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Recombination-Defect Reaction in InP P^+-N Junctions

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The annealing behaviors of a specific electron trap induced by room-temperature gamma-ray irradiation at E_c-0.79 eV in LEC n-InP have been investigated in comparison with those of radiation-induced defects in GaAs. The E_c-0.79 eV trap anneals rather rapidly at not-elevated temperatures near room temperature through the first order process with the activation energy of 0.98 eV; this feature is in contrast with that of radiation-induced defects in GaAs. The recombination-enhanced annealing of the specific trap is clearly observed only at forward current densities exceeding 8 A/cm^2. The small recombination rate at the E_c-0.79 eV trap is possibly the main cause of an observed weak recombination enhancement in InP.

§1. Introduction

The rapid and gradual degradations in the performance of light emitting diodes (LED's) and lasers of GaAs, GaP, InP and their alloys are observed only under operation at high forward current densities. It is convinced that "phonon kick" mechanism due to a vibrational energy emitted at defects during nonradiative recombination transition is the main cause of such degradations. Moreover, it is generally recognized that lasers and LED's made of GaAs, GaP and their alloys sometimes show failures in the rapid degradation mode originating from dislocation multiplications under intense recombination levels while in InP and narrow gap InGaAsP devices only gradual degradations are observed. From this experimental and rather empilical fact it is believed that the magnitude of the vibrational energy emitted during nonradiative carrier capture at defects or, more generally, the magnitude of the energy gap is responsible for this distinguished difference. In fact, Ettenberg and Nuese[1] have observed that the average life of LED's fabricated from ternary alloys of the InGaAsP family increases roughly exponentially with decreasing energy gap. However, this explanation is not explicitly clear-cut because the values of the energy gap of GaAs (1.43 eV[2]) and InP (1.34 eV[3]) are not significantly different from each other. It seems not to be satisfactory to understand the difference in the degradation characteristics between GaAs and InP devices only in terms of the energy gap.

Yamakoshi et al[4] have investigated the temperature accelerated degradation of InGaAsP LED's and found the activation energy for the homogeneous (gradual) degradation mode to be 1.0 eV which is much larger than that (0.56 eV) for AlGaAs LED's. Moreover, they observed that threading and misfit dislocations, which act as efficient nonradiative recombination centers in GaAs and AlGaAs, are not so in InP and InGaAsP. An inefficiency of dislocations for nonradiative recombination has been also observed in bulk InP by Maeda and Takeuchi.[5]

In order to clarify the nature of the difference in the degradation characteristics between GaAs and InP injection devices and to simulate the homogeneous degradation process in them, the annealing behaviors of gamma-ray induced defects in n-InP were investigated. We will discuss the thermal and recombination-enhanced annealings of a particular electron trap at E_c-0.79 eV in InP p^+-n junctions in comparison with the case of GaAs and GaAsP.[6]

§2. Experimental

P^+-n junctions of InP were fabricated by thermal diffusion of Cd from Cd_3P_2 source to LEC undoped n-type crystals ($n=2.5\times10^{16}$ cm^{-3}). The thermal diffusion was made at 550 $^\circ$C for 30 min. Ohmic contacts to n- and p-regions were prepared by alloying with Au-Ge-Ni and Au-Zn, respectively. After mounting onto TO-5 headers and wiring by silver paint with a high curing temperature, the diodes were irradiated with gamma-ray from ^{60}Co at room temperature. The gamma-ray flux was 10^6 rö/ hr·cm^2 and the ambient temperature during the irradiation was at most 30 ^oC. The total dose was 1-1.5x10^8 rö/cm^2 which corresponds to 2-3x10^{16} photons/cm^2. DLTS technique was used to monitor the behaviors of a specific trap. Before irradiation, no traps were detected. However, after irradiation with 2x10^{16} photons/cm^2, a dominant electron trap was clearly introduced as shown in Fig. 1 which depicts DLTS signals measured at various values of the rate window. From Fig. 1, the depth of the dominant electron trap and the capture cross section σ_∞ are determined to be E_c-0.79 eV and 4.12 x10^{-12} cm^2, respectively. The introduction rate of the trap at E_c-0.79 eV was estimated to be about 0.05 cm^{-1}; this value can be compared with those observed for 1 MeV electron-induced traps.[7,8]

The behaviors of the dominant E_c-0.79 eV electron trap are described in the next section.

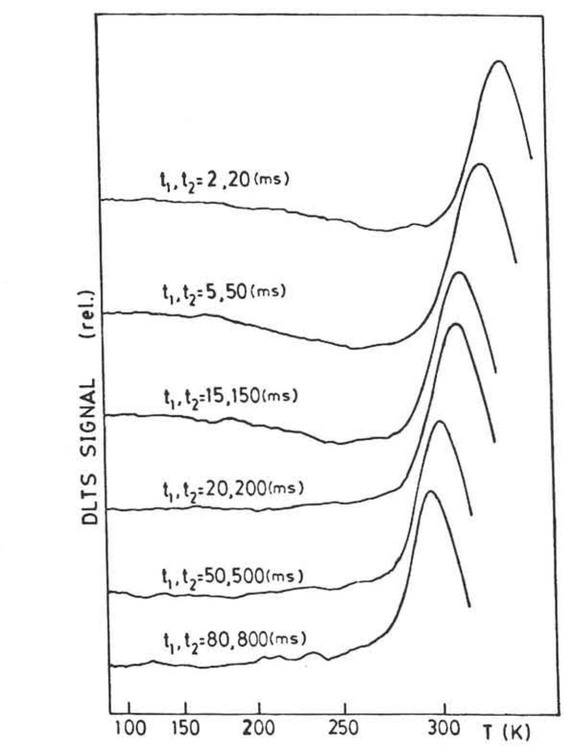

Fig. 1 Transient capacitance spectra of an as-irradiated sample at various rate windows.

§3. Results and Discussion

In spite of the situation that the irradiation for 100-150 hrs was done at room temperature, the introduced defects at E_c-0.79 eV were not fully stable even at room temperature and anneals gradually during storage. The isothermal annealing experiment at temperatures ranging from 50 to 80 ^oC revealed the recovery process of this defect to be the first-order reaction as shown in Fig. 2, where the unannealed fraction is defined as the ratio of the defect density in the annealed sample to the as-irradiated one.

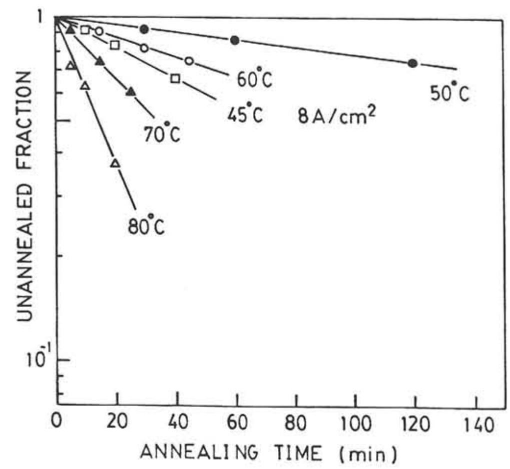

Fig. 2 Isothermal annealing characteristic of the E_C-0.79 eV trap without and with the forward current.

The annealing rate constant λ determined from the slope of the straight lines in Fig. 2 is plotted in Fig. 3. The pre-exponential factor λ_0 and the activation energy E_A in the relation $\lambda = \lambda_0 \exp[-E_A/kT]$ can be estimated to be 8.84x 10^{10} s^{-1} and 0.98 eV, respectively,[9] from Fig. 3. For comparison the thermal annealing behavior of the E3 electron trap in gamma-ray irradiated GaAs [6] is shown together in Fig. 3. The values of E_A and $_0$ for the E3 trap in GaAs are 1.34 eV and 10^{12} s^{-1}, respectively. The isochronal annealing stage corresponding to the recovery of the E3 trap in GaAs locates roughly at 250 ^oC, showing an annealing temperature considerably higher than that for the E_c-0.79 eV trap in InP.

The recombination-enhanced annealing effect was studied by applying a forward bias at temperatures between 50 to 20 ^oC. At forward current densities below 5 A/cm^2, no enhancement of the annealing exceeding the purely thermal process

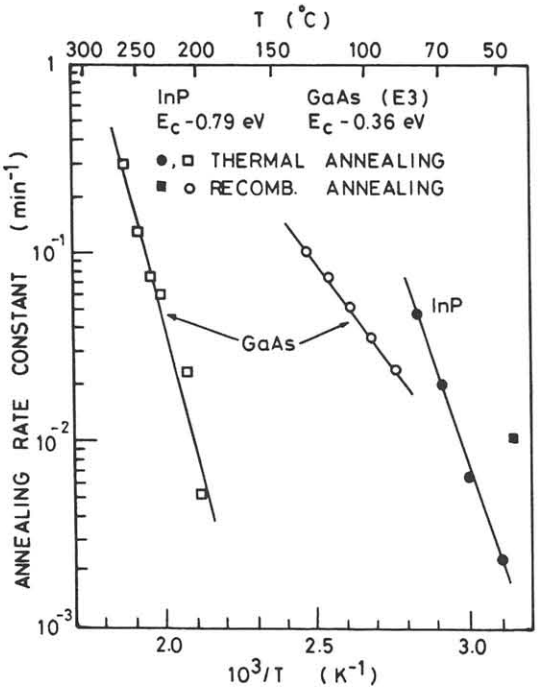

Fig. 3 Temperature dependence of the annealing rate constant for the E_C-0.79 eV trap in InP (,) and the E3 trap in GaAs (,). Recombination-enhanced annealing constant of the E3 trap in GaAs was measured at 1 A/cm^2, while the E_C-0.79 eV trap in InP at 8 A/cm^2.

was observed. However, when the forward current density was increased over 8 A/cm^2, an occurrence of the enhanced annealing was found. This result is in clear contrast with the case of defects in GaAs; for instance the annealing of the E3 trap can be remarkably enhanced by the assistance of the forward current of only 1 A/cm^2.[6)] To estimate the actual junction temperature at the high forward current density of 8 A/cm^2, the peak position of the edge emission spectrum at room temperature was measured as function of forward current density. When the forward current was increased over 4 A/cm^2, the edge emission peak began to move to lower energies due to Joule heating at the junction. By refering the report on the temperature dependence of the edge emission peak,[10)] we were able to estimate the actual junction temperature at 8 A/cm^2 to be 45 °C. As seen in Figs. 2 and 3 the occurrence of the enhanced annealing is evident at 8 A/cm^2. The enhancement of about factor five is achieved in this case.

As to the reason for the significant difference in the enhanced annealing characteristic of radiation-induced defects between InP and GaAs, the following possibilities can be considered.

(a) Lower nonradiative recombination rate in InP than in GaAs.

(b) Lower efficiency of the energy transfer between electronic transition process and atomic motion in InP than in GaAs.

The observation[4,5)] that dislocations in InP and InGaAsP are not efficient recombination centers suggests the first possibility. At low injection levels the recombination rate R for an electron trap in n-type materials is proportional to the forward current density J and is given as

$$R = \sigma_p v_p p \qquad (1)$$

where σ_p is the hole capture cross section, v_p the thermal velocity of holes and p the density of the injected holes. The hole density p is given by the relation

$$p = \gamma J L_p / q D_p \qquad (2)$$

where L_p and D_p are the diffusion length and the diffusion constant of holes respectively, q the electronic charge and γ the injection efficiency. Furthermore, the nonradiative lifetime τ_{NR} for the trap is

$$\tau_{NR} = (\sigma_p v_p N_t)^{-1} \qquad (3)$$

where N_t is the density of the trap corresponding to the E_c-0.79 eV trap in our case. If we assume that the recombination process is governed only by radiative process (τ_R) and nonradiative transition at the E_c-0.79 eV trap (τ_{NR}), the emission intensity L under hole injection can be expressed simply as

$$L = L_0 \tau_{NR}/(\tau_R + \tau_{NR}) \qquad (4)$$

where L_0 is the emission intensity in the sample free of the trap. The measurements of the electroluminescence intensity for samples irradiated (total dose=$1.5x10^8$ rö/cm^2, $N_t=1.5x10^{15}$ cm^{-3}) and annealed-out ones gave L/L_0 =0.68 and then τ_{NR}/τ_R =2.1 from eq. (4). In order to estimate the recombination rate R, we have to know the capture cross section for holes σ_p of the E_c-0.79 eV trap. However, since the value is not known at present unfortunately, we assume tentatively τ_R to be 10^{-6} s.[11)] This value gives a reasonable value for σ_p; i.e. using eq. (3), τ_{NR}/τ_R =2.1, N_t=1.5x 10^{15} cm^{-3} and $v_p=10^7$ cm/s, we obtain $\sigma_p=3.2x10^{-17}$ cm^2 at room temperature. Moreover, assuming D_p= 1.3 cm^2/s (μ=500 $cm^2/V\cdot s$) and γ=1, the recombination rate R at 1 A/cm^2 is $4.2x10^6$ s^{-1} for the

E_c-0.79 eV trap in n-InP. On the other hand, for the E3 electron trap in GaAs (N_t=7x10^{14} cm^{-3}) the recombination rate at 1 A/cm^2 is about 2.3x10^7 s^{-1} at 100 ^{o}C.[12,13] This difference in the recombination rate at the same forward current density for the E_c-0.79 eV trap in InP and the E3 trap in GaAs is consistent with the experimental observation of the recombination-enhanced annealing (Fig. 3). Although the second possibility (b) could be checked in principle by measuring the enhanced annealing under the same recombination conditions, it is not easy at present because the detailed structures of the defects are not known.

In summary, we investigated the annealing behaviors with and without forward current on a specific electron trap at E_c-0.79 eV in gamma-ray irradiated InP p^+-n junctions from the point of view of clarifying the difference in the degradation mode between InP and GaAs injection devices. The following two points are significant.

(i) The E_c-0.79 eV electron trap can easily anneal at temperatures at which actual devices are in operation. This may suggest that the easiness of migration of point defects prevent the rapid pile-up of complex defects which are responsible for the homogeneous degradation.

(ii) Recombination enhancement of defect annealing in InP is much weaker than that in GaAs. The recombination rate for the E_c-0.79 eV electron trap in InP is almost an order of magnitude lower than that for the E3 electron trap in GaAs at the same forward current density.

These two peculiar features of defects in InP are responsible for the difference in the degradation characteristics between InP and GaAs.

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