Traps in molecular-beam epitaxial $In_{0.53}(Ga_xAl_{1-x})_{0.47}As/InP$

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Deep-level transient spectroscopy measurements have been made on molecular-beam epitaxial $In_{0.53}(Ga_xAl_{1-x})_{0.47}As$ lattice matched to InP. Several electron and hole traps, with activation energies ranging from 0.14 to 0.79 eV, have been identified and characterized. In particular, systems of electron traps ($0.30 \leqslant \Delta E_T \leqslant 0.79$ eV) and hole traps ($0.14 \leqslant \Delta E_T \leqslant 0.31$ eV) with monotonically changing activation energies have been identified in these alloys. We believe these traps are dominant in this alloy system.

I. INTRODUCTION

The most promising materials that have emerged for optical fiber communication are InGaAsP and InGaAlAs quaternaries and suitable multiquantum wells of the ternaries InGaAs and InAlAs, all lattice matched to InP. Although InGaAsP can be grown fairly easily by liquid- and vapor-phase epitaxy,[1] there are problems associated with their growth by molecular-beam epitaxy (MBE). In the wavelength range of interest, InGaAlAs provides the same degrees of freedom (band gap, refractive index, lattice parameter, etc.) as InGaAsP for band-gap engineering and heterostructure device design. These alloys are also much easier to grow since In, Ga, and Al all have unity sticking coefficients at normal MBE growth temperatures. There are, however, some fundamental problems related to the epitaxy of these alloys.

Conventional epitaxial growth techniques have not been very successful due to a number of reasons. Due to the large difference in the bonding energies of In, Ga, and Al to As, it is very difficult to grow epitaxial layers with uniform composition by conventional liquid- and vapor-phase epitaxy. Significant miscibility gaps and clustering effects are predicted in the phase diagram of this material system.[2] Also, by using these epitaxial methods, it is difficult to control the exact composition to form an InGaAlAs epitaxial layer lattice matched to InP substrates. Since MBE is a far-from-equilibrium growth technique, it is possible to grow the alloys using this technique, and with proper control and variation of growth parameters, crystals with minimal clustering effects can be obtained.

In evaluating the quality of semiconductor materials for device applications it has been found that centers with deep energy levels in the forbidden energy gap of large band-gap semiconductors play an important role. Deep levels essentially act as carrier recombination and trapping centers and affect device performance adversely. It is to be realized that growth of these compounds by MBE is limited by the surface kinetics of the adatoms. Depending on growth temperature and growth rate, surface roughness, formation of vacancies, and interstitials and clustering can take place. Some of these phenomena can give rise to deep-level traps. Very little, however, is known of the deep traps in InGaAlAs. In this paper we report the results of a detailed study of electron and hole traps in MBE InGaAlAs alloys with varying composition.

II. EXPERIMENTAL TECHNIQUES

Molecular-beam epitaxial growth of Si-doped InGaAlAs was carried out on S-doped InP substrates which were degreased successively in trichloroethane, acetone, and methanol, and were etched in 0.5% bromine-methanol and $5:1:1::H_2SO_4:H_2O_2:H_2O$. The temperatures for growing the quaternaries were deduced from the optimized InGaAs and InAlAs growth temperatures and characterization by photoluminescence experiments. Typical substrate temperatures, depending on the Al mole fraction of the alloy, were between 480 and 520 °C, and are shown in Table I. The typical growth rate was around 1 μm/h.

The lattice mismatch between the InP substrate and the quaternary epitaxial layer was determined from single-crystal x-ray diffraction measurements using the $CuK\alpha_1$ and $CuK\alpha_2$ doublet. In particular, the mismatch $\Delta a/a$ in the three alloys in which deep levels were investigated are $\leqslant 7\times 10^{-4}$. Table I gives some of the measured electrical properties in these crystals. The band gap of the alloys, determined from room-temperature absorption measurements, are also listed in Table I. Low-temperature photoluminescence measurements were made with a 1-m Jarrell-Ash scanning spectrometer and chopped 5145 Å light from an argon-ion laser. The photoluminescence linewidth (full width at half maximum) are 6.1, 6.6, and 12.2 meV in $In_{0.53}(Al_xGa_{1-x})_{0.47}As$ with $x = 0.11$, 0.36, and 0.64, respectively. These are amongst the narrowest linewidth values reported to date for the alloys.[3,4]

Circular Schottky diodes with an area of 2×10^{-3} cm^2 were made by forming top Au contacts on the n-type layers and evaporated and alloyed Au-Ge ohmic contacts on the n^+ InP substrate. For the characterization of minority-carrier (hole) traps in n-type material, p^+ (Be-doped)-n junctions were grown and mesa-etched diodes with appropriate ohmic contacts were formed by conventional photolithography and lift-off techniques. The diode areas were

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TABLE I. Electrical properties of InGaAlAs grown by MBE.

Composition	Growth temperature T_g (°C)	Band gap at 300 K (eV)	n (cm^{-3})	μ(300 K) (cm^2/V s)
$In_{0.53}Ga_{0.42}Al_{0.05}As$	485	0.81	4.0×10^{15}	5500
$In_{0.53}Ga_{0.30}Al_{0.17}As$	495	0.98	1.0×10^{15}	4000
$In_{0.53}Ga_{0.17}Al_{0.30}As$	510	1.17	1.4×10^{16}	2500

TABLE II. Characteristics of electron traps in InGaAlAs.

Composition	Activation energy ΔE_T (eV)	Capture cross section σ_∞ (cm^2)	Trap density N_T (cm^{-3})	Trap label
$In_{0.53}Ga_{0.42}Al_{0.05}As$	0.57	5.3×10^{-12}	5.3×10^{12}	A
	0.30	1.4×10^{-14}	4.0×10^{14}	B
$In_{0.53}Ga_{0.30}Al_{0.17}As$	0.64	9.1×10^{-13}	4.5×10^{13}	C
$In_{0.53}Ga_{0.17}Al_{0.30}As$	0.70	1.6×10^{-12}	4.8×10^{14}	D
	0.79	1.3×10^{-10}	3.1×10^{13}	E

TABLE III. Characteristics of hole traps in InGaAlAs.

Composition	Activation energy ΔE_T (eV)	Capture cross section σ_∞ (cm^2)	Trap density N_T (cm^{-3})	Trap label
$In_{0.53}Ga_{0.42}Al_{0.05}As$	0.14	2.1×10^{-17}	9.1×10^{13}	P
	0.19	3.2×10^{-18}	5.1×10^{13}	Q
$In_{0.53}Ga_{0.30}Al_{0.17}As$	0.16	...	5.6×10^{14}	X[a]
$In_{0.53}Ga_{0.17}Al_{0.30}As$	0.21	1.4×10^{-15}	2.3×10^{14}	R
	0.31	...	1.7×10^{14}	Y[a]

[a] Approximately determined from the DLTS peak position using Eq. (1).

2×10^{-3} cm^2. Deep-level transient spectroscopy (DLTS) measurements were made with a 1-MHz Boonton capacitance meter and appropriate signal averaging and processing circuitry. The measurements were made by scanning the temperature of the sample in a variable temperature cryostat in the range 80–400 K.

III. RESULTS AND DISCUSSION

Representative data obtained from DLTS measurements for electron and hole traps are shown in Figs. 1 and 2, respectively. The peaks and shoulders correspond to trap emissions and the heights of these features are related to the trap density. The activation energy and capture cross section of the different traps are obtained by changing the rate windows, t_2 and t_1, and repeating the temperature scans. The Arrhenius plots of the various electron and hole traps are shown in Figs. 3 and 4, respectively. The activation energy of traps, whose emissions appear as shoulders in the DLTS scans, were calculated from the approximate relationship

$$\Delta E_T = 23.7kT. \quad (1)$$

The characteristics of the different traps are given in Tables II and III.

There are several interesting and important features, which should be noted in the trap characteristics. First, in

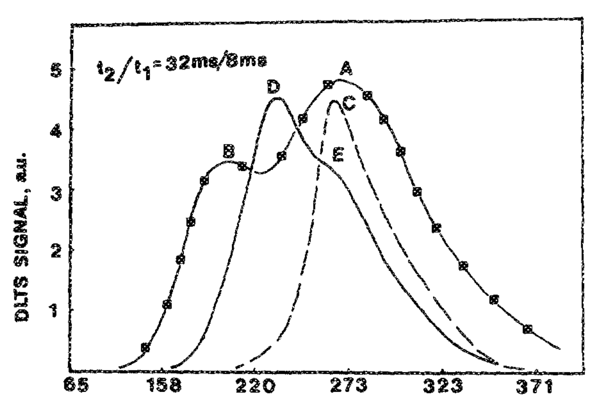

FIG. 1. Typical DLTS data showing electron traps in MBE $In_{0.53}(Ga_xAl_{1-x})_{0.47}As$.

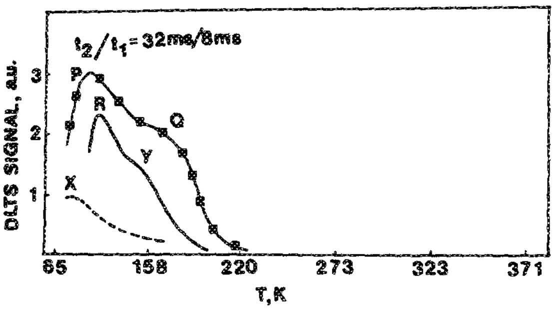

FIG. 2. Typical DLTS data showing hole traps in MBE $In_{0.53}(Ga_xAl_{1-x})_{0.47}As$.

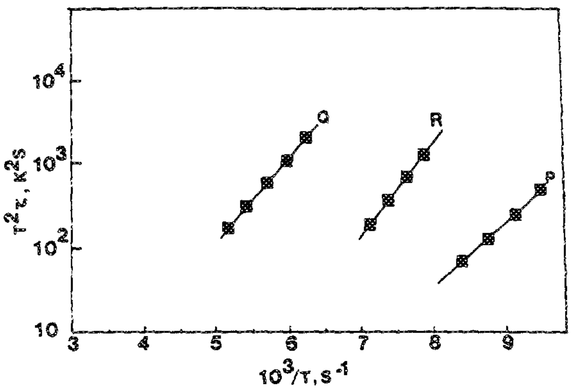

FIG. 4. Arrhenius plots for hole traps identified in MBE $In(GaAl_{1-x})_{0.47}As$.

looking at the Arrhenius plots of Figs. 3 and 4 and the data in Tables II and III, it is apparent that, in general, the capture cross sections of the electron traps are rather high while those of the hole traps are small. A similar trend was observed by us for traps in $In_{0.52}Al_{0.48}As$.[5] In general, traps with large capture cross sections behave as attractive centers, while those with small capture cross sections are repulsive centers. The similarity of the trend in the cross sections and activation energies makes us believe that several of these traps may have a common origin. In fact, on comparing the trap data of Tables II and III and the Arrhenius plots with the respective data and plots for $In_{0.52}Al_{0.48}As$,[5] it is observed that electron trap *D* has characteristics similar to the trap labeled EA4 in the ternary material. Similarly hole trap *R* has characteristics similar to the trap labeled HA1 in the ternary. The capture cross section of a deep-level trap is related to the defect structure and its configuration in the lattice, which in turn can be decided by alloy formation and the localization of impurity atoms. Complex centers, like the *D-X* center in AlGaAs,[6] have very small capture cross sections and are extended states in the lattice. They have a large lattice relaxation and capture carriers by a multiphonon emission process. Attractive centers with large cross-section capture carriers either by involving phonons, or by a two-carrier Auger-like process.[7]

Figure 5 shows the measured activation energy of the electron and hole traps in the different alloys, measured with respect to the conduction-band edge (obtained from room-temperature optical transmission measurements) and with respect to the valence-band edge taken at zero energy, respectively. The energies of the traps EA4 and HA1 in $In_{0.52}Al_{0.48}As$ are also[5] included. Also included is the energy of a dominant trap identified in MBE $In_{0.53}Ga_{0.47}As$,[8] which completes the picture for the entire lattice-matched range of compositions. It is evident from Fig. 5 that, in addition to some electron and hole traps which are scattered in energy and do not follow any particular trend, there are systems of electron and hole traps whose ionization energies fall on a straight line. These lines very approximately follow the locus of the midgap energy of the alloys. It may, therefore, be concluded that these traps in the different alloys are the same deep level which originates from a dominant native defect or impurity. The common source of impurities in all the alloys is In. The native defects could be vacancies or interstitials, and it is difficult to ascertain the exact origin at this point. It can only be said that the system of electron traps with $0.30 \leqslant \Delta E_T \leqslant 0.79$ and hole traps with $0.14 \leqslant \Delta E_T \leqslant 0.31$ are dominant traps in this important quarternary alloy system.

IV. CONCLUSION

Detailed DLTS measurements have been made on InGaAlAs quarternary alloys lattice matched to InP. The electronic and optical properties of the alloys were deter-

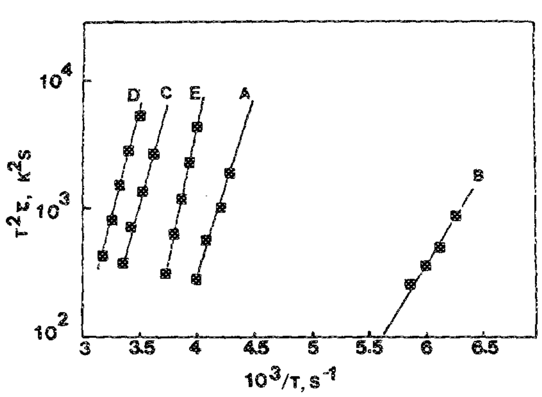

FIG. 3. Arrhenius plots for electron traps identified in MBE $(InGa_xAl_{1-x})_{0.47}As$.

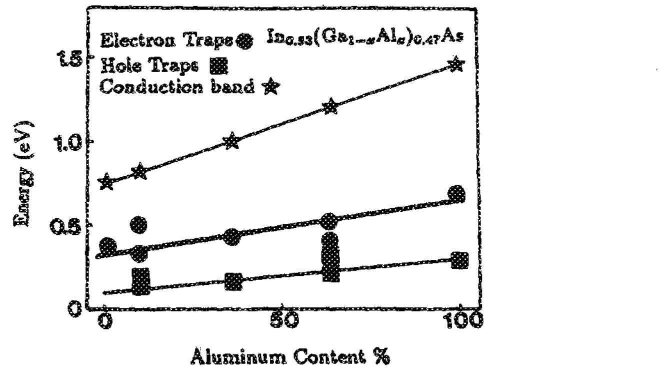

FIG. 5. Measured variation in activation energy of the electron and hole traps with respect to the conduction-band edge for different alloy compositions of InGaAlAs. The solid lines are joins of the data points.

mined by Hall- and low-temperature photoluminescence measurements, respectively. Several electron and hole traps have been identified and characterized in the different alloys. In particular, we have identified a system of electron traps with $0.30 \leqslant \Delta E_T \leqslant 0.79$ eV and hole traps with $0.14 \leqslant \Delta E_T \leqslant 0.31$ eV in the range of band gaps ($0.74 \text{ eV} \leqslant E_g \leqslant 1.43$ eV) which we believe are dominant traps in the alloy system with a common origin.

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