PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 74, No. 1
January 2010
pp. 97–107

I–V, *C–V* and deep level transient spectroscopy study of 24 MeV proton-irradiated bipolar junction transistor

K V MADHU, S R KULKARNI and R DAMLE*
Department of Physics, Jnanabharati, Bangalore University, Bangalore 560 056, India
*Corresponding author. E-mail: ramkrishnadamle@bub.ernet.in

MS received 22 June 2009; accepted 11 August 2009

Abstract. This paper describes the effect of 24 MeV proton irradiation on the electrical characteristics of a pnp bipolar junction transistor 2N 2905A. *I–V*, *C–V* and DLTS measurements are carried out to characterize the transistor before and after irradiation. The properties of deep level defects observed in the bulk of the transistor are investigated by analysing the DLTS data. Two minority carrier levels, $E_C - 0.27$ eV and $E_C - 0.58$ eV and one majority carrier level, $E_V + 0.18$ eV are observed in the base collector junction of the transistor. The irradiated transistor is subjected to isochronal annealing. The influence of isochronal annealing on *I–V*, *C–V* and DLTS characteristics are monitored. Most of the deep level defects seem to anneal out above 400°C. It appears that the deep level defects generated in the bulk of the transistor lead to transistor gain degradation. A comparison of proton- and electron-induced gain degradation is made to assess the vulnerability of pnp transistor as against npn transistors.

Keywords. Bipolar junction transistor; gain degradation; *I–V* and *C–V* characteristics; deep level transient spectroscopy; deep level defects; Shockley–Read–Hall recombination.

PACS Nos 71.55.-i; 72.20.Jv; 78.70.-g; 61.82.Fk

1. Introduction

The study of the effects of space radiation on semiconductor devices is important to assess the performance of devices in radiation-rich environments. Satellites and spacecrafts that fly in near-earth orbits (below 3.8 Earth radius) are extremely susceptible to radiation damage caused by the high flux of protons trapped in the Earth's magnetosphere [1]. Bipolar junction transistor (BJT) is an important semiconductor device used for space applications. BJTs are found to be particularly vulnerable to protons. In BJTs, the damage caused by the protons increases both bulk recombination and surface recombination and subsequently decreases transistor current gain [2]. Despite the fact that considerable efforts have been made by several groups to study the evolution of radiation damage in silicon bipolar junction transistors [3,4], it appears that no single model accounts for the mechanism of gain degradation.

The effect of ionizing radiation on vertical npn BJTs have been studied extensively. Vertical npn transistors exhibit significant gain degradation. However, it is assumed that vertical pnp transistors are relatively resistant to ionizing radiation, an observation, which is not very well established [5]. Further, it is interesting to compare the extent of gain degradation in BJT-exposed proton radiation as against electron-induced gain degradation. The effects of 8 MeV electron irradiation on pnp BJT 2N 2905A was studied and reported earlier by our group [6]. It was observed that the forward current gain (h_{FE}) of the transistor decreases considerably when irradiated by electrons with fluence of the order 10^{12} electrons cm^{-2} (which corresponds to a dose of 200 krad in silicon). Annealing of the transistor at 150°C for 2 h results in only marginal recovery of h_{FE}. The reported work also indicated that the pnp transistor degrades as much as the npn transistor of the similar family. In the present work, the radiation response of a pnp BJT 2N 2905A designed for space applications is studied. The BJT is exposed to 24 MeV protons and I–V, C–V and DLTS measurements are made to gather an insight into the mechanism of transistor gain degradation. An attempt is also made to compare the extent of gain degradation in pnp and npn transistors exposed to proton and electron beams.

Exposure of semiconductor devices to high energy particle radiation generates many defects. The nature of these defects depends on the properties of target as well as impinging particle. To investigate these defects, several techniques are in practice. Deep level transient spectroscopy (DLTS) is now an established technique for detecting and characterizing the defects in semiconductor devices. DLTS is a high-frequency capacitance transient thermal scanning method useful for observing a wide variety of traps in semiconductor devices [7]. This technique is capable of displaying the spectrum of traps in a crystal as positive and negative peaks on a flat base line as a function of temperature. From the analysis of DLTS spectrum, one can measure the activation energy, concentration profile and capture cross-section of the defects observed.

2. Experimental details

Commercial BJT 2N 2905A, pnp manufactured using indigenous technology by Continental Device India Ltd. (CDIL) have been selected for the present study. The transistor is exposed to 24 MeV protons at Inter University Accelerator Center, New Delhi in the biased condition (common emitter mode; collector–emitter voltage, $V_{\mathrm{CE}} = 10$ V and base current, $I_{\mathrm{B}} = 50$ μA).

Output characteristics of the transistor are studied at a constant base current (I_{B}) of 50 μA. The collector voltage (V_{CE}) is varied from -0.1 to 1 V in steps of 0.01 V. C–V characteristics of the base–collector junction of the transistors are studied by varying the base–collector voltage from 0 to 5 V in steps of 0.01 V. The spectra from DLTS are recorded for the collector–base junction of the transistor before and after irradiation. The DLTS system (IMS-2000, M/s. Lab Equip, India) employed for the present study consists of a boxcar averager, a pulse generator, a thousand point digitizer, a voltage generator and a high speed capacitance meter.

The pulse generator is capable of generating pulses of widths ranging from 100 ns to 10 s. The pulse height could be programmed from −12 to +12 V. The boxcar averager is capable of generating seven rate windows. The time constants can be varied from 1 ms to 2 s. In the present study, a reverse bias of 5 V is applied to the collector–base junction of the transistor. The filling bias voltage or pulse height is fixed at −5 V and the pulse width is fixed at 20 ms. DLTS signals corresponding to seven rate windows (fixed at 1.3, 3.3, 8.3, 20.8, 51.7, 127.9 and 312.7 s^{-1}) are obtained enabling construction of Arrhenius plots from a single temperature scan. The trap concentration, activation energy and capture cross-section of different deep levels are determined from DLTS spectra.

The irradiated transistor is subjected to isochronal (30 min) annealing. During isochronal annealing, the temperature is varied from 100 to 500°C in steps of 50°C and the I–V (current–voltage) and C–V (capacitance–voltage) characteristics of the transistor are studied at each temperature step. DLTS spectra are recorded at every step of annealing and the characteristics of several deep level defects are monitored.

3. Results and discussion

3.1 *I–V measurements*

Figure 1 exhibits the collector characteristics of the bipolar junction transistor irradiated with 24 MeV protons. It is observed that collector current of the transistor decreases by nearly an order of magnitude on irradiation. One important aspect of characterization of BJTs for radiation-induced effects is radiation-induced gain degradation. It is well-known that the transistor gain degradation can occur due to the generation of recombination centres in the base region due to displacement damage caused by irradiation. When recombination centres are generated in the base region of the transistor, it leads to an increase in the base current by decreasing the minority carrier lifetime [8,9]. A decrease in the minority carrier lifetime will be reflected in the degradation of forward current gain of the transistor. A comparison in the variation of forward current gain (h_{FE}) values of the transistor upon electron and proton irradiations is presented in table 1. The gain degradation seems to be significant in proton-irradiated transistor when compared to the electron-irradiated transistor.

Figure 2 exhibits the collector characteristics of the transistor at different isochronal annealing temperatures. Collector characteristics appear to improve to some extent after the isochronal annealing above 400°C. As a result, h_{FE} of the transistor recovers appreciably after annealing above 400°C. On the other hand, h_{FE} of the electron-irradiated transistor is found to recover only marginally even after annealing at 150°C for 2 h (reported earlier by our group, [6]). The fact that the gain of the transistor does not recover after annealing indicates that the gain degradation is predominantly due to displacement damage and surface recombination and total ionizing dose (TID) effect in the emitter–base region perhaps contribute little to gain degradation.

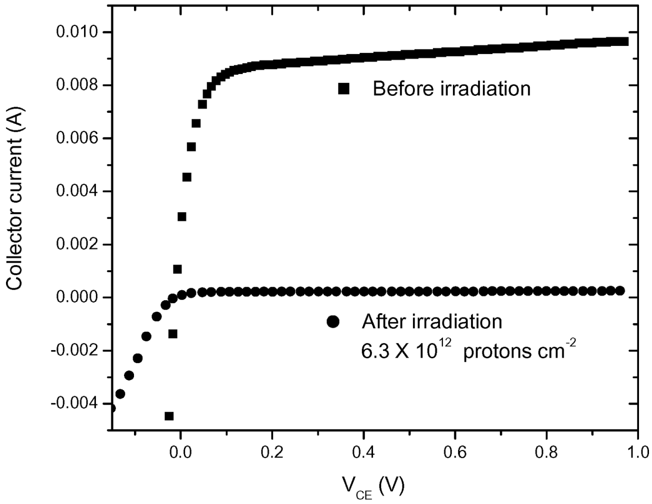

Figure 1. Collector characteristics of the transistor before and after the proton irradiation (at constant $I_B = 50$ μA).

Table 1. Forward gain of the transistor before and after irradiation.

		h_{FE}	
Transistor type	Type of irradiation	Before irradiation	After irradiation
2N 2905A, pnp	8 MeV electron	180 (at $V_{CE} = 0.55$ V)	80 (at $V_{CE} = 0.55$ V)
2N 2905A, pnp	24 MeV proton	180 (at $V_{CE} = 0.55$ V)	5 (at $V_{CE} = 0.55$ V)

The 24 MeV proton-induced gain degradation in npn transistor of the similar family (2N 2219A) reported earlier by our group [10] reveals that npn transistor undergoes considerable gain degradation due to displacement damage. A comparison of the gain degradation in the present pnp transistor indicates that the pnp transistor also undergoes as much degradation as that of npn transistor, which is an important observation.

3.2 *C–V measurements*

Figure 3 exhibits the capacitance–voltage (C–V) characteristics (a plot of $1/C^2$ vs. voltage) of the base–collector junction of the transistor before and after irradiation by protons. During the C–V measurement, the reverse bias is applied from 0 to -5 V in steps of -0.01 V. For the unirradiated device, the C–V curve is almost linear in the measured voltage range indicating the uniformity of shallow doping concentration. However, for the irradiated device, the curves deviate from the linearity. Similar signatures are observed by Giri and Mohapatra in Ar^+-ion implanted Schottky diodes [11]. Deep level defects generated in the base–collector junction

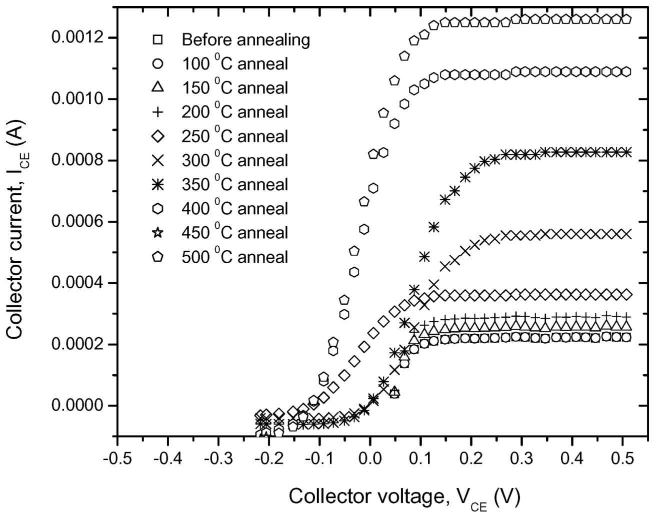

Figure 2. Collector characteristics of the proton-irradiated transistor after isochronal (30 min) annealing at different temperatures (at constant $I_{\mathrm{B}} = 50$ μA).

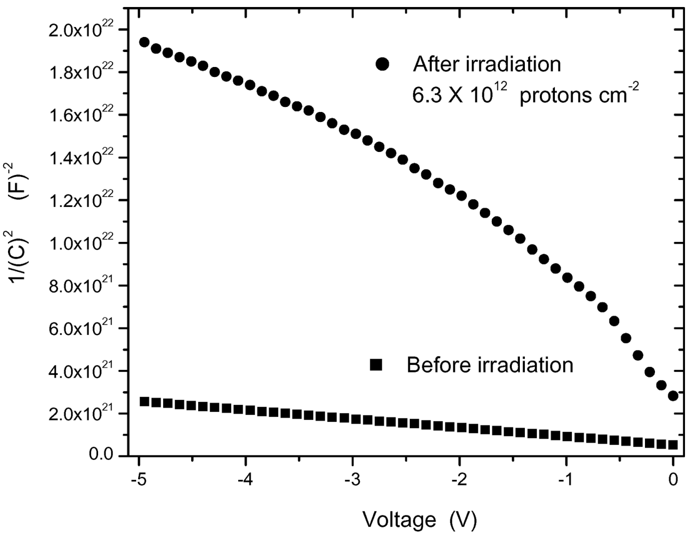

Figure 3. Capacitance–voltage characteristics of the base–collector junction of the transistor before and after proton irradiation.

reflect the nonlinearity of C–V curves [12]. Figure 4 shows the C–V characteristics of the transistor at different isochronal (30 min) annealing temperatures. The linearity of C–V characteristics appear to improve after annealing above 350°C.

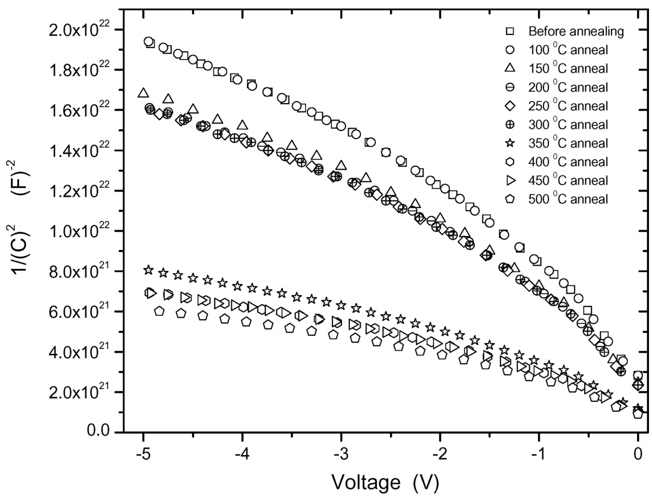

Figure 4. Capacitance–voltage characteristics of the base–collector junction of the proton-irradiated transistor after isochronal (30 min) annealing at different temperatures.

3.3 *DLTS measurements*

In principle, irradiation by any ion can damage transistors through both ionization and displacement. Ionization is a surface phenomenon. Displacement damage is a bulk phenomenon which results in the generation of several types of defects such as vacancy, interstitial, di-vacancy, Frenkel pair, vacancy–impurity complexes, namely, A-centre (V–O), E-centre (V–P), boron–carbon interstitial clusters and di-interstitial or higher-order complexes called D-centre [8].

The deep level defects generated by proton irradiation are characterized using DLTS technique. Figure 5 exhibits the DLTS spectrum of base–collector junction of the transistor before and after irradiation. Two minority carrier levels and one majority carrier level are observed in the DLTS spectrum. Activation energy (ΔE) and capture cross-section (σ) of the deep levels are calculated using the equation

$$\tau T^2 = \frac{\exp[(\Delta E)/kT]}{\gamma\sigma}. \quad (1)$$

In eq. (1), γ is the material coefficient and all other symbols have usual meaning [13]. A plot of $\ln(\tau T^2)$ vs. $1/T$ is known as the Arrhenius plot. The activation energy ΔE is obtained from the slope of the plot and the capture cross-section is obtained by extrapolating the plot on the y-axis. Figure 6 exhibits the Arrhenius plots of the observed deep level defects. The trap concentration, capture cross-section and introduction rate of all the deep level defects are calculated from the DLTS spectra and presented in table 2.

The recombination of electron–hole pairs at the defect levels generated upon displacement damage is the most important physical phenomenon responsible for the gain degradation. Mainly four kinds of recombination processes are observed in

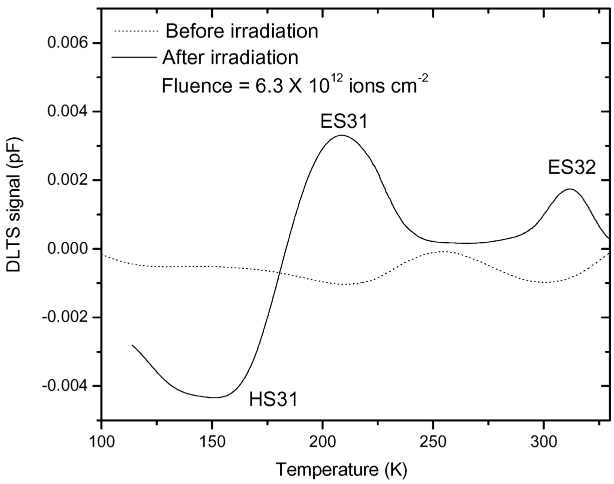

Figure 5. DLTS spectrum of 24 MeV proton-irradiated transistor. Rate window is fixed at 51.7 s^{-1}.

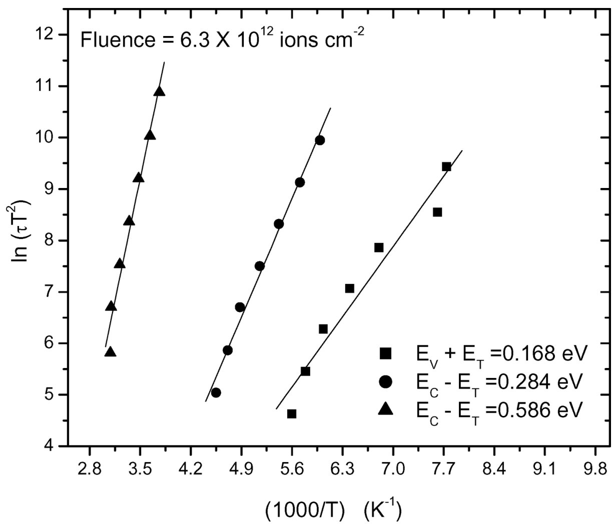

Figure 6. Arrhenius plots for the 24 MeV proton-irradiated transistor.

semiconductor devices: (i) Shockley–Read–Hall (SRH) or multi-phonon recombination, (ii) radiative recombination, (iii) Auger recombination and (iv) non-radiative recombination [13]. Radiative recombination is important in direct band gap semiconductors like GaAs. Auger recombination is observed in either direct or indirect band gap semiconductors when the carrier concentration is high. Further, the radiative, non-radiative and Auger recombination lifetimes are independent of trap concentration [13]. SRH recombination is particularly important in indirect band gap semiconductors such as Si [14–18]. SRH recombination lifetime (for low level injection) is calculated using the equation

Table 2. Data obtained from DLTS analysis of the 24 MeV proton-irradiated transistor.

Proton fluence (ions cm^{-2})	Defect label	Activation energy (±0.01 eV)	Trap concentration (cm^{-3})	Crop cross-section (cm^2)	Introduction rate η (cm^{-1})	Recombination lifetime (s)	Defect type	Comparison with reported defect in the literature: Defect (eV)	Ref.
	HS31	$E_V + 0.17$	8.4×10^{12}	1.75×10^{-24}	1.36×10^3	8.08	(V–I) complex	$E_V + 0.18$	[19]
6.3×10^{12}	ES31	$E_C - 0.28$	5.9×10^{12}	8.85×10^{-18}	9.52×10^2	2.07×10^{-6}	(V–O–B) complex	$E_C - 0.27$	[20]
	ES32	$E_C - 0.59$	3.5×10^{12}	1.22×10^{-15}	5.72×10^2	2.01×10^{-8}	Interstitial cluster	$E_C - 0.58$	[21]

(V–I) complex: (vacancy–impurity) complex.
(V–O–B) complex: (vacancy–oxygen–boron) complex.

$$\tau_{\text{SRH}} = \frac{1}{\sigma_n v_{\text{th}} N_{\text{T}}}, \tag{2}$$

where σ_n is the minority carrier capture cross-section, ν_{th} is the thermal velocity of the carriers and N_{T} is the total trap concentration. Similarly, the radiative recombination lifetime is given by

$$\tau_{\text{rad}} = [B(p_0 + n_0 + \Delta n)]^{-1}, \tag{3}$$

where B is the radiative recombination coefficient (for Si, $B \sim 10^{-14}$ cm^3 s^{-1}), p_0 is the equilibrium majority carrier concentration, n_0 is the equilibrium minority carrier concentration and Δn is the excess minority carrier concentration. Auger recombination lifetime is given by

$$\tau_{\text{Auger}} = [c_p(p_0^2 + 2p_0\Delta n + \Delta n^2) + c_n(n_0^2 + 2n_0\Delta n + \Delta n^2)]^{-1}, \tag{4}$$

where c_p and c_n are Auger recombination coefficients (for Si, c_p, $c_n \sim 10^{-31}$ cm^6 s^{-1}). Both Auger and radiative recombination can occur through intermediate levels but are dominant only in direct band gap semiconductors [13]. These recombination mechanisms are utilized in light-emitting phosphors where semiconductors like CdS are deliberately doped with impurities of a particular kind to generate light of particular wavelength. Since SRH recombination depends on trap concentration, it appears to be more predominant in our case. The values of SRH recombination lifetimes calculated using DLTS data and eq. (2) are tabulated in table 2.

The transistor is subjected to isochronal annealing and the characteristics of each defect are monitored by recording DLTS spectra. Figure 7 exhibits the variation of concentration of different deep level defects as a function of isochronal (30 min) annealing temperature. The total defect concentration decreases and the effective recombination lifetime increases with an increase in isochronal (30 min) annealing

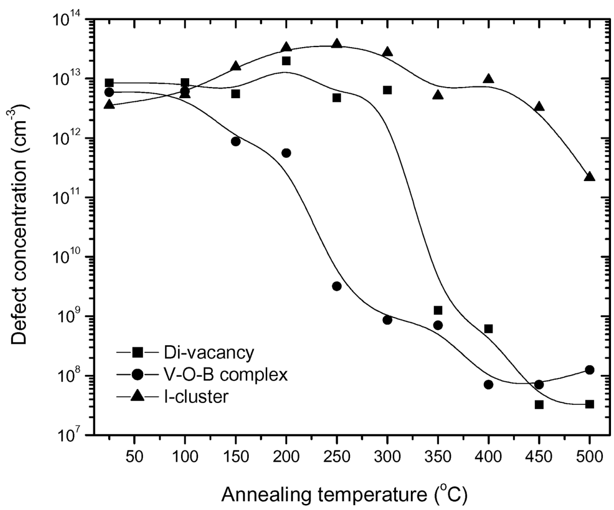

Figure 7. Variation of defect concentration as a function of isochronal (30 min) annealing temperature in the proton-irradiated transistor.

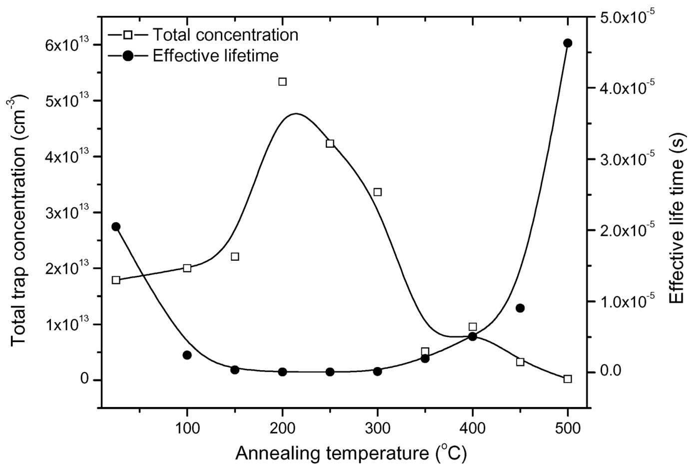

Figure 8. Variation of total trap concentration and effective lifetime as a function of isochronal (30 min) annealing temperature in the proton-irradiated transistor.

temperature as shown in figure 8. A study of change in defect concentration with annealing temperature is useful in determining the type of defects. The identification of the defect type is made on the basis of their fingerprints such as activation energy, annealing temperature and capture cross-section by comparing with those reported in the literature [19–21]. Table 2 depicts the defect type, identification of the defect type by comparison with literature and the data obtained from DLTS analysis.

4. Conclusions

Commercial pnp BJT 2N 2905A undergoes gain degradation upon irradiation by 24 MeV protons due to displacement damage in the base region of the transistor. The gain degradation is significant when compared to 8 MeV electron-induced degradation. The pnp transistor appears to degrade as much as its npn counterpart. Isochronal annealing of the proton-irradiated pnp transistor leads to appreciable recovery of h_{FE}. On the other hand, the gain of the 8 MeV electron-irradiated transistor recovers only marginally after annealing at 150°C. This would indicate that the surface recombination and TID effect perhaps contribute little to gain degradation in electron-irradiated transistor. DLTS studies show that the defects anneal above 350°C. The defects generated in the base region of the transistor by displacement damage appear to be responsible for an increase in base current through SRH or multiphonon recombination and consequent transistor gain degradation.

Acknowledgements

One of the author (K V Madhu) thanks UGC-IUAC for a fellowship to carry out the present work. Financial support in the form of ISRO-RESPOND research project is acknowledged. The authors thank Dr V Pandian of M/s. Lab Equip. for many helpful discussions.

References

[1] E G Stassinopoulos and J P Raymond, *Proc. IEEE* **76**, 1423 (1988)
[2] A H Johnston and R E Plaag, *IEEE Trans. Nucl. Sci.* **NS-34**, 1474 (1987)
[3] G P Summers, E A Wolicki, M A Xapsos, P Marshall, C J Dale, M A Gehlhauen and R D Olice, *IEEE Trans. Nucl. Sci.* **NS-33**, 1282 (1986)
[4] H J Barnaby, R D Schrimpf, A L Sternberg, V Berthe, C R Cirba and R L Peace, *IEEE Trans. Nucl. Sci.* **48**, 2074 (2001)
[5] R N Nowlin, E W Enlow, R D Schrimpf and W E Combs, *IEEE Trans. Nucl. Sci.* **39**, 2026 (1992)
[6] S R Kulkarni, M Ravindra, G R Joshi and R Damle, *Nucl. Instrum. Methods* **B251**, 157 (2006)
[7] D V Lang, *J. Appl. Phys.* **45**, 3023 (1974)
[8] J R Srour, J M Cheryl and P W Marshall, *IEEE Trans. Nucl. Sci.* **50**, 653 (2003)
[9] S D Brotherton and P Bradley, *J. Appl. Phys.* **53**, 5720 (1982)
[10] S R Kulkarni, Asiti Sharma, G R Joshi, M Ravindra and R Damle, *Radiat. Eff. Defect. Solids* **158**, 647 (2003)
[11] P K Giri and Y N Mohapatra, *J. Appl. Phys.* **84**, 1901 (1998)
[12] L C Kimerling, *J. Appl. Phys.* **45**, 1839 (1974)
[13] D K Schroder, *Semiconductor material and device characterization* (John Wiley, 1990) pp. 309 and 361–362
[14] K Watanabe and C Munakata, *Semicond. Sci. Technol.* **8**, 230 (1993)
[15] J C Pickel, A H Kalma, G R Hopkinson and C J Marshall, *IEEE Trans. Nucl. Sci.* **50**, 671 (2003)
[16] A Hangleiter, *Phys. Rev.* **B35**, 9149 (1987)
[17] W Shockley and W T Read, *Phys. Rev.* **87**, 835 (1952)
[18] V K Khanna, *Eur. J. Phys.* **25**, 221 (2004)
[19] W H Marcel, *J. Appl. Phys.* **68**, 2702 (1990)
[20] P M Mooney, L J Cheng, M Suli, J D Gerson and J W Corbett, *Phys. Rev.* **B15**, 3836 (1977)
[21] J L Benton, K Halliburton, S Libertino and D J Eaglesham, *J. Appl. Phys.* **84**, 4749 (1998)