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^{60}Co γ irradiation effects on the current–voltage (*I–V*) characteristics of Al/SiO$_2$/p-Si (MIS) Schottky diodes

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Abstract

It is well known that the exposure of any semiconductor surfaces to the ^{60}Co γ-ray irradiation causes electrically active defects. To investigate the effect of γ-ray irradiation dose on the electrical characteristics of metal–insulator–semiconductor (MIS) Schottky diodes, the fabricated devices were exposed to γ radiation at a dose of 2.12 kGy/h. The total dose range was from 0 to 450 kGy at room temperature. The density of interface states N_{ss} as a function of $E_{ss}-E_v$, the values of series resistance R_s and the bias dependence of the effective barrier height Φ_e for each dose were obtained from the forward bias *I–V* characteristics. Experimental results show that the γ-irradiation gives rise to an increase in the zero bias barrier height Φ_{BO}, as the ideality factor n, R_s and N_{ss} decreases with increasing radiation dose.

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Keywords: γ-ray effects; MIS Schottky diodes; *I–V* characteristics; Interface states; Series resistance

1. Introduction

Metal–insulator–semiconductor (MIS)-type Schottky diodes and metal–oxide–semiconductor (MOS) capacitors are extremely sensitive to high-level radiation such as ^{60}Co γ-ray, high-level electrons, neutrons or ions. The exposure of these devices to high-level particles results in a considerable amount of lattice defects. These defects act as recombination centers the generated carriers. Therefore, it is interesting to investigate the effects of the defect centers on the performance of these devices. Further, the development of radiation resistance MIS and MOS structures is necessary for widespread applications. Recently, several groups have investigated the effect of γ-ray irradiation dose on the electrical characteristics of MIS and MOS structures [1–15]. Goetzberger [15] argued that the charge trapped within 30 Å at the interface could produce fluctuations in surface potential capable of trapping electrons and holes.

Winokur et al. [11–13], Zainninger et al. [5] and Ma [8–10] were among the pioneers who made systematic observations on the irradiation behavior of radiation-induced interface traps in MIS and MOS devices. Especially there are two important effects of radiation to be considered: (a) the transient effects due to the electron–hole pair generation and (b) permanent effect due to the bombardment of devices with radiation, causing changes in the crystal lattice. The radiation-generated holes may diffuse in the insulator, but are less mobile than the electrons; many stationary holes traps are also present.

In this work, we report on results of ^{60}Co γ-ray irradiation on the electrical characteristics of the Al/SiO$_2$/p-Si Schottky diodes, exposed to maximum cumulative dose of 450 kGy at room temperature. After each dose, we present the changes in electrical characteristics evaluated using forward and reverse bias *I–V* measurements. Before and after each dose, the density of N_{ss} profiles as a function of E_{ss}–E_v was extracted from the forward bias *I–V* characteristics. In addition, experimental results for the diodes are compared with results published for these type semiconductor devices.

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2. Experimental detail

The Al/SiO_2/p-Si (MIS) Schottky diodes used in this study were fabricated using boron-doped single crystals silicon wafer with $\langle 100 \rangle$ surface orientation having 280 μm thickness, 2″ diameter and 8 Ω cm resistivity. For the fabrication process, Si wafer was degreased in organic solvent of $CHClCCl_2$, CH_3COCH_3 and CH_3OH consecutively and then etched in a sequence of H_2SO_4 an H_2O_2, 20% HF, a solution of $6HNO_3$: 1 HF: 35 H_2O, 20% HF and finally quenched in de-ionized water for a prolonged time. Preceeding each cleaning step, the wafer was rinsed thoroughly in de-ionized water of 18 MΩ cm resistivity.

Immediately after surface cleaning, high-purity Al metal (99.999%) with a thickness of ~2000 Å was thermally evaporated from the tungsten filament onto the whole back surface of the wafer at the pressure of $\sim 2\times10^{-6}$ Torr in oil vacuum pump system. The ohmic contact was formed by sintering the evaporated Al back contact at 700 °C for 60 min in a resistance-heated furnace in dry oxygen with a flow rate of 2 lt/min. This process served both sintering the Al and forming the required thin interfacial insulator layer (SiO_2) on the upper surface of the Si wafer. After oxidation, circular dots of ~1 mm diameter and ~2000 Å thick Al were deposited onto the oxidized surface of the wafer through a metal shadow mask in a liquid-nitrogen-trapped vacuum system at a pressure of $\sim 2\times10^{-6}$ Torr. The thickness of the metal layer and the deposition rates were monitored with the help of quartz crystal thickness monitor. The interfacial insulator layer thickness was estimated to be about 34 Å from high-frequency (1 MHz) measurement of the interface insulator capacitance in the strong accumulation region of the MIS Schottky diode [14].

The current–voltage (*I–V*) measurements were carried out using a Keithly 220 programmable constant-current source and a Keithly 614 electrometer. The measurements were performed before and after ^{60}Co γ-ray source irradiation with the dose of 2.12 kGy/h and total dose range was 0–450 kGy at room temperature. All measurements were carried out with the help of a microcomputer through an IEEE-488 AC/DC converter card.

3. Results and discussion

According to the thermionic emission (TE) theory for a metal–insulator–semiconductor (MIS) Schottky diode, the relation between an applied forward bias and current can be written as [16]

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

where V is the applied voltage across to rectifier contact, n is the ideality factor, R_s is the series resistance including bulk and contact resistance, T is the absolute temperature in K, q is the electronic charge, k is the Boltzmann constant and I_0 is the reverse saturation current and can be written as

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

where A is the diode area, A^* is the effective Richardson constant of 32 $Acm^{-2}K^{-2}$ for p-type Si and Φ_{BO} is the zero-bias barrier height. The ideality factor is a measure of the conformity of the diode current to be pure thermionic emission, and it is calculated from the slope of the linear region of the forward bias ln(*I*)–*V* plot according to Eq. (1)

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

where $d(V–IR_s)/d\ln I$ is the slope of linear region of ln(*I*)–*V* plots. Also the voltage-dependent ideality factor $n(V)$ can be written from Eq. (1) as

$$n(V) = \frac{q}{kT}\frac{(V-IR_s)}{\ln(I/I_0)} \tag{3b}$$

Fig. 1 shows a typical forward and reverse bias semi-logarithmic current–voltage (*I–V*) characteristics of the MIS Schottky diode before and after γ-ray irradiation at room temperature. As can be seen in Fig. 1, each plot consists of a good linear range with different slopes in intermediate-bias regions. The value of the reverse current was observed to decrease with the increase in the radiation dose up to a level of 450 kGy, whereas, the effect of the irradiation on the forward bias current was almost

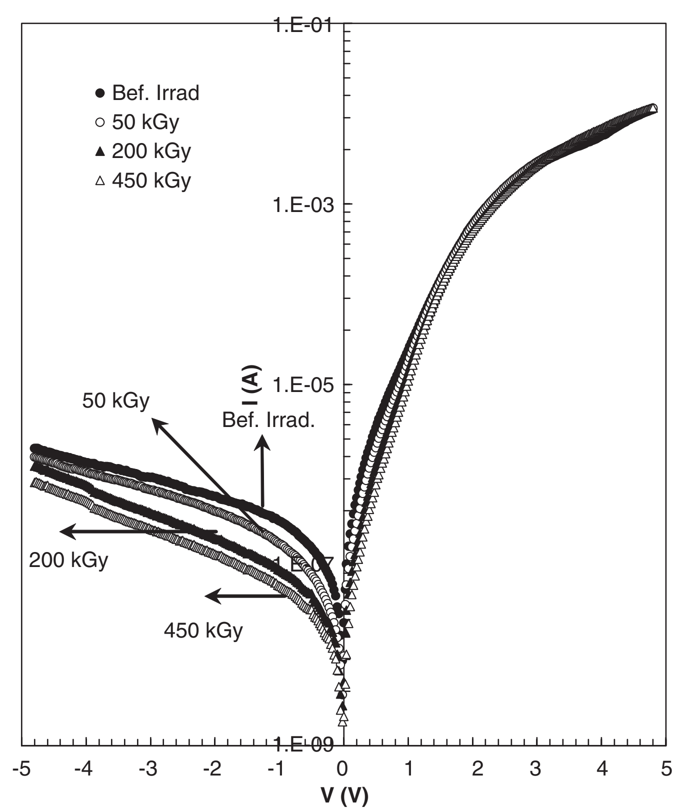


Fig. 1. Forward and reverse bias *I–V* characteristics of Al/SiO_2/p-Si (MIS) Schottky diode before and after γ-ray irradiation.

negligible. This radiation-induced enhancement observed in the reverse bias I–V characteristics could be attributed to the decrease in interfacial defect density, contrasting to the work [3].

Fig. 2 shows the dependence of the normalized current $(I–I_0)/I_0$ on increase in radiation dose up to 450 kGy under the applied voltages of −1, −2 and −3 V. The values of the normalized current were observed to increase with increasing radiation dose. These curves may roughly be considered to have three regions. As can be seen from Fig. 2, there is a slow increase in the values of currents monitored with the increase in radiation dose of around 50 kGy. In the second region, between 50 and 200 kGy, the values of currents change a little or remain constant. In the third region, after a dose of 300 kGy, a very fast increase in the value of current was observed. Similar curves were observed for different devices [17,18].

The values of ideality factor n were found to have effected with irradiation and changed from 2.010 at 0 kGy to 1.554 at 450 kGy. The zero-bias barrier height ($\Phi_{BO} = \Phi_B$) was obtained from intercepts of the forward-bias $\ln I$ vs. V plot for each irradiation dose. The values of dose-dependent Φ_{BO} and n are given in Table 1. Evaluation of the forward bias I–V data reveals an increase in zero-bias barrier height Φ_{BO} but a decrease of ideality factor n

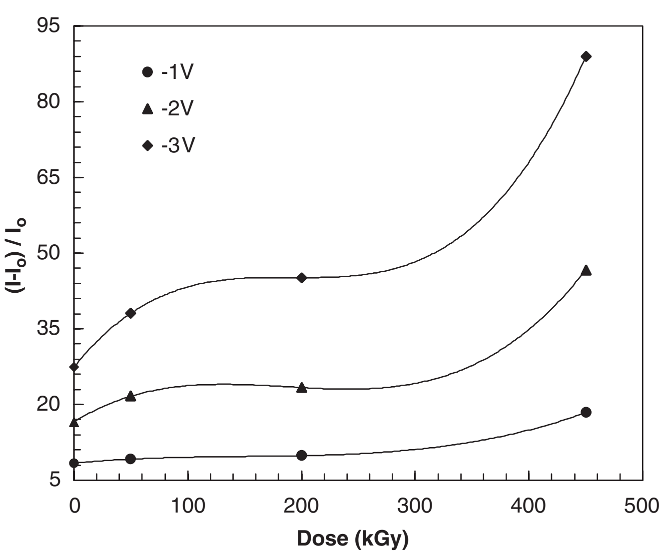


Fig. 2. Dependence of normalized current $(I–I_0)/I_0$ on radiation dose under an applied voltages of −1, −2 and −3 V, respectively, for the MIS Schottky diode.

with increasing irradiation dose. These behaviors of the ideality factor suggest that the current transport mechanism consists of both the trap-assisted tunneling and the thermionic emission [16]. Similar results have been commonly observed in I–V measurements of MIS Schottky diode and they are attributed to the presence of a thin insulating layer between the metal and semiconductor. The image–force effect, recombination-generation, and tunneling may be other possible mechanisms that could lead to an ideality factor value greater than unity [15,19–23].

Fig. 3 shows the variations in both ideality factor and barrier height as a function of radiation dose. As can be seen in Fig. 3, the values of n were found to decrease while the values of Φ_B increase exponentially with increasing radiation dose. The results account for a net reduction in carrier density in the depletion region of MIS Schottky diode through the occurrence of traps and recombination centers associated with radiation damage [20,21].

The interface states for electrons or holes must not necessarily introduce energy levels in the band gap; i.e., only the density of states in the valence and conduction bands may be affected. The non-linearity of I–V characteristics of the Schottky diode at high bias values indicates a continuum of interface states, which in equilibrium with the semiconductor [24]. Nevertheless, the Schottky diodes exhibit excellent rectification characteristics with a relatively low leakage current density. The effective barrier height Φ_e is assumed to be bias-dependent due to the presence of an interfacial insulator layer and interface states located at the SiO_2/Si interface. The applied voltage dependence of the barrier height can be written as

$$\frac{d\Phi_e}{dV} = \beta = 1 - \frac{1}{n(V)} \tag{4}$$

where β is the voltage coefficient of the effective barrier height Φ_e and is given by [23–26]

$$\Phi_e = \Phi_{BO} + \beta(V - IR_s) = \Phi_{BO} + \left(1 - \frac{1}{n(V)}\right)(V - IR_s) \tag{5}$$

The Φ_e is a parameter that includes the effects of both interface states in equilibrium with the semiconductor [24]. For MIS Schottky diodes having interface states N_{ss} in equilibrium with semiconductor, the ideality factor n is given by

$$n(V) = 1 + \frac{\delta}{\varepsilon_i}\left[\frac{\varepsilon_s}{W_D} + qN_{ss}\right] \tag{6a}$$

Table 1
Radiation dependency of various parameters determined from I–V characteristics of Al/SiO_2/p-Si (MIS) Schottky diode

Irradiation (kGy)	I_0 (A)	n	$\cdot_B$ (eV)	$R_s(dV/d(\ln I))$ (Ω)	$R_s(H(I))$ (Ω)	W_D (cm)	N_{ss} (eV^{-1}/cm^2)
Bef. irrad.	3.28×10^{-8}	2.010	0.694	166.40	159.39	2.73×10^{-4}	6.22×10^{12}
50	1.75×10^{-8}	1.940	0.710	156.14	150.61	2.61×10^{-4}	5.79×10^{12}
200	8.17×10^{-9}	1.655	0.730	147.12	142.82	2.44×10^{-4}	4.02×10^{12}
450	2.79×10^{-9}	1.554	0.758	138.82	135.54	2.20×10^{-4}	3.40×10^{12}

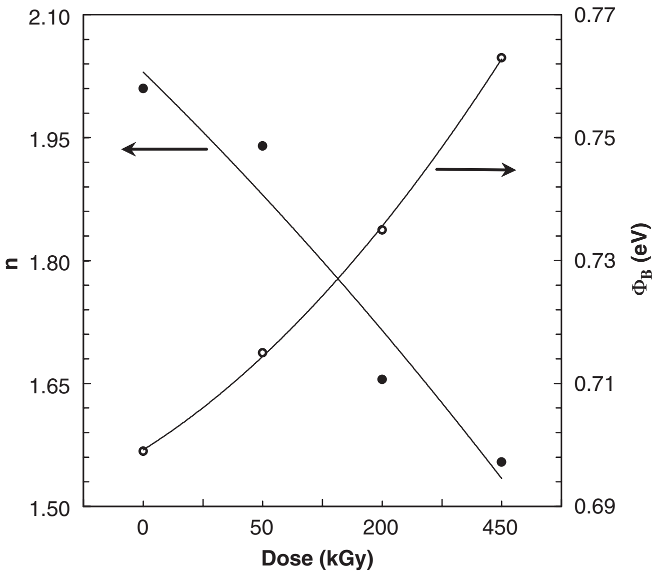


Fig. 3. Variation of ideality factor and barrier height as a function of γ-ray dose for the MIS Schottky diode.

where ε_i and ε_s are the permittivity of the insulator layer(SiO_2) and the semiconductor, respectively, and W_D is width of the depletion region. This expression of voltage-dependent ideality factor is identical to Eq. (18) of Card and Rhoderick [24]. The expression for the interface state density as deduced by Card and Schroder [24,27] is reduced to [16,28]

$$N_{ss}(V) = \frac{1}{q}\left[\frac{\varepsilon_i}{\delta}(n(V)-1) - \frac{\varepsilon_s}{W_D}\right] \tag{6b}$$

where δ is the thickness of the interfacial insulator layer. The other parameters are defined as before. The thickness δ can be obtained for the MIS Schottky diode from sufficiently high-frequency ($f \geqslant 500$ kHz) C–V measurements using the equation $C_i = \varepsilon_i \varepsilon_0 A/\delta$, where C_i is the capacitance of the interfacial insulator layer (SiO_2) [29,30] and ε_0 is the permittivity of free space. The depletion layer width being deduced from the experimental C–V measurements at high frequency is given by [29]

$$W_D = \sqrt{\frac{2\varepsilon_s}{qN_A}\psi_s} \tag{7}$$

where ψ_s is the surface potential and N_A is the carrier concentration. Furthermore, in p-type semiconductors, the energy of interface states E_{ss} with respect to the top of the valance band, E_v, at the surface of semiconductor is given as [24,25,31]

$$E_{ss} - E_v = q(\Phi_e - V) \tag{8}$$

For each radiation dose, the density of N_{ss} distribution profiles as a function of E_{ss}–E_v were obtained from the forward bias I–V characteristics taking into account Φ_e with and without R_s by substituting the values of voltage-dependent $n(V)$, $\varepsilon_s = 11.8\varepsilon_0$, $\varepsilon_i = 3.8\varepsilon_0$ and $\delta = 34$ Å in Eq. (6b).

Fig. 4 shows the density of interface states (N_{ss}) distribution profiles as a function E_{ss}–E_v for each dose at room temperature. The exponential increase of the interface states density from mid-gap towards the bottom of the conductance band is very apparent [9,13,14,32,33]. As seen in Fig. 4, the magnitude of the N_{ss} with and without the R_s at $0.38E_v$ (eV) is in the range from 7.16×10^{13} to 4.09×10^{13} eV^{-1} cm^{-2} (Bef. Irrad.), and at the same E_v value it is in the range from 5.48×10^{13} to 3.36×10^{13} eV^{-1} cm^{-2} (450 kGy). The values of N_{ss} obtained by taking the R_s into account are lover than those of without the R_s. The above explanations clearly show that the R_s value should be taken into account in determining the interface state density distribution profiles.

In addition, the values of series resistance R_s were carried out using another method developed by Cheung [34]. The Cheung's functions

$$\frac{dV}{d(\ln I)} = IR_s + n\left(\frac{kT}{q}\right) \tag{9}$$

$$H(I) = V - n\left(\frac{kT}{q}\right)\ln\left(\frac{I}{AA^*T^2}\right) \tag{10}$$

and

$$H(I) = IR_s + n\Phi_B \tag{11}$$

should give a straight line for the data of downward curvature region in the forward bias I–V characteristics. The term IR_s is the voltage drop across the series resistance of Schottky diode. In Fig. 5(a) and (b), the experimental

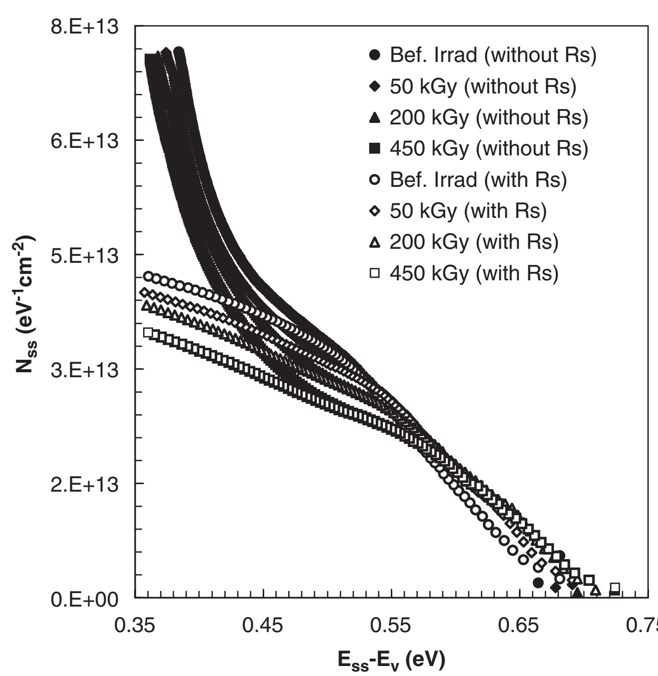
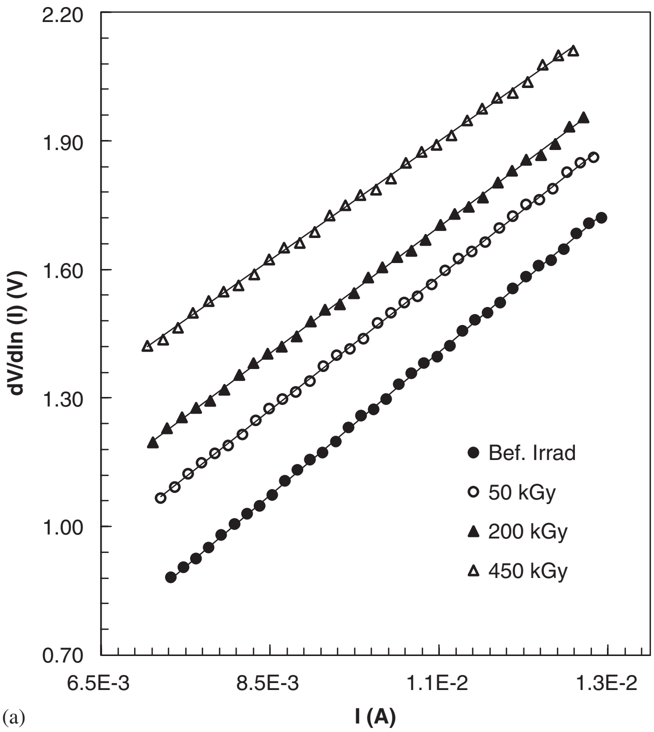
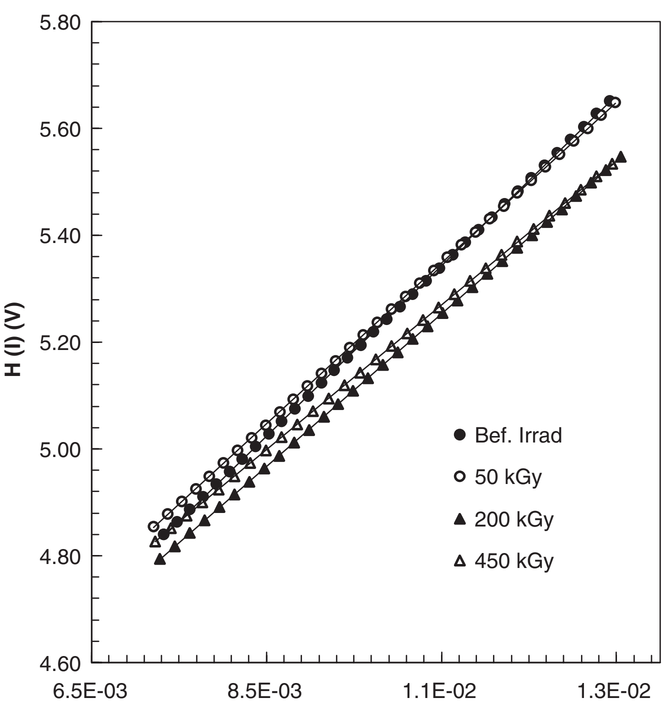


Fig. 4. The density of interface states (N_{ss}) distribution profiles as a function E_{ss}–E_v obtained from the forward bias I–V characteristics for each dose.



(a)



(b)

Fig. 5. (a) Experimental $dV/d\ln(I)$ vs. I and (b) $H(I)$ vs. I plots for the MIS Schottky diode at different irradiation doses.

$dV/d\ln(I)$ vs. I and $H(I)$ vs. I plots are presented at different irradiation doses for the diode, respectively. Thus, the slope and y-axis intercept of the plot $dV/d\ln(I)$ vs. I will give R_s and nkT/q, respectively. As a function of radiation, the values of R_s were derived from Fig. 5(a) and (b).

The plot of $H(I)$ vs. I according to Eq. (11) in Fig. 5(b)) gives a straight line with the y-axis intercept equal to $n\Phi_{BO}$. The slope of this plot also provides the second determination of R_s which can be used to check the consistency of Cheung's approach. The values of series resistance calculated from Eqs. (9) and (11) for each irradiation dose are presented in Table 1. As can be seen in Table 1, the values of series resistance $R_s(dV/d(\ln I))$ and $R_s(H(I))$ calculated from Cheung's function $dV/d(\ln I)$ and $H(I)$, respectively decrease strongly with increasing irradiation, and are in good agreement with one other [14,35,36].

4. Conclusion

Al/SiO_2/p-Si (MIS) Schottky diodes were subjected to ^{60}Co γ-irradiation (from 0 to 450 kGy), and the effect of γ-irradiation on the current–voltage (I–V) characteristics of MIS Schottky diodes has been studied using I–V measurements. The value of the reverse current was observed to decrease with increasing radiation dose; however, the effects of irradiation on the forward bias current were almost negligible. It was found that the exposure to increasing cumulative γ-ray doses caused the barrier height to remains essentially constant with a marginal improvement in ideality factor. The n values obtained from I–V characteristics are higher than unity, and this is attributed to the presence of a thin interfacial insulator layer between the metal and semiconductor. This is especially true in diodes with the current density of dislocations which are exposed to increasing doses of energy irradiation, because any radiation-induced changes within the dislocation-free area of the insulator–semiconductor interface may not manifest in the forward bias I–V characteristics. The density of interface states N_{ss} decreases with increasing radiation dose, being attributed to the decrease in the recombination centers.

Acknowledgments

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