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Effects of ^{60}Co γ-ray irradiation on the electrical characteristics of Au/n-GaAs (MS) structures

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Abstract

In order to interpret the effect of ^{60}Co γ-ray radiation dose on the electrical characteristics of metal–semiconductor (Au/n-GaAs) Schottky barrier diodes (SBDs), these devices were stressed with a zero bias during ^{60}Co γ-ray source irradiation with the dose rate $2.12\,\mathrm{kGy\,h^{-1}}$ and the total dose range was 0–500 kGy at room temperature. Experimental results show that γ-irradiation induces an increase in the barrier height $\Phi_b(C–V)$ obtained from reverse-bias $C–V$ measurements, whereas barrier height $\Phi_b(I–V)$ obtained from forward-bias $I–V$ measurements remained essentially constant. This negligible change of $\Phi_b(I–V)$ is attributed to the low barrier height in regions associated with the surface termination of dislocations. The experimental $I–V$ and $C–V$ characteristics prove that there is a reaction for extra recombination centers in case of SBDs exposed to γ-ray radiation. Also, the ideality factor n and donor concentration decrease with increasing dose rate. Both $I–V$ and $C–V$ characteristics of the Schottky diode indicate that the total dose radiation hardness of GaAs devices may be limited by the susceptibility of the Au–GaAs interface to radiation-induced damage. The density of interface states N_{SS} distribution profiles as a function $E_{CC}–E_{SS}$ for each dose rate was extracted from the forward-bias $I–V$ characteristics taking into account the bias dependence of the effective barrier height Φ_e at room temperature. N_{SS} decreases with increasing dose rate and above 250 kGy it remains constant. Such a behavior of N_{SS} is attributed to the existence of the native insulator layer between the metal and semiconductor that passivates the surface of semiconductor, and thus the increase of the N_{SS}.

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Keywords: ^{60}Co γ-ray; Au/n-GaAs contacts; Interface states; $I–V/C–V$ characteristics; Series resistance

1. Introduction

Metal–semiconductor (MS) Schottky diodes, metal–insulator–semiconductor (MIS)-type Schottky diodes or solar cells and metal–oxide–semiconductor (MOS) capacitors are extremely sensitive to high-level radiation (such as ^{60}Co γ-ray and high-level electrons, neutrons and ions). Irradiation of the semiconductor devices with high-level radiation leads to production of lattice defects in the form of vacancies, defect clusters and dislocation loops near the MS interface. These defects act as recombination centers trapping the generation carriers. When these devices are exposed to high-level radiation, significant changes can occur in their electrical characteristics. Therefore, it is of interest to investigate the damage defect centers introduced by irradiation and to study their effect on the performance of these types of semiconductor devices. Further, improvements in radiation resistance of MS, MIS and solar cells are necessary for widespread applications.

A survey of the literature reveals that a large number of studies have been reported in the area of effect of radiation on MS or MIS Schottky diodes [1–6], MOS devices/capacitors [7–19] and solar cells [20,21]. It is well known that the density of interface states between metal and semiconductor interfaces in the MS Schottky diodes has

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been studied more than that in the MIS-type Schottky diodes due to the existence of native insulator layer between metal and semiconductor that passivates the surface of semiconductor. Winokur et al. [10,12], Zainninger et al. [4] and Ma [7,9] were among the first to make a systematic observation of their irradiation behavior of radiation-induced interface traps in MIS and MOS devices. Interface traps, also referred to as interface states or surface states, are electronic energy levels located at the MS interface. Under an AC modulation voltage signal, the interface potential changes back and forth at the modulation frequency.

Gallium arsenide (GaAs) is one of the advantageous semiconductors for high-speed and low-power devices. Due to its importance in GaAs technology, radiation effects on MS devices have attracted a lot of attention during the last decades and a variety of studies has been performed by many authors [1,6,22]. A few aspects of this subject have not been considered in detail; among them, the modification of the conduction characteristics across the irradiated oxide has attracted only a modest attention from the scientific community. However, the performance of GaAs devices, including MS field effect transistors and heterostructure bipolar transistors, depends on the surface and interface defect density.

In this work, we present results of a study on the effect of ^{60}Co γ-ray irradiation on the electrical characteristics of an Au/n-GaAs Schottky barrier diode (SBD) exposed to maximum cumulative dose of 500 kGy. The characteristics of the Au/n-GaAs SBD, before and after irradiation, were investigated using current–voltage (*I–V*), capacitance–voltage (*C–V*) and conductance–voltage (*G–V*) measurement techniques. Before irradiation, the Schottky barrier height $\Phi_b(C–V)$ obtained from *C–V* measurements was larger than $\Phi_b(I–V)$ obtained from forward-bias *I–V* measurements. The barrier height $\Phi_b(C–V)$ increases with increasing dose rate, whereas the barrier height $\Phi_b(I–V)$ remained essentially constant. Furthermore, it is shown that at a higher irradiation dose (500 kGy), *I* vs. *V*, *C* vs. *V* and *G/w* vs. *V* plots almost reach satisfaction. The major purpose of this work is to investigate damage effect centers induced by γ-ray irradiation and study their effect on performance of the Au/n-GaAs MS Schottky diodes. In addition, experimental results for the Au/n-GaAs MS Schottky diode are compared with results published for these types of semiconductor devices.

2. Experimental detail

The MS Schottky diodes used in this study were fabricated by evaporating Au on oxidized bulk (1 0 0) n-type GaAs wafers with a carrier concentration of $10^{17}\,cm^{-3}$. Before making contacts, the n-GaAs wafers were dipped in $5H_2SO_4 + H_2O_2 + H_2O$ solution for 1 min to remove surface damage layer and undesirable impurities and then in $H_2O + HCl$ solution followed by a rinse in deionized water of 18 MΩ. The wafer was dried with high-purity nitrogen and inserted into the deposition chamber immediately after the etching process. Au–Ge (88% and 12%, respectively) for ohmic contacts was evaporated on the back of the wafer in a vacuum-coating unit of 10^{-5} Torr. Low-resistance ohmic contacts were formed by thermal annealing at 450 °C for 3 min in flowing N_2 in a quartz tube furnace. Then, the wafer was inserted into the evaporation chamber for formation of the reference Schottky contacts. The Schottky contact was formed by evaporating Au as dots with a diameter of about 1.5 mm on all of the n-GaAs surfaces. The current–voltage (*I–V*) measurements were carried out using a Keithly 220 programmable constant-current source and a Keithly 614 electrometer. The capacitance–voltage (*C–V*) and conductance–voltage (*G–V*) measurements were carried out using an HP 4192A LF impedance analyzer (5 Hz–13 MHz). The AC signal was generated by a low-distortion oscillator with the amplitude attenuated to 40 mV_{p-p} to meet the small signal requirement for thin oxide capacitors. All measurements (*I–V*, *C–V* and *G–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.

3. Results and discussion

3.1. Current–voltage (I–V) characteristics

The room-temperature forward- and reverse-bias current–voltage (*I–V*) characteristics of GaAs SBDs, before and after γ-ray irradiation from a ^{60}Co source, are shown in Fig. 1. As seen in Fig. 1, before and after irradiation,

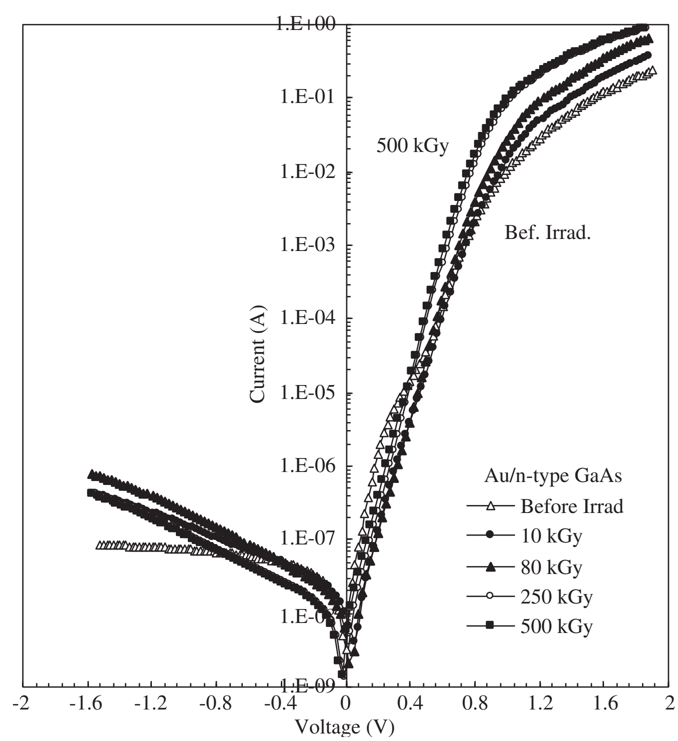

Fig. 1. Forward- and reverse-bias *I–V* characteristics of n-type GaAs(1 0 0) Schottky diodes before and after exposure to accumulated ^{60}Co γ-ray doses up to 500 kGy.

each plot consists of a good linear range with different slopes in intermediate-bias regions. The measured *I–V* characteristics were analyzed using the conventional Schottky barrier thermionic emission theory model [13,14,23]:

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

where I_0 is the saturation current derived from the straight line intercept of $\ln I$ axis at zero bias and is given by

$$I_0 = AA^* T^2 \exp\left(-\frac{q\Phi_{bo}}{kT}\right) \tag{1b}$$

where V is the applied voltage, q is the electron charge, A is the diode area, k is the Boltzmann constant, T is the absolute temperature, A^* is the effective Richardson constant of $8.16\,\mathrm{A\,cm^{-2}\,K^{-2}}$ for n-type GaAs, Φ_{bo} is the zero-bias barrier height and n is the ideality factor. From Eq. (1a), the ideality factor n can be written as

$$n = \frac{q}{kT}\frac{\mathrm{d}V}{\mathrm{d}\ln(I)} \tag{2}$$

where $\mathrm{d}V/\mathrm{d}\ln(I)$ is the slope of the linear region of $\ln I$ vs. V plots. The values of ideality factor n were found to have a stronger dose rate and range from 2.894 at 0 kGy (before irradiation) to 2.006 at 500 kGy (after irradiation). The zero-bias Schottky barrier height ($\Phi_{bo} = \Phi(I-V)$) was obtained from intercepts of the forward-bias $\ln I$ vs. V plot for each dose rate. Values of dose-dependent ideality factor n and barrier height are given in Table 1. As seen in Table 1, especially the ideality factors (n) determined from semi-log-forward *I–V* plots were found to be a strong function of irradiation dose range. The ideality factor was found to decrease while the barrier height increased with increase in dose range. But at high irradiation dose ranges (250–500 kGy), these values remain constant. In conclusion, the results have been commonly observed in *I–V* of MS diode and attributed to the presence of a thin insulating layer between the metal and semiconductor [15,24].

3.2. Capacitance–voltage (C–V) and conductance–voltage (G–V) measurements

The *C–V* characteristics of the GaAs SBDs, before and after γ-ray irradiation, between 0 and 500 kGy at 500 kHz, are shown in Fig. 2, which manifests the presence of the trapping centers [17,18,25]. As seen in Fig. 2, the *C–V* curves did not show a significant difference among the measurements made in the range of radiation dose 250–500 kGy. Fig. 3 shows the reciprocal of the squared capacitance per unit area as a function of the bias for before and after γ-irradiation between 0 and 500 kGy, respectively. Analysis of the *C–V* characteristics was realized using the expression for the bias dependence of the depletion capacitance of the SBD. In MS contacts, the depletion layer capacitance is given as follows [25,26]:

$$C^{-2} = \frac{2(V_0 + V)}{\varepsilon_s \varepsilon_0 q A^2 N_D} \tag{3a}$$

$$\Phi_{CV} = V_d + \left(\frac{kT}{q}\right)\ln\left(\frac{N_C}{N_D}\right) \tag{3b}$$

where A is the diode area, V is the applied reverse bias, V_0 is the intercept of the C^{-2} vs. V plot with the voltage axis, q is the electronic charge, ε_s is the dielectric constant of the semiconductor ($13.1\varepsilon_0$ for n-type GaAs), ε_0 is the dielectric constant of vacuum ($8.85\times10^{-14}\,\mathrm{F\,cm^{-1}}$), N_D is equivalent to the free electron concentration when all shallow donor levels are ionized, which by plotting C^{-2} vs. V and N_C is the effective density of states in the conduction band of

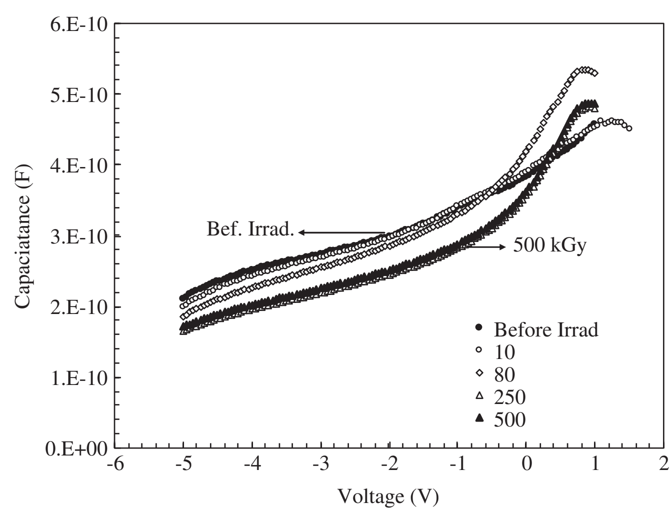

Fig. 2. *C–V* characteristics of the Au/n-GaAs Schottky diodes before and after different radiation doses.

Table 1
Electrical parameters of Au/n-type GaAs SBDs obtained before and after irradiation at different dose ranges

Irradiation (kGy)	n	Φ_{IV} (eV)	Φ_{CV} (eV)	N_D ($\mathrm{cm^{-3}}$)	R_S (*C–V* and *G–V*) (for $V = 5\,\mathrm{V}$) (Ω)	$R_S(\mathrm{d}V/\mathrm{d}\ln I)$ (Ω)	$R_S H(I)$ (Ω)
Pre-irradiation	2.894	0.692	0.925	9.11×10^{15}	8.15	1.84	1.97
10	2.339	0.752	0.948	8.22×10^{15}	8.33	1.60	1.59
80	2.134	0.763	1.015	6.26×10^{15}	6.66	1.57	1.24
250	2.006	0.763	1.241	4.97×10^{15}	4.76	1.12	1.10
500	2.006	0.763	1.263	4.59×10^{15}	4.72	1.05	1.10

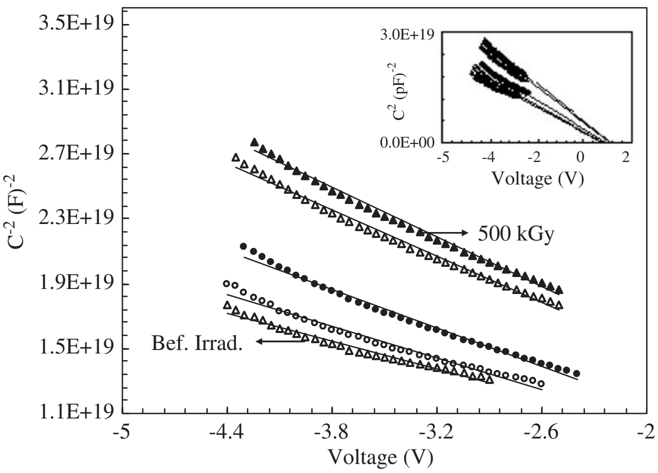

Fig. 3. C^{-2}–V diode characteristics before and after irradiation. Extracted Schottky barrier height (Φ_{CV}) as a function of cumulative γ-ray doses.

GaAs. The barrier height $\Phi_b(C–V)$ from the inset of Fig. 3 is

$$\Phi_b(C-V) = V_0 + \frac{kT}{q} + E_F - \Delta\Phi \tag{4}$$

where E_F is the energy difference between the bulk Fermi level and conductance band edge and $\Delta\Phi$ is the image force barrier lowering. Before irradiation, the $C–V$ measurements revealed a Schottky barrier height of $\Phi_{CV} = 0.925\,\text{eV}$ and a carrier concentration of $9.11 \times 10^{15}\,\text{cm}^{-3}$. Before and after irradiation, the $\Phi_b(C-V)$ values obtained with the effect of γ-ray exposure on the $C–V$ is shown in Fig. 4, 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, Φ_{CV}, obtained from the experimental $C–V$ characteristics, is due to an increase in V_0 shown in Fig. 3. These results indicate that in the γ-irradiated diodes, while the barrier height Φ_{IV} remains constant, the barrier height Φ_{CV} increases slightly with increase in radiation dose.

Fig. 5 shows the measured $G_m/w–V$ characteristics of an Au/n-type GaAs Schottky diode at various dose ranges (with ^{60}Co γ-rays at doses up to approximately 500 kGy). Conductance 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 [27]. The applied AC signal causes the Fermi level to oscillate about the mean positions governed by the DC bias, when the semiconductor device is in the depletion. Both $C–V$ and $G–V$ characteristics for high-frequency (for 500 kHz) applied voltage (Figs. 2 and 5, respectively) were found to have changed with dose rate. The series resistance is an important parameter to designate the noise ratio of device as dependent on irradiation dose. Therefore, both the real values and voltage dependence of the series resistance R_S were calculated from Eq. (5) according to Ref. [27] and are

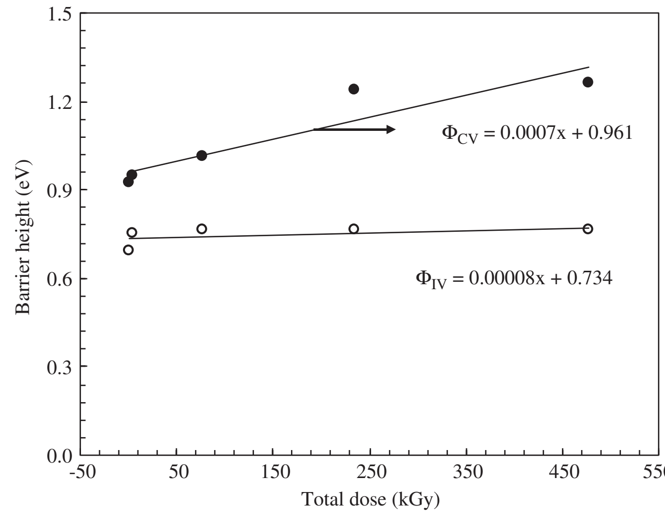

Fig. 4. Barrier heights obtained as a function of cumulative γ-ray doses.

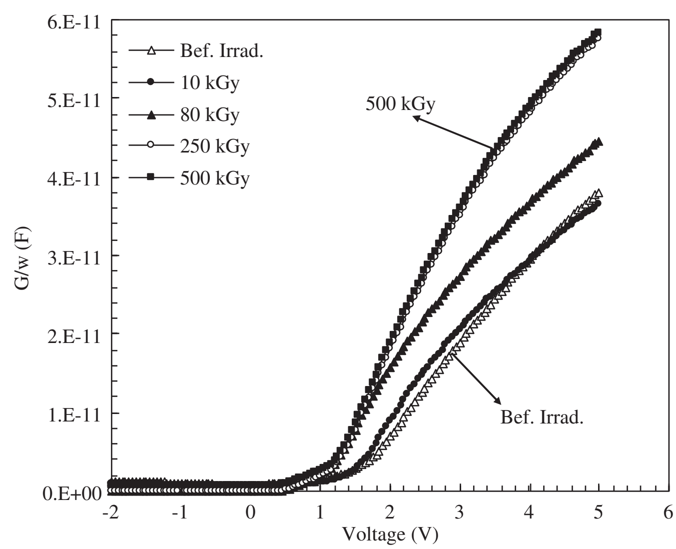

Fig. 5. Conductance (G/w) voltage dependences before and after irradiation.

given in Table 1 and Fig. 6, respectively. As seen in Fig. 6, in depletion and inversion regions, the value of the series resistance decreases with increasing irradiation dose:

$$R_S = \frac{G_{ma}}{G_{ma}^2 + (\omega C_{ma})^2} \tag{5}$$

where G_{ma} and C_{ma} are values of conductance and capacitance obtained in strong accumulation region. In addition, values of series resistance R_S were achieved using another method developed by Cheung [28]. Cheung's functions

$$\frac{dV}{d(\ln I)} = IR_S + n\left(\frac{kT}{q}\right) \tag{6}$$

$$H(I) = V - n\left(\frac{kT}{q}\right)\ln\left(\frac{I}{AA^*T^2}\right) \tag{7}$$

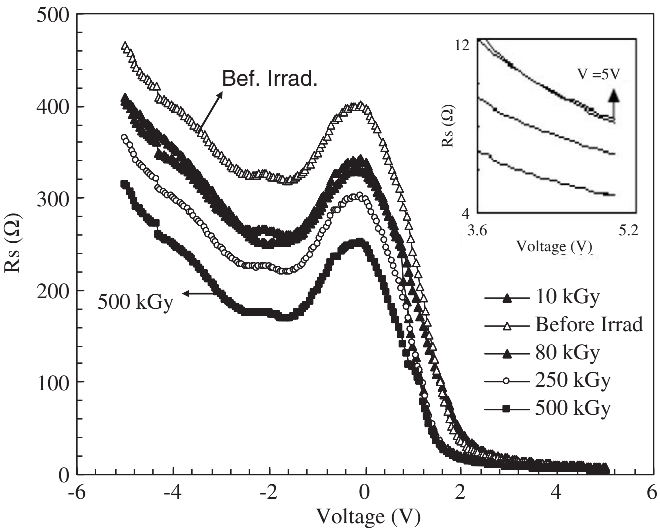

Fig. 6. Series resistance (R_S) vs. gate bias under different doses at 500 kHz.

and

$$H(I) = IR_S + n\Phi_b \tag{8}$$

should give a straight line for the data of downward curvature region in the forward-bias I–V characteristics. Here, Φ_b is the barrier height obtained from I–V measurements. The term IR_S is the voltage drop across the series resistance of diode. In Figs. 7(a) and (b), experimental $dV/d(\ln I)$ vs. I and $H(I)$ vs. I plots are presented at different irradiation doses. Thus, plots of $dV/d(\ln I)$ vs. I and $H(I)$ vs. (I) will give R_S as the slope. Values of series resistance obtained for each irradiation dose using Eqs. (6) and (8) are given in Table 1. As seen in Table 1, the obtained R_S values are in good agreement with each other and decrease strongly with increasing irradiation dose.

The interface states for electrons or holes, while the density of states is always affected by interfaces, 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 at high bias values indicated a continuum of interface states which equilibrate with the semiconductor [24]. Nevertheless, the SBD exhibited excellent rectification characteristics with a relatively low leakage current density. The effective height Φ_e is given by

$$\Phi_e = \Phi_{bo} + \alpha(V - IR_s) = \Phi_{bo} + \left(1 - \frac{1}{n(V)}\right)(V - IR_s) \tag{9}$$

considering the applied voltage dependence of the barrier height, where α is the voltage coefficient of the effective barrier height, Φ_e, used in place of the barrier height, Φ_b, and it is a parameter that combines the effects of both interface states in equilibrium with the semiconductor [24].

Assuming $N_{sa} \to 0$ ($N_{SS} = N_{SB}$), values of interface states density N_{SS} in equilibrium with semiconductor were

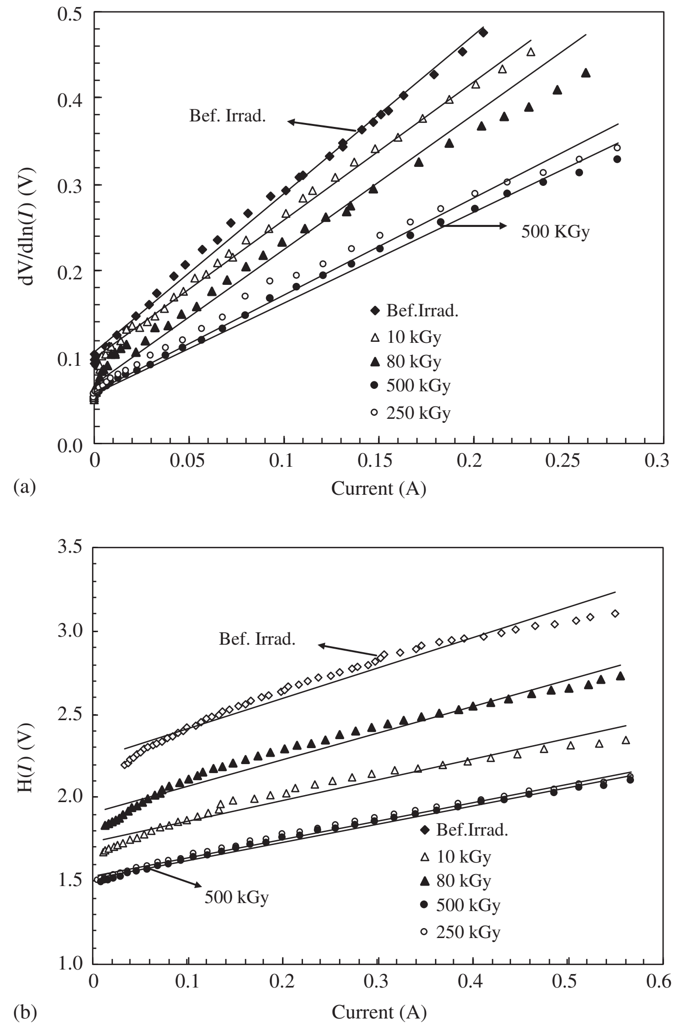

Fig. 7. (a). Plots of $dV/d\ln(I)$ vs. I and (b) $H(I)$ vs. I for Au/n-GaAs Schottky diode at different irradiation doses.

obtained by substituting the voltage-dependent n values, $\varepsilon_s = 13.1\varepsilon_0$, $\varepsilon_i = 4\varepsilon_0$, $\delta = 33$ Å and $W_D = 2.59\ \mu m$ in Eq. (9) and are given in Fig. 8 and Table 1. The expression for the interface state density as deduced by Card and Schroder [24,29] is reduced to

$$N_{SS}(V) = \frac{1}{q}\left[\frac{\varepsilon_i}{\delta}(n(V) - 1) - \frac{\varepsilon_s}{W_D}\right] \tag{10}$$

where W_D is the space charge width, ε_s and ε_i are the interfacial layer permittivity and the semiconductor permittivity, respectively. The interfacial insulator layer thickness, δ, was obtained from high-frequency (500 kHz) C–V characteristics using the equation for insulator layer capacitance ($C_{ox} = \varepsilon_i\varepsilon_0 A/\delta$), where $\varepsilon_i = 4\varepsilon_0$ [23,27] and ε_0 is the permittivity of free space. Furthermore, in an n-type semiconductor, the energy of interface states, E_{SS}, with respect to the bottom of the conduction band at the surface of semiconductor is given by [30,31]

$$E_C - E_{SS} = q(\Phi_e - V). \tag{11}$$

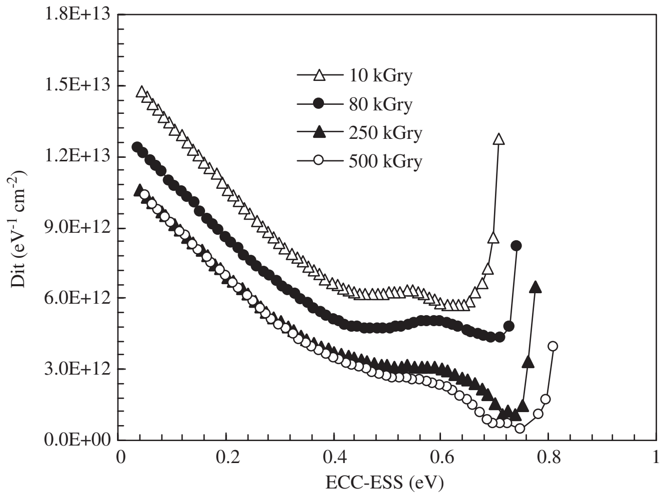

Fig. 8. Density of interface states N_{SS} as a function of $E_{SS}–E_V$ obtained from the $I–V$ data at different γ-ray doses.

The energy distribution of the interface states is shown in Fig. 8. As be seen from Fig. 8, the increase in the interface state density from the midgap towards the top of conduction band is very apparent. This distribution of interface states, calculated using Eq. (10), is seen to increase from the threshold towards the midgap. Fig. 8 shows the radiation dose dependence of N_{SS} converted to a function of E_{SS} using Eqs. (10) and (11) at various radiation dose ranges. It is clear that the increase in interface states is greater in the upper part of the band gap.

4. Conclusion

GaAs MS Schottky diodes were subjected to ^{60}Co γ-irradiation (from 0 to 500 kGy), and the effect of γ-irradiation on the electrical characteristics of Au/n-GaAs Schottky diodes has been studied using $I–V$ and $C–V$ measurements. The forward current–voltage characteristics were significantly degraded by the irradiation, even at the lowest doses (10 kGy). Exposure to increasing cumulative γ-ray doses was found to have the following effects: (i) a manifested increase in the Schottky barrier height obtained from $C–V$ measurements and (ii) the effective barrier height obtained from forward $I–V$ measurements remains essentially constant with a marginal improvement in ideality factor. 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. Therefore, the values of barrier height (Φ_{CV}) and barrier height ($\Phi_{IV} = \Phi_{bo}$) extracted using the conventional models for Schottky diode $C–V$ and $I–V$ characteristics may differ significantly. This is especially true in diodes with the current density of dislocations which are exposed to increasing doses of energy irradiation, for any radiation-induced changes within the dislocation-free area of the metal–GaAs interface may not manifest in the forward-bias $I–V$ characteristics, but may significantly affect the $C–V$ characteristics. The N_{SS} distribution profiles as a function $E_{CC}–E_{SS}$ for each dose rate were extracted from the forward-bias $I–V$ characteristics by taking into account the bias dependence of the effective barrier height Φ_e at room temperature. The N_{SS} decreases with increasing dose rate and above 250 kGy it remains constant. Such a behavior of N_{SS} is attributed to the existence of a native insulator layer between the metal and semiconductor that passivates the surface of semiconductor, and thus the increase of the N_{SS}. In summary, the results discussed here confirm that Schottky barriers with good electrical characteristics are in close agreement with values obtained from $I–V$ and $C–V$ measurements.

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