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Deep centers in InGaAs/InP layers grown by molecular beam epitaxy

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The deep level transient spectroscopy (DLTS) method was applied to study deep centers in lattice mismatched InGaAs/InP layers grown by molecular beam epitaxy. The composition and the strain state of the layers were determined using X-ray diffraction technique. Electron trap with thermal activation energy $E_C - (0.06 \pm 0.03)$ eV and electron capture cross-section $\sigma_e = 9.0\times10^{-19}$ cm^{-2} have been detected in $In_{0.524}Ga_{0.476}As$ layers being under tensile strain. Additionally two other centers with thermal activation energy $E_C - (0.10 \pm 0.02)$ eV, and $E_C - (0.48 \pm 0.02)$ eV have been revealed in $In_{0.533}Ga_{0.467}As$/InP layers subjected to small compressive strain. The electron capture cross-sections of these traps, determined from emission processes, are equal to $\sigma_e = 6.7\times10^{-18}$ cm^{-2} and $\sigma_e = 1.6\times10^{-14}$ cm^{-2}, respectively. Due to temperature stresses, defect states in the $In_{0.533}Ga_{0.467}As$/InP layers are modified and the center $E_C - (0.06 \pm 0.03)$ eV is created. This center is identical to that observed in $In_{0.524}Ga_{0.476}As$ layers, as it has been confirmed by electron capture process measurements. The $E_C - (0.06 \pm 0.03)$ eV state exhibits a point-like defect character.

Keywords: InGaAs, deep centers, deep level transient spectroscopy (DLTS).

1. Introduction

High saturation velocity and electron mobility make the InGaAs ternary compounds an attractive material for high-speed optical devices. In evaluating the quality of semiconducting materials for device applications, it has been found that centers with deep energy levels in the forbidden gap of semiconductors play an important role. Deep levels essentially act as carrier recombination or trapping centers and adversely affect device performance. In addition to the energy position of deep levels in the forbidden gap, information is needed about their capture and emission rates for carriers, concentrations, capture cross-sections and spatial distributions. The characteristics of deep centers in ternary InGaAs compounds strongly depends on the composition and strain state of an epitaxial layer. Only $In_{0.53}Ga_{0.47}As$ is lattice matched to InP, unlike materials with other composition grown on InP. Therefore $In_xGa_{1-x}As$ on InP can be subjected to tensile as well as compressive strain due to lattice parameter differences induced by suitable alloy composition changes.

The first identification of traps in liquid phase epitaxy (LPE) and vapor phase epitaxy (VPE) grown $In_{0.53}Ga_{0.47}As$ was made by BHATTACHARYA *et al.* [1]. Since then, the deep states in molecular beam epitaxy (MBE) grown material have been characterized by several groups. In deep level transient spectroscopy (DLTS) studies, deep centers at 0.33 eV [2], 0.37 eV [3], 0.41 eV [4], and 0.45 eV [2] above the valence band E_v have been detected. They were attributed to Fe and are believed to be electron traps. DANCAS *et al.* [5] detected the deep state at E_v + 0.32 eV and ascribed it to the Fe acceptor level located at the heterointerface. In addition, two acceptor levels at E_v + 0.11 eV and E_v + 0.15 eV have been observed.

In this paper characteristics of deep states present in undoped *n*-type InGaAs/InP strained layers are reported.

2. Experimental details

Set of 2.5 μm thick $In_xGa_{1-x}As$ samples of different composition, resulting in different lattice mismatch, were grown by MBE on the (001) oriented InP substrates. The undoped layers were grown at the rate 1 μm/h and at the substrate temperature of T_{sub} = 510°C. The material was *n*-type and electron concentration in the layers at 300 K was about 9×10^{15} cm^{-3}. Very thin films of undoped $In_{0.52}Al_{0.48}As$ lattice matched to InP were grown on the top of InGaAs layer. Finally Schottky barriers of 500 μm diameter were fabricated by evaporating Au.

The structural properties of the InGaAs epitaxial layers were determined from X-ray diffraction studies. The measurements were performed at 300 K using the high-resolution diffractometer (MRD Philips) in the triple-axis diffractometer (TAD) configuration. The composition of the layers was determined from the relaxed lattice parameter a_{relax} of the material. It was calculated using the following equation:

$$a_{relax} = \frac{a_{\perp} + 2Ca_{||}}{1 + 2C}$$

where: $a_{\perp}$ is the lattice parameter perpendicular to the layer/substrate interface, $a_{||}$ is the lattice parameter parallel to that interface; $C = (1 - \nu)/(1 + \nu)$, where ν is the Poisson ratio, equal to 0.311 and 0.352 for GaAs and InAs, respectively. The ν value of InGaAs layer was calculated from the linear dependence of both values.

The DLTS measurements were accomplished using a computer-controlled Semitrap DLS-82E system.

3. Experimental results and discussion

Two types of InGaAs/InP layers have been studied. Typical $2\theta/\omega$ scan of X-ray diffraction for the first type of structures, labeled *A*, is presented in Fig. 1. In the

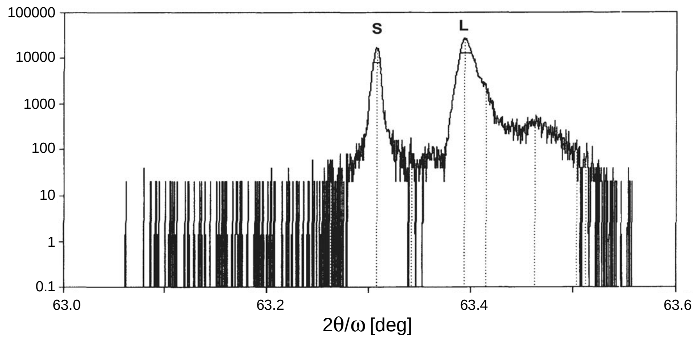

Fig. 1. X-ray diffraction scan in TAD configuration for $In_{0.524}Ga_{0.476}As/InP$ structure (*A*-type).

performed experiment 2θ is the angle between the incident beam and reflected beam, whereas ω is the angle between the incident beam and the wafer surface.

The layer and the substrate related peaks measured are narrow and well separated. Broadening of diffraction peak observed in this mode is related to the lattice parameter scattering. The values of full width at half maximum (FWHM) of the substrate and the InGaAs layer are equal to 24 and 41 arc sec, respectively. It is a proof of high quality of the epitaxial layer. As it follows from the measured value of the in-plane lattice parameter $a_{||}$, the layer is fully strained. The composition of the $In_xGa_{1-x}As$ layer was found to be $x = 0.5243$.

X-ray diffraction scan for the second type of structure, labeled *B*, is presented in Fig. 2. The layer is almost matched to the substrate and therefore substrate and layer related peaks are not well separated. The total FWHM value equal to 63 arc sec was detected. The composition of the $In_xGa_{1-x}As$ layer was found to be about $x = 0.534$.

Typical majority carrier DLTS spectrum for *A*-type structure is shown in Fig. 3. The results are presented at high value of emission rate $e_n = 5000\ \mathrm{s}^{-1}$, in order to visualize the main peak observed at low temperature. The concentration of the defects related to this peak is high, and amounts to about $5\times10^{14}\ \mathrm{cm}^{-3}$, as it results from capacitance measurements. No changes of the spectra were observed during DLTS studies.

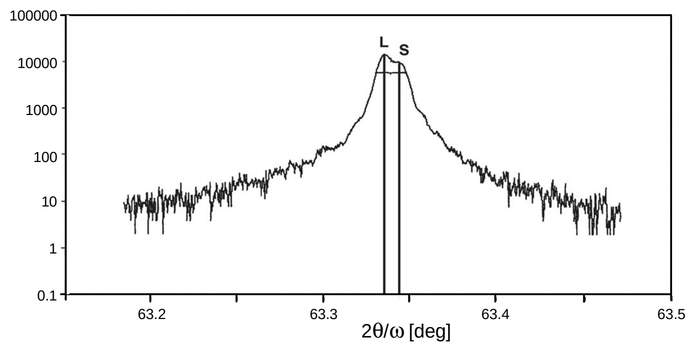

Fig. 2. X-ray diffraction scan in TAD configuration for $In_{0.534}Ga_{0.466}As/InP$ structure (*B*-type).

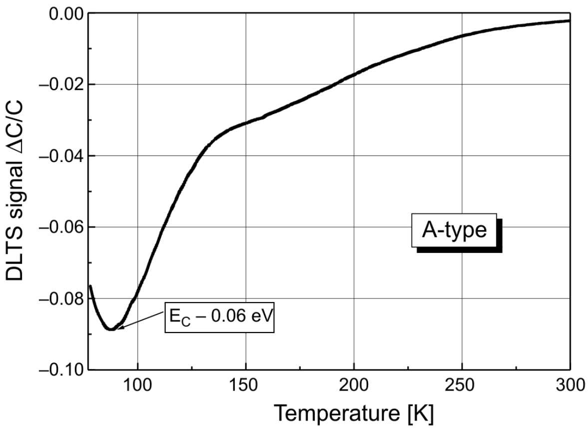

Fig. 3. DLTS spectrum for the majority of carrier traps in $In_{0.524}Ga_{0.476}As/InP$ layer. Emission rate $e_n = 5000\ s^{-1}$.

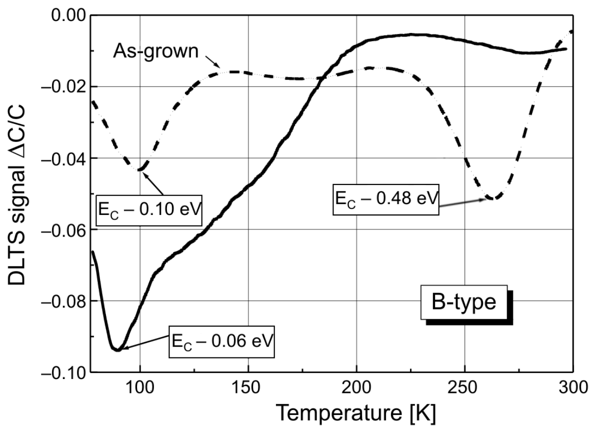

Fig. 4. DLTS spectra for the majority of carrier traps in $In_{0.534}Ga_{0.466}As/InP$ structure. Emission rate $e_n = 5000\ s^{-1}$.

The spectra detected for as-grown *B*-type InGaAs/InP layers are shown in Fig. 4. Two well-defined peaks of similar height have been observed at temperatures $T = 100$ K and $T = 260$ K. The concentration of both deep states was lower than $2.5\times10^{14}\ cm^{-3}$. After numerous DLTS scans, accompanied by many temperature changes from 300 to 77 K, significant modification of DLTS spectrum was observed. One dominating peak, well defined at low temperature, appeared instead of two peaks existing previously. The temperature peak position, and its heights were very similar to those observed in DLTS spectra for *A*-type structure.

The Arrhenius plot of deep states detected in InGaAs/InP layers is presented in Fig. 5. The thermal activation energies of the two deep states in as-grown $In_{0.534}Ga_{0.466}As/InP$

layer, being under small compression (*B*-type), are $E_C - (0.10 \pm 0.02)$ eV, and $E_C - (0.48 \pm 0.02)$ eV. The electron capture cross-sections of these traps, determined from emission processes, are equal to $\sigma_e = 6.7\times10^{-18}$ cm^{-2} and $\sigma_e = 1.6\times10^{-14}$ cm^{-2}, respectively.

The thermal activation energy of the deep state detected in the $In_{0.534}Ga_{0.466}As/InP$ layer, under tensile stress (*A*-type) is equal to $E_C - (0.06 \pm 0.03)$ eV. The same Arrhenius plot was determined for the defect states generated during thermal stresses in $In_{0.534}Ga_{0.466}As/InP$ layer. In order to compare both levels, the additional measurements of electron capture cross-section have been performed – Fig. 6. The changes in DLTS peak height versus pulse duration time for the levels are similar. The $E_C - (0.06 \pm 0.03)$ eV state exhibits point-like defect character.

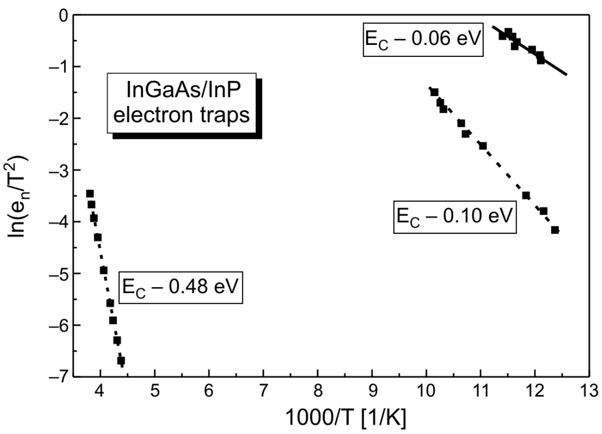

Fig. 5. Arrhenius plot of deep states present in MBE grown lattice mismatched InGaAs/InP layers.

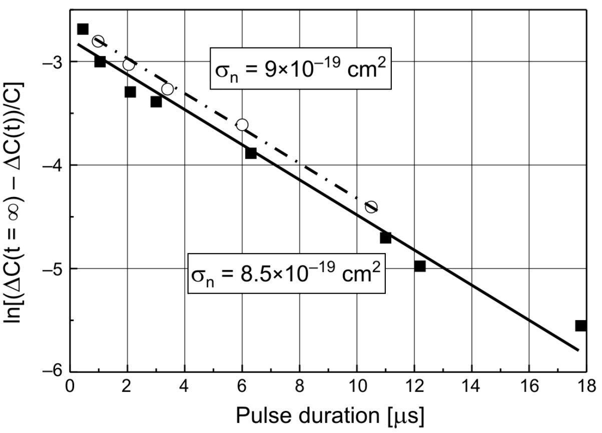

Fig. 6. Changes in DLTS peak height as a function of pulse duration time.

Not only the thermal activation energy but electron capture cross-section for the low temperature states observed in both layers were identical, thus proving the same origin of the low temperature states.

None of the traps observed in *n*-type InGaAs/InP have been reported earlier. All traps including Fe-related deep states were previously observed in *p*-type material and their thermal activation energies have been determined with respect to the edge of valence band. Nevertheless, Fe-related electron traps placed near the middle of the InGaAs energy gap can be detected by DLTS in *n*-type material as well. On the other hand, the concentration of the traps is rather high, not less than 2.5×10^{14} cm^{-3}. It is hard to believe that Fe can be present at such concentration in intentionally undoped MBE grown layers.

Observed deep state generation during DLTS studies may suggest the origin of this observed defect. Temperature induced stress changes of strained layers might result in the generation of misfit dislocations. However, the level is not related to the extended defect since point-like instead of repulsive electron capture processes have been detected. Nevertheless, stress induced creation of the $E_C - (0.06 \pm 0.03)$ eV state can suggest that vacancies or interstitial atoms are present. Therefore one can tentatively assume that low temperature state is related to a complex connected with lattice defect.

4. Conclusions

DLTS measurements performed on MBE grown lattice mismatched InGaAs/InP structure revealed three electron traps. Electron trap with thermal activation energy $E_C - (0.06 \pm 0.03)$ eV and electron capture cross-section $\sigma_e = 9.0\times10^{-19}$ cm^{-2} have been detected in $In_{0.524}Ga_{0.476}As$ layers being under tensile strain. The state exhibits a point-like defect character. Additionally two other centers with thermal activation energy $E_C - (0.10 \pm 0.02)$ eV, and $E_C - (0.48 \pm 0.02)$ eV have been detected in $In_{0.533}Ga_{0.467}As$/InP layers subjected to small compressive strain. Due to temperature stresses, defect states in the $In_{0.533}Ga_{0.467}As$/InP layers are modified and the center $E_C - (0.06 \pm 0.03)$ eV is created.

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