Deep levels in as-grown and Si-implanted $In_{0.2}Ga_{0.8}As$–GaAs strained-layer superlattice optical guiding structures

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Trap levels in ~2-μm $In_{0.2}Ga_{0.8}As$(94 Å)/GaAs(25 Å) strained-layer superlattices, suitable for optical waveguides, have been identified and characterized by deep-level transient spectroscopy and optical deep-level transient spectroscopy measurements. Several dominant electron and hole traps with concentrations $\sim 10^{14}$ cm^{-3}, and thermal ionization energies ΔE_T varying from 0.20 to 0.75 eV have been detected. Except a 0.20-eV electron trap, which might be present in the $In_{0.2}Ga_{0.8}As$ well regions, all the other traps have characteristics similar to those identified in molecular-beam epitaxial GaAs. Of these, a 0.42-eV hole trap is believed to originate from Cu impurities and the others are probably related to native defects. Upon Si implantation and halogen lamp annealing, new deep centers are created. These are electron traps with $\Delta E_T = 0.81$ eV and hole traps with $\Delta E_T = 0.46$ eV. Traps occurring at room temperature may present limitations for optical devices.

I. INTRODUCTION

Relaxation of the requirements of lattice matching of individual layers in a superlattice gives more freedom in tailoring material properties. Such strained-layer superlattices (SLS)[1,2] have found applications in electronic and optoelectronic device fabrication.[3] The most widely investigated strained-layer systems are InGaAs–GaAs and the GaAsP–GaAs(GaP). Our work reported here concerns the former. We have recently demonstrated optical guiding in InGaAs–GaAs SLS[4] based on the refractive index change due to alloying and strain.[5]

An important materials aspect has been hitherto unknown. Deep levels can be created in the SLS due to growth conditions, rearrangement of atoms in the growing strained layer, impurities, and interfacial defects. For optical device applications it is important to know the origin and properties of deep centers, which are usually nonradiative in nature. It has recently been shown by Becker and Williamson[6] that photorefractive effects in $LiNbO_3$ channel waveguides can be caused by carrier trapping and reemission both in the guiding and nonguiding regions. Deep-level traps in GaAsP–GaP SLS have been investigated and reported by Barnes *et al.*,[7] but except for some preliminary work by Bhattacharya *et al.*[4] on InGaAs–GaAs SLS, no detailed study has been made.

In the work being reported here we have investigated deep levels in InGaAs–GaAs SLS before and after Si implantation and rapid thermal annealing. The latter are useful for lateral confinement in optical guides, modulators, and multichannel directional couplers. It has been shown by Arnold *et al.*[8] that excellent structural integrity is maintained in a SLS after implantation and annealing.

II. EXPERIMENTAL PROCEDURES

$In_{0.2}Ga_{0.8}As$–GaAs SLS were grown by molecular-beam epitaxy (MBE) on Si-doped (001) GaAs substrates. A 0.3-μm GaAs layer ($n = 2\times10^{18}$ cm^{-3}) was first grown, followed by a 0.5-μm $In_{0.1}Ga_{0.9}As$ layer ($n = 2\times10^{18}$ cm^{-3}) and 2–3 μm of undoped SLS. The growth tempera-

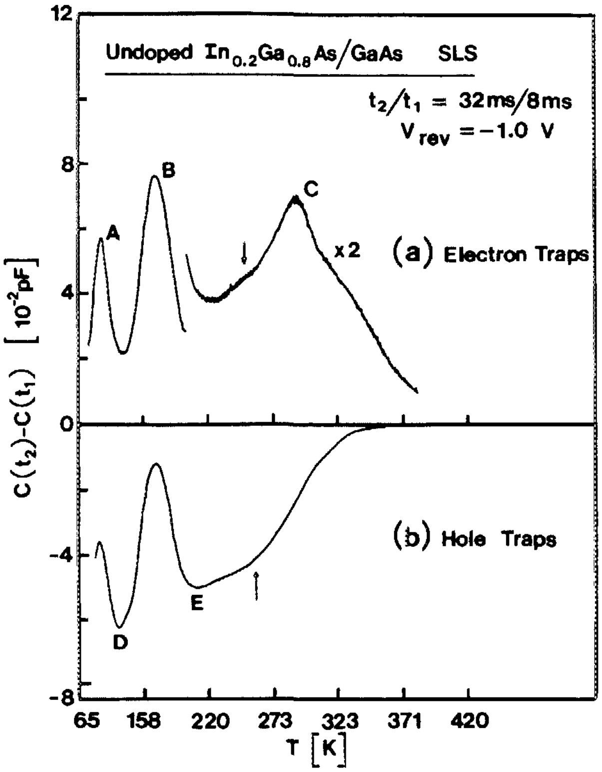

FIG. 1. (a) DLTS and (b) optical DLTS data obtained from a 94-Å-$In_{0.2}Ga_{0.8}As$/25-Å-GaAs strained-layer superlattice structure showing the electron and hole traps present.

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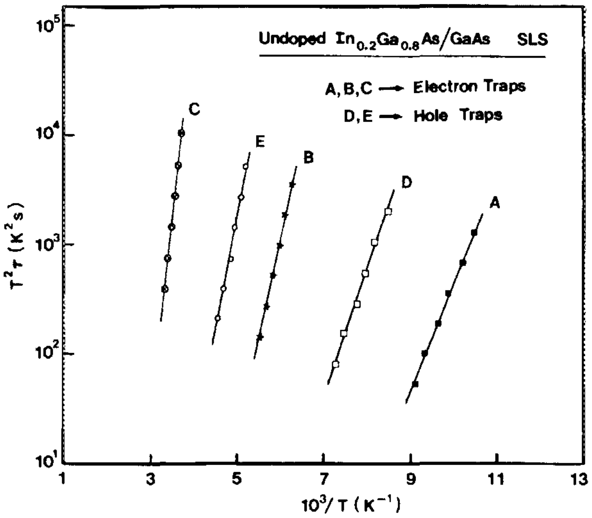

FIG. 2. Arrhenius plots for the electron and hole traps observed in 94-Å-$In_{0.2}Ga_{0.8}As$/25-Å-GaAs strained-layer superlattices.

ture varied between 520 and 540 °C. For the structures investigated here the SLS consists of 25-Å GaAs barrier regions and 94-Å $In_{0.2}Ga_{0.8}As$ well regions. The thicknesses and compositions were verified by analysis of double-crystal x-ray data, details of which have been published earlier.[5] Growth of the SLS is usually monitored by *in situ* static RHEED measurements and the rearrangement of atoms in the strained layer can be observed from the patterns. In some structures a top p^+ GaAs layer was grown to enable fabrication of junction diodes.

Deep-level transient spectroscopy (DLTS) and optical DLTS measurements were made on Au Schottky diodes and junction diodes. The measurements were made with a 1-MHz capacitance meter. The pulse amplitudes were generally equal to the quiescent reverse bias and the pulse duration was 8 ms. The ratio of the sampling times t_2/t_1 was equal to 4 and t_1 was varied from 2 to 64 ms. Some SLS structures were implanted at room temperature with 3×10^{12} cm^{-2} Si^+ at an energy of 120 keV. The implanted layers were then activated by short-term halogen lamp annealing. The duration and temperature of such annealing were 15 s and 700–750 °C, respectively. The net electron concentration in the undoped SLS layers was determined from capacitance-voltage measurements to be 5×10^{15} cm^{-3}. The high donor concentration possibly arises from S and Si impurities in the source In.

III. RESULTS

Typical data obtained from DLTS measurements on the SLS are shown in Fig. 1(a). The various positive-going peaks and shoulders indicate electron traps present in the SLS. The concentration of all the traps, determined by the relation

$$N_T \simeq 4.23(\Delta C/C_0)(N_D - N_A) \quad (\text{for } t_2/t_1 = 4), \quad (1)$$

are of the order of 10^{14} cm^{-3}. Pulsed optical excitation of the Schottky barrier, which produces capture and subsequent thermal reemission from hole traps (in *n*-type material) gave the ODLTS data shown in Fig. 1(b). Here the negative-going peaks signify hole traps, and two dominant levels are identified. The Arrhenius plots for the electron and hole traps are shown in Fig. 2 and their characteristics are listed in Table I. It should be noted that the capture cross sections listed in this table are obtained from the emission rate prefactors.

New levels, an electron trap, and a hole trap are observed in the implanted and annealed layers. The DLTS and ODLTS data are shown in Figs. 3(a) and 3(b) and their Arrhenius plots are given in Fig. 4. It is important to note that the characteristics of the 0.75- and 0.81-eV electron traps in undoped and implanted SLS, respectively, are different. So is the case for the 0.42- and 0.46-eV hole traps in the two categories of materials.

IV. DISCUSSION

Detailed studies of traps in MBE GaAs have been made by Lang *et al.*[9] and Blood and Harris.[10] Nine electron trap levels, labeled M0–M8 have been identified by these two groups. No data are available on traps in $In_{0.2}Ga_{0.8}As$ other than some early work on vapor-phase epitaxial $In_xGa_{1-x}As$ on GaAs substrates by Mircea *et al.*[11] and on LPE[12] and MBE[13] $In_{0.53}Ga_{0.47}As$ grown on InP substrates. We will use their published data as bases for comparison. The 0.75-eV electron trap in as-grown $In_{0.2}Ga_{0.8}As$–GaAs SLS has characteristics similar to the center labeled M6 by Lang *et al.*[9] The weak shoulder at ~260 K corresponds to the trap M5. Similarly, the 0.37-eV trap corresponds to M3

TABLE I. Characteristics of electron and hole traps observed in undoped 94-Å-$In_{0.2}Ga_{0.8}As$/25-Å-GaAs strained-layer superlattice.

Trap type	Trap label	Activation energy ΔE_T (eV)	Capture cross section[a] σ_∞ (cm^{-2})	Trap concentration N_T (10^{14} cm^{-3})	Possible identity
Electron traps	A	0.20	1.25×10^{-13}	1.8	Trap M1 observed in MBE GaAs
	B	0.37	4.3×10^{-13}	2.6	Trap M3 observed in MBE GaAs
	C	0.75	1.0×10^{-11}	1.0	Trap M6 observed in MBE GaAs
Hole traps	D	0.24	2.3×10^{-15}	1.0	New
	E	0.42	6.8×10^{-15}	0.8	Related to copper

[a] Determined from the emission rate prefactor.

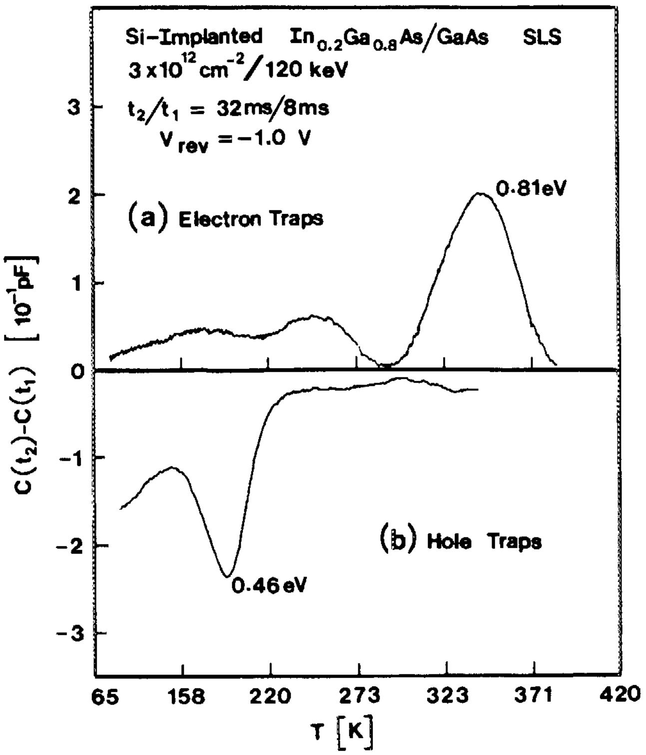

FIG. 3. (a) DLTS and (b) optical DLTS data obtained from a 94-Å-$In_{0.2}Ga_{0.8}As$/25-Å-GaAs strained-layer superlattice implanted with 3×10^{12} cm^{-2} Si^+ at 120 keV and annealed at (a) 700 °C/15 s and (b) 750 °C/15 s under a halogen lamp. The dominant electron trap is annealed out at 750 °C/15 s.

and the 0.20-eV trap corresponds to M1. The 0.37-eV trap also corresponds to the level labeled EL6 in bulk GaAs. It was, in general, concluded[9,10] that the traps in GaAs are due to either chemical impurities or impurity-defect complexes. More recently, Skromme *et al.*[14] have performed measurements on Si-doped high-purity MBE GaAs and have found the densities of these traps to be independent of the background and have mentioned that the traps may not be related to impurities. Finally, it should be noted that traps similar to the 0.20-eV level have been observed by us in MBE $In_{0.53}Ga_{0.47}As$.[13] Based on the above, we conclude that most of the traps observed here are in the GaAs barrier layers. The trap densities measured in the SLS are $\sim 10^{14}$ cm^{-3}, whereas in GaAs the densities vary in the range 10^{12}–10^{14} cm^{-3}, depending on growth conditions. The higher concentrations in the SLS are attributed to lower growth temperatures and use of As_4 species.

Hole traps in MBE GaAs have been characterized by Stall *et al.*[15] and Bhattacharya *et al.*[16] With reference to the data presented in Fig. 1(b), the 0.42-eV trap has characteristics similar to Cu impurities in GaAs.[15,17] The impurities possibly originate from the substrate as suggested by Stall *et al.*[15] The shoulder at ~260 K could be due to Cr impurities.[15] This assignment is, however, only tentative. The 0.24-eV trap has not been observed in GaAs and may be characteristic of the SLS.

The concentrations of most of the electron traps, except the 0.20-eV level which is not detected due to a higher background carrier concentration, remains fairly constant upon implant and anneal. In addition, a new trap level is created. The dominant peak in Fig. 3(a) corresponds to a 0.81-eV electron trap, whose characteristics are very different from the EL2 center. We find that the trap is not detected if annealing is done at 750 °C for 15 s. The depth profile of the trap was measured by varying the reverse bias in steps and using an incremental injection bias at each step. This profile, shown in Fig. 5, almost replicates the dopant profile. We

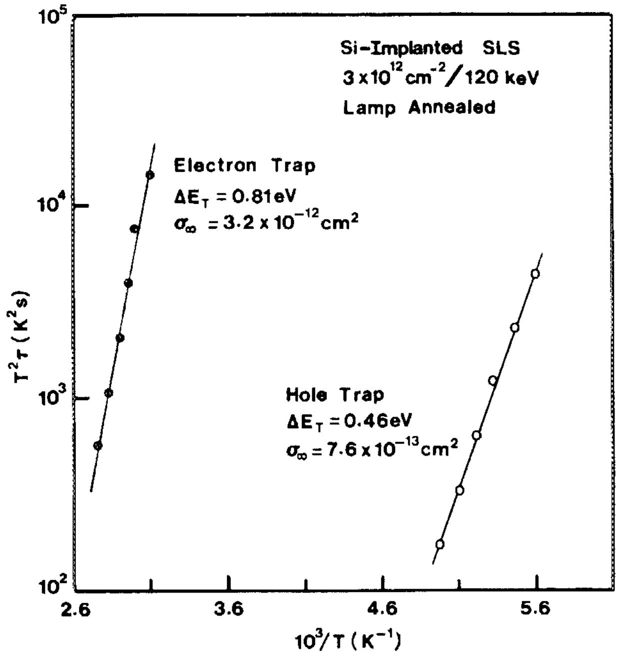

FIG. 4. Arrhenius plot of the electron and hole traps observed in Si-implanted and lamp-annealed $In_{0.2}Ga_{0.8}As$/GaAs strained-layer superlattice.

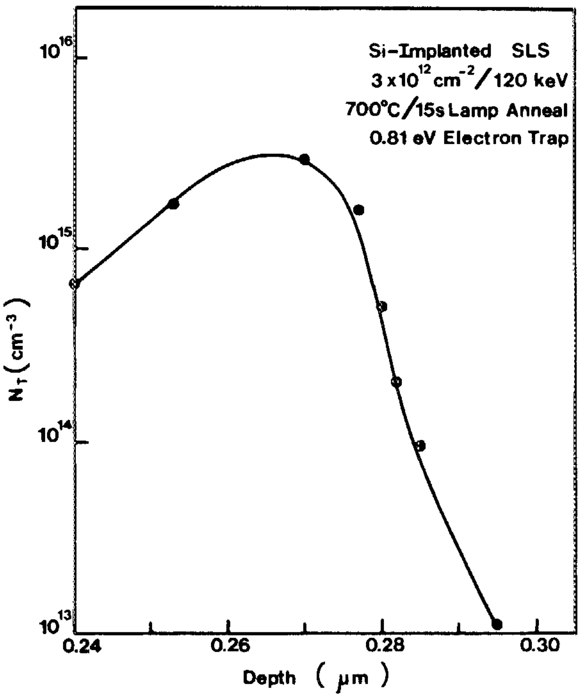

FIG. 5. Depth profile of the 0.81-eV electron trap observed in implanted and annealed SLS.

therefore believe that this center is related to implant damage. The ODLTS data of implanted samples annealed at 700 °C show unresolved peaks corresponding to a fairly large density and most of the traps in as-grown SLS are also present. Upon annealing at 750 °C only a single trap of large density, as shown in Fig. 3(b), remains. It is most likely that all the centers of large density are related to the implant and anneal processes.

Finally, a note on the emission time constants of the electron traps observed near room temperature in as-grown and implanted SLS. The 0.75- and 0.81-eV traps have emission time constants equal to 6 ms and 1.7 s, respectively. They will therefore directly affect high-speed electronic devices and optical modulators made with such materials.

ACKNOWLEDGMENT

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