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Tuning of Schottky barrier height of Al/n-Si by electron beam irradiation

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ABSTRACT

The effect of electron beam irradiation (EBI) on Al/n-Si Schottky diode has been studied by I–V characterization at room temperature. The behavior of the metal-semiconductor (MS) interface is analyzed by means of variations in the MS contact parameters such as, Schottky barrier height (Φ_B), ideality factor (n) and series resistance (R_s). These parameters were found to depend on the EBI dose having a fixed incident beam of energy 7.5 MeV. At different doses (500, 1000, 1500 kGy) of EBI, the Schottky contacts were prepared and extracted their contact parameters by applying thermionic emission and Cheung models. Remarkably, the tuning of Φ_B was observed as a function of EBI dose. The improved n with increased Φ_B is seen for all the EBI doses. As a consequence of which the thermionic emission is more favored. However, the competing transport mechanisms such as space charge limited emission, tunneling and tunneling through the trap states were ascribed due to $n > 1$. The analysis of XPS spectra have shown the presence of native oxide and increased radiation induced defect states. The thickness variation in the MS interface contributing to Schottky contact behavior is discussed. This study explains a new technique to tune Schottky contact parameters by metal deposition on the electron beam irradiated n-Si wafers.

1. Introduction

The rectifying metal-semiconductor (MS) or Schottky contacts find number of applications in semiconductor device technology, since the metal contacts to the semiconductor connects the devices to the outer world. Due to the absence of minority carrier injection, Schottky contacts are found to be ideal for microwave and switching applications. They are also used in the implementation of metal gates in MOSFET or MISFET devices. For the last several decades, lot of work has been done in improving and understanding the behavior of MS interface, as the nature of interface is crucial to the operation of Schottky barrier diode. However the thermionic emission (TE) model in the forward regime of I–V characteristics is always deviated from the ideal Schottky behavior. This is because, the TE model assumes homogeneity of the Schottky barrier, but in reality the barriers are inhomogeneous. To account deviations from the ideal behavior, the other Schottky diode parameters such as, ideality factor (n) and series resistance (R_s) were proposed to play important role in determining the device performance [1–5].

The Schottky contact behavior is mainly dependent on the Schottky barrier height (Φ_B), because the transport across the MS interface is mainly controlled by Φ_B. From the well-known Schottky-Mott theory, Φ_B depends on the work function of a chosen metal (ϕ_m) and semiconductor with definite electron affinity (χ_s). However the experimental results showed the Φ_B insensitivity to ϕ_m due to high surface state density of the semiconductor. As a result of surface states, interfacial layer, microscopic metal clusters [6], it is difficult to fabricate Schottky junctions with barriers near the ideal values as predicted from the Schottky-Mott theory. For this reason, the measured barrier heights are used in the device design.

The ability to vary Φ_B for different applications is important for the device optimization [7]. There are different techniques to modify Φ_B for the same semiconductor material. Such techniques can be grouped broadly into post metal and pre metal contact deposition treatments. To mention a few, surface passivation [8,9], insertion of an interfacial thin different semiconductor layer [10,11], surface hydrogenation [12,13], deep level impurities [14], by native oxide processing [15], introducing a surface layer of different dopant

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concentration on semiconductor [16], swift heavy ion irradiation [17] and the inclusion of nanoparticles in the MS interface [18]. All these techniques showed the Φ_B dependence on the preparation of MS interface. In this view, the present paper discusses modifications in Φ_B along with the other Schottky diode parameters when a metal contact is established on the electron beam irradiated semiconductor wafer. This method could serve as a Φ_B new technique to tailor

In the present work Si Schottky diode has been investigated with Al as a metal contact. Because Al has a strong tendency to sit on Si and forms no intermetallic compounds. Hence Al keeps a simple chemistry in the MS interface. Further the literature availability of electron beam irradiation on Al/n-Si contacts is scarce. The studies also give an insight on electrical stability of n-Si for radiation doses up to 1500 kGy. The present study will be taken up further for other Schottky diodes under different irradiation conditions and with the effect of thermal treatments.

2. Experimental

Phosphorus doped n-type Si ⟨100⟩ wafer with doping concentration 1.5×10^{14} cm^{-3} was procured from Sigma Aldrich®, India. The diced n-Si wafers ($10 \times 10 \times 0.5$ mm) were then subjected to electron beam irradiation (EBI) using 10 MeV linear accelerator (LINAC), Raja Ramanna Centre for Advanced Technology (RRCAT) India. The beam energy, beam diameter and dose rate during EBI was 7.5 MeV, 30 mm and 6.5 kGy/s respectively. The dose rate measurements on the sample surface were carried out using Alanine Electron paramagnetic resonance (EPR) dosimetry system. The electron beam energy was fixed during irradiation process. The n-Si wafers were irradiated for different doses (500, 1000, 1500 kGy) at room temperature. After EBI, the surface studies were performed by x-ray photoelectron spectroscopy (XPS) using Omicron energy analyzer (EA-125) with Al-kα (1486.6 eV) as a source of x-rays.

The Schottky contacts on the electron beam irradiated n-Si wafers were established using the thermal evaporation technique. Al was used as a metal contact to n-Si, since it is chemically inactive and makes no silicide bonds [1]. A mask of area 0.4 cm^2 was used and a base pressure of 8×10^{-6} mbar was maintained during Al metal deposition. The thickness of deposited Al film was kept at 20 nm. The I–V characterization was carried out using Keithly 2450 source meter under dark conditions. The copper pressure contacts were used as back ohmic contacts during measurements.

3. Results and discussion

The modifications in rectifying behavior of all the Al/n-Si contacts are shown in Fig. 1. I–V characteristics in the forward bias region can be explained by well-known TE model, since the experimental results tend to agree more loosely with prediction of thermionic theory than diffusion theory. According to TE model, the current I through the barrier when the applied voltage V is given by [2,3]

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

where,

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

is the reverse saturation current, A is effective area of the diode, A^{**} is the Richardson constant (for n-Si, A^{**} = 112 A cm^{-2} K^{-2} [19]), q is charge of the electron, Φ_B is Schottky barrier height, k is Boltzmann constant and T is absolute temperature. The parameter n called ideality factor in Eq. (1) accounts for non-ideal behavior of the Schottky diode [2]. The slope and intercept of the semi-log plot (Fig. 2.) gives n and Φ_B respectively. The inset plot in Fig. 2. shows voltage region from which parameters are extracted and are reported in Table 1.The parameters were extracted in the voltage range where the best line of fit (0.99) was obtained.

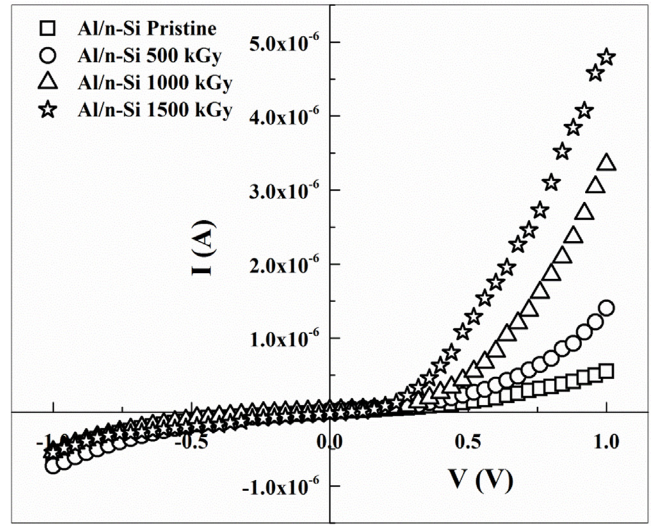

Fig. 1. I–V characteristics of Al/n-Si Schottky diodes at different radiation doses.

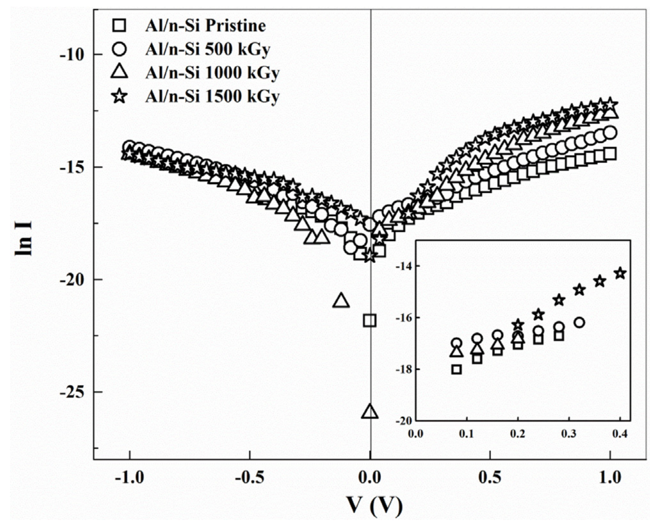

Fig. 2. Semi-log plot of Al/n-Si Schottky diodes at different radiation doses (The inset plot shows voltage region from which parameters are extracted).

Table 1
Schottky diode parameters of Al metal contacts to electron beam irradiated n-Si wafer.

Diode	TE model		Cheung model		
	Φ_B(eV)	n	Φ_B(eV)	n	R_s(kΩ)[a]
Al/n-Si Pristine	0.86	7.58	0.87	6.11	225.83
Al/n-Si 500 kGy	0.84	12.59	0.84	8.62	164.47
Al/n-Si 1000 kGy	0.85	10.22	0.85	5.76	69.54
Al/n-Si 1500 kGy	0.88	3.32	0.89	2.59	103.89

[a] Obtained from H(I) vs I plot.

The deviation from linearity (Fig. 2) is caused due to the interface states, series resistance associated with bulk of n-Si and back ohmic pressure contacts [19,20]. But a change in I–V characteristics of all the Schottky diodes was attributed to modifications in Φ_B. Radiation induces modifications on the surface of n-Si by generating defect states near the surface as well as in the bulk. When Schottky

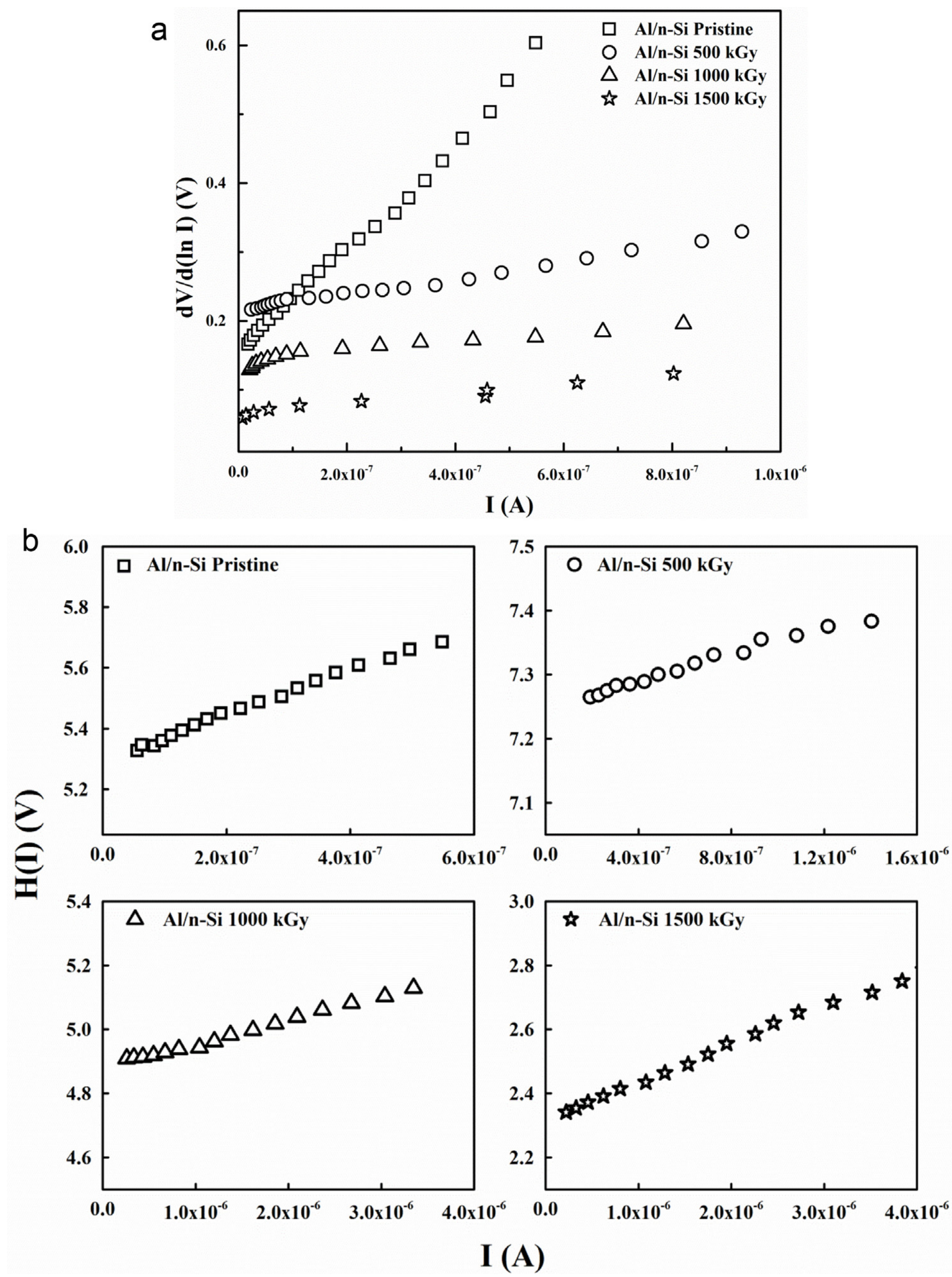

Fig. 3. a. dV/d(ln I) vs I plot for Al/n-Si diodes for different radiation doses. b. H(I) vs I plot for Al/n-Si diodes for different radiation doses.

contacts were fabricated on the irradiated n-Si, the properties of MS interface particularly Φ_B can be effectively controlled by these irradiation induced defect states. This modified Φ_B brings variations in the I–V characteristics. It has been further noticed that, there is an increase in defect states with radiation dose which in turn increases Φ_B. The increase in the defect states with the dose is confirmed form XPS analysis (Fig. 5). However the n values calculated by applying TE model was noticeably high, because TE model ignores the effect of series resistance (R_s) between metal and semiconductor. Ignoring the effect of R_s will lead to erroneous determination of Schottky contact parameters. The R_s along with n and Φ_B can be determined graphically by using Cheung's functions [21]. By taking into account of R_s, the TE model Eq. (1) for $V > 3kT/q$ takes the form

$$I = I_s \exp[\frac{q(V - IR_s)}{nkT}] \tag{3}$$

The differentiation of Eq. (3) with respect to I gives

$$\frac{dv}{d(\ln I)} = R_s I + \frac{nkT}{q} \tag{4}$$

The slope and intercept of the plot $\frac{dv}{d(\ln I)}$ vs I (Fig. 3a.) give R_s and n respectively.

The Φ_B can be obtained by defining a new function $H(I)$ such that

$$H(I) = R_s I + n\Phi_B \tag{5}$$

where,

$$H(I) = V - \frac{nkT}{q} \ln\left(\frac{I}{AA^{**}T^2}\right) \tag{6}$$

The intercept of $H(I)$ vs I plot gives Φ_B (Fig. 3b). The Cheung's plots were determined from data of the downward curvature

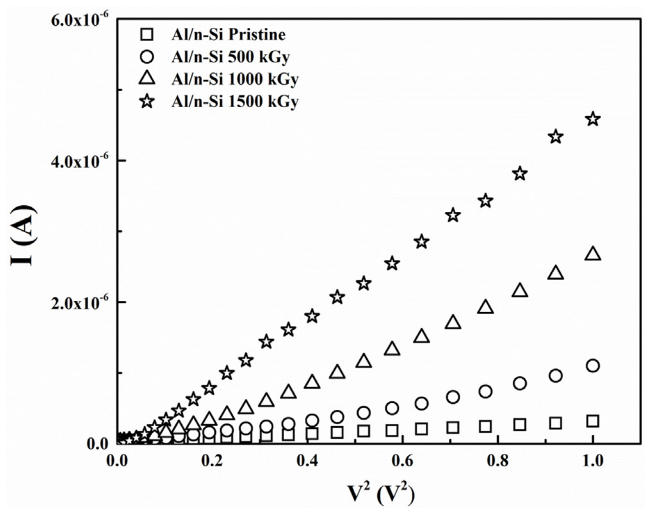

Fig. 4. Power law characteristics of Al/n-Si Schottky diodes at different radiation doses.

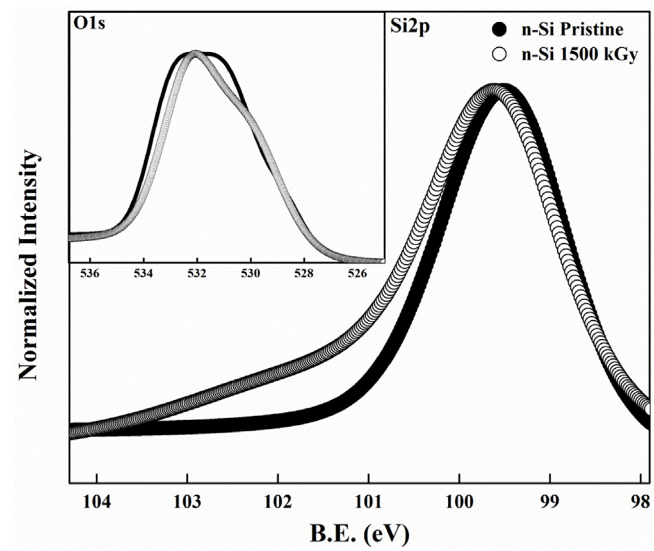

Fig. 5. Si2p core XPS spectra of pristine and electron beam irradiated n-Si wafer (inset shows the core XPS spectra of O1s).

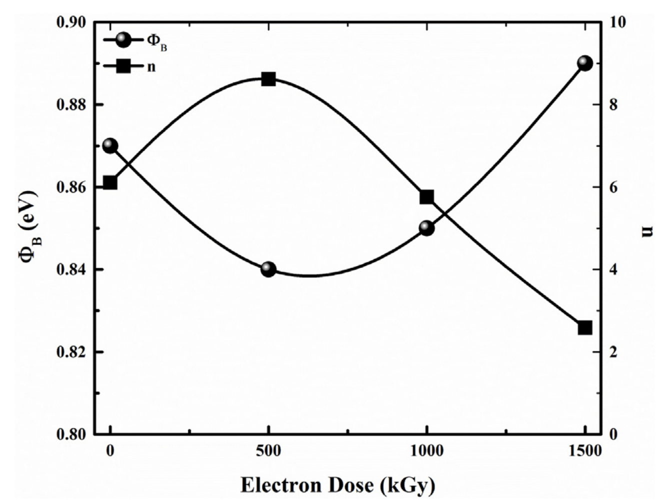

Fig. 6. Modifications in the Schottky barrier height (Φ_B) and ideality factor (n) of Al/n-Si Schottky diodes at different radiation doses.

region in the forward I–V plot [19]. The obtained values are reported Table 1.

In the present investigation definite correlations are observed among Schottky diode parameters with radiation dose. The n value calculated from TE model was found to be more than the value calculated from Cheung model. This is due to high value of series resistance which is not considered in TE model. For the Al/n-Si Pristine as well as irradiated Schottky diodes, a high value of n is attributed to high value of R_S [19]. The presence of thin interfacial oxide film is usually modelled as R_S. Larger the thickness of interfacial oxide film, the greater will be the R_S [7]. Further a high value of R_S is ascribed to the dependence of potential barrier on the applied bias, organic impurities present in the laboratory conditions prior to contact preparation, non-ideal ohmic back pressure contacts [7,19–22]. All these factors have contributed to the low rectification.

In a Schottky diode at lower forward bias, a very small increase in voltage should give much increased amount of current. But in the present case, the increase in current was not much greater due to the interface and ohmic contact effects. It is well known that, Si gets thermally oxidized even at room temperature. Although, the oxide layer may be sputtered out as a result of EBI, but soon after EBI the oxides will again accumulate on the surface of Si. This forms an interface between crystalline Si and amorphous SiO_2 and gives rise to strained and dangling bonds. Within the forbidden bandgap at theSiO_2/Si interface, the dangling bonds act as interface traps. The interface traps can be either an acceptor or donor but its charge state changes when it crosses the Fermi level (E_F). It is positive above E_F and negative below E_F [23]. The positive ions in the oxide are usually accumulated on the surface of n-Si. This allows the characteristics of Al/n-Si contacts to show small increased forward current and soft reverse characteristics [24]. In other words, the value of $n > 1$ tells other transport mechanisms competing with thermionic emission of electrons. It is evident that, the I–V characteristics exhibited nearly power law relationship except at lower and higher voltages (Fig. 4) According to power law $I \propto V^m$, where $m \sim 2$ is usually attributed for space charge limited emission. This space charge limited emission current is strongly dependent on trap density in the material. For the significant trap densities or interface states, space charge limited currents may dominate for certain range of voltage. In particular the interface states are effective only at moderate voltages, where the defects are activated by recombination processes. Therefore thermionic emission and space charge limited emission currents are the competing transport mechanisms in all Schottky diodes [25–29].

From the XPS survey scan of pristine and irradiated n-Si wafers, a signal from O1 s core level electron is observed, which is attributed to the presence SiO_2 on Si surface. This is evident from Fig. 5. where the core spectra of Si2p and O1s (in the inset) are shown. The intensities and linewidths are independently used to characterize the regions. The broadening of core Si2p spectra shows the presence of SiO_2. However the extent to which the interface of Si and SiO_2 was modified depends on the dose of EBI. With the increase of dose, a considerable distortion in the asymmetric nature of Si2p spectra was noticed. The increase in width of the peak with EBI dose suggesting a greater number of irradiation induced defects and the formation of several localized chemical states in Si/SiO_x interface. The thickness of the SiO_x layer at the surface has been calculated from the intensities of XPS Si2p spectra by using the method described by Watts and Wolstenholme [30]. The calculated SiO_x thickness (d) was found to be 9.4 nm for the pristine and 9.2 nm at the irradiation dose of 1500 kGy.

Fig. 6. shows the inverse relationship between n and Φ_B. A decrease of d (0.20 nm) has led to decrease in n value from 6.11 to 2.59 due to EBI. The R_s and n decreases with increased EBI dose. But for Al/n-Si 1500 kGy, R_s is increased even though there is a decrease in d. This may be due to the increased number of defect states in the SiO_x/Si interface as seen from XPS (Fig. 5.). From the literature, for an n-type semiconductor with metal contact, a decrease of Φ_B with increase in d has been noticed. But in the present case an increase of Φ_B with decrease in d is observed. Thus electron beam irradiation has effectively induced modifications in Φ_B.

Since the thickness of interfacial oxide interface (d) is not more than 10 nm, tunneling mechanism can occur in the current transport process. In addition, the trap-assisted tunneling is also expected to take place. The interface states created by EBI is expected to act as available energy states in the otherwise forbidden band gap or as the recombination centers [31–33]. All these different transport mechanisms have contributed to the non-ideal characteristics in all the Schottky diodes. The non-saturation behavior observed in the reverse bias is caused due to image force lowering of Φ_B and the interfacial layer between metal and semiconductor. The image force lowering is high when the electric field is high. However, no significant changes were observed in reverse bias. This may be due to the decreased value of d with increase in Φ_B. However, the diode Al/n-Si 500 kGy has shown a very small increased leakage current due to enhanced tunneling effects.

The high value of n may be attributed inhomogeneous nature of Φ_B. This Φ_B inhomogeneity or the presence of pinch-off around mean Φ_B may be caused due to the grain boundaries [6] of deposited Al metal contact. The inhomogeneity in Φ_B is controlled by electron tunneling from one material into another, forming an extrinsic interfacial electric-dipole layer [5,34,35]. The improved value of n clearly suggests that EBI has effectively reduced Φ_B inhomogeneity.

From the above inferences, it can be established that the formation of Φ_B and transport mechanisms in the Schottky diodes are dependent on the various parameters such as interfacial layer at the MS interface, density of interface states or defects. The MS interface behavior can be effectively modified by EBI induced defect states on the surface as well as in bulk. This results in deviations of I–V characteristics depending on delivered radiation dose. Thus it is possible to tune Φ_B by means of electron beam irradiation.

4. Conclusions

The Schottky diodes were fabricated on electron beam irradiated n-Si wafer. The non-ideality is caused due to electron irradiation induced defect states along with the formation of several localized chemical states in Si/SiO_x interface. These defects act as available energy states in the energy bandgap. All the Al/n-Si Schottky diodes exhibited metal-insulator-semiconductor (MIS) configuration. The different transport mechanisms have also contributed to the non-ideal behavior of Schottky diodes. The optimized radiation dose is found to be 1000 kGy, since at this dose the device is exhibiting better performance in terms of diode parameters. With the present study it is possible to tune Schottky barrier height of Al/n-Si by electron beam irradiation.

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