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DLTS Study of Deep Levels in Si-Doped $In_xAl_{1-x}As$ Layers Grown by Molecular Beam Epitaxy

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Deep levels in Si-doped MBE $In_xAl_{1-x}As$ (x=0.39-0.61) layers were systematically investigated for the first time by DLTS measurements and PL measurements, changing the alloy composition. Two kinds of deep electron traps, E1 and E2 were observed for all the alloy compositions. From the observed dependence of trap level position on the alloy composition, observed traps were not DX-center-like donors but most probably normal deep donors associated with Γ-band.

1. Introduction

$In_xAl_{1-x}As$ is the most important barrier and buffer material for InP based electric and optoelectronic devices. However, no systematic study has so far been made on deep levels present in $In_xAl_{1-x}As$ except few works [1-3] done only on the composition lattice-matched to InP (x=0.52).

The purpose of this paper is to investigate deep levels in molecular beam epitaxy (MBE)-grown Si-doped $In_xAl_{1-x}As$ epitaxial layers by deep level transient spectroscopy (DLTS) measurements and photoluminescence (PL) measurements, changing the alloy composition. From DLTS measurement, two kinds of deep traps, E1 and E2 were observed for all the alloy compositions in the samples studied in this paper. The energy position of the E1 trap obtained by DLTS measurement was in excellent agreement with one obtained by PL measurement. From the observed dependence of the trap level position on the alloy composition, it is concluded that these observed traps are not DX-center-like donors but most probably normal deep donors associated with Γ-band.

2. Sample structure

All samples in this study were grown by conventional MBE technique. The sample structure is shown in **Fig. 1.** It consisted of $In_{0.52}Al_{0.48}As$ buffer layer lattice-matched to (001) InP substrate, gradual compositional $In_xAl_{1-x}As$ buffer layer, and $In_xAl_{1-x}As$ epitaxial layer without strain successively. The thicknesses of each layers were 200-400nm, 200-300nm and 1.2-1.6μm, respectively. For all samples, the reflective high electron energy diffraction (RHEED) pattern was streak during the growth of the top layer and the surface morphology was mirror-like. The growth temperature, the growth rate and the V/III beam equivalent pressure ratio were 520°C, 0.7-1.0μm/h corresponding to the InAs mole fraction, x, and about 100, respectively. Aluminum metal was *in-situ* deposited on these $In_xAl_{1-x}As$ surfaces by using the Al k-cell equipped in the same MBE chamber in order to prevent the epitaxial layers from oxidation. The Schottky electrode whose diameter was 540μm was fabricated by photolithography and wet chemically etching with sodium hydroxide (NaOH). The Al metal of the samples for PL measurement was also etched with NaOH.

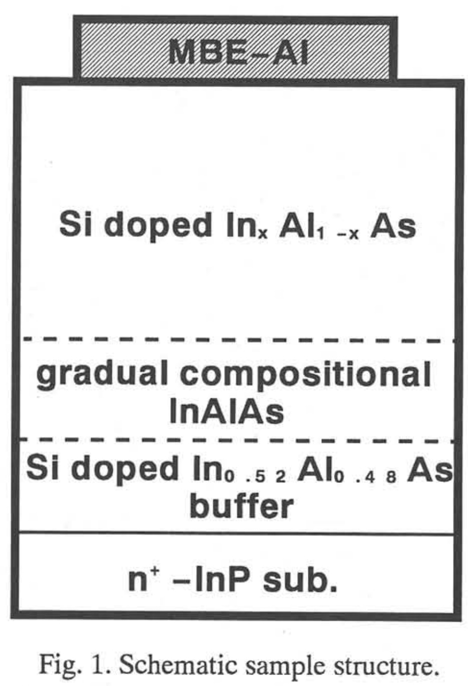

Fig. 1. Schematic sample structure.

For all samples, the Si–doping density was kept in the range of $0.9–1.1x10^{17}$ cm^{-3}. The doping density was checked by $C–V$ carrier profiling and was found to be uniform from the Schottky interface into a depth of 800nm.

The alloy composition of the $In_xAl_{1-x}As$ was adjusted by group–III beam flux ratio calibrated by the period of RHEED intensity oscillation. The actual alloy compositions were further checked by X-ray diffraction (XRD) measurement as shown in **Fig. 2**. As seen in this figure, it was found that the alloy composition was well controlled in our MBE system.

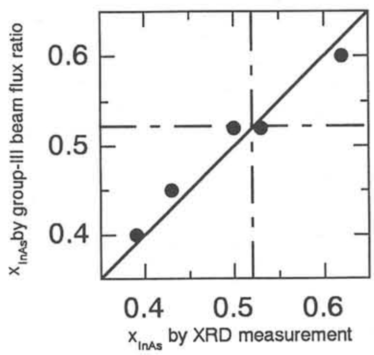

Fig. 2. Actual x_{InAs} of InAlAs determined by XRD measurement.

3. Deep levels in $In_xAl_{1-x}As$

DLTS measurements were made using the temperature scan range of 20–330K, the reverse bias voltage of -0.5 to –1.5V, the pulse width of 1ms and the rate window, t_1/t_2 of 1ms/4ms to 4ms/16ms, respectively. **Figure 3** shows examples of observed DLTS spectra in the case of t_1/t_2 = 4ms/16ms. As seen in **Fig. 3**, two kinds of electron traps, E1 and E2 were clearly seen. The E1 trap density was found to be almost constant for all the alloy composition investigated in this study and its value was about $1–2x10^{15}$ cm^{-3}, whereas the E2 trap density increased with the increase of the AlAs mole fraction.

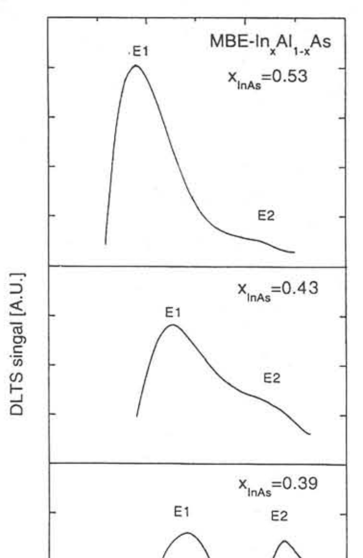

Fig. 3. Examples of DLTS spectra in Si–doped MBE InAlAs for different x_{InAs}.

PL measurement was done at 30K in the detection wavelength range of 0.55–1.80μm using Ar^+ laser (λ = 514.5nm) and Ge photodetector. **Figure 4** shows the observed PL spectra in the case of the sample with x = 0.43. As you can seen in this figure, four peaks were detected by PL measurement, including band edge emission from InAlAs and InP. One peak detected as EP1 in **Fig. 4** seems to be due to a deep trap in the InAlAs epitaxial layer. The broad peak which exists in 0.7–1.1 eV appears to be due to defect in InP substrate [4]. These peaks were also observed in other samples with different alloy compositions.

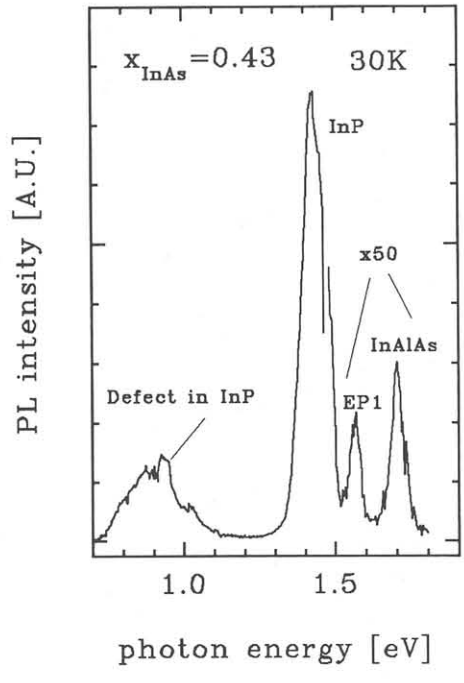

Fig. 4. PL spectra at 30K in Si–doped $In_{0.53}Al_{0.47}As$.

Figure 5 summarizes Arrhenius plots of the observed deep level traps in Si–doped MBE $In_{0.52}Al_{0.48}As$ lattice–matched to InP, including the data obtained by other groups [1–3]. As shown in **Fig. 5**, the E1 and E2 trap levels were located at 0.07 and 0.40 eV below the conduction band minimum, respectively. These results were in good agreement with the results obtained by Hoenow *et al.* [1] and Hong *et al.* [2], but not agreement with the results obtained by Luo *et al.*[3].

The observed alloy composition dependence of the deep trap levels is summarized in **Fig. 6**. It was found that both of E1 and E2 levels slowly moved into deeper position with the increase of the AlAs mole

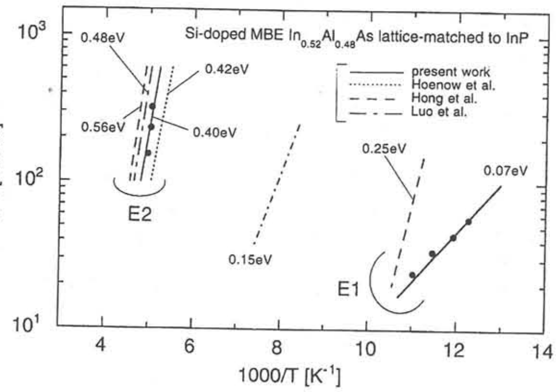

Fig. 5. Arrhenius plots of E1 and E2 traps in Si–doped MBE InAlAs lattice–matched to InP.

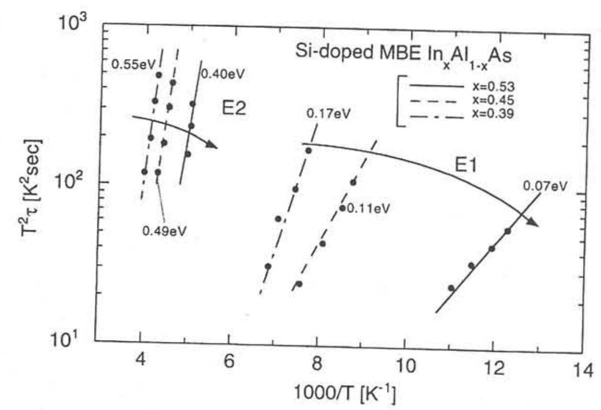

Fig. 6. Arrhenius plots of E1 and E2 traps in Si–doped MBE $In_xAl_{1-x}As$ for various alloy compositions.

fraction of the $In_xAl_{1-x}As$ epitaxial layer. The energy position of the E1 trap obtained by DLTS measurement is in excellent agreement with that of the EP1 peak obtained by PL measurement. This shows that the E1 trap was a radiative center. However, the PL emission peak corresponding to the E2 trap level detected by DLTS measurement was not detected by PL measurement for all samples. This means either that E2 trap is non–radiative or that it is radiative but its emission peak is buried below other stronger peak because E2 has smaller concentration.

The energy positions of the E1 and E2 traps are plotted in a deep–level diagram taking the hybrid orbital charge neutrality level E_{HO} as the reference [5] in **Fig. 7**. It is clearly seen that behavior of the E1 and E2 levels are different from behavior of EL2 and DX-center in AlGaAs whose positions remain the same for different alloy compositions. Thus, although Hong *et al.* have mentioned that E1 trap is DX–center like, the observed E1 and E2 are most probably normal deep donors associated with Γ–band.

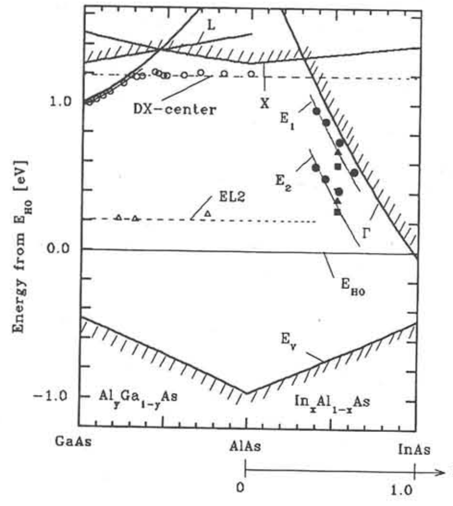

Fig. 7. Deep–level diagram taking E_{HO} as the reference.

4. Summary

Deep levels in Si–doped $In_xAl_{1-x}As$ epitaxial layers grown by conventional MBE were investigated by DLTS measurements and PL measurements, changing the alloy composition for x=0.39–0.61. From DLTS measurement, two kinds of deep electron traps, E1 and E2, were observed for all the alloy compositions investigated. The E1 trap density was almost constant for all the alloy composition, while the E2 trap density increased with the increase of the AlAs mole fraction. The E1 trap was also observed by PL measurement, but not the E2 trap. It is concluded that these observed traps are not DX–center–like donors but they are most probably normal deep donors associated with Γ–band.

5. Acknowledgement

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References

[1] H. Hoenow, H.–G. Bach, J. Böttcher, F. Gueissaz, H. Künzel, F. Scheffer and C. Schramm: *Proc. of the 4th IPRM (1992, IEEE Cat. #92CH3104–7) 136.*

[2] W.–P. Hong, S. Dhar, P.K. Bhattacharya and A. Chin: J. Electron. Mater. **16** (1987) 271.

[3] J.K. Luo, H. Thomas and I.L. Morris: Electron. Lett. **28** (1992) 798.

[4] H. Fujikura, T. Iwa–ana and H. Hasegawa: Jpn. J. Appl. Phys. **33** (1994) 919.

[5] H.Hasegawa and H. Ohno: J. Vac. Sci. & Technol. **B4** (1986) 1130.