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Electrical characterisation of high energy ^{12}C irradiated Au/n-GaAs Schottky Barrier Diodes

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Abstract

Au/n-GaAs Schottky Barrier Diodes (SBDs) have been fabricated on LEC grown silicon doped ⟨1 0 0⟩ GaAs single crystals. The SBDs were irradiated by 70 MeV high energy carbon ions with various ion fluences of 1×10^{11}, 1×10^{12} and 1×10^{13} ions cm^{-2}. Current–voltage (I–V) and capacitance–voltage (C–V) characteristics of unirradiated and irradiated diodes were analysed. The change in reverse leakage current increases with increasing ion fluence. This is due to the irradiation induced defects at the interface and its increase with the fluence. The diodes were annealed at different temperatures (473, 573 and 673 K) to study the effect of annealing. The rectifying behavior of the irradiated SBDs improves as the annealing temperature increases. But at 673 K, the diode behavior has been deteriorated irrespective of the fluences. Better enhancement in barrier height and also improvement in the ideality factor has been observed at the annealing temperature of 573 K. A decrease in the capacitance has been observed with increasing fluence. For the irradiated and annealed SBDs, the increase in capacitance has been observed. Scanning Electron Microscopic analysis was carried on the irradiated samples to delineate the projected range and to observe defects induced by high energy carbon irradiation.

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1. Introduction

The studies of the modification in semiconductor devices due to ion irradiation are of both technological importance and scientific interest. Irradiation of the semiconductors with ion beam introduces electrically active defects which results in changing the property of the material at the surface or deep into the surface depending upon the energy of the ion [1]. The defects act either as traps or as recombination centers in the semiconductors, depending on the capture cross-sections of the electrons and holes. Further in outer space, the electronic devices in satellites are inadvertently exposed to cosmic radiation, comprising a variety of high energy particles, which degrade their performance [2].

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Although there are reports on the low energy irradiation induced damage [3,4], there are not enough significant and detailed works available on high energy irradiation. The high energy particles penetrate the semiconductor devices and cause lattice damage in the form of vacancy, interstitial and defect complexes [5]. High energy ions pass through the semiconductor material with fewer elastic collisions with atoms. However, ionization of the Ga and As atoms may occur due to inelastic collisions of the energetic ion with the electrons of Ga and As leading to defect formation. The very high energy carbon ions go deep inside (several tens of micron) the GaAs, causing disturbances in the electron clouds around the Ga and As atoms from the surface upto the range of the ion through ionization by inelastic electronic collisions. The effect of carbon irradiation on GaAs heterojunction bipolar transistors [6] and laser diodes [7] have been reported. Recently, it has been reported [8] that very high energy (293 MeV) carbon irradiation degrades the SBD device properties by increasing the reverse leakage current. We report here on the change in the electrical properties of the high energy (70 MeV) incident carbon ions in GaAs SBDs.

2. Experimental

SBDs were fabricated on LEC grown (1 0 0) silicon doped ($n = 2\times10^{17}$ cm^{-3}) GaAs substrates grown at Crystal Growth Centre. The substrates were thinned down to a thickness of about 250 μm and then they were polished by conventional chemo-mechanical process. The metalization and ohmic contact formation were described elsewhere [4]. 70 MeV $^{12}C^{6+}$ ions from 15 UD Pelletron tandem accelerator [9] were used for the irradiation studies on Au/n-GaAs SBDs. Samples were irradiated from the metal side with various ion fluences (1×10^{11}, 1×10^{12}, 1×10^{13} cm^{-2}) at 300 K in an experimental chamber maintained at 10^{-7} mbar vacuum after metallization. The irradiated samples were also subjected to SEM analysis after etching. Etching was carried out using 8 mg $AgNO_3$:1 g CrO_3:1 ml HF:2 ml H_2O, to delineate the projected range of 70 MeV carbon ions in GaAs and to observe the defects.

3. Results and discussions

3.1. Current–voltage characteristics

Irradiation induced effect on any metal-semiconductor interface changes the *I–V* characteristics because the defect act either as trap assisted tunneling or as recombination current flow mechanism. Fig. 1 shows the dark *I–V* characteristics of the control and 70 MeV carbon irradiated Au/n-GaAs SBDs (fluence of 1×10^{11}, 1×10^{12} and 1×10^{13} ions cm^{-2}). The series resistance increases as a function of the incident particle fluence. This may be due to the introduction of trap levels at various positions in the band-gap. The trap levels, reduce the free carrier density which in turn leads to an increase in the resistivity of the material. Fig. 2 shows the change in reverse leakage current (ΔI_R) measured at 1.0 V as a result of 70 MeV

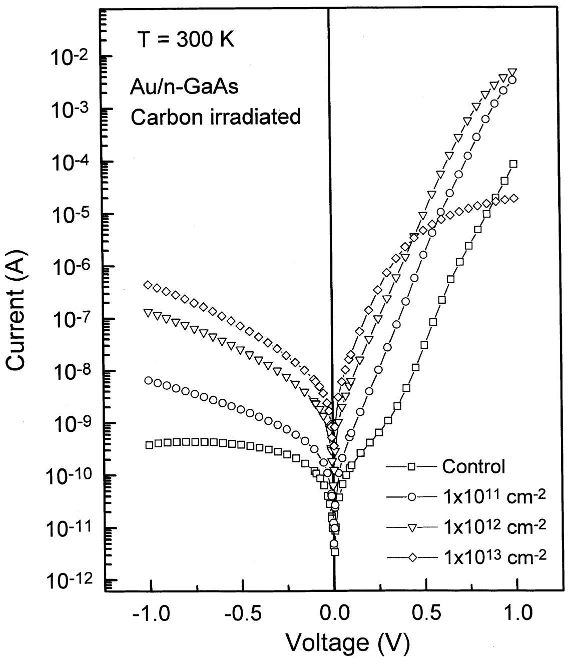

Fig. 1. Current–voltage characteristics of control, 1×10^{11}, 1×10^{12} and 1×10^{13} cm^{-2} carbon irradiated SBDs.

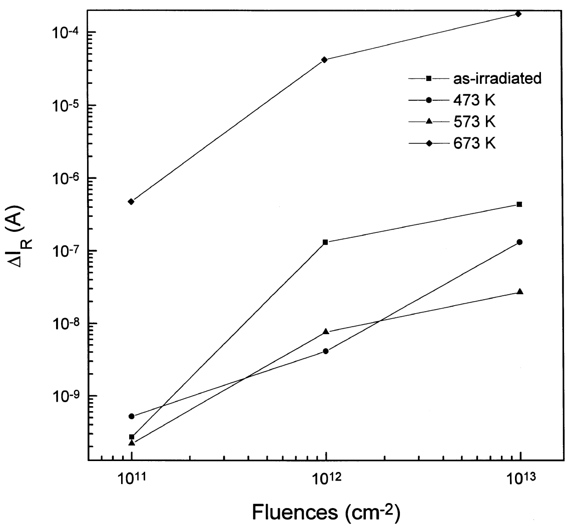

Fig. 2. Change in reverse leakage current measured at 1 V of as-irradiated and annealed (473, 573 and 673 K) SBDs as a function of carbon fluence (1×10^{11}, 1×10^{12} and 1×10^{13} cm^{-2}).

carbon ion irradiation for the three different incident fluences, annealed at 473, 573 and 673 K. It is clearly seen that there is a linear increase in the current with incident particle fluence and irradiated annealed SBDs. The results show that residual defects such as generation centers enhance the reverse current as well as crystal structure defects and electrically active defects, which influence the effective carrier concentration of the GaAs. The reverse current characteristics is controlled by all of these residual defects. We observed that the ΔI_R was sensitive to high energy carbon ion irradiation induced defects.

The SBDs have been characterised using thermionic-emission equation and is given by [4]

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

where

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

where A^{**} is the effective Richardson constant (A cm^{-2} K^{-2}); T is the absolute temperature (K); n is the ideality factor; k_B is the Boltzmann's constant (J K^{-1}); ϕ_B is the barrier height (eV); J_s is the saturation current density (A cm^{-2}); V is the applied voltage and J is the current density (A cm^{-2}). The barrier height (ϕ_B), ideality factor (n), saturation current density (J_s) and series resistance (R_s) values are given in Table 1. It has been observed that the barrier height decreases as a function of the incident particle fluence. The ideality factor deviates from unity, clearly indicating that the current flow mechanism across the interface is also due to the generation-recombination and leakage currents. A reduction in the barrier height of the potential barrier and an increase in the tunneling component of the forward current are due to the radiation induced defects at the interface. Series resistance of the SBDs is determined using J vs $\mathrm{d}V/\mathrm{d}[\ln(J)]$. The high energy particle of fluence 1×10^{13} ions cm^{-2} induce large

Table 1
The barrier height (ϕ_B), ideality factor (n), saturation current density (J_s) and series resistance (R_s) values of the control, as-irradiated, irradiated and annealed Au/n-GaAs SBDs

Fluences		ϕ_B (eV)	n	J_s (A cm^{-2})	R_s (Ω)
Control		0.90	1.04	5.31×10^{-10}	21
1×10^{11} cm^{-2}	As-irradiated	0.84	1.99	4.83×10^{-9}	24
	473 K	0.87	2.52	1.41×10^{-9}	–
	573 K	0.92	1.51	2.40×10^{-10}	14
1×10^{12} cm^{-2}	As-irradiated	0.78	2.15	6.36×10^{-8}	35
	473 K	0.85	2.49	3.82×10^{-9}	–
	573 K	0.85	1.95	3.83×10^{-9}	16
1×10^{13} cm^{-2}	As-irradiated	0.73	2.60	4.19×10^{-7}	5.49×10^4
	473 K	0.78	2.19	6.62×10^{-8}	3.26×10^4
	573 K	0.84	1.28	5.53×10^{-9}	1.68×10^3

number of defects when the incident particles come to a rest in the semiconductor and hence the defects are far from the interface which increases the series resistance.

The barrier height increases with annealing temperature at 473 K for all fluences as compared to as-irradiated SBDs. This is due to the reduction of the irradiation induced defects upon annealing. The observed ideality factor at 473 K increases as compared to the as-irradiated SBDs and this is attributed to the increase in the recombination current and it is probably due to the presence of recombination centers introduced during irradiation. For higher fluences the saturation current is high compared to control SBDs, which may be due to the irradiation induced defects at the interface, that induce tunneling through the barrier. The J vs $\mathrm{d}V/\mathrm{d}[\ln(J)]$ plot is not linear for the irradiated (fluence 1×10^{11} and 1×10^{12} ions cm^{-2}) annealed (473 K) SBDs and hence the series resistance values are not tabulated. For the SBDs annealed at 573 K, the barrier height increases whereas the ideality factor decreases, this may be due to the removal of the carbon induced defects at the interface. Hence, if the Au/n-GaAs SBDs were subjected to high energy carbon irradiation (1×10^{11}, 1×10^{12} and 1×10^{13} ions cm^{-2}) followed by annealing at 573 K, leaky diodes can be switched to good rectifying SBDs. Goodman et al. [8] annealed the SBDs under argon atmosphere and showed that some defects could be removed after annealing at 573 K. The SBDs annealed at 673 K for all fluences show severe degradation of the rectifying behavior (like ohmic behavior). This may be due to the introduction of similar defects due to intense ionization of the semiconductor material itself. On the other hand, the recombination within the depletion region is the most important effect at the interface of the irradiated (673 K) annealed diodes, and is largely, if not completely, responsible for the degradation of the rectifying behavior of the SBDs.

3.2. Capacitance–voltage characteristics

C–V measurements were carried out at room temperature using an automated system of 1 MHz Boonton capacitance meter. The dark C–V characteristics have been analyzed using the depletion capacitance equation

$$C = \frac{\varepsilon A}{W_\mathrm{d}} = \sqrt{\frac{q\varepsilon N A^2}{2(V_\mathrm{bi} - V - V_\mathrm{T})}}, \tag{3}$$

where A is the area of the diode; N is the free carrier concentration; V_T is the thermal voltage ($=k_\mathrm{B}T/q$); 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

$$\phi_\mathrm{B} = V_\mathrm{bi} + V_\mathrm{T}\ln\left(\frac{N_\mathrm{C}}{N_\mathrm{D}}\right). \tag{4}$$

N_C is the effective density of states at the conduction band and N_D is the donor concentration. Before irradiation, the carrier concentration (2×10^{17} cm^{-3}) and the barrier height (0.9 eV) values have been evaluated using the C–V data. The barrier height value is in good agreement with those calculated from our I–V measurements. The capacitance decreases as a function of fluence whereas the capacitance increases with increasing fluences for low energy proton irradiated SBDs [4]. The capacitance values of the irradiated diodes were lower than that of the control diodes and showed very weak dependence of the applied voltage. This is expected in view of the series resistance present in the device after irradiation. The decrease in the capacitance is also attributed to thermal emission of the carriers and the effect of diffusion potential by the induced defects. The capacitance of the irradiated annealed diodes increases for all fluences with annealing temperature (473 and 673 K) due to the completely ionized but uncompensated donors and the reduction in the bulk ionization. A decrease in capacitance was observed in the irradiated SBDs annealed at 573 K. This seems to be a defect-induced doping effect, because for a higher annealing temperature this effect could be partly eliminated. Fig. 3 shows $1/C^2$ vs V characteristics of control, 1×10^{11}, 1×10^{12} and 1×10^{13} cm^{-2} irradiated SBDs. It is observed that the carrier concentration of the irradiated diode decreases as a function of fluence compared to the control diode (2×10^{17} cm^{-3} for control to 2.59×10^{15} cm^{-3} for fluence 1×10^{13} ions cm^{-2}) and this may be due to compensation of the Si donors.

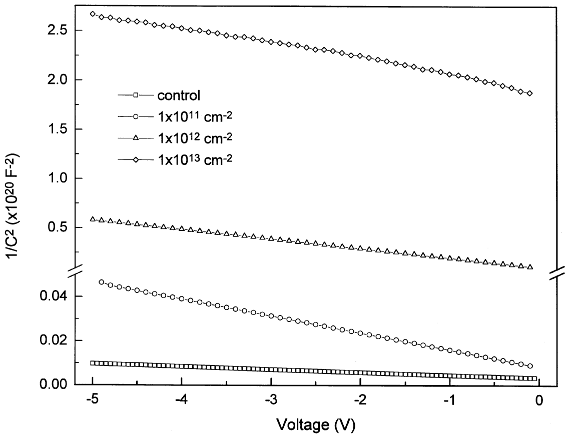

Fig. 3. $1/C^2$ vs V characteristics of control, 1×10^{11}, 1×10^{12} and 1×10^{13} cm^{-2} carbon irradiated SBDs.

For the irradiated annealed diodes the concentration decreases due to the ionization of uncompensated donors. The change in free carrier density with an increase in the incident carbon ion fluence has been reported [8]. Due to irradiation a lot of vacancies are created at the interface. These vacancies play a major role at the depletion region of the irradiated SBDs. Using TRIM 95 calculation [10], the vacancy concentration created by the carbon ions at the interface are estimated as 10^{19} ions cm^{-3} and at the end of range as 10^{21} ions cm^{-3}. The ionization of the defects at the interface are almost equal to that at the projected range of the defects. The SEM micrograph (Fig. 4) shows the cross-sectional view of the high energy carbon ion irradiated sample. The 70 MeV energy carbon ions irradiated in Au/n-GaAs has been observed at about 65 μm (range calculated using TRIM 95 is 69 μm). The defects are created by inelastic collisions and are expected to peak at the interface (near 2 μm) and at the end of the range (63 μm).

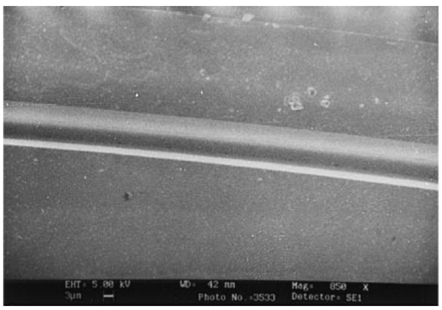

Fig. 4. SEM micrograph (cross-sectional view) of 70 MeV carbon irradiated Au/n-GaAs SBD showing the implanted region.

4. Conclusions

Current–voltage and capacitance–voltage characteristics were analyzed on the 70 MeV carbon ions irradiated Au/n-GaAs SBDs. The *I–V* measurements shows an increase in the change in reverse leakage current as a function of the incident particle fluence due to the irradiation induced defects at the interface. The diode characteristics of the irradiated and annealed SBDs improved compared to that of the as-irradiated SBDs. The irradiated SBDs annealed at 573 K have good rectifying behavior due the removal of interface defects upon annealing. After irradiation there is an increase in the series resistance. The recombination current dominates the current flow through the interface. The current increases as the particle fluence increases. *C–V* characteristics show the degradation of the capacitance as a function of fluence. It was found that the capacitance increases with annealing temperature at 473 and 673 K. The projected range of the irradiated defects was analyzed using SEM.

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