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Electrical properties of Sn/p-Si (MS) Schottky barrier diodes to be exposed to ^{60}Co γ-ray source

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Abstract

In this research, we have investigated the electrical properties of metal-semiconductor (Sn/p-Si) Schottky barrier diodes (SBDs) under ^{60}Co gamma (γ)-rays. These devices is stressed with a zero-bias during ^{60}Co γ -ray source irradiation with the dose rate 2.12 kGy/h and total dose range was 0–500 kGy at room temperature. Electrical measurements of Sn/p-Si SBDs have been performed using current–voltage (*I–V*) and capacitance-voltage (*C–V*) techniques. Experimental results show that gamma-irradiation induces an increase in the barrier height $\Phi_b(C\text{–}V)$ obtained from reverse-bias *C–V* measurements with increasing dose rate. However, the barrier height $\Phi_b(I\text{–}V)$ obtained from forward-bias *I–V* measurements remained almost constant. This negligible change of $\Phi_b(I\text{–}V)$ is attributed to the low barrier height in regions associated with the surface termination of dislocations. On the other hand, the values of the ideality factor obtained from *I–V* measurements increased with increasing dose rate. The results show that the main effect of the radiation is the generation of laterally inhomogeneous defects near the semiconductor surface.

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1. Introduction

The metal–semiconductor (MS) contact based devices are very sensitive to the electrical properties of MS interface [1] and any mechanism that affects the interface also influences the performance of these devices. The electrical studies of MS diode or Schottky diodes on Si have been of considerable interest due to their widespread application in microwave FET's, RF detectors and solar cells. These Schottky diodes also play a crucial role for high-speed logic circuits, integrated and opto-electronic technologies. Silicon was the first material used for solar cells in space and it has remained the most popular choice ever since due to its history of reliable performance. The investigations in this work [2] are of utmost importance for their applications in space and radiation environments. Swift heavy ion irradiation is one of the mechanisms able to modify the MS interface. The electrical characteristics of the Schottky diode are extremely sensitive to interface state density at the MS interface.

In the past few years, the radiation response of MS structures has been found to change significantly when these structures are exposed to preirradiation treatments at elevated doses. Radiation doses greater than a kilogray (1 Gray = 100 Rad.) exposure may cause strong electrical changes in the MS structures. Radiation testing in Si space cells has been carried out in order to clarify the mechanism on such severe radiation degradation in space [3–6]. The radiation usually of interest in the study of degradation of materials and devices consists of energetic or fast massive particles (i.e., electrons, protons, neutrons or ions). There has always been considerable interest in studying irradiation damage. This is due to its interesting physics as well as the technological importance. High-energy particle bombardment, such as proton, neutron, electron and pion

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irradiation, as well as γ-ray irradiation, is often used [7–10]. The radiation-induced defects studied here often have energy states in the band gap and therefore, it is of interest to investigate the damage defect centres introduced by radiation and to study their effect on the performance of these types of semiconductor devices.

The electrical characteristics of MS structures in the Schottky barrier diodes (SBDs) have been studied more than that in the metal–insulator-semiconductor (MIS) type Schottky diodes due to the existence of native insulator layer between metal and semiconductor that passivates the surface of semiconductor. Further, improvements in radiation resistance of MS, MIS and solar cells are necessary for widespread applications. Some researchers have studied in the area of effect of radiation on MS or MIS Schottky diodes [11–13], metal-oxide-semiconductor (MOS) devices/capacitors [14–17], solar cells [18–19] and radiation effects in nitric oxide (NO) passivated SiO_2/SiC gate oxides [20]. Winokur et al. [21,22], Zainninger et al. [23] and Ma [24,25] were among the first, to make a systematic observation of their irradiation behaviour of radiation induced interface traps in MIS and MOS devices. Sing et al. [26] have studied irradiation effects on the electrical characteristics of Au/n-Si SBD.

In our previous study [10], we studied the effects of ^{60}Co γ-ray irradiation on the electrical characteristics of Au/n-GaAs SBD exposed to maximum cumulative dose of 500 kGy. In this work, we present results of a study on the effect of ^{60}Co γ-ray irradiation on the electrical characteristics of a Sn/p-Si SBD exposed to a maximum cumulative dose of 500 kGy. Diode characteristics, before and after irradiation, were investigated using capacitance–voltage (*C–V*) and current–voltage (*I–V*) measurements. The most widely used methods to measure the Schottky barrier height (SBH) were the *I–V* and *C–V* techniques [27]. Prior to irradiation, the SBH extracted from *C–V* is found to be consistent with that obtained from forward bias *I–V*, however the barrier height extracted from *C–V* measurements manifests a large increase after exposure to 10 kGy whereas the barrier height extracted from the forward bias *I–V* characteristics remained essentially constant. Furthermore, it is shown that at higher irradiation dose (500 kGry), *I* vs. *V* and *C* vs. *V* plots, are almost reach to satisfaction.

2. Experimental techniques

The metal semiconductor Schottky diodes used in this study were fabricated by evaporating Sn on oxidised bulk (1 0 0) p-type Si wafers with a carrier concentration of $10^{14}\,cm^{-3}$. The carrier concentration values were obtained from *C–V* measurements in the different dose ranges. The wafer was chemically cleaned using the RCA cleaning procedure. The RCA cleaning procedure was as follows: a 10 min boil in $NH_3 + H_2O_2 + 6H_2O$ followed by a 10 min boil in $HCl + H_2O_2 + 6H_2O$. The RCA cleaning with HF dip shows a predominant coverage of the surface with hydride groups. The native oxide on the front surface of the substrate was removed in HF:H_2O (1:10) solution for 30 s and finally the wafer was rinsed in de-ionised water for 30 s. Then, low-resistivity Ohmic back contact to p-type Si(1 0 0) wafers was made by using Al, followed by a temperature treatment at 570 °C for 3 min in N_2 atmosphere. The Schottky contacts were formed by evaporation of Sn dots with diameter of about 1.5 mm (diode area $= 1.76 \times 10^{-2}\,cm^2$). All evaporation processes were carried out in a turbo molecular fitted vacuum-coating unit at about 10^{-7} Torr.

The *I–V* measurements were carried out by the use of a Keithly 220 programmable constant current source and a Keithly 614 electrometer. The *C–V* measurements were performed by using HP 4192A LF impedance analyser (5 Hz–13 MHz) and the test signal of 40 m V_{rms}. All measurements *I–V* and *C–V* were performed in the dark before and after ^{60}Co γ-ray source irradiation with the dose rate 2.12 kGy/h and total dose range was 0–500 kGy at room temperature, and measurements were carried out with the help of a microcomputer through an IEEE-488 AC/DC converter card.

3. Results and discussion

One of the most widely used methods to measure the SBH was the *I–V* technique [27]. Fig. 1 shows the *I–V* characteristics of the Sn/p-Si SBDs under both forward and reverse bias, before and after γ-ray irradiation from a ^{60}Co source. The *I–V* measurements showed that resistively deposited Sn SBDs exhibited excellent rectification proper-

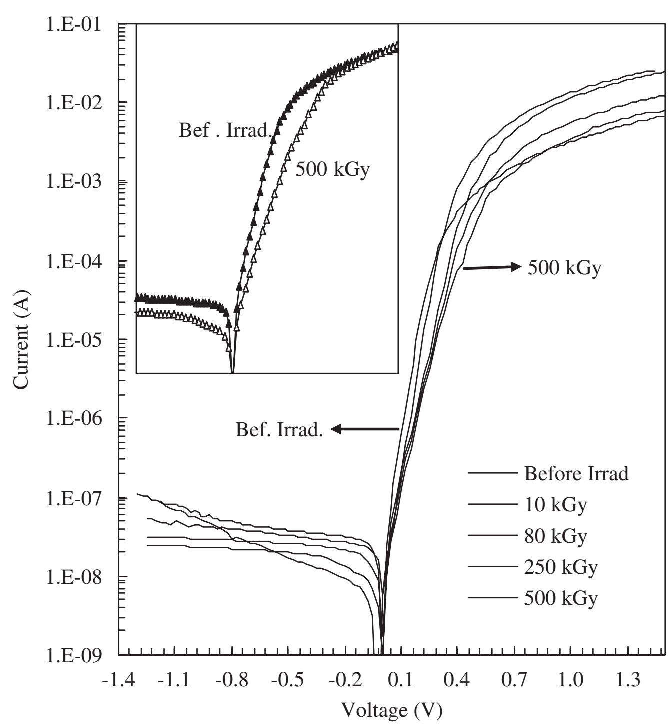

Fig. 1. Forward *I–V* characteristics of Sn/p-Si diode before and after irradiation.

ties. The measured I–V characteristics were analysed using the conventional Schottky barrier thermionic emission theory model [28–30]

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

where I_0 is the saturation current derived from the straight line intercept of $\ln I$ axis at zero bias, and ideality factor n is introduced to take into account the deviation of the experimental I–V data from the ideal thermionic model, and the value of ideality factor should be one for an ideal contact. The saturation current I_0 is given by

$$I_0 = AA^* T^2 \exp\left(-\frac{q\Phi_{b0}}{kT}\right). \tag{2}$$

From Eqs. (1) and (2), the ideality factor n and barrier height $\Phi_b(I$–$V)$ can be written respectively as

$$n = \frac{q}{kT}\frac{\mathrm{d}V}{\mathrm{d}\ln(I)} \tag{3}$$

and

$$\Phi_{b0} = \frac{kT}{q}\ln\left(\frac{AA^* T^2}{I_0}\right) \tag{4}$$

where A^*, A and Φ_{b0} represent the Richardson constant ($32\,\mathrm{A\,cm^{-2}\,K^{-2}}$ for p-type Si), the contact area and the SBH respectively. The other symbols have their usual meaning. From the slope of $\ln I$ vs. V curve in Eq (3), the value of ideality factors are calculated. I_0 is determined from the intercept of $\log I$ vs. V curve on the y-axis. Putting these values of I_0 in Eq. (4), the values of SBHs were calculated.

The I–V characteristics before irradiation as well as after irradiation Schottky diodes at various doses ranging from 10 to 500 kGy are shown in Fig. 1. Using Eq. (3) the values of ideality factor of the diode at different irradiation doses was calculated and is plotted as dependence total doses in Fig. 2. As a function of irradiation dose, the ideality factor values are greater than one and this indicates that there is a contribution of the recombination current, although thermionic process is the main transport mechanism. These values are given in Table 1. As can be seen in Fig. 2 and Table 1, the ideality factor n exhibits an increasing trend with increasing dose. Before irradiation the ideality factor n was found to be 1.11. After irradiation, the ideality factor changes from 1.29 (at 10 kGy) to 1.71 (at 500 kGy). The increase of ideality factor is indicating an increase of defect density at the interface with increasing γ-irradiation dose and/or the increase of the ideality factor is due to the lateral inhomogeneity of barrier height.

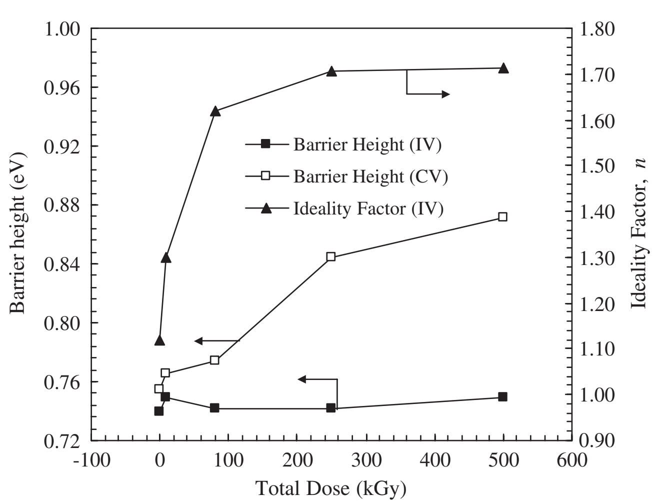

Fig. 2. Ideality factor (full triangles) and barrier heights extracted from the I–V (full squares) and C–V (open squares) measurements of Sn/p-Si Schottky barrier diodes as a function of the dose of γ-irradiation.

The barrier height $\Phi_b(I$–$V)$ obtained from I–V measurements depends on the electric field across the MS contact and consequently on the applied voltage. Using Eq. (4) the values of barrier height Φ_{b0} of the diode at different irradiation doses was calculated and this is plotted as a function of total doses in Fig. 2. In this case the SBH for unirradiated diode is 0.739 eV. However, after irradiation, the experimental values of barrier height change from 0.749 (at 10 kGy) to 0.750 (at 500 kGy).

Another often used and convenient technique to measure the SBH was the C–V technique. From C–V measurements, it was observed that the capacitance increases for irradiated diodes and has dependence on the applied bias. This may be due to the change in dielectric constant at the interface [31]. Fig. 3 shows the C^{-2}–V curve of Sn/p-type Si schottky diodes before and after γ-irradiation. The barrier height $\Phi_b(C$–$V)$ is determined from the intercept on the voltage axis of the $1/C^2$ vs. V characteristics at 300 K through the relation

$$\frac{\mathrm{d}(C^{-2})}{\mathrm{d}V} = \frac{2}{q\varepsilon_s\varepsilon_0 A^2 N_A} \tag{5}$$

$$\Phi_b(C - V) = V_D + \left(\frac{kT}{q}\right)\ln\left(\frac{N_V}{N_A}\right) - \Delta\phi \tag{6}$$

where A is the diode area, V is the applied reverse bias, V_D ($= V_0 + kT/q$) is diffusion potential, V_0 is the intercept of C^{-2} vs. V plot with the voltage axis, q is the electronic charge, ε_s is the dielectric constant of the semiconductor ($11.8\varepsilon_0$ for p-type Si), ε_0 is the dielectric constant of vacuum (8.85×10^{-14} F/cm), N_A is acceptor doping density, which is evaluated by plotting C^{-2} vs. V, N_V is the effective density of states in the valance band and $\Delta\phi$ is the image force barrier lowering. Before irradiation, the C–V measurements revealed SBH of $\Phi_{CV} = 0.754$ eV and an acceptor doping density of $9.41 \times 10^{14}\,\mathrm{cm^{-3}}$. The carrier concentration values obtained from C–V measurements in the different dose range are given in Table 1. The decrease in acceptor doping density due to MS interfaces with increase in radiation dose is due to generation and recombination through the interface states between the oxide and semiconductor insulator interface. Furthermore, the forward bias injects holes that recombine with the electrons already present in the depletion region. The density of mobile carriers is reduced as a result and the

Table 1
Electrical parameters of Sn/p-type Si Schottky barrier diodes obtained before and after irradiation at different dose range

Irradiation (kGy)	n	Φ_{IV} (eV)	Φ_{CV} (eV)	R_S ($dV/d\ln I$) (Ω)	R_S $H(I)$ (Ω)	N_A (cm^{-3})
Pre-irrad.	1.118	0.740	0.754	144.08	146.44	9.41×10^{14}
10	1.299	0.749	0.766	36.28	41.96	8.84×10^{14}
80	1.620	0.742	0.774	36.13	40.44	9.26×10^{14}
250	1.706	0.741	0.844	77.39	75.42	6.48×10^{14}
500	1.712	0.750	0.872	123.25	106.28	4.99×10^{14}

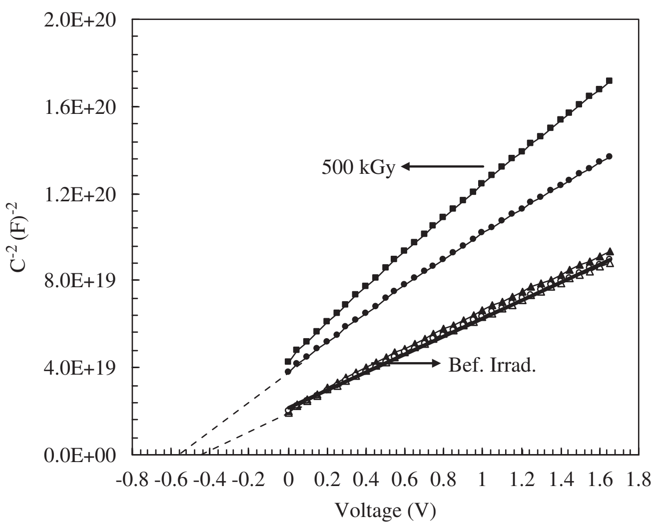

Fig. 3. C^{-2}–V diode characteristics before and after irradiation. Extracted SBH (Φ_{CV}) as a function of cumulative γ-ray doses.

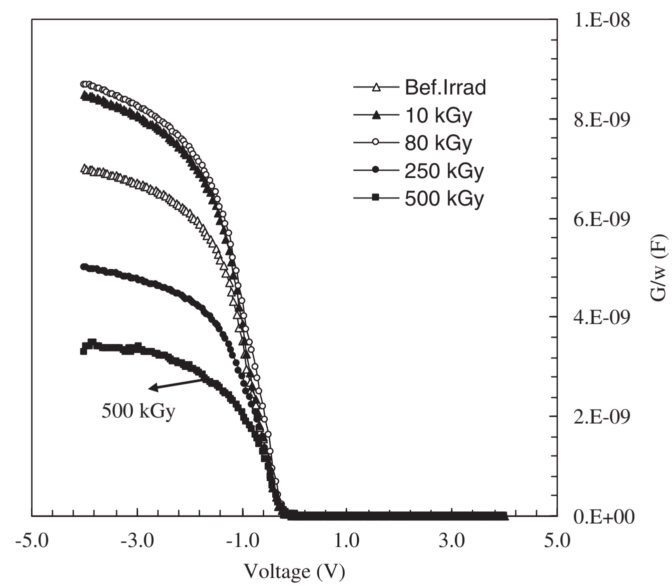

Fig. 4. The conductance (G/w) voltage dependences before and after irradiation.

space charge is enhanced further. Before and after irradiation, the $\Phi_b(C–V)$ values obtained after γ-ray exposure on the C^{-2}–V is shown in Fig. 3, where it is clear that the intercept of the C^{-2} vs. V characteristics changes with increasing total dose toward more positive voltages while the $\Phi_b(I–V)$ remains constant. The increase in barrier height, $\Phi_b(C–V)$, obtained from the experimental C–V characteristics is due to an increase in V_0 in Fig. 3. This discrepancy can be explained by the different nature of the I–V and C–V measurement methods and/or the difference between the barrier height calculated from the I–V and C–V measurements is mainly due to the presence of a thin compensated layer at the interface [32]. The variations of ideality factor and barrier height with irradiation fluencies are shown in Fig. 2 and Table 1. As can be seen in Fig. 2 and Table 1, these results indicate that in the γ-irradiated diodes, while the barrier height Φ_{IV} remains almost constant, the barrier height Φ_{CV} increases slightly with an increase in radiation dose.

The conductance–voltage ($G_m/w-V$) measurements at high frequency (500 kHz) were performed at different irradiation doses. Fig. 4 shows the measured $G_m/w-V$ characteristics of Sn/p-type Si SBD at various dose ranges. This technique is based on the conductance losses resulting from the exchange of majority carriers between the interface states and majority carrier band of the semiconductor when a small ac signal is applied to the semiconductor devices [10,33]. The $G_m/w-V$ characteristics for high frequency (for 500 kHz) applied voltage were found to have change with dose rate from range to range. Also, the G_m/w decreases with increasing dose rate. This behaviour is attributed to the production of the lattice defects in the form of vacancies, defect clusters, and dislocation loops near the MS interface due to the increase of the irradiation.

The real series resistance of metal-semiconductor devices can be subtracted from the measured capacitance (C_{ma}) and conductance (G_{ma}) in strong accumulation region at high frequency [34]. The series resistance is an important parameter to designate noise ratio of device as dependant on irradiation dose. Therefore, both the real values and voltage dependence of the series resistance R_S were calculated from Eq. (7) according to reference [33]

$$R_S = \frac{G_{ma}}{G_{ma}^2 + (\omega C_{ma})^2} \tag{7}$$

where G_{ma} and C_{ma} are values of the conductance and capacitance obtained in strong accumulation region. As can be seen in Fig. 5, in depletion and inversion regions the value of the series resistance increased with increasing

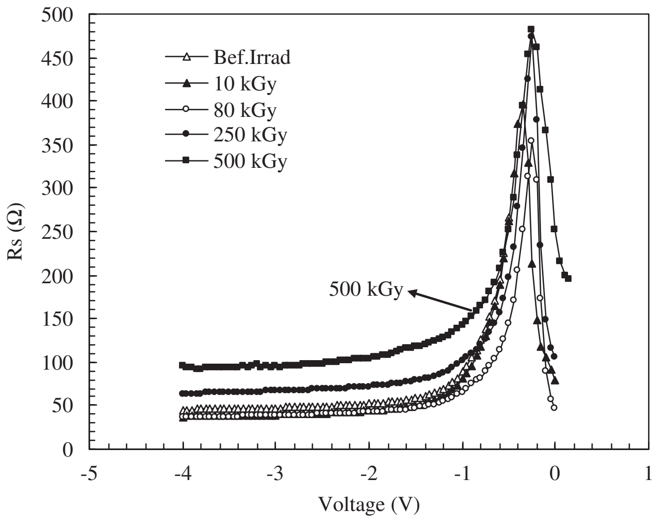

Fig. 5. The series resistance (R_S) vs. gate bias under different doses at 500 kHz. The value of series resistance at low reverse voltages remains constant due to the *I–V* curves exhibits ohmic behaviours.

radiation dose. The values of R_s become maximum at about between $-1\,V < V < 0.25\,V$. These peaks shifted to accumulation region with increasing irradiation dose. This behaviour of the series resistance has been attributed to particular distribution of interface state [35]. Furthermore, bulk series resistance values were also determined from the functions developed by Cheung and Cheung [36]

$$\frac{dV}{d(\ln I)} = IR_s + n\left(\frac{kT}{q}\right) \tag{8}$$

which should a straight line for the data of downward curvature region of the forward bias *I–V* measurements.

$$H(I) = V - n\left(\frac{kT}{q}\right)\ln\left(\frac{I}{AA^*T^2}\right) = IR_s + n\Phi_b \tag{9}$$

where Φ_b is the barrier height obtained from intercept of *H(I)* vs. *I* plots. The term IR_s is the voltage drop across series resistance of diode. Thus, the slopes and *y*-axis intercepts of the $dV/d(\ln I)$ vs. *I* plot will give R_S and nkT/q, respectively. The plots associated with these functions are given in Fig. 6(a). The series resistance values were determined from Eq. (8). A plot of *H(I)* vs. *I* according to Eq. (9) will also give a straight line with the *y*-axis intercept equal to $n\Phi_b$. The plots associated with these functions are given in Fig. 6(b). Here, the series resistance values were determined from Eq. (9). Furthermore, the values of series resistance obtained for each irradiation dose using Eqs. (8) and (9) are given in Table 1. As can be seen in Table 1, the changes in the values of R_S obtained from $dV/d(\ln I)-I$ and $H(I)-I$ plots are in agreement with each other. The effect of the series resistance R_S is usually modelled with a series combination of a diode and a resistor with resistance R_S, through which the current flows.

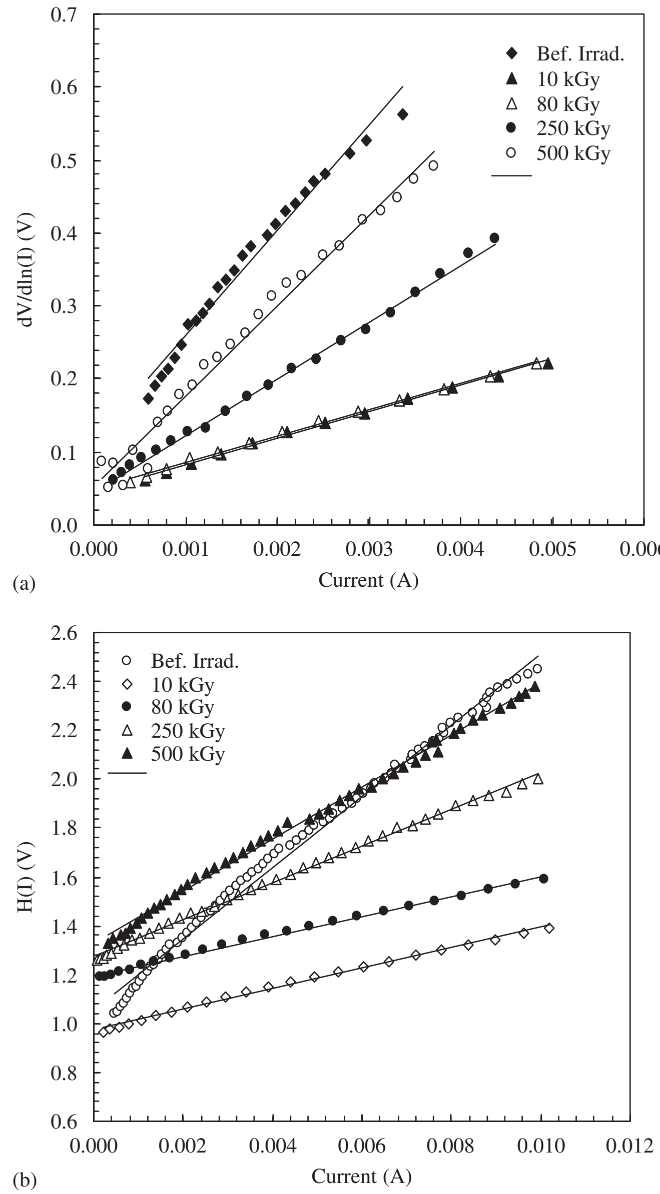

Fig. 6. (a) Plots of $dV/d\ln I$ vs. *I* and (b) *H(I)* vs. *I* for Sn/p-Si Schottky diode at different irradiation dose.

4. Conclusion

The effect of γ-irradiation on the electrical characteristics of Sn/p-Si SBDs has been studied using experimental dates obtained from *I–V* and *C–V* measurements. The *n* values are higher than 1 obtained from *I–V* characteristics attributed to the presence of a thin insulating layer between the metal and semiconductor. After the γ-irradiation, an increase in the ideality factors have been observed all doses, and this increase is attributed to the irradiation-induced defects at MS interface. The increase of the ideality factor may be also due to an increasing interface state density at the Sn/p-Si interface. Barrier heights obtained from *I–V* and *C–V* measurements are not always the same. While the barrier height $\Phi_b(C–V)$ increased, the barrier height

$\Phi_b(I–V)$ remained almost constant. The difference between the apparent barrier heights calculated from the $I–V$ and $C–V$ measurements is mainly due to the presence of a thin compensated layer at the interface. These results indicate that the bombardment reduced the effective doping level inhomogeneously in the Si substrate in layer near the surface.

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