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Effect of ^{60}Co γ-ray irradiation on electrical properties of GaAs epilayer and GaAs p–i–n diode

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ABSTRACT

GaAs epilayers and p–i–n diodes structures grown using metal–organic vapor phase epitaxy were irradiated at room temperatures by ^{60}Co γ-ray radiation with varying the dose up to 50 kGy. The carrier concentration and mobility on GaAs epilayer decreases while leakage current of p–i–n diode increases at higher radiation dose (10–50 kGy). However at lower dose (<6 kGy) carrier mobility remain same but leakage current still shows significant increase. Furthermore carrier mobility of irradiated GaAs epilayers recovers partially (68%) after annealing at 300 °C while leakage current of p–i–n diode does not show any noticeable recovery. These effects are mainly due to the creation of more deep levels compared to shallow levels as determined from photoluminescence, Hall, current–voltage and electrochemical capacitance voltage analysis.

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1. Introduction

Semiconductors are extremely sensitive to high-level radiation dose (such as γ-ray, high-energy electrons, neutrons and ions). Irradiation of semiconductor with high-energy radiation leads to production of lattice defects in the form of vacancies, defect clusters and dislocations [1–4]. These effects can lead to the formation of energy levels within the band gap which can act as trapping and recombination centers for carriers depending upon their energy level position within the gap. This alters the material parameters and hence the properties of devices like metal–semiconductor Schottky diodes, metal–oxide–semiconductor, p–i–n detectors, and solar cells [5–9]. Since detectors are frequently exposed to high level of radiation dose, radiation hardness, or the extent up to which a material can tolerate the radiation, is a critical parameter for selection of detector materials [10,11]. Hence investigations of the defect centers produced by irradiation of high energetic particles and their effect on the performance of devices are of interest.

The type and degree of damage or defect created depends on several parameters of the material involved like the atomic mass, density of the host atoms and the temperature of the material during irradiation. It also depends on the energy, atomic mass, charge, and fluence of the incident species. Among these energetic particles, ^{60}Co γ-rays are the most convenient source for defect studies [12–16]. We have determined the ^{60}Co γ-ray radiation hardness properties of GaAs epitaxial layer and p–i–n diodes structures grown by metal–organic vapor phase epitaxial (MOVPE). In this work we present the effect of ^{60}Co γ-ray irradiation on electrical parameters (like carrier mobility, carrier compensation and leakage current) of MOVPE grown GaAs epilayer and p–i–n detector structures. These electrical parameters were evaluated from current–voltage (*I–V*), electrochemical capacitance voltage (ECV) and Hall measurement. Furthermore, the effect of radiation on GaAs epilayers were also investigated using photoluminescence (PL) spectroscopy. We observe strong effect of γ-ray irradiation on properties of GaAs and p–i–n diodes at 10 kGy and shows similar trend even up to 50 kGy. Hence, further higher radiation dose were not explored. At the lower dose range (<10 kGy), it was observed that, leakage current was more affected as compared to the mobility. We have investigated the possible causes for this observation.

2. Experimental details

For Hall measurement, the undoped GaAs epilayers were grown on semi-insulating GaAs substrate at 700 °C using MOVPE. Trimethyl Gallium (TMGa) and Arsine (AsH_3) were used as precursors. These undoped GaAs epilayers show carrier mobility of 78,262 cm^2/Vs at 77 K. Donor and acceptor densities (N_D and N_A) are 1.09×10^{15} cm^{-3} and 4.4×10^{14} cm^{-3} respectively. The intrinsic (i) layer of similar nature of thickness 4 μm is sandwiched between 300 nm of p type ($p \sim 2 \times 10^{18}$ cm^{-3}) and 300 nm of n type ($n \sim 10^{18}$ cm^{-3}) to form the p–i–n detector structure. 2% Silane (SiH_4) in H_2 and Diethyl Zinc (DEZn) were used for n- and

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p-type doping, respectively. The complete structure is grown on n$^+$ GaAs ($\sim 1 \times 10^{18}$ cm^{-3}) substrate to allow ohmic contacts to be made on the back surface. Ohmic contacts were made using thermal evaporation of Ti/Pt/Au and Au–Ge/Ni/Au at $2–5 \times 10^{-6}$ mbar vacuum for p- and n-type, respectively. To isolate the devices, mesa structures were fabricated by wet chemical etching of top p-layer with H_2O_2:H_2O:H_2SO_4 (1:1:5) solution [17]. Five sets of GaAs epilayer and processed p–i–n detector structures were irradiated with different dose, i.e. 2, 6, 10, 30, 50 kGy with dose rate 2 kGy per hour. The fluence equivalents are 2×10^{14}, 6×10^{14}, 1×10^{15}, 3×10^{15} and 5×10^{15} γ/cm^2, respectively. Irradiations were carried out in a 2490 curie gamma chamber [18]. Room temperature *I–V* measurements were carried out using a Keithley 238 measurement unit. Hall measurements at 100 µA current were carried out from 44 K to 300 K. ECV depth profiling of p–i–n structures were carried out using Tiron (1,2-dihydroxybenzene-3,5-disulfonic acid disodium salt) electrolyte in an Accent Optics PN4300 setup. Low temperature (10 K) PL spectra were recorded by exciting the samples with a diode laser ($\lambda \sim 808$ nm) of 100 mW power and dispersed with 1/4 m monochromator and detected by silicon photodiode. Measurements were carried out before irradiation, after irradiation and after thermal annealing of irradiated samples at 300 °C for 15 min in 99.999% pure nitrogen ambient.

3. Results and discussion

3.1. Irradiation effect on epitaxial GaAs

Fig. 1a and b shows carrier density and mobility of GaAs epilayers for both irradiated and unirradiated samples over a temperature range from 44 K to 300 K. The carrier density and mobility decreases with increasing radiation dose. As can be seen from the inset of Fig. 1a, the change in observed mobility is more pronounced in 60–100 K range where ionized impurity scattering is the dominant phenomena [19–21]. This indicates that with increase radiation dose, more shallow impurity states are introduced. It was also observed that at lower dose (<10 kGy), mobility was not affected significantly. The 77 K mobility is related to the total ionized impurities by an analytical relation [19]

$$\mu_{ii} = \frac{24\pi^3\varepsilon^2\hbar^3 n}{(N_D + N_A)Z^2e^3m^2\left[\ln(1+y) - \frac{y}{1+y}\right]}, \tag{1}$$

where Z is the ionic charge, m is the effective mass of carrier, ε is the dielectric constant, e is the electronic charge and y is given by $y = 3^{1/3}4\pi^{8/3}\varepsilon\hbar^2 n^{1/3}/e^2 m$. The lowering of mobility at this temperature range indicates the increase in number of shallow states ($N_D + N_A$), which are ionized at this temperature ($\sim$70 K). Fig. 1b shows decrease in $N_D - N_A$ (as obtained from saturation region) with increased radiation dose. These observations confirm that N_A has increased more rapidly than N_D with radiation dose. This indicates the compensation values (N_A/N_D) increases with radiation dose. These increased values of compensation are shown in Table 1. In undoped GaAs, Gallium vacancies act as acceptor (N_A) and Arsenic vacancies act as donor (N_D), so the results indicate more Gallium vacancies (V_{Ga}) are introduced than Arsenic vacancies (V_{As}) in the investigated dose range. Since even after 10 kGy of dose, the decrease in mobility is below 2.5%, we have analyzed in detail the effects after irradiating up to 30 kGy and 50 kGy. As explained by Clays and Siemon, [25] the change in carrier concentration is related to the absorbed dose by an empirical relation, $\Delta n = 9.92 \times 10^5 D^a$ cm^{-3}, where D is dose in Rad and 'a' is the carrier removal parameter. The obtained values of 'a' are 1.21 and 1.19 for the samples irradiated with 30 and 50 kGy dose respectively and closely matches with the other report [14].

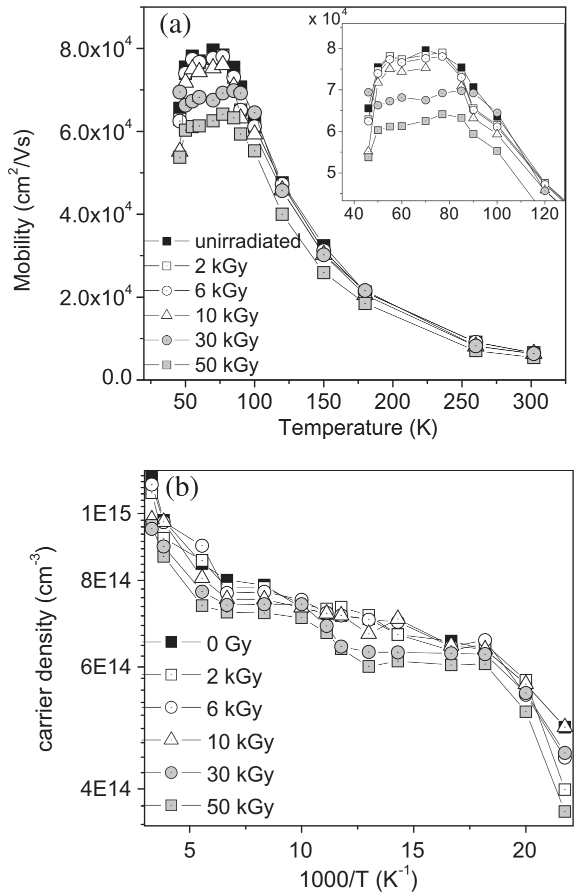

Fig. 1. Mobility (a) and carrier concentration (b) as a function of temperature for various irradiated dose.

Fig. 2 shows the PL spectra of GaAs epilayers, where peaks related to irradiated samples were compared with the unirradiated one. The defect related peaks in irradiated samples are multiplied by five for clear visualization. The spectra from the irradiated samples are deconvoluted and shown in the insets. The peak at 1.51 eV (i) is assigned to the band edge peak of GaAs. The peaks positioned at 1.45 eV (iii), 1.40 eV (iv) and 1.36 eV (v) are related to V_{As}, V_{Ga} and the Donor–Acceptor-Pair (DAP) recombination, respectively [22,23]. The small peak at 1.48 eV (ii) is most likely from the carbon related complexes [24]. Carbon insertion into MOVPE grown GaAs is frequently observed, and is known to come from TMGa precursor [25]. In the same figure, spectra for annealed samples are also shown. The decrease in PL intensity of sub band gap features after annealing can be noticed, indicating the annihilation of some of the defect related states. From the PL measurement, it was not possible to comment about the spectral position of deep levels as they are mostly non-radiative in nature.

3.2. Irradiation effect on p–i–n devices

As explained earlier, the carrier mobility in the material changes after irradiation due to introduction of defect states. Thus change in leakage current of the devices is also expected. Leakage current of the p–i–n devices increases with radiation dose as shown in Fig. 3a. The ideally factor (η) of the unirradiated p–i–n device, which is close to two, indicates leakage current is dominated by generation–recombination (g–r) mechanism. Hence increase in leakage current with radiation dosage confirms the increase of g–r centers. The total number of g–r centre giving rise

Table 1
A comparison of mobility and carrier concentrations after irradiation and after thermal annealing.

	Preirradiation	30 kGy	30 kGy + anneal	50 kGy	50 KGy + anneal
Mobility (77 K) (cm^2/Vs)	78,262	68,270	73,560	62,350	74,067
Mobility (300 K) (cm^2/Vs)	6710	6590	6952.5	6504	7015.2
N_D (10^{15} cm^{-3})	1.09	1.23	1.15	1.4	1.15
N_A (10^{15} cm^{-3})	0.44	0.6	0.50	0.77	0.49
Compensation (%)	40.03	48.78	43	55	43

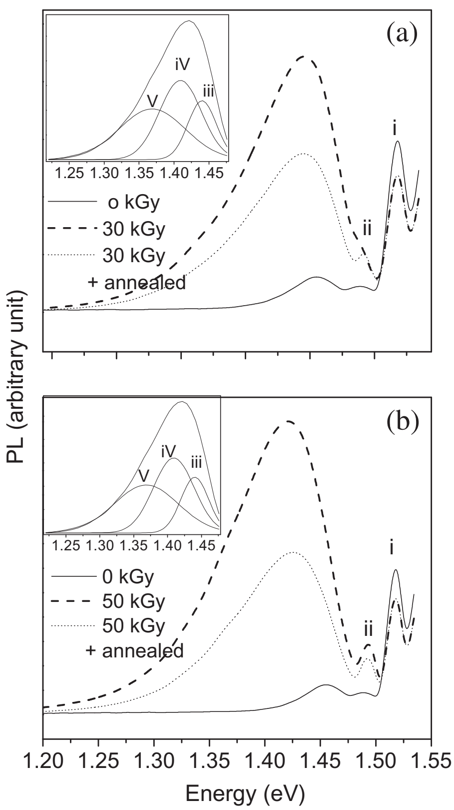

Fig. 2. PL spectra of unirradiated sample shown with PL of irradiated sample up to 50 kGy (a) and 30 kGy (b). In the same graph, PL from annealed sample is also shown. Insets show the deconvoluted peaks showing different curves.

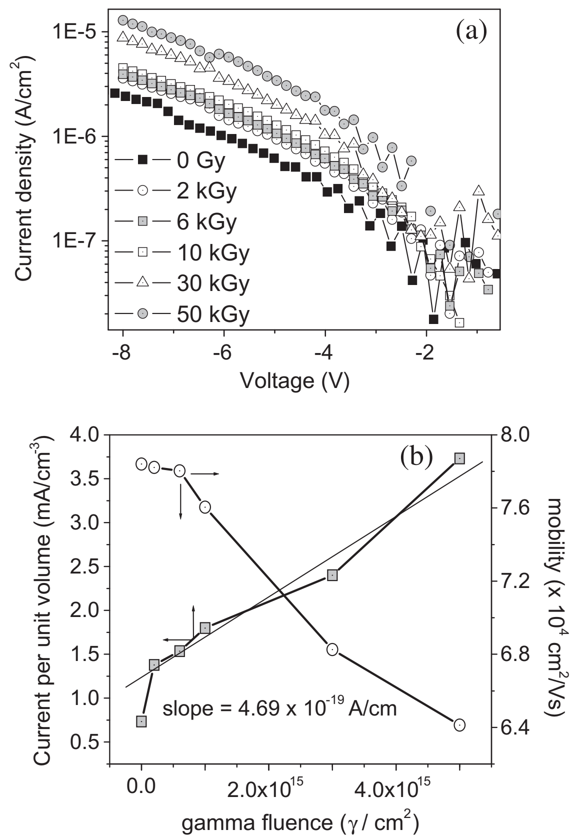

Fig. 3. (a) Leakage current density as a function of irradiated dose. (b) Leakage current at full depletion and 77 K mobility as a function of gamma fluence.

to increase in leakage current of p–i–n device is proportional to the depletion layer thickness if the device is uniformly irradiated, as in our case. Thus, the leakage current per unit volume is plotted as a function of gamma fluence. Here the volume is defined as the area multiplied by the width of i layer of p–i–n devices. The slope of the curve gives the radiation hardness in unit of A/cm [26]. The radiation hardness value 4.7×10^{-19} A/cm ($\pm 2.1 \times 10^{-20}$ A/cm) is obtained from Fig. 3b. The order of this value is similar to that obtained from GaAs Schottky devices [14].

Fig. 3b shows a comparison between change in leakage current and mobility with gamma fluence. The trend in change was observed to be different, particularly at lower dose (<10 kGy). In this range, the mobility does not change, but the leakage current of p–i–n increases significantly. We have investigated the reason for this difference. Some authors cite the interface or ohmic contact degradation as a possible reason for the increase in leakage current [14]. To examine the possibility of ohmic contact degradation, we have irradiated the device before and after making contact and even after 30 kGy and 50 kGy dose no significant difference was observed. (Fig. 4). Similarly, the possible degradation of the interfaces between p- and i-layer was investigated by (ECV) profiling, (Fig. 5) and very little change was found, which could not explain the observed increase in leakage current. Similar result is expected at the i and n-GaAs interface. Thus it appears that, the contact and interfaces degradations have very little contribution to the increase in leakage current.

In the literature, various radiation induced traps have been identified in GaAs with electron traps in the energy range of 25–900 meV and hole traps in the energy range of 90–290 meV [16–28]. With γ-irradiation, creation of several deep levels is reported [15]. The concentrations, energy levels and capture cross sections of the traps present in the material manifests themselves in the change of mobility, carrier density and leakage current. These trap levels can trap charge carrier or recombine and generate e–h pairs that will result in change in compensation (N_A/N_D) ratio [29,30]. Since low temperature mobility is affected by the presence of shallow levels ($\sim$10 meV) and leakage current is affected by the presence of deep levels (via Shockley–Reed–Hall recombination), the

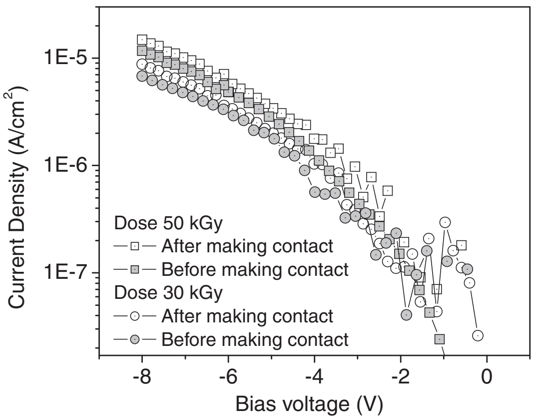

Fig. 4. Comparison of current–voltage curves for the devices irradiated before and after making contacts.

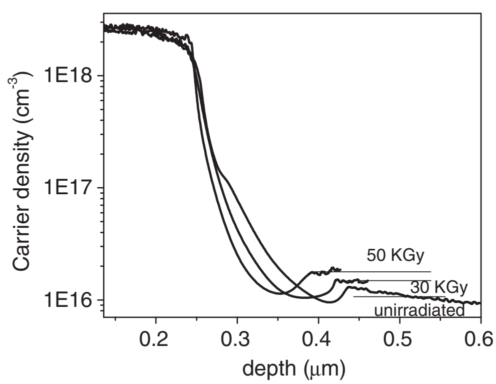

Fig. 5. Carrier density profile across p – i junction by ECV measurement.

initial increase in leakage current indicates increased production rate of deep levels in the investigated dose range with little to no effect on the Hall mobility in GaAs bulk material at low irradiation dose (<10 kGy).

The defects produced by irradiation such as gallium and arsenic vacancies and its interstitials form shallow and deep level states within the band gap depending upon their charge states [23]. However, the less stable shallow levels defects transform to more stable deep level defects at room temperature by changing their charge states or interacting with the impurities already present in the material, thus forming states that are more complex. The concentration of shallow and deep level defects increases with irradiation dose and after sufficiently higher dose, there are some shallow level present which contribute to the change in mobility. Since we carried out irradiation and subsequent measurements at room temperature, it is possible that at low radiation dose shallow defects got converted into more stable deep levels defects. As a result, we observed only leakage current increase in the device characteristics. However, at high radiation dose due to partial conversion of shallow to deep level defects we observed increase in leakage current as well as reduction in carrier mobility.

In order to verify the above possible mechanism, we use thermal treatment to anneal some of the defect states. Stein [31] has experimentally found two-step annealing, at which the mobility recovers. The first is around room temperature (300 K) and the other is around 570 K. Since our samples were kept at room temperature between irradiation and measurements, the first step of annealing has already been done. We annealed our samples at 300 °C (573 K) for 15 min in N_2 ambient and repeated all the measurements.

Figs. 6 and 7 show the experimental results for mobility and carrier concentrations of irradiated samples after annealing. As can be seen from Fig. 6 and Table 1, after annealing, mobility recovers considerably. Recovery in the carrier concentrations and compensation can also be seen from Fig. 7 and Table 1. It can be concluded that some of the shallow states, contributing to the carrier scattering get annealed. Consistent results were obtained from

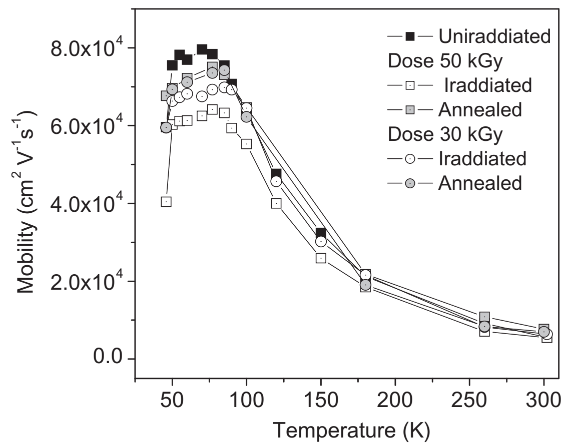

Fig. 6. Partial recovery of mobility upon thermal annealing at 300 °C for 15 min.

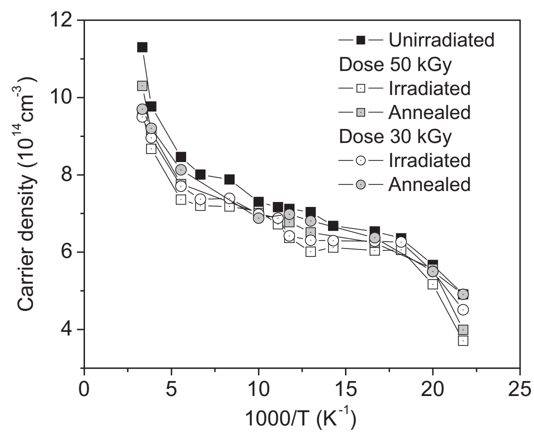

Fig. 7. Partial recovery of carrier concentrations upon thermal annealing at 300 °C for 15 min.

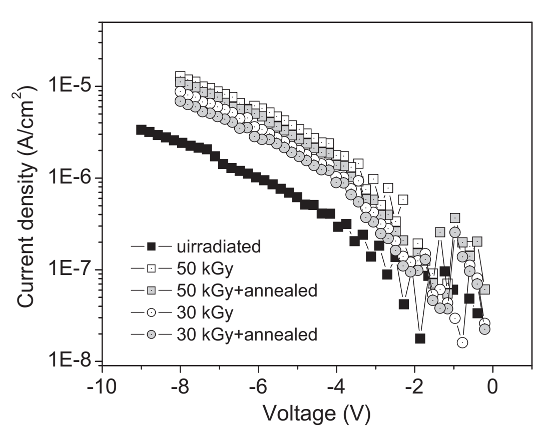

Fig. 8. A comparison of leakage current for unirradiated devices, irradiated devices and for the devices after irradiation and annealing.

PL measurement (Fig. 2), where the peaks related to defect levels get reduced. However, when we examine the effect of thermal annealing on leakage current, very little recovery was observed. (Fig. 8) This is an indication that while shallow levels get annealed at 300 °C, deep levels are not affected significantly. This suggests more stable deep levels are formed, which require larger annealing temperatures. Lim et al. [32] has observed by Differential Thermal Analysis (DTA) that in GaAs, around 420–480 °C some of the defects get annealed. These defects may be responsible for increase in leakage current in our case.

4. Conclusion

The carrier density, compensation, mobility, leakage current and radiation hardness value of ^{60}Co γ-ray irradiated epitaxial GaAs and GaAs p–i–n diodes were determined. Steady increase in leakage current with irradiation dose while threshold like behavior in mobility was observed. This is attributed to the rearrangement of defects and impurities at room temperature during irradiation. Radiation hardness value 4.7×10^{-19} A/cm $(\pm 2.1 \times 10^{-20}\ \mathrm{A/cm})$ of GaAs based p–i–n detectors suggest usability at higher dose range.

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