

Influence of Growth Conditions and Alloy Composition on Deep Electron Traps of MBE Grown n-AlGaAs

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Dependence of concentration and thermal activation energy of deep electron traps in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ grown by MBE on growth conditions and alloy composition ($0 \leq x \leq 1$) has been studied by DLTS measurements. The thermal activation energy varies with alloy composition. Each deep level in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ corresponds to that in GaAs. The concentrations of the electron traps reduce with increasing growth temperature or decreasing a group V/III beam flux ratio. The effect of the beam flux ratio is less than that of the growth temperature.

1. Introduction

Molecular beam epitaxy (MBE) has become a useful technique for growing thin films of GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ with high controllability of thickness, doping level and alloy composition, which is required to realize high speed electron devices and optoelectronic devices. These device characteristics are very sensitive to material quality. It was suggested that high threshold current density of previous MBE grown GaAs- $\text{Al}_x\text{Ga}_{1-x}\text{As}$ DH lasers was due to nonradiative centers formed in the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ clad layers.¹⁾ It was reported²⁾ that the threshold current density of MBE DH lasers was markedly reduced with increasing growth temperature. The origins of the nonradiative centers are deep traps such as vacancies, impurity complexes. In order to obtain a high quality layer, it is important to investigate the dependence of the concentration of the deep traps on growth conditions and to make the origins clear. Few detailed studies of deep levels in MBE grown $\text{Al}_x\text{Ga}_{1-x}\text{As}$ changing growth conditions and alloy composition have been reported.^{3,4)}

We report here a deep level transient spectroscopy (DLTS) study of electron traps in Si-doped n- $\text{Al}_x\text{Ga}_{1-x}\text{As}$ grown by MBE. The deep levels in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ are correlated with those in GaAs, by determining the dependence of the

thermal activation energies of the deep levels as a function of alloy composition. On some main deep levels, the dependence of the concentration on alloy composition, growth temperature and a group V/III beam flux ratio ($\text{As}_4/(\text{Ga}+\text{Al})$) are studied.

2. Experimental

The Si-doped epitaxial $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layers, following GaAs buffer layer of 1.0 - 1.5 μm thickness, were grown by MBE on Si-doped or Cr-doped semi-insulating GaAs $\langle 100 \rangle$ oriented substrates.

Two series of samples were fabricated. The first series of samples were fabricated to mainly study the dependence of deep electron traps on alloy composition. Each sample had a single $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layer grown without varying the growth condition during the growth. The layer thickness was about 3 μm . The first series of samples were grown with the constant V/III flux ratio (γ) of around 2. Different samples were prepared by varying the growth temperature (T_g) from 680 to 780°C and the alloy composition from 0 to 1.

The second series of samples were fabricated to mainly study the dependence of deep electron traps on growth conditions. The samples consisted of three layers successively grown with varying only one of the growth

conditions and keeping the other conditions constant during the growth. The thickness of each layer was about 1 μm . The alloy composition of the second series of samples was kept constant at $x \sim 0.2$. The other growth conditions were varied as follows: T_g is 660 to 780 $^\circ\text{C}$, γ is 1.5 to 7.5. The doping level of the Si impurity was 7×10^{16} to $1.5 \times 10^{17} \text{ cm}^{-3}$ in both series of samples.

The growth temperature was measured by a thermocouple pushed against the rear of a Mo-block on which the GaAs substrate was mounted. Background pressures prior to growth and during growth were below 2×10^{-10} and $1 \sim 3 \times 10^{-7}$ Torr, respectively.

Schottky barrier contacts of 500 μm in diameter were formed on $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layers by evaporating Au. Ohmic contacts were made by alloying Au-Ge-Ni. Before the formation of the Schottky barrier contacts, the second series of samples were chemically etched down to each of the three layers.

The deep level investigation was carried out using an automated DLTS system. The capacitance resolution of the DLTS system was 1×10^{-15} F, and the response time of the capacitance meter was 1 msec. The temperature resolution was $\pm 2\text{K}$ in the range of 90 to 420 K when the temperature rising rate was set at 100 K/h. The measurement was performed in the constant-voltage mode. The width of the trap filling pulse was 10 msec. The values of quiescent reverse bias were suitably chosen to minimize the effect of field-enhanced trap emission.

3. Results and Discussion

Deep electron traps have been found in nearly all samples investigated. Seven different electron traps were distinguished. They were labelled as E1, E2, E3, ..., and E7. Their activation energies and capture cross sections of the electron traps in $\text{Al}_{0.07}\text{Ga}_{0.93}\text{As}$ are summarized in Table 1. The activation energy of E1 level is not given in Table 1, because the signal due to E1 level was not observed in the temperature range studied. Extrapolation from the data on E1 level at higher values of alloy composition suggests that the energy is about

0.13eV at $x=0.07$. Not all samples showed all of the seven levels. Some levels having neighboring DLTS signals were occasionally unresolved.

The thermal activation energies of the levels were determined as a function of alloy composition. The thermal activation energies of all levels monotonically increased with x in the range of $x < 0.3$. Each thermal activation energy of the levels except E1 and E2 levels in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ extrapolated to $x=0$ well corresponded to that of each level in our MBE grown GaAs and the reported data^{5,6)} of GaAs. The correspondence between our labelled levels and reported levels are as shown in Table 1: E7, E6, E5, E4 and E3 correspond to EL2⁵⁾, EL3⁵⁾, M₄⁶⁾, EL7⁵⁾ and M1⁶⁾, respectively. The thermal activation energies of E1 and E2 extrapolated to $x=0$ indicate possible presence of electron trap levels in GaAs, which are below about 0.15eV. No DLTS experiments on such shallow levels in GaAs have been reported.

The deep levels whose concentrations are influenced by growth conditions and/or alloy composition were E2, E3, E4, E5, E6, and E7. The concentrations of different levels show different dependence on the alloy composition. For $x > 0.25$, the main traps were E2 and E3 levels. For $x < 0.25$, the main trap was E6 level. However, the signals of all deep traps in GaAs were usually very weak and often undetectable in many samples.

Figure 1 shows the dependence of the

Table 1. Characteristics of electron traps observed in MBE grown $\text{Al}_{0.07}\text{Ga}_{0.93}\text{As}$. Possible comparisons with reported data are also shown.

| Level | Activation energy (eV) | Capture cross section (cm^2) | * Possible Comparisons |
|-------|------------------------|---|------------------------|
| E1 | — | — | |
| E2 | 0.20 | 4.5×10^{-15} | |
| E3 | 0.28 | 1.6×10^{-14} | (M1) |
| E4 | 0.39 | 6.5×10^{-15} | (EL7) |
| E5 | 0.55 | 1.3×10^{-13} | (M4) |
| E6 | 0.63 | 3.0×10^{-14} | (EL3) |
| E7 | 0.83 | 2.6×10^{-14} | (EL2) |

(* EL : Martin et al.⁵⁾, M : Lang et al.⁶⁾)

concentration of E6 level on the V/III flux ratio for different growth temperatures in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ of $x=0.22$. The increase of the V/III flux ratio, i.e. the increase of As_4 pressure, results in the increase of E6 level concentration. A significant result from Fig. 1 is very strong dependence of E6 level concentration on growth temperature. The increase of growth temperature rapidly reduces the concentration below 10^{14} cm^{-3} in $\gamma < 2$. The effect of the growth temperature for E5 level was less than for E6 level. In E2 and E3 levels, the dependences of the concentration on the V/III flux ratio were larger than that in E6 level.

The dependence of the concentrations of E6 and E3 levels on alloy composition are shown in Figs. 2 and 3, respectively. We can see that the concentration of E6 level increases with increasing x up to 0.43 at the highest growth temperature of 780°C , but x dependence of the concentration is weak at the low temperatures of 680 and 720°C . From Fig. 2, it is also obvious that growth temperature greatly influences the

formation of E6 level. Therefore, from the γ and T_s dependence in our data, it seems that E6 level is associated not with extrinsic impurities but with native defects, such as Ga vacancy or vacancy complexes. However, the x dependence for $T_s = 780^\circ\text{C}$ suggests that oxygen also contributes to the formation of E6 level.

The concentration of E3 level has very strong dependence on alloy composition as shown in Fig. 3. The concentration of this level is less than 10^{14} cm^{-3} at $x < 0.2$ and $T_s=780^\circ\text{C}$. However, as x increases to 0.43, the concentration exponentially increases to 10^{17} cm^{-3} and then decreases with increasing x . E2 level was also found to show a similar behavior to that of E3 level. The x dependence is similar to that of DX (donor-vacancy complex)-center which is reported as the persistent-photoconductivity trap center by Lang et al.^{7) and Zhou et al.⁸⁾ It is highly possible that E2 and E3 levels are the same levels to DX-center.}

E4 level was not the main traps in all the samples studied. The concentration of E4 level

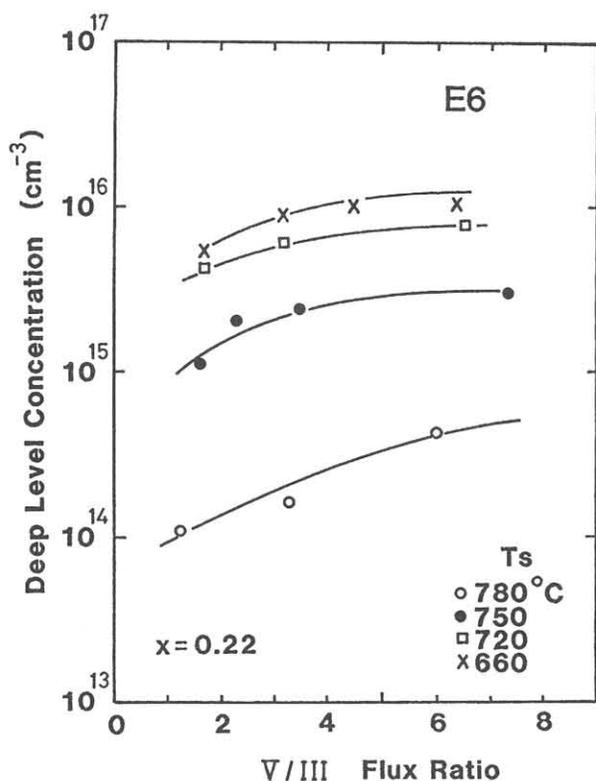


Fig. 1. Dependence of the concentration of E6 level on V III beam flux ratio for different growth temperatures in MBE grown $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$.

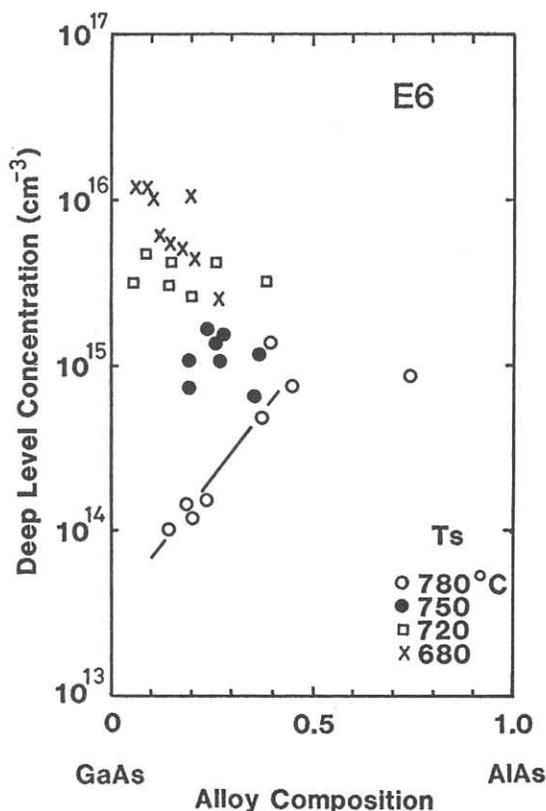


Fig. 2. Dependence of the concentration of E6 level on alloy composition for different growth temperatures in MBE grown $\text{Al}_x\text{Ga}_{1-x}\text{As}$.

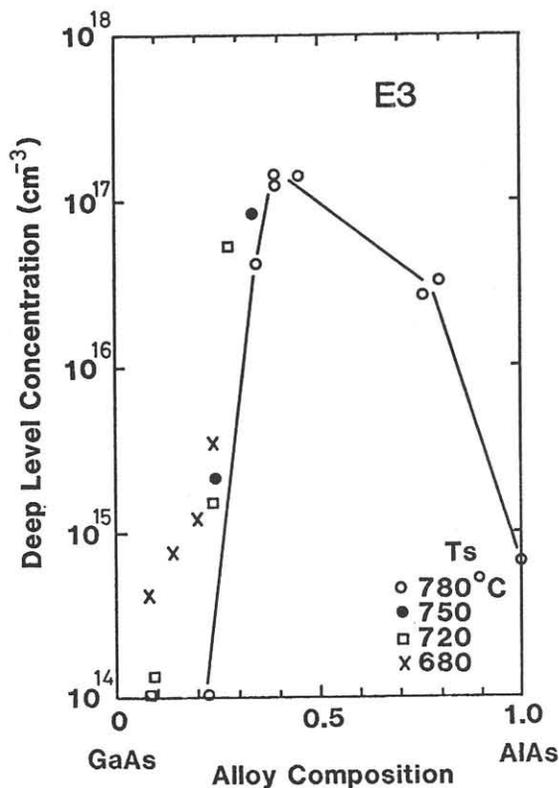


Fig. 3. Dependence of the concentration of E3 level on alloy composition for different growth temperatures in MBE grown $\text{Al}_x\text{Ga}_{1-x}\text{As}$.

greatly depended on the V/III flux ratio and growth temperature. This level was not detected in the range of $\gamma < 3$ and $T_s > 720^\circ\text{C}$. E4 and E5 levels were often found as large peaks in DLTS spectra of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ which were grown when a quadrupole mass analyzer showed the presence of an arsenic oxide in the growth chamber. Therefore, these levels seem to be related to oxygen.

4. Conclusion

We have found that the thermal activation energies of deep electron traps in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ grown by MBE vary with x . The thermal activation energies of these traps in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ extrapolated to $x=0$ well correspond to the data of GaAs. Thus, the correlations between the levels in GaAs and those in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ have been established.

The most dominant trap of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ grown by MBE in the range of $x < 0.25$ is E6 (corresponding to EL3 in GaAs) level, and not E7 (corresponding to EL2 which is often dominant in bulk GaAs) level. The concentration of E6 level is influenced by growth temperature and the

V/III flux ratio, which suggests Ga vacancy or vacancy-complexes as the origin of E6 level. The concentration of this trap can be reduced to the order of 10^{13} cm^{-3} by increasing T_s up to 780°C and decreasing γ below 2.

The most dominant traps in the range of $x > 0.25$ are E2 and E3 (corresponding to M1 in GaAs) levels. The alloy composition dependence indicates that these levels are the same as DX-center.

It seems that the formation of E4 (corresponding to EL7 in GaAs) and E5 (corresponding to M4 in GaAs) levels is related to oxygen.

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