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In-situ study of electrical transport in Pd/n-Si under high energy ion irradiation

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Abstract

The understanding of the influence of energetic ions on the transport properties of semiconductor materials is essential to design the devices for use in a radiation environment. In this article, an *in-situ* investigation of the effect of 100 MeV O^{7+} irradiation on the current-voltage characteristics of the Pd/n-Si Schottky barrier structure is carried out. It is observed that the interface barrier parameters (Ideality Factor, Schottky barrier height and reverse saturation current) are a strong function of ion fluence. The voltage dependence of the conduction mechanisms indicates the presence of defects near the interface as well as in bulk silicon. The energy loss mechanisms of energetic ions in the Pd/n-Si structure are used to explain the observed results after irradiation.

Keywords: Ion irradiation, Electronic energy loss, *I-V* characteristics, Schottky barrier

Introduction

The metal-semiconductor (MS) contacts with the Schottky barrier at the interface have widespread applications in integrated circuits, solar cells, photovoltaic devices, sensors and particle detectors[1–4]. In recent years, the thin film MS Schottky diode structures used as sensors for atomic and molecular gas phases[3]. In particular, Pd/n-Si Schottky barrier structures have been used as a hydrogen sensor[5,6]. The MS contacts also work as a research tool to study the properties of materials[7–10]. So, it is really important to get the knowledge of the MS interface barrier formation and modification mechanisms for desired device operations. As the barrier at MS interface controls the transport mechanism, any mechanism altering the interface will modify the carrier transport properties of the Schottky barrier device also. The semiconductor devices used in avionics, space satellites, nuclear reactor and accelerator laboratories are exposed to energetic ions and radiation continuously. This exposure to radiation and energetic ions can modify the MS interface, which will lead to the modified barrier parameters and the transport properties[11–13]. Therefore, irradiation studies with energetic ions are extremely helpful to simulate the device's performance in a radiation ambiance. The high energy ions, in which electronic stopping (S_e) is dominating over nuclear stopping (S_n) known as swift heavy ions (SHI). The SHI irradiation can modify the MS interface properties without implantation near the interface. Depending on the strength of S_e and S_n, the SHI irradiation can be utilized to modify the Schottky barrier and transport properties in a controlled fashion either by generating the defects near the MS interface or removing the present defects by dynamic annealing[10,14]. Besides creating the defects in a controlled way, the energetic heavy ions are also used for doping and modifying the transport properties in bulk as well as nanostructures[15–19]. So, understanding the influence of SHI irradiation on the performance of Schottky barrier devices is an important field of research with technological applications to design better radiation-hard electronic devices. The studies concerning the influence of high energy irradiation on silicon and other semiconductor devices have been reported in the literature[14,20–22] but a perfect understanding of the carrier conduction mechanism in SHI irradiated devices is still far from complete. Specifically, the Pd/n-Si structure is not studied extensively under high energy ion exposure. The silicon device processing can be improved by understanding the basic mechanisms of creation and annealing of the irradiation induced defects. The SHI irradiation induced modification of MS interfaces can be investigated by systematically investigating the electrical transport across them. The detailed analysis of current-voltage (*I-V*) characteristics of the Schottky barrier interface provides the knowledge of barrier formation and charge conduction mechanism. Since the MS interface properties control the electrical transport so a little variation in barrier parameters is generally observed even the devices are formed on the same wafer. Therefore, fluence dependent investigations must be performed *in situ* on the same sample to observe the true effect of irradiation with varying ion fluence. In this paper, a detailed analysis of *I–V* characteristics of the Pd/*n*-Si Schottky structure irradiated with 100 MeV O^{7+} at various ion fluences is presented. The ion fluence is varied from 1×10^{9} to 1×10^{13} ions cm^{-2}. The values of ion fluence are selected to avoid any possibility of ion beam mixing or phase formation at the MS interface. The *I–V* characteristics are taken *in situ* on the same Pd/n-Si Schottky barrier structure maintaining all other physical parameters (temperature, vacuum conditions and ion flux) identical.

Experimental Details

In this study, the Pd/n-Si Schottky diodes were created on Phosphorus doped n-Si (100) wafer having resistivity 1-10 Ω-cm. A standard RCA cleaning process was used to remove all the contaminants from the surface of the wafer. The wafer was deoxidized in a 2% hydrofluoric acid.

The Ohmic contacts on the back side of the cleaned Si wafer were made by the deposition of the Ti/Au (20/180 nm) layer by resistive evaporation, which was followed by the annealing at 500 °C for 20 minutes in an argon gas atmosphere. The Schottky contacts on the front side were created by depositing 100 nm of Pd metal having 2 mm diameter circular dots using the physical mask in a vacuum of order $\sim 10^{-6}$ mbar. The SHI irradiation of Pd/n-Si devices with 100 MeV O^{7+} ion beam at room temperature was performed using the 15UD tendem accelerator facility at IUAC, New Delhi. The *in situ I-V* measurements were recorded using an Agilent Semiconductor Analyzer (B1500A) after a specific ion fluence value by stopping the ion beam. The value of ion flux during the ion irradiation was maintained 7.5×10^{8} ions cm^{-2} s^{-2}.

Results and Discussion

The experimentally observed *in situ I-V* characteristics for Pd/n-Si Schottky barrier structure before and after ion irradiation with 100 MeV O^{7+} ion beam are shown in Fig. 1. The measurements are taken at several ion fluences varying from 1×10^{10} ions cm^{-2} to 1×10^{13} ions cm^{-2}. In Fig. 1, forward bias *I-V* curves are linear at lower voltage bias values on a semilogarithmic scale, which gets saturated at higher bias. It is observed that after ion irradiation, the *I-V* curves at lower applied bias (up to 0.4 Volts) remains unaltered up to a fluence value of 1×10^{12} ions cm^{-2} while the value of current is decreased at high applied bias (> 0.4 Volts) with increasing irradiation fluence. Interestingly, the higher value of irradiation fluence ($>1\times10^{12}$ ions cm^{-2}) results in a shift of linear region in *I-V* curves to a higher voltage value and an increase in current at a higher bias region compared to a fluence of 1×10^{12} ions cm^{-2}. To understand these observations, the thermionic emission model of current conduction in the Schottky barrier structure is applied[1]. According to this model, the current due to majority carriers is given by

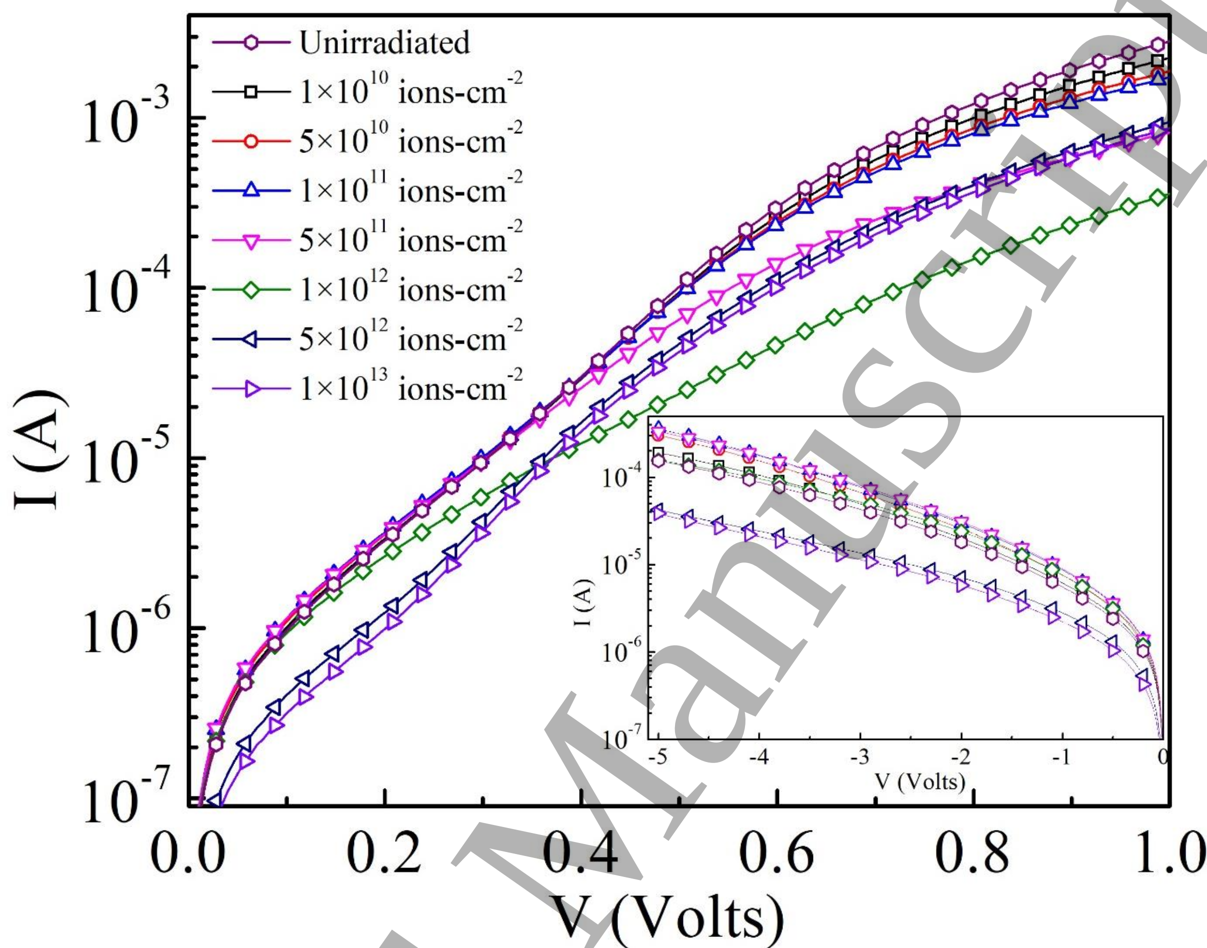

Figure 1: The forward biased I-V characteristics of the Pd/n-Si structure as a function of ion fluence. The inset shows the reverse bias I-V curves.

$$I = I_0\left[exp\left(\frac{qV}{nkT}\right) - 1\right] \quad (1)$$

across the MS interface. Here n is the ideality factor and q, V and T have their typical meanings. The reverse saturation current (I_0), with device area A (0.0314 cm^2), Richardson's constant A^*(112 A cm^{-2} K^{-2} for n-Si) and Schottky barrier height (ϕ_B) is expressed as

$$I_0 = AA^*T^2 exp\left(-\frac{q\phi_B}{kT}\right) \quad (2)$$

and $$\phi_B = \frac{kT}{q} ln\left(\frac{AA^*T^2}{I_0}\right) \quad (3)$$

The slope and intercept of the linear section of the forward bias ln(I) vs V curve (up to 0.4 V) is used to extract the values of n and I_0. The value of n structure is extracted using the relation

$$n = \frac{q}{kT}\left(\frac{dV}{d\ln(I)}\right) \quad (4)$$

The influence of 100 MeV O^{7+} ion beam on the Pd/n-Si Schottky barrier parameters (n and ϕ_B) with varying ion fluence is shown in Fig. 2. The value of ϕ_B for the unirradiated diode is 0.73eV, which is in accord with earlier reported values[23]. Initially, the ϕ_B decreases after ion irradiation and a value of 0.69 eV is found at an ion fluence of 1×10^{12} ions/cm^2. Further increment in irradiation fluence results in a significant increase in ϕ_B compared to the unirradiated Pd/n-Si Schottky barrier structure. The shifting of the I-V curve to a higher bias voltage also indicates the increased value of the barrier. The value of ϕ_B becomes 0.76 eV at a fluence value of 1×10^{13} ions/cm^2. It is worth noting that the value of reverse leakage current (I_R) also decreases after irradiation at a fluence of 1×10^{12} ions/cm^2 or more as shown in the inset of Fig.1. The value of I_R for unirradiated diode at 5V is 1.5×10^{-4} A, which increases to a value of 3.6×10^{-4} A after irradiation at a fluence of 1×10^{12} ions cm^{-2}. Afterward, the I_R decreases as the ion fluence increases and a value of 3.8×10^{-5} A is measured after irradiation with 1×10^{13} ions cm^{-2}, which is about one-fourth of the value of without irradiation. These results are new compared to reported irradiation studies in silicon devices where irradiation results in a decreased value of ϕ_B and increased I_R up to a critical ion fluence and at the higher irradiation fluences, these parameters get saturated[11,16,20,24]. These results indicate that the Schottky barrier characteristics at the Pd/n-Si interface is improved after irradiation at higher fluence.

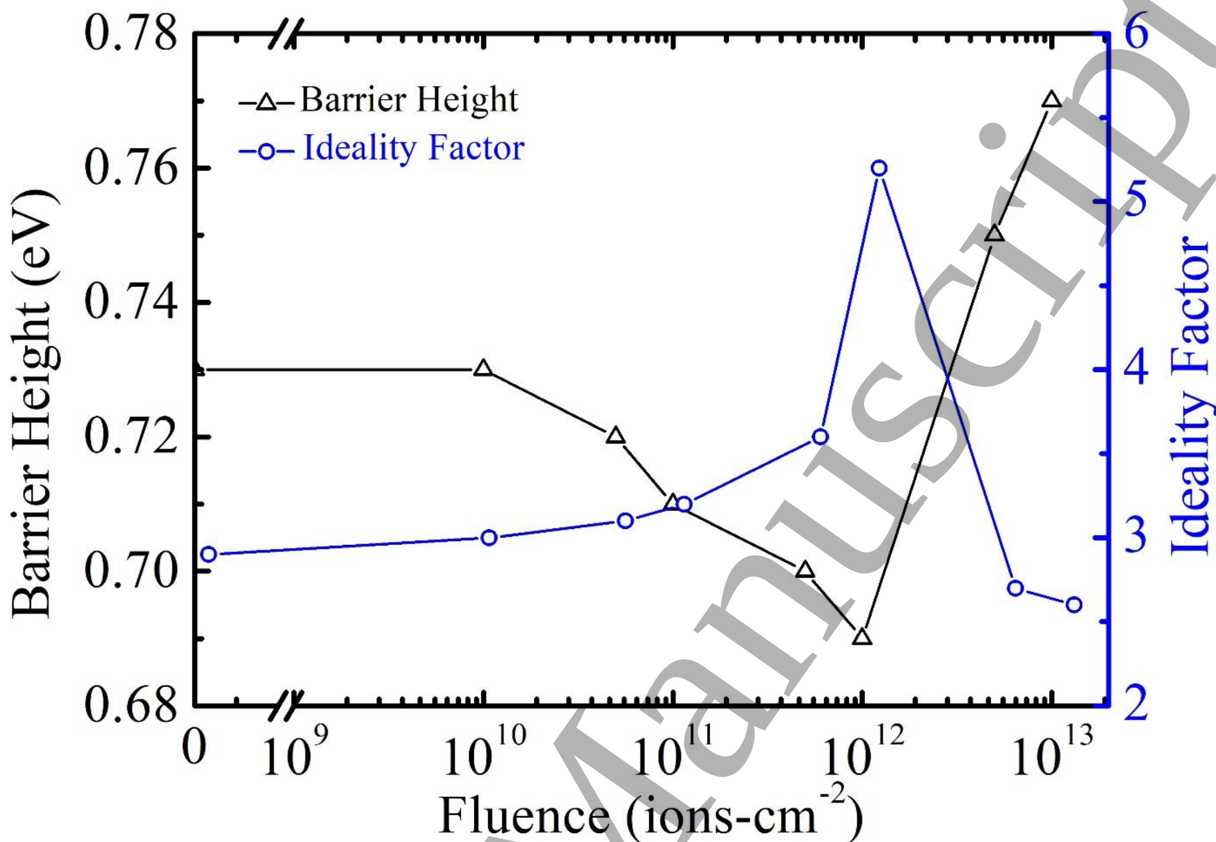

Figure 2: Barrier height and Ideality factor of Pt/n-Si Schottky structure as a function of ion irradiation fluence.

The calculated value of *n* for the unirradiated Pd/n-Si Schottky barrier structure is 2.9, which is significantly high from the ideal value for thermionic emission (*n*=1). It is known that interface states due to surface or crystal defects strongly influence the MS interface properties. In addition, the presence of a native thin oxide layer at interface (formed during the device fabrication process) can trap the charges and leads to an increased interface states density[1]. These interface states increase the contribution of trap assisted tunneling and recombination current in thermionic emission current, which results in high value of *n*. It is observed that *n* shows the reverse behavior of the ϕ_B after irradiation, initially increased to a value of 5.2 till a fluence of 1×10^{12} ions/cm^2. Thereafter, its value decreased and a value of 2.6 is observed at 1×10^{13} ions/cm^2. The barrier inhomogeneity at the interface and the high series resistance also leads to non-ideal behavior in Si Schottky barrier structures[7,25]. However, the behavior of *I-V* curves at a higher bias (V>0.4 V) cannot be explained by thermionic emission considering the series resistance effect in this case.

The experimental *I-V* data is plotted on a log-log scale in figure 3 to get a better understanding of transport mechanisms and influence of ion irradiation on these mechanisms. The occurrence of two different slopes in the forward bias *I-V* curves of Pd/n-Si Schottky barrier structure at a double logarithmic scale indicates the presence of different carrier transport mechanisms, which dominates at different bias range. It is known that the domination of the free carriers over the injected carriers shows a linear *I-V* dependence at a low bias range as observed in Fig. 3. The current follows a power law ($I \propto V^{\alpha}$) dependence at higher bias voltages indicating a space charge limited current (SCLC) mechanism[26,27]. The SCLC is realized when the number of injected carriers exceeds the thermally generated intrinsic free charge carriers. The value of the exponent α indicates the presence or absence of the traps. Generally, for a trap free SCLC mechanism, a value of two is observed for exponent while a trap assisted SCLC conduction mechanism shows exponents more than two[28]. For the unirradiated Pd/n-Si structure, the value of α at room temperature is ~3.8, which indicates that the transport mechanism at higher bias is controlled by the traps. These traps may be due to process induced surface or crystal defects. The presence of a native thin oxide layer at the Pd/n-Si interface also can result in defects states. After irradiation, the value of α decreases with increasing ion irradiation fluence to a value of 3.2 at 1×10^{12} ions/cm^2. However, further increase in ion fluence results in an increased value of α to 3.9 and 4.0 at 5×10^{12} ions/cm^2 and 1×10^{13} ions/cm^2, respectively.

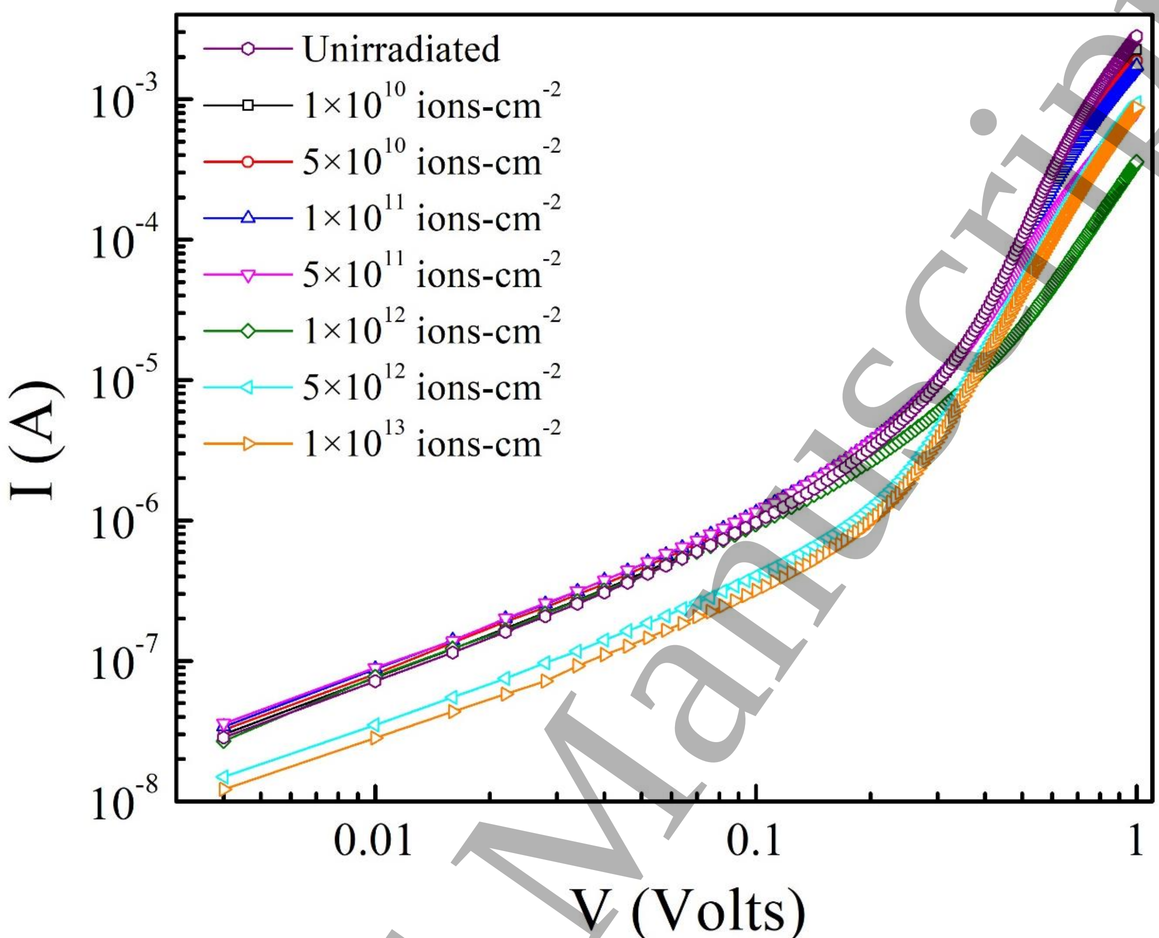

Figure 3: I-V characteristics of Pd/n-Si Schottky structure on a double logarithmic scale

According to the exponential trap distribution model, the current in SCLC is given by[29–31]

$$I_{SCLC} = Aq^{1-l}\mu N_c \left(\frac{\varepsilon_0 \varepsilon_r}{N_t}\right)^l f(l) \frac{V^{l+1}}{d^{2l+1}} \ , \qquad (5)$$

Here l is exponent ($l = \alpha$-1), μ is carrier mobility, N_c is the effective density of states, N_t is the trap density and the d is the distance between the electrodes. Here it is to be noted that the assumption of exponential distribution of trap states is only valid for α >2. The function $f(l)$ in Eq. 5 is given by

$$f(l) = \left(\frac{1}{l+1}\right)^l \left(\frac{2l+1}{l+1}\right)^{l+1} , \qquad (6)$$

where $l=T_T/T$, and T_T represents the characteristic trap temperature. The value of l can be determined from the experimental *I-V* curves directly. The analysis of *I-V* curves at higher bias using eq. 5 gives the value of the trap density. A built-in potential in asymmetric structures like Pd/*n*-Si also considered in the analysis[31]. For unirradiated Pd/*n*-Si structure, the extracted value of N_t is 5.8×10^{14} cm^{-3}, which increases to a value of 2.0×10^{15} cm^{-3} after ion irradiation at a fluence of 1×10^{12} cm^{-2}. It is found that further increment in ion fluence results in a decreased value of N_t to a value of 1.0×10^{14} cm^{-3}.

To understand these observations, the knowledge of the role of energy loss mechanisms of 100 MeV O^{7+} ions in the Pd/*n*-Si structure is necessary. The variation of energy loss due to inelastic and elastic collisions (S_e and S_n) inside the Pd/n-Si Schottky structure is shown in Fig. 4. It can be seen in the figure that S_e is the dominant process at the Pd/n-Si interface and S_n dominate only at the end of ion range. The average value of S_e and S_n for 100 MeV O^{7+} at Pd/*n*-Si interface is 1.50 keV/nm and 8.91×10^{-4} keV/nm respectively. The value of S_e is about three orders of magnitude higher than the S_n. The standard SRIM 2013 code is used to perform these energy loss calculations. In high energy ion irradiation, a huge amount of energy is transferred through the electron-phonon coupling, which makes the temperature of the region around the ion track very high in small time duration known as “thermal spike”[32]. This abnormal excitation of the system results in point defects (vacancies/interstitials) around the ion track or cascade region. A partial annealing of preexisting defects due to the high value of S_e of ions in silicon has also been observed[33,34]. The generated defect density along the ion track has an order of 10^{19} cm^{-3} with a diffusion length of a few nanometers in silicon[15,35]. Though most of the generated defects recombine and only a few percent survive. The defect density in the sample increases with the increasing ion irradiation

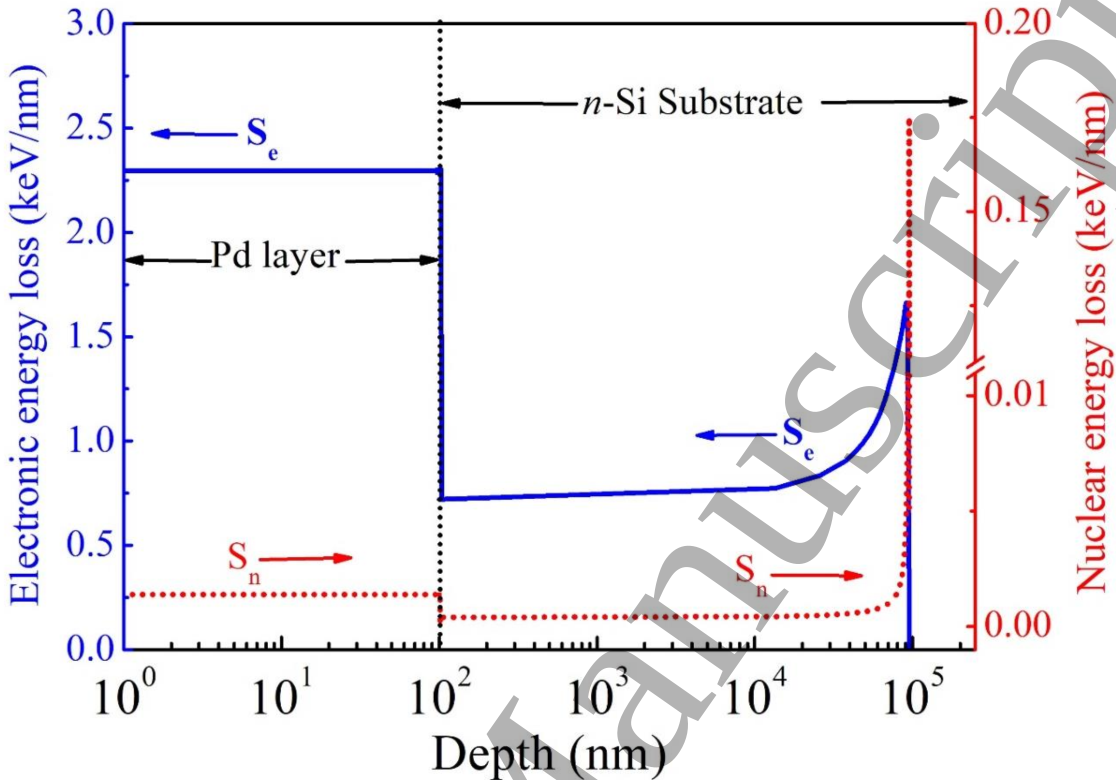

Figure 4: *The variation of S_e and S_n of 100 MeV O^{7+} ion in Pd/n-Si.*

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fluence, which results in an increase in interface states density (D_s) with irradiation fluence. As the Schottky barrier parameters are dependent on the MS interface properties and the presence of interface states influence these parameters drastically. The increase in D_S leads to an increase in leakage current and n after irradiation as shown in Fig 2. The increased value of n indicates the contribution of other transport mechanisms other than the thermionic emission and results in a decreased value of ϕ_B. We observed that the irradiation with 100 MeV O^{7+} ions decreases the value of ϕ_B at the Pd/n-Si interface up to a fluence of 1×10^{12} ions-cm^{-2}. The average distance between the ion cascade region decreases with the increasing ion fluence. The maximum number of point defects is produced when the defect zones around the ion path cover the whole area. When the cascade regions around the ion track overlap, annealing of the existing defects can occur. The point defects(vacancies/interstitials) have low migration energy in Si which makes them mobile at room temperature leading to the high probability of recombination with increasing fluences. The decreased value of D_s due to annealing of defects is observed in a decreased value of leakage current. So, a fluence value of more than 5×10^{11} ions-cm^{-2} results in annealing of defects owing to the high S_e value of the 100 MeV O^{7+} ions. These results show a noticeable annealing effect of high energy ions which causes an increase in ϕ_B and reduced leakage current at high irradiation fluence. The lower value of the ideality factor and reduced trap concentration also confirm the annealing of defects after high fluence irradiation. The 100 MeV $^{16}O^{7+}$ ions used in this study have a high S_e to S_n ratio (~1680), and a low value of S_n at the MS interface. The small value of S_n causes less defect creation and the high S_e leads to the annealing of defects, which results in the improved Schottky barrier parameters.

Conclusion

In this work, the effect of 100 MeV O^{7+} ion irradiation on the Pd/n-Si Schottky barrier structure has been studied. The *I-V* curves and the Schottky barrier parameters are altered due to defects in the interface and bulk silicon after irradiation. The diverse transport mechanisms such as the thermionic emission and space charge limited conduction at different bias voltages are discussed in terms of varying ion irradiation fluence. It is revealed that the conduction is trap assisted space charge limited at higher bias voltages. A prominent annealing effect of 100 MeV $^{16}O^{7+}$ ions in Pd/n-Si due to the high value of S_e compared to S_n results in improved barrier parameters. These results show that the properties of semiconductor devices can be modified with an optimal choice of ion beam and irradiation fluence.

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