottky barrier devices. The resistance of the Schottky barrier device is the sum of total resistance value of the resistors in series and the resistance in the semiconductor device in the direction of current flow. The series resistance was evaluated from the forward bias I–V data using the method developed by Cheung and Cheung [16]. The forward bias I–V characteristics due to thermionic emission of a Schottky structure with the series resistance can be expressed

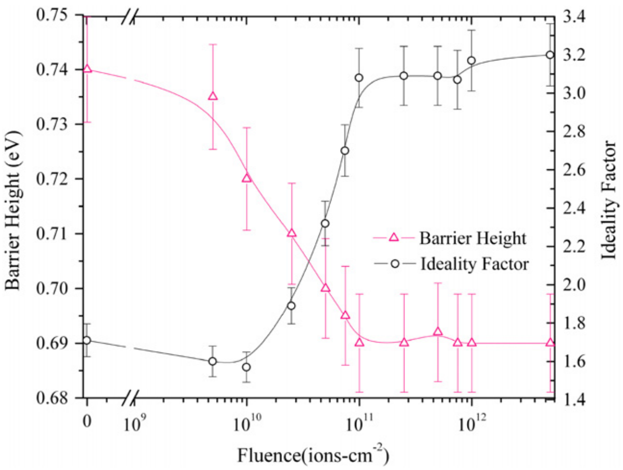

Figure 2. Irradiation fluence dependence of the SBH and ideality factor for Au/n-Si Schottky structure.

as Cheung's functions

$$\frac{\mathrm{d}V}{\mathrm{d}(\ln I)} = IR_s + n\left(\frac{kT}{q}\right), \tag{4}$$

$$H(I) = V - n\left(\frac{kT}{q}\right)\ln\left(\frac{I}{AA^*T^2}\right) \tag{5}$$

and

$$H(I) = IR_s + n\Phi_b, \tag{6}$$

The term IR_s is the voltage drop across the series resistance of Schottky diode. In figures 3(a) and (b), experimental $\mathrm{d}V/\mathrm{d}(\ln I)$ versus I and $H(I)$ versus I plots are presented at different ion fluences for Au/n-Si (1 0 0) SBD. Equation (4) will give a straight line for the data of downward curvature region of I–V characteristics. A plot of $\mathrm{d}V/\mathrm{d}(\ln I)$ versus I will give R_s as the slope and $n(kT/q)$ as the y-axis intercept. As a function of irradiation fluence the values of ideality factor n, barrier height and series resistance R_s derived from figures 3(a) and (b) are given in table 1.

Using the n value determined from equation (4), plots of $H(I)$ versus I will also give a straight line with y-axis intercept equal to $n\Phi_b$. The slope of these plots also provides a second determination of R_s, which can be used to check the consistency of this approach. Figure 4 shows the experimental series resistance values obtained from the semi-log forward bias I–V characteristics as a function of irradiation fluence.

One of the most important characteristics of the MS interface is the nature of the potential barrier between the Fermi level in the metal and the conduction band edge of the semiconductor at the interface. Since electrical contacts to semiconductors necessitate MS interfaces and depending upon this potential barrier height, interfaces exhibit a modest resistance to current flow in either direction or a high resistance in one direction and low resistance in the opposite direction [17]. The charge at MS interfaces can account for the difference between the predicted and the observed SBH. It is more important to know how the barrier height varies with the applied voltage. The potential across the interface varies with bias because of the change in the interface states charge

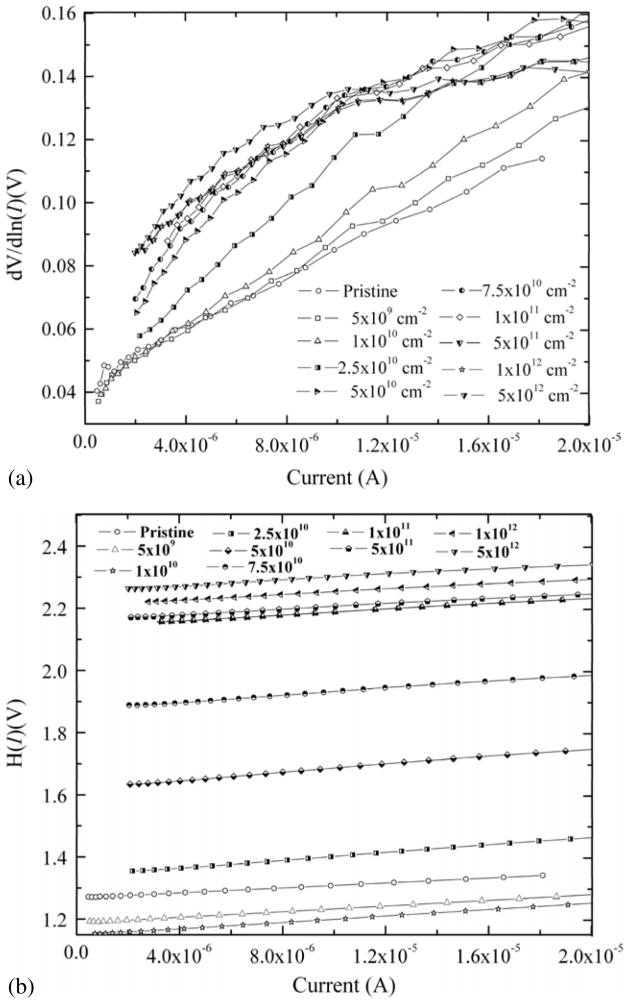

Figure 3. (a) Plots of $\mathrm{d}V/\mathrm{d}\ln(I)$ versus I and (b) $H(I)$ versus I for Au/n-Si(1 0 0) Schottky structure at different irradiation fluences.

as a result of the applied voltage, which modifies the SBH. The effective BH Φ_e is given by [18, 19]

$$\Phi_e = \Phi_b + \beta V = \Phi_b + \left(1 - \frac{1}{n(V)}\right)V. \tag{7}$$

The Φ_e is assumed to be bias dependent due to the presence of a native oxide interfacial layer and interface states located at the interfacial layer–semiconductor interface. β is the voltage coefficient of the effective BH Φ_e and is a parameter that combines the effects of both the interface states and interfacial layer thickness for the cases in which interface states are in equilibrium with the semiconductor. For the interface states in equilibrium with the semiconductor, the interface states density N_{ss} is given by [15]

$$N_{SS} = \frac{1}{q}\left(\frac{\varepsilon_i}{\delta}(n-1) - \frac{\varepsilon_S}{W}\right), \tag{8}$$

where W is the space charge width, N_{ss} is the density of interface states in equilibrium with the semiconductor, ε_s and ε_i are the permittivities of the semiconductor and the interfacial layer, respectively. δ is the thickness of the interfacial native oxide layer. The thickness of native oxide layer and

Table 1. Irradiation fluence dependence of various parameters determined from forward bias I–V characteristics of Au/n-Si(1 0 0) Schottky structure.

Fluence (ions cm^{-2})	Ideality factor (n)	Barrier height (eV)	Resistance (R_s) from $dV/d\ln(I)$–I (Ω)	Resistance $H(I)$–I (Ω)	Density of interface states N_{SS} (eV^{-1} cm^{-2})
0	1.71	0.740	3956	3992	4.71×10^{12}
5.0×10^{9}	1.60	0.735	4535	4542	4.00×10^{12}
1.0×10^{10}	1.57	0.730	5162	5203	3.85×10^{12}
2.5×10^{10}	1.89	0.710	6064	6172	6.15×10^{12}
5.0×10^{10}	2.32	0.700	6500	6550	9.06×10^{12}
7.5×10^{10}	2.70	0.690	5436	5602	1.16×10^{13}
1.0×10^{11}	3.08	0.690	4543	4634	1.40×10^{13}
2.5×10^{11}	3.09	0.690	4504	4543	1.43×10^{13}
5.0×10^{11}	3.09	0.690	4402	4348	1.43×10^{13}
1.0×10^{12}	3.17	0.690	4424	4216	1.43×10^{13}
5.0×10^{12}	3.20	0.690	4620	4560	1.43×10^{13}

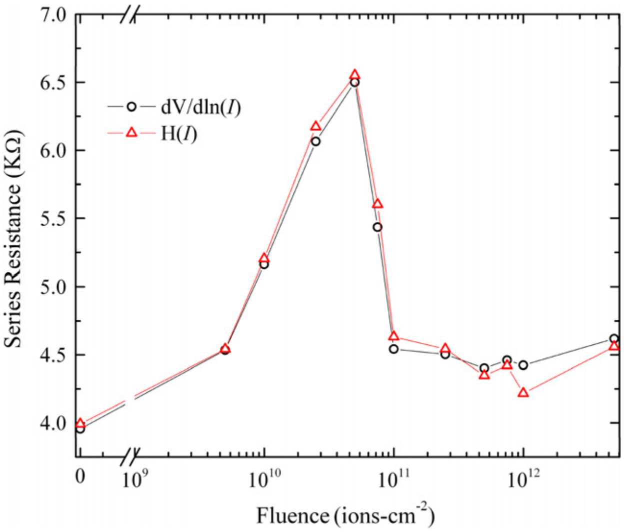

Figure 4. Variation of series resistance with irradiation fluence for Au/n-Si(1 0 0) Schottky structure.

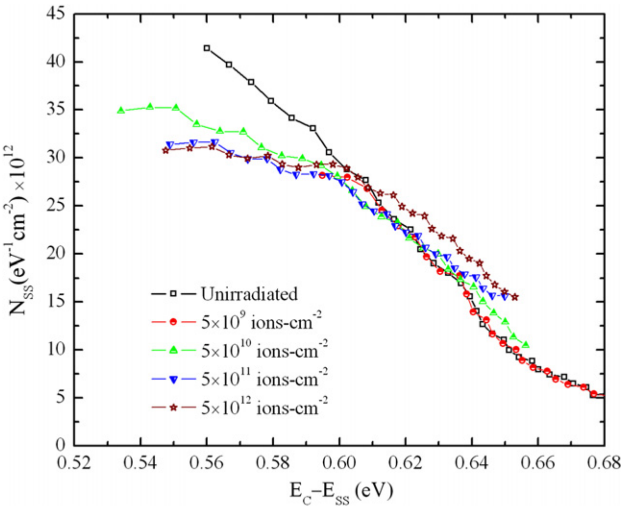

Figure 5. The energy distribution profile of the interface state densities N_{ss} obtained from the forward bias I–V characteristics of the Au/n-Si(1 0 0) Schottky structure at different irradiation fluencies.

depletion layer width can be obtained from high frequency C–V measurements using the equations [13]

$$C_i = \frac{\varepsilon_i \varepsilon_0 A}{\delta}, \tag{9}$$

and

$$W_D = \sqrt{\frac{2\varepsilon_S V_{bi}}{qN_D}}, \tag{10}$$

where V_{bi} is the surface potential and N_D is the dopant carrier concentration. Furthermore, in n-type semiconductors, the energy of the interface states E_{ss} with respect to the bottom of the conduction band at the surface of semiconductor is given as

$$E_C - E_{SS} = q\Phi_e - qV. \tag{11}$$

The energy distribution or density curves of the interface states can be determined from experimental data of this region of the forward bias I–V in figure 1. The resulting dependence of N_{ss} converted to a function of E_{ss} using equation (11) at various irradiation fluencies is shown in figure 5. For the as prepared sample the interface state density has an exponential rise (from 5×10^{12} eV^{-1} cm^{-2} in E_C–0.68 eV to 4.5×10^{13} eV^{-1} cm^{-2} in E_C–0.56 eV) with bias from the mid-gap towards the bottom of conduction band. The obtained values of interface states density are of the same order as reported in the literature by some authors for Schottky structures [14, 20]. The density of interface states N_{SS} increases with increasing irradiation fluence and after a fluence of 1×10^{11} ions cm^{-2} remains almost constant as the irradiation fluence increases further. The ideality factor shows the same trend with irradiation fluence as the interface states density. An increase in density of interface states results in a high value of ideality factor indicating that other current transport mechanisms (field emission, tunneling, etc) dominate over the thermionic emission. These current mechanisms lead to an increase in leakage current value with increasing irradiation fluence as shown in figure 1. After an irradiation fluence of 1×10^{11} ions cm^{-2} leakage current also gets saturated for the obvious reason of unchanging interface state density. The SBH decreases as the interface state density increases. When SBD is irradiated with a fluence 5×10^{10} ions cm^{-2}, the SBH decreases to 0.70 ± 0.01 eV and as fluence increases to 1×10^{11} ions cm^{-2}, the SBH decreased to a value of 0.69 ± 0.01 eV and remained immune to irradiation fluence as fluence increased up to 5×10^{12} ions cm^{-2}. To understand the observed modifications in the SBD properties

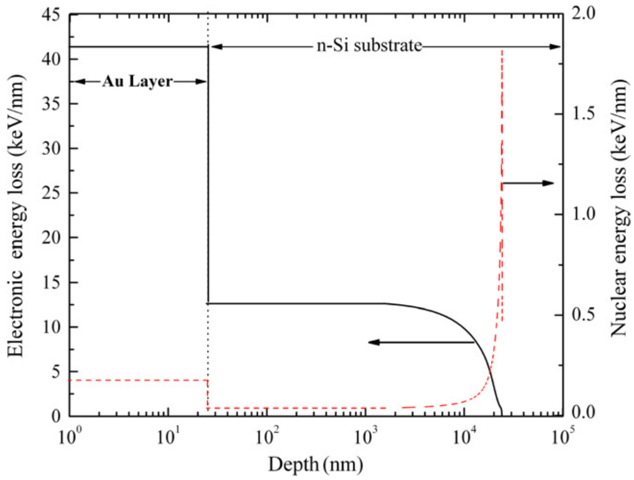

Figure 6. The electronic and nuclear energy losses of 180 MeV $^{107}Ag^{14+}$ ions as a function of depth inside Au/*n*-Si (1 0 0) Schottky diode.

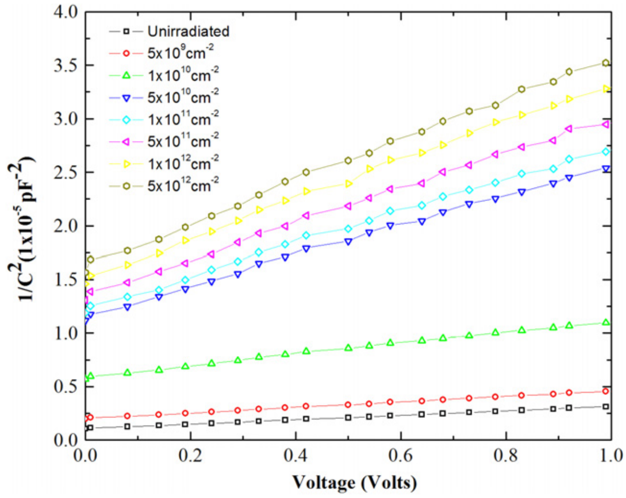

Figure 7. Reverse bias capacitance–voltage characteristics of Au/*n*-Si (1 0 0) Schottky diode at different ion irradiation fluences.

it is necessary to analyse the possible implications of ion transport through the sample. When 180 MeV $^{107}Ag^{14+}$ ion passes through the MS interface, it losses energy via nuclear energy loss S_n resulting from elastic collisions of the ion with the target atoms causing their displacement from the regular lattice sites, and electronic energy loss S_e which induces ionization/excitation of electrons inside the solid. For 180 MeV $^{107}Ag^{14+}$ ion, the variation of S_n and S_e as a function of depth inside the sample is shown in figure 6. All the energy loss calculations were performed using the standard Monte Carlo simulation program [21] called SRIM-2006. The ion stops deep inside the substrate far away from the MS interface. At the MS interface the S_n value is 0.03 keV nm^{-1} while S_e is 12.6 keV nm^{-1} (in the Si substrate). It is well established that S_n causes creation of defects such as vacancies and interstitials at the interface [22] while S_e produces strong ionization of the target atoms near the MS interface. During their relaxation, the electronic excitation can produce several specific structural defects and phase transition [23, 24] as well. These defects have their energy levels deep inside the semiconductor band gap and lead to an increase in the interface state density at the MS interface. These deep level defects trap the carriers and act as the scattering centres for the mobile carriers, hence, decreasing the carrier concentration and their mobility. This decrease in carrier concentration and mobility results in an increase in series resistance. Two theoretical models, namely, thermal spike [25] and Coulomb explosion [26] model are used to explain the local excitation of the lattice by energy transfer from the highly excited electronic system to the lattice atoms. Both mechanisms can result in atomic transport and thus SHI irradiation of solids leads to material modification depending on the properties of the materials and deposited energy density [27, 28]. According to the widely used thermal spike model, rapid energy transfer through electron–phonon coupling makes the system abnormally excited and the region around the ion track gets suddenly heated to a very high temperature within a small time duration [29]. A lot of vacancies are, therefore, produced everywhere along the ion track. The number of vacancies generated is of the order of 10^{19} cm^{-3}, which has a typical diffusion length of 25 nm in Si [30, 31]. At the lower fluences, the resistance increases because the number of vacancies increases as the irradiation fluence increases. At an irradiation fluence of 5×10^{10} ions cm^{-2} the defect regions around the ion tracks cover the whole area and produce maximum vacancies and interstitials. After these fluences, defect regions around the tracks start overlapping. The decrease in the value of resistance after fluence 5×10^{10} ions cm^{-2} indicates that the product of the mobility and the free carrier concentration has increased. From *C–V* characteristics as shown in figure 7, we found that carrier concentration decreases with increasing irradiation fluence. It implies an increase in the mobility, which may be because of crystallinity improvement due to the vacancies, migration and vacancy–interstitial recombination. Recently, it is has been observed that SHI irradiation results in annealing of point defects due to electronic energy loss when an amorphous Si wafer was irradiated with 100 MeV Ag^{7+} ion beam [32]. It is evident from figure 6 that at the MS interface the S_e value is about 350 times larger than S_n. This high value of S_e may cause partial annealing of point defects produced by S_n. So the cumulative effects of S_n and S_e result in constancy of interface state density. This constancy of interface states leads to immunity of diode parameters with respect to fluence. After the irradiation fluence of 1×10^{11} ions cm^{-2} the SBH, ideality factor and series resistance remain almost constant up to a fluence 5×10^{12} ions cm^{-2}. It means that after fluence of 1×10^{11} ions cm^{-2} the rate of creation of defects and the rate of annealing of defects become equal resulting in constancy of interface state density as well as Schottky barrier parameters with respect to fluence.

4. Conclusions

In this experiment an Au/*n*-Si(1 0 0) Schottky diode was irradiated by 180 MeV $^{107}Ag^{14+}$ ion beam at various fluences and effects of SHI irradiation on electrical characteristics of the Schottky diode have been studied using *in situ I–V* measurements. It is found that Au/*n*-Si Schottky diode characteristics are very sensitive at lower irradiation fluences. After a critical fluence diode parameters remains nearly constant with irradiation fluence. This is due to the cumulative effect of large electronic energy loss and nuclear energy loss at the MS interface. When annealing of defects balances the rate of creation of defects, constancy in the diode parameters with respect to irradiation fluence occurs.

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