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Electron traps in GaAs:Sb grown by liquid phase epitaxy

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Deep level transient spectroscopy studies of GaAs:Sb layers, grown by liquid phase epitaxy reveal the existence of two electron traps with activation energies of 0.4 and 0.54 eV. High temperature annealing of the material reduced the density of the former trap while that of the latter is increased substantially. Density of the 0.54 eV trap is also found to be controlled by the Sb content in the material. These two results, together with the obtained signature of the 0.54 eV trap, suggest that it is the same as the Sb_{Ga} related electron trap observed previously in GaAs:Sb materials grown by other techniques. Annealing increases the density of this trap by creating more Sb_{Ga} defects as a consequence of Ga out-diffusion from the material. Photocapacitance measurements indicate the presence of a 0.75 eV electron trap in the annealed layers, which is identified with the second charge state of the Sb_{Ga} electron trap. © *1995 American Institute of Physics.*

I. INTRODUCTION

Recent studies on GaAs, doped with antimony (Sb) have shown that the material contains an electron trap whose origin is directly related to Sb. The properties of this trapping center have been investigated quite extensively using Hall effect and photoluminescence (PL)[1], electron paramagnetic resonance (EPR),[2,3] photo-EPR,[4] deep level transient spectroscopy (DLTS),[5,6] and photocapacitance[7] techniques. These studies reveal that the observed level has the properties of a double donor[2] with its two charge states located at about 0.5 and 0.7 eV below the conduction band.[6,7] It is also more or less confirmed that the origin of the electron trap is the antisite defect, Sb_{Ga}.[2,4] This electron trap has so far been observed in bulk crystals grown by liquid encapsulated Czochralski (LEC) technique[1–4,6] and in epitaxial layers grown by metalorganic vapor phase epitaxy (MOVPE).[5,7] In both the techniques, growth is done under arsenic-rich conditions favoring the formation of Ga-vacancies which, in turn, may support the generation of Sb_{Ga} defects. We have grown GaAs:Sb layers under gallium-rich conditions using liquid phase epitaxy (LPE) and investigated the traps present in the material using DLTS and photocapacitance techniques. An electron trap, with properties similar to that of the Sb-related trap discussed above, has been detected in the material whose concentration is found to increase in layers subjected to a high temperature post-growth anneal. The details of our experiments, results, and the conclusions derived are presented in this paper.

II. EXPERIMENT

A. Materials growth

GaAs layers with thickness in the range 8–10 μm, were grown on semiinsulating GaAs substrates in a conventional sliding boat LPE system. Details of our growth system and the growth procedure were published elsewhere.[8] Sb metal of 99.9999% purity obtained from Johnson-Matthey Chemicals, U.K., was added to the growth melt for doping the layers. The resultant concentration of Sb in the layer material was determined by secondary ion mass spectroscopy (SIMS) technique. An estimate of the Sb content in the more heavily doped materials was also obtained by using low temperature PL techniques.[9] For Sb concentration exceeding 10^{20} cm^{-3}, faint cross-hatched patterns started appearing on the layer surface indicating increased lattice mismatch at the layer-substrate interface. Van der Pauw–Hall measurements confirmed that the material is n-type with free carrier concentration in the range $(1-3)\times10^{15}$ cm^{-3} and 77 K Hall mobility around 30 000 cm^2 V^{-1} s^{-1}. The material was found to be fully stoichiometric within the resolution of the SIMS technique and the major electrically active impurities were detected as oxygen, silicon, and carbon.

B. Annealing and test device fabrication

Each test sample was cut into two pieces and one of the pieces was subjected to an anneal at 800 °C for 1 h under ultrapure hydrogen flow in the LPE furnace with the sample placed into one of the wells of the graphite boat with a graphite cover on top. Thermal decomposition of the layer surface during annealing was reduced by using GaAs proximity caps. No change in the carrier concentration or the type was noticed in the material after annealing.

Schottky-barrier diodes were fabricated on the cleaned surface of the layer by evaporating semi-transparent gold dots of diameter 0.5 mm in a Varian electron beam system under a vacuum of 10^{-8} Torr. Gold evaporation was made on both the unannealed and the annealed samples in the same run. Alloyed In-Sn ohmic contacts were formed in the proximity of the gold dots.

C. DLTS measurements

The test device was mounted on the cold finger of an APD Cryogenics Displex closed cycle helium cryogenic system. Temperature scan of the device was made in the range 100–300 K. For measurements above 300 K, the device was

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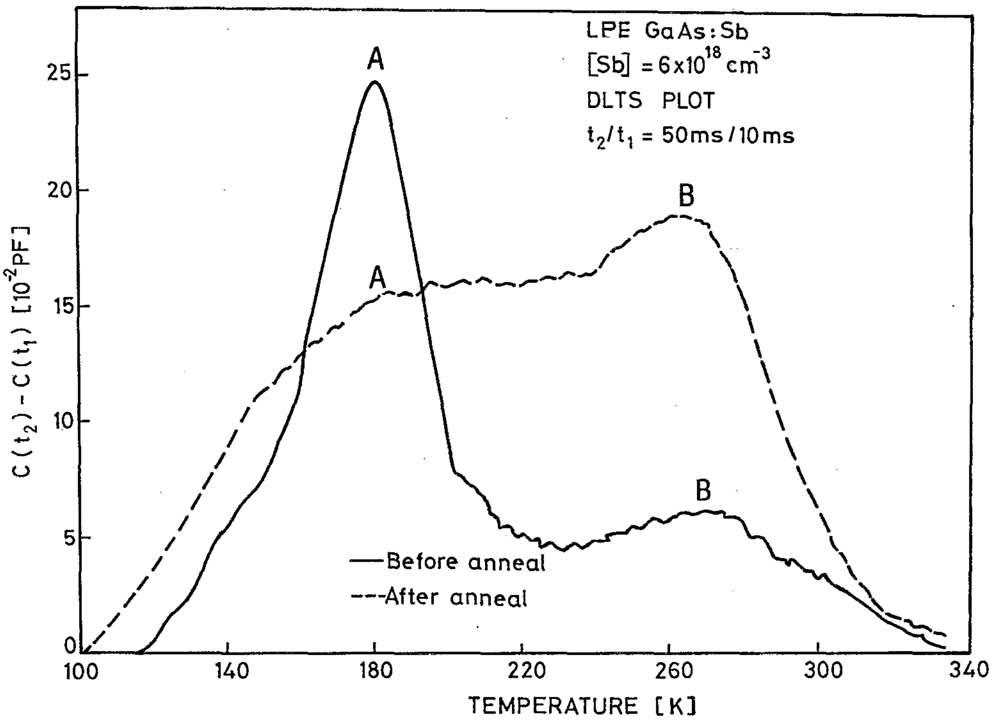

FIG. 1. DLTS plot of electron traps in as-grown and annealed LPE GaAs layers with moderate Sb doping.

mounted on a separate jig, provided with a heater and a thermocouple. The DLTS measurement setup was implemented using a HP 4280A 1 MHz C-V meter, controlled by a HP 9000/836 computer. Individual capacitance transients at different temperatures were recorded in the computer and the necessary analysis was done under software control.

D. Photocapacitance measurements

Photocapacitance measurements were done at 10 K with the test device mounted on the Displex cryostat. The optical system consisted of an Oriel 1/4-meter grating monochromator with a stabilized xenon arc lamp source. Appropriate filters were used at the output end of the monochromator to block the higher order light from the grating. Light was allowed to fall on the Schottky junction through the quartz window of the cryostat and the semitransparent gold metallization. Steady-state photocapacitance spectra were recorded in the photon energy range of 0.62–1.26 eV. In all experiments, the diode was held at a reverse bias of -1 V.

III. RESULTS

A. DLTS

Figure 1 shows the deep level spectra for a GaAs:Sb layer with an Sb concentration of 6×10^{18} cm^{-3}, taken before and after annealing. The spectrum for the as-grown sample shows a sharp peak at around 175 K corresponding to the presence of an electron trap A. A second weak and broad peak is observed at about 265 K which may be due to another electron trap B. After annealing, the height of peak A is reduced and it merges into a broad DLTS spectrum in which the most prominent feature is the peak due to trap B. We repeated the experiment with a layer having higher Sb-doping of 2×10^{19} cm^{-3}. The DLTS trace for the as-grown sample, as is seen from Fig. 2, is quite broad with a single peak due to trap A. There is also a weak shoulder at about 260 K, which may again be due to trap B. As in the case of the moderately doped material, annealing reduced the concentration of trap A whereas that of trap B is enhanced. Arrhenius plots for traps A and B were constructed by careful analysis of the capacitance transients and are presented in Fig. 3. Activation energies of the traps together with their capture cross-sections, extracted from the prefactors of the Arrhenius plots, are also indicated in Fig. 3. Trap concentrations in various samples are measured from the height of the corresponding DLTS peaks and are listed in Table I. It is evident that the concentration of trap A does not depend on the density of Sb in the material, whereas that of trap B is significantly increased in the material with higher Sb doping.

B. Photocapacitance

Steady-state photocapacitance measurements were performed on the same samples used in DLTS measurements. The results are presented in Figs. 4 and 5. The as-grown layer in Fig. 4 shows an initial fall in photocapacitance due to the presence of hole traps in LPE GaAs,[10] followed by a steady rise starting at about 0.9 eV. This capacitance rise is attributed to the complementary transitions from the same hole traps. For the annealed sample, however, there is an additional increase of capacitance at about 0.75 eV, indicat-

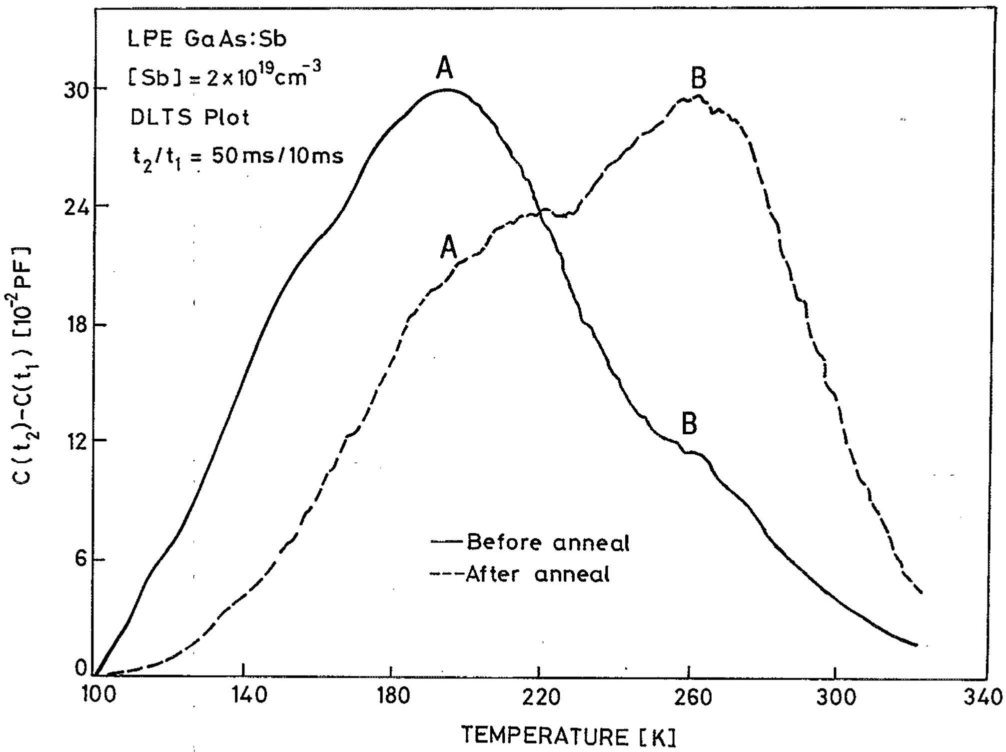

FIG. 2. DLTS plot of electron traps in as-grown and annealed LPE GaAs layers with high Sb doping.

ing emission from an electron trap with a photoionization energy of the same value. Similar behavior of the photocapacitance data is observed more prominently in Fig. 5 for the layer with higher Sb-doping.

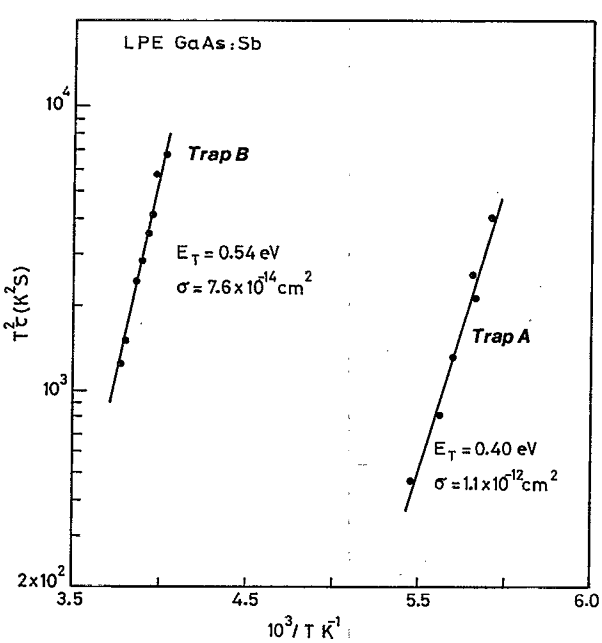

FIG. 3. Arrhenius plots of electron traps in LPE GaAs:Sb.

IV. DISCUSSION

From the signature of the electron trap A in Fig. 3, we can identify it with the electron trap EB6 or E3, previously found in electron-irradiated LPE GaAs.[11] However, there is no previous report regarding the existence of this trap in as-grown LPE GaAs. Origin of the trap is believed to be due to defects or complexes arising out of crystallographic disorders existing in the material, which explains the reduction of the density of the same upon annealing.

Electron trap B shows two distinctly observable properties. First, the concentration of this trap is increased with that of Sb in the material. Secondly, annealing of the material at high temperatures increases the concentration of trap B. In an earlier experiment,[12] an electron trap with properties similar to that of the well-known trap EL2 was created in molecular beam epitaxial (MBE) GaAs by high temperature annealing under Si_3N_4 cap. This result was explained by assuming the out-diffusion of Ga atoms from the layer material to the Si_3N_4 cap, with the subsequent formation of As_{Ga} defects at the vacant Ga sites which are believed to be the

TABLE I. Concentration of electron traps in LPE GaAs:Sb layers.

Sb doping density (cm^{-3})	Concentration of trap A (cm^{-3})		Concentration of trap B (cm^{-3})	
	Before anneal	After anneal	Before anneal	After anneal
6×10^{18}	1.7×10^{13}	9×10^{12}	4×10^{12}	1.2×10^{13}
2×10^{19}	1.8×10^{13}	1.2×10^{13}	6×10^{12}	1.7×10^{13}

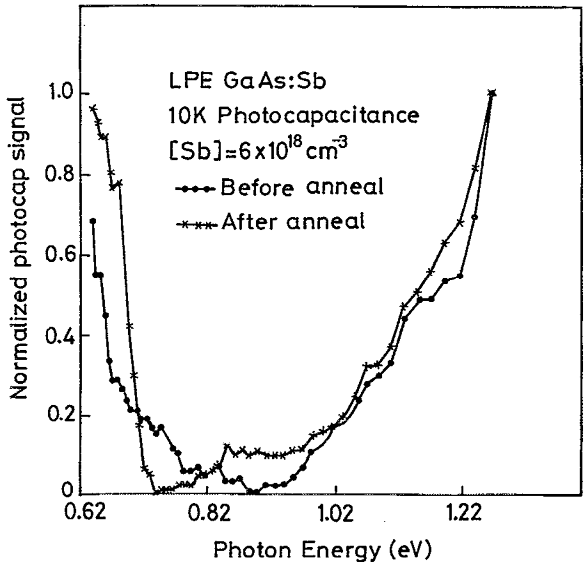

FIG. 4. Steady state photocapacitance spectra of the samples whose DLTS data are shown in Fig. 1.

source of EL2. Similar results were obtained by other workers on furnace annealed[13] and on rapid thermal annealed (RTA)[14] MBE GaAs and the phenomenon was ascribed to the high thermal stress at the semiconductor-dielectric interface during thermal annealing. The Ga out-diffusion model has been recently confirmed by Katayama *et al.*[15] by their RTA experiments on SiO_2-coated bulk GaAs wafers and they indicate that interfacial thermal stress actually enhances the out-diffusion of Ga. The similarity between the results of the above experiments and that of ours is that we are also generating trap *B* by furnace anneal although its signature is very much different from that of EL2. The measured signature of trap *B* and its relation with Sb concentration in the material suggests that it is the same as the Sb_{Ga}-related electron trap obtained previously in MOVPE-grown GaAs:Sb.[5] Formation of this defect is not, in general, favored in LPE GaAs, grown under Ga-rich conditions. This is consistent with the observed low density of trap *B* in our samples, prior to annealing. Anneal-induced out-diffusion of Ga will facilitate the formation of Sb_{Ga}, much in the same way as that of As_{Ga} defects in annealed MBE GaAs layers and the concentration of trap *B* will increase. However, simultaneous generation of EL2 is not observed in our experiments since according to Ref. 2, Sb, because of its much higher affinity towards Ga-vacancies, forms Sb_{Ga} defects at the expense of As_{Ga}. Further, from the experimental results of Wada and Inoue,[16] we may note that the loss of As near the surface of GaAs during annealing decreases the concentration of EL2.

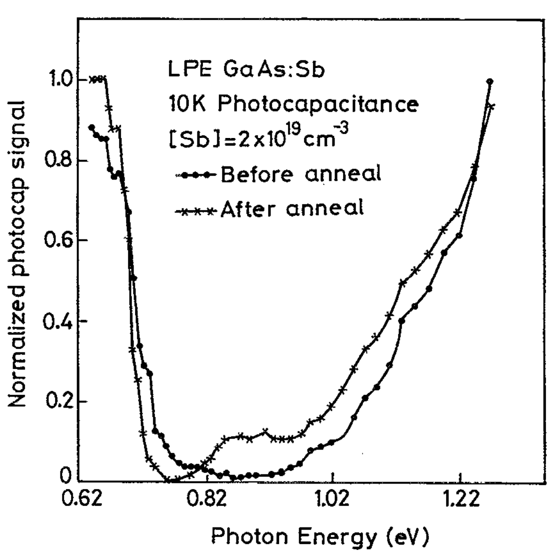

FIG. 5. Steady state photocapacitance spectra of the samples whose DLTS data are shown in Fig. 2.

The photocapacitance spectra of the annealed samples in Figs. 4 and 5 indicate the presence of an electron trap with a photoionization threshold near 0.75 eV. We may note from previous reports that the Sb_{Ga} electron trap is a double donor with its second charge state having an energy of 0.7 eV.[6,7] We can, therefore, attribute the 0.75 eV threshold, obtained from the photocapacitance experiments, to the $+/2+$ transition of trap *B*. However, this transition is not being observed in the as-grown samples, suggesting that the density of trap *B* in such materials is actually low.

Finally, it should be mentioned that we did not use any encapsulant over our GaAs layers during annealing. We believe that in this case, out-diffused Ga atoms piled up near the surface.

V. CONCLUSIONS

From DLTS and photocapacitance experiments we have shown that an electron trap, which is present in low concentrations in as-grown LPE GaAs:Sb materials, can be created in appreciable concentrations using high temperature annealing. Concentration of the trap also follows that of Sb in the material. It is suggested that the electron trap originates from Sb_{Ga} defects whose generation is favored in annealed materials due to Ga out-diffusion.

DLTS results further confirm the existence of a second electron trap in the material with an activation energy of 0.4 eV. Concentration of the this trap is reduced upon annealing. It is supposed that the trap is related to simple native defects or complexes and is the same as the trap EB6 detected previously in electron-irradiated GaAs.

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