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Investigations on the effect of alpha particle irradiation-induced defects near Pd/n-GaAs interface

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Abstract

Pd/n-GaAs Schottky barrier diodes (SBDs) have been fabricated using liquid-encapsulated Czochralski (LEC) grown silicon-doped GaAs (1 0 0) single-crystal substrates. The diodes were implanted using low-energy (70 keV) alpha particles of fluence 1×10^{14}, 1×10^{15} and $1\times10^{16}\,cm^{-2}$ to study the effect of irradiation-induced defects very close to the interface. Current–voltage (I–V) and capacitance–voltage (C–V) characteristics of control, irradiated and annealed diodes have been carried out under dark conditions and analyzed. After the irradiation, the rectifying behavior of the diode deteriorates with the fluence. The irradiated diodes annealed at 573 and 673 K show a decrease in the reverse leakage current and an enhancement in the barrier height due to the reduction of the irradiation-induced defects. The capacitance values of the irradiated diodes have been observed to be less than those of the control diodes and they increase with increasing ion fluences whereas those of the irradiated and annealed diodes decrease for all fluences due to passivation on the GaAs surface and/or the removal of the irradiation-induced defects in the SBDs. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Irradiation; Schottky barrier diode; Control; I–V measurement; C–V measurement; Annealing

1. Introduction

Ion implantation in gallium arsenide (GaAs) has been extensively investigated for VLSI applications and for the realization of novel electronic devices. The direct band gap and high electron

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mobility allows the production of discrete and integrated optoelectronic devices and the fabrication of very high-speed transistors, quantum well diodes, laser diodes and microwave oscillators [1]. Irradiation of the semiconductor with energetic particles leads to the production of lattice defects in the form of vacancies, defect clusters and dislocation loops near the surface [2,3]. The defects created at the interface using low-energy ion irradiation have a strong influence on the performance of the devices [4]. Low-energy light-ion irradiation provides a way to control the depth distribution of recombination centers. Localized layers with a high density of lifetime killers can be created at any depth within the active layer of the devices by varying the ion energy. The deep-level defects in the band gap can act as both traps and recombination centers depending on the injection/depletion conditions, capture cross section of the electrons and holes and energy position. Traps reduce the semiconductor free carrier density whereas recombination centers introduce generation-recombination current in rectifying devices [2].

The low-mass ion (proton and alpha particle) irradiation in GaAs has become an important technique to create high-resistivity region for electrical isolation in devices and circuits fabricated using GaAs substrates. It has been found that the implanted protons or implantation-induced defects in metal/semiconductor interface interact with defects to passivate them and improve the device performance [5]. Space solar cells are subjected to continuous bombardment by various energetic protons, electrons, neutrons and alpha particles. Among them, proton and alpha particles are identified as the major cause for device failure [3]. The annealing behavior of the radiation damage and other measurements indicate that defect complexes of several types must be involved in the carrier removal mechanism [2]. Raman scattering studies on alpha- and proton-implanted n-GaAs have been recently reported [6]. Further, the studies confirmed the passivation of free carriers by the implanted ion and its defects. Recently, it has been reported that the Pd–GaAs Schottky barrier diodes (SBDs) are used as hydrogen sensors due to the diffusion of hydrogen through the metal film [7]. Therefore, it is of interest to investigate the damage defect centers introduced by irradiation and to study their effect on the performance of the metal–semiconductor contacts. In this article, we report on the extensive investigations carried out on the current–voltage and capacitance–voltage of 70 keV alpha particle irradiation (fluences 1×10^{14}, 1×10^{15} and 1×10^{16} cm^{-2}) induced defects on the Pd/n-GaAs SBDs and the effect of annealing.

2. Experimental

For the present investigations, the SBDs have been fabricated using Liquid-encapsulated Czochralski (LEC) grown silicon-doped ($n = 4 \times 10^{17}$ cm^{-3}) GaAs (1 0 0) single-crystal substrates at Crystal Growth Centre. The substrates were mechanically lapped and polished through chemo-mechanical process and thoroughly cleaned using warm acetone, methanol and tricholoroethylene. The cleaned substrates were etched in $HCl : H_2O$ (1 : 1) for 60 s to remove any native oxide present on the surface and then immediately loaded into an e-beam evaporation system. Circular palladium (Pd) Schottky contact area of 7.86×10^{-3} cm^2 and thickness 1200 Å was realized through a metallic mask on the polished surface under a vacuum of 2×10^{-6} Torr. Before the front side metallization, Au/Ge/Ni alloy of Ohmic contact thickness 2000 Å was deposited on the rear side of the substrate and annealed at 703 K for 2 min under nitrogen atmosphere.

The fabricated SBDs have been irradiated using a 150 kV tandem accelerator at IGCAR, Kalpakkam. The irradiation experiments have been carried out at room temperature under a vacuum of 1×10^{-7} torr. Low-energy (70 keV) alpha particle irradiation (three different fluences of 1×10^{14}, 1×10^{15} and 1×10^{16} cm^{-2}) was chosen in such a way that the irradiation-induced defects have been uniformly introduced in a controlled manner at the interface and within the depletion layer of the Pd/n-GaAs Schottky barrier. Using TRIM 95 calculations [8], the projected range of the alpha particle into the Pd/n-GaAs SBDs is found to be 2400 Å and the straggling is 1100 Å. The irradiated SBDs were annealed at 573 and 673 K for 5 min under nitrogen atmosphere. Current–voltage (I–V) characteristics of the SBDs were measured using a computer-controlled system and the capacitance–voltage (C–V) characteristics were measured using an automated 7200 Boonton capacitance meter at a frequency of 1 MHz. All the measurements were carried out at room temperature under dark conditions.

3. Results and discussion

3.1. Current–voltage characteristics

Irradiation-induced effects on any material change the electrical characteristics and produces many defect levels within the depletion layer of the GaAs SBDs [9]. In the present investigations, 70 keV alpha particle introduces physical damage into the host lattice and deteriorates the electrical performance of the Pd/n-GaAs, which includes the series resistance, change in the barrier height and the non-ideal I–V characteristics of the diodes. The SBDs have been characterized using thermionic emission equation and is given by

$$J = J_s\left[\exp\left(\frac{qV}{nk_B T}\right) - 1\right], \tag{1}$$

where

$$J_s = A^{**}T^2 \exp\left(\frac{-q\phi_B}{k_B T}\right), \tag{2}$$

$$\phi_B = \frac{k_B T}{q}\ln\left(\frac{A^{**}T^2}{J_s}\right), \tag{3}$$

with A^{**} being the effective Richardson constant (A cm^{-2} K^{-2}), T the absolute temperature (K), n the ideality factor, k_B the Boltzmann constant (J K^{-1}), q the electronic charge, ϕ_B the barrier height (eV), J_s the saturation current density (A cm^{-2}), V the applied voltage and J the current density (A cm^{-2}).

Fig. 1 shows the I–V characteristics of control and as-irradiated (fluence 1×10^{14}, 1×10^{15}, 1×10^{16} cm^{-2}) Pd/n-GaAs SBDs. The saturation current density increases with respect to the fluence. This is attributed to the irradiation-induced defects at the interface. The change in the reverse leakage current (ΔI_R) is the parameter which is most sensitive to the incident particle fluence and it was found to increase with fluence. The results show that the recombination centers enhance the reverse current as well as the electrically active defects which are originally present in

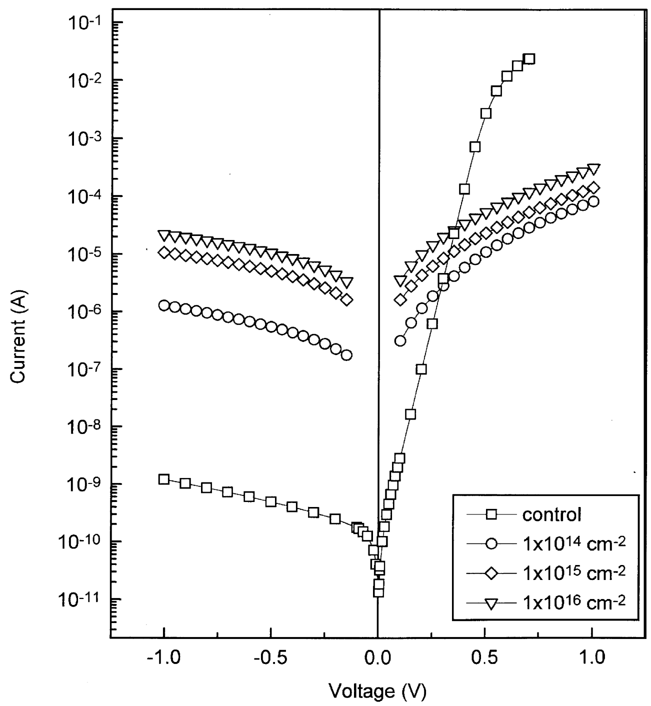

Fig. 1. Current–Voltage characteristics of control and alpha particle irradiated (1×10^{14}, 1×10^{15} and $1\times10^{16}\,cm^{-2}$) Pd/n-GaAs SBDs.

the semiconductor. Fig. 2 shows the ΔI_R measured at -1.0 V as a result of the three different incident particle fluences and annealed at 573 and 673 K. It is clearly seen that for the SBDs irradiated and annealed at 673 K, a decrease in the ΔI_R has been observed. The barrier height (ϕ_B), ideality factor (n), saturation current density (J_s), series resistance (R_s) and change in reverse leakage current (ΔI_R) are given in Table 1. The decrease in the barrier height of the as-irradiated and annealed diodes compared to the control diode is due to the fact that majority of the carriers tunneling through the interfacial layer. Thurzo et al. [10] have reported that the defects in the surface layer of the semiconductor contribute to a lowering in the rectifying behavior. In the present work, it is due to the alpha particle irradiation that creates many damage centers in the Pd/n-GaAs interface. The effect of increasing fluences is to increase the density of defect levels resulting in greater degradation of the rectifying characteristics. The ideality factor increases due to the inhomogeneity of the interface due to the alpha particle damage: it shows that the current flow mechanism is also due to other mechanisms but the thermionic emission is the dominant mechanism. The series resistance values of the SBDs are determined using a plot of J versus $dV/d[\ln(J)]$. The series resistance of the SBD increases after irradiation. The low-energy alpha particle introduces a large number of defects when the incident particles come to a rest in the semiconductor that could result in the increased series resistance.

Fig. 3 shows the I–V characteristics of control, as-irradiated (fluence $1\times10^{16}\,cm^{-2}$) and annealed (573 and 673 K) Pd/n-GaAs SBDs. It is observed that the saturation current density

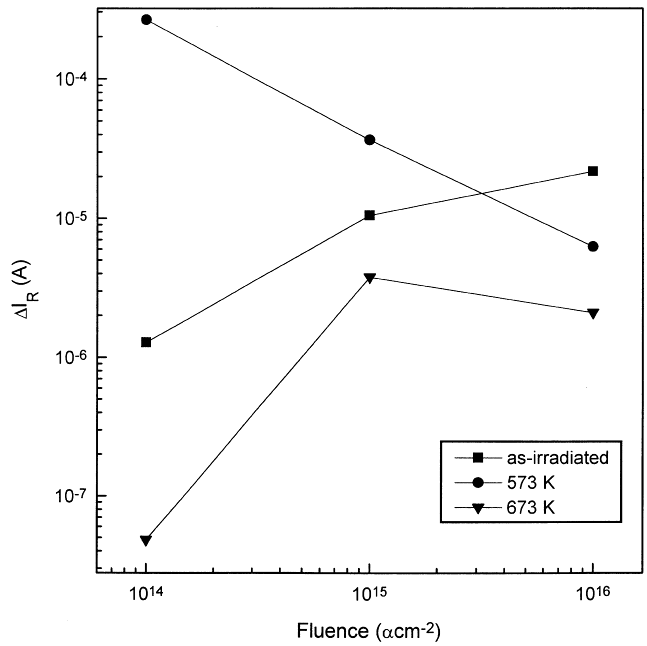

Fig. 2. Change in reverse leakage current measured at 1 V for as-irradiated and annealed 573 and 673 K) SBDs as a function of alpha particle fluence (1×10^{14}, 1×10^{15} and 1×10^{16} cm^{-2}).

Table 1
The barrier height (ϕ_B), ideality factor (n), saturation current density (J_s) series resistance (R_s) and change in reverse leakage current values (ΔI_R) of the control, as-irradiated, irradiated and annealed Pd/n-GaAs SDBs

Fluences		ϕ_B (eV)	n	J_s (A/cm^2)	R_s (Ω)	ΔI_R (A)
Control		0.83	1.03	9.3×10^{-9}	9	
1×10^{14} cm^{-2}	As-irradiated	0.64	3.3	1.3×10^{-5}	—	1.28×10^{-6}
	673 K	0.74	1.9	3.3×10^{-7}	—	4.82×10^{-8}
1×10^{15} cm^{-2}	As-irradiated	0.59	4.4	8.9×10^{-5}	—	1.05×10^{-5}
	673 K	0.62	2.8	3.0×10^{-5}	10	3.76×10^{-6}
1×10^{16} cm^{-2}	As-irradiated	0.56	5.2	2.7×10^{-4}	—	2.18×10^{-5}
	673 K	0.63	2.2	1.8×10^{-5}	21	6.25×10^{-6}

decreases with respect to the annealing temperature due to the reduction of the alpha particle-induced defects. An enhancement of the barrier height has been observed for all the fluences as compared to the as-irradiated diodes. It is due to the removal of the irradiation-induced defects upon annealing and/or passivation on the GaAs surface. The observed ideality factor of the annealed SBDs decreases compared to the as-irradiated SBDs: the decrease in the recombination current is due to the removal of the recombination centers introduced during the irradiation. The concentration of the recombination centers depends upon the total incident particle fluence.

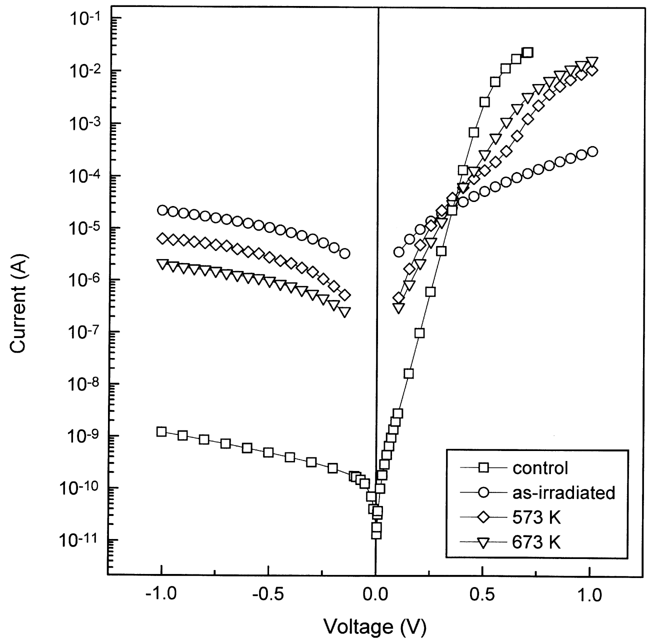

Fig. 3. Current–voltage characteristics of control, as-irradiated and annealed (573 and 673 K) SBDs for fluence of $1\times10^{16}\,\mathrm{cm}^{-2}$.

3.2. Capacitance–voltage characteristics

The dark C–V characteristics have been analyzed using the depletion capacitance equation

$$C=\frac{\varepsilon A}{W_d}=\sqrt{\frac{q\varepsilon NA^2}{2(V_{bi}-V-V_T)}},\tag{4}$$

where A is the area of the diode, N is the concentration of ionized donor atoms, V_T is the thermal voltage ($=k_BT/q$), V is the applied bias, W_d is the depletion width and V_{bi} is the built-in voltage which is related to the barrier height (ϕ_B) by the following equation:

$$\phi_B=V_{bi}+V_T\ln\left(\frac{N_C}{N_D}\right)\tag{5}$$

N_C being the effective density of states at the conduction band and N_D the donor concentration. The C–V results for the SBDs plotted as $1/C^2$ versus V give a straight line whose slope has been used to calculate the carrier concentration (N_D) values.

Fig. 4 shows the C–V characteristics of control and irradiated (1×10^{14}, 1×10^{15} and $1\times10^{16}\,\mathrm{cm}^{-2}$) SBDs. The capacitance values increase as a function of the fluence for low-energy alpha particle-irradiated SBDs but they are less than those of the control diode. During the irradiation, the induced defects increase the majority carrier concentration in the depletion region. It might lead to increase in the capacitance and to further increases as the fluences increase. The

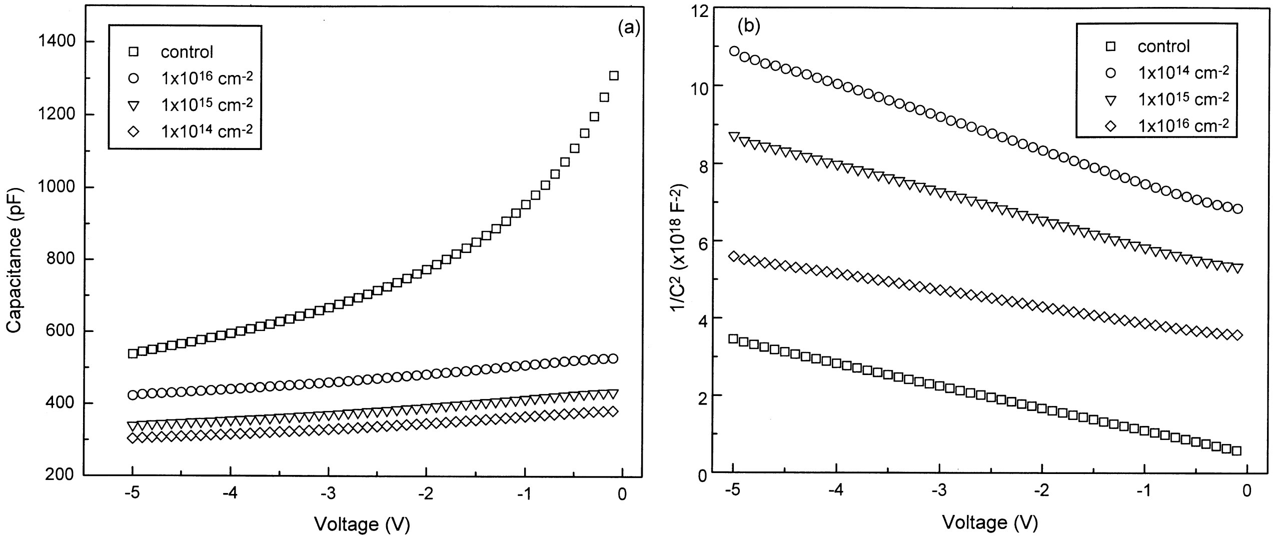

Fig. 4. C–V (a) and $1/C^2 - V$ (b) characteristics of control and irradiated (1×10^{14}, 1×10^{15} and 1×10^{16} cm^{-2}) SBDs.

increase in the capacitance is also attributed to the increase in the dielectric permittivity of the depletion layer [11]. The increase in the free electrons of a metal–semiconductor interface due to the dielectric permittivity has been studied using hyper Raman scattering [12]. The capacitance values of the irradiated diodes show weak dependence of the applied voltage. This is expected in view of the series resistance present in the circuit due to the damage layer created by the irradiation in the GaAs. Further, the carrier concentration is reduced by the alpha particle irradiation as compared to the control diodes through the mechanism of passivation and defects trapping at the interface and within the depletion region. Auret et al. [9] have reported that radiation damage produces many defect levels within the depletion layer of the GaAs SBDs. The capacitance values of the irradiated and annealed diode decrease for all fluences due to the irradiation-induced carrier removal at the interface. Fig. 5 shows the C–V characteristics of the irradiated (fluence of 1×10^{14} cm^{-2}) and annealed (573 and 673 K) SBDs. For the irradiated and annealed diodes the carrier concentration decreases due to the irradiation-induced acceptor-like defects and these defects trap free electrons thereby partially compensating the ionized donors in the depletion region.

Due to irradiation a large number of vacancies are created at the interface. These vacancies play a major role at the depletion region of the irradiated SBDs. Using TRIM 95 calculations [8], the alpha particle and vacancy concentrations as a function of depth are shown in Fig. 6.

4. Conclusions

Extensive investigations have been carried out on the I–V and C–V characteristics of Pd/n-GaAs SBDs irradiated with 70 keV alpha particle of fluences 1×10^{14}, 1×10^{15} and 1×10^{16} cm^{-2}. The I–V measurements show an increase in the change in reverse leakage current as a function of

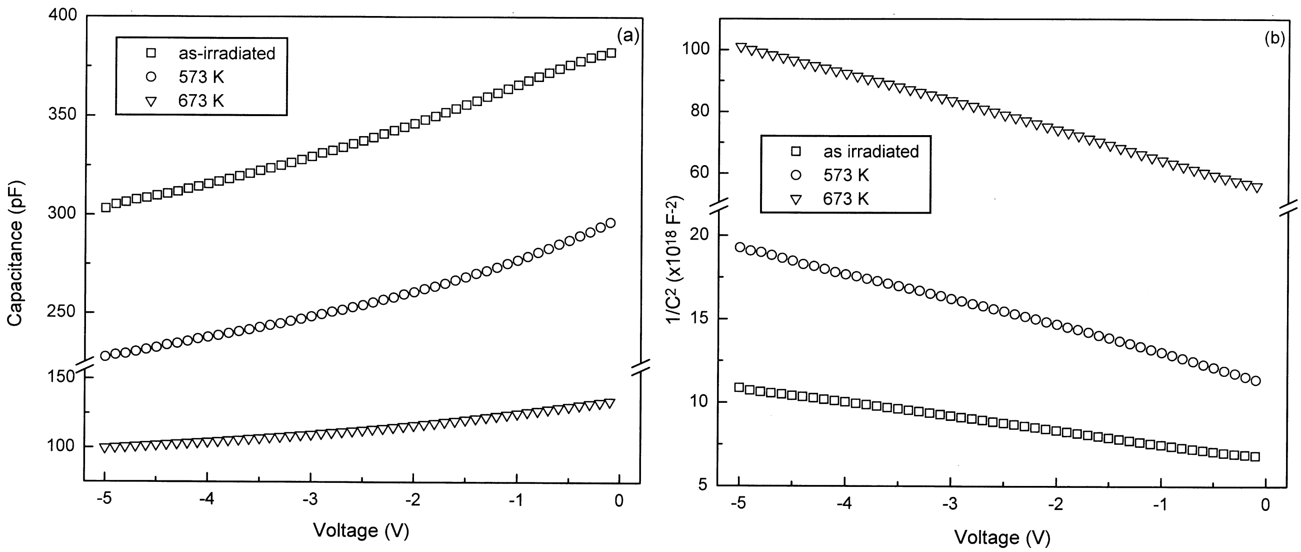

Fig. 5. C–V (a) and $1/C^2$–V (b) characteristics of as-irradiated (fluence 1×10^{14} cm^{-2}) and annealed (573 and 673 K) SBDs

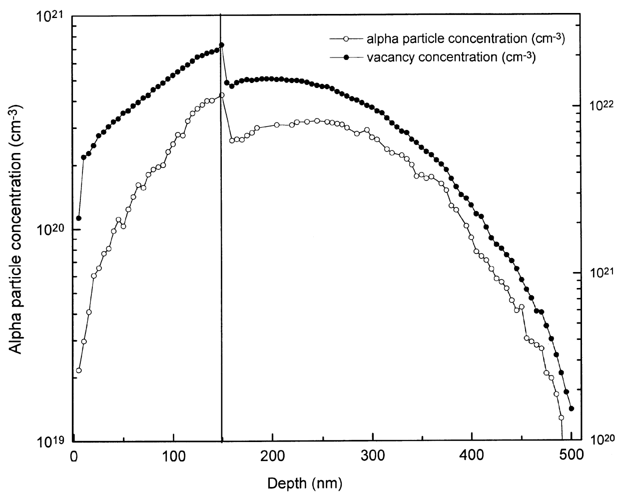

Fig. 6. Alpha particle and vacancy concentrations versus depth of 70 keV alpha particle in Pd/n-GaAs.

the incident particle fluence due to the irradiation-induced defects at the interface. After the irradiation, an increase in the ideality factor, series resistance and decrease in the barrier height values have been observed for all the fluences. The irradiated diodes were annealed at 573 and 673 K. The diode characteristics of the irradiated and annealed SBDs improved as compared to the as-irradiated SBDs. This is due to the reduction of the irradiation-induced defects upon annealing and passivation on the GaAs surface. The C–V characteristics show that the capacitance values of the SBDs increase as a function of the fluences but remain less than the control diodes. The reduction in the carrier concentration by the alpha particle irradiation as compared to the control diodes is through the mechanism of passivation and defects trapping at the interface and within the depletion region. The capacitance of the irradiated and annealed diode is found to decrease for all the fluences due to the irradiation-induced acceptor-like defects and these defects are responsible for carrier removal at the interface.

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