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Capture kinetics at deep-level defects in lattice-mismatched GaAs-based heterostructures

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Abstract

Two deep-level traps associated with lattice-mismatch induced defects in GaAs/InGaAs heterostructures have been revealed by means of deep-level transient spectroscopy (DLTS). An electron trap, at $E_c - 0.64$ eV, has been attributed to electron states associated with threading dislocations in the ternary compound while a hole trap, at $E_v + 0.67$ eV, has been ascribed to misfit dislocations at the heterostructure interface. Detailed investigation of the dependence of DLTS-line amplitude and its shape on the filling time of the traps with charge carriers allowed us to specify the type of electronic states related to both traps. In terms of the model of electronic states associated with extended defects, which takes into account the rate at which the states reach their internal electron equilibrium, we relate the electron trap to "localized" states and the hole trap to "bandlike" ones.

Keywords: Semiconductor heterostructures; Dislocations; Deep levels; Capture kinetics

1. Introduction

Lattice-mismatched GaAs-based heterostructures are of continual interest because of their application in high-speed and optoelectronic devices. Epitaxial growth of those heterostructures is accompanied by a strain in the epitaxial layer that results from a difference in lattice parameters between the substrate and the layer. If the thickness of the layer exceeds its critical value the strain is relieved by the formation of misfit dislocations. In heteroepitaxial semiconductor systems with zinc-blende structure and small lattice mismatch, grown on (0 0 1)-oriented substrates, orthogonal arrays of regular 60° misfit dislocations are formed at the interface [1]. The misfit dislocations are accompanied by threading dislocations which propagate into the epitaxial layer. Both kinds of dislocations can give rise to energy levels in the band gap which act as recombination centres or traps for free carriers. Due to translational symmetry along dislocation lines, one-dimensional energy bands rather than isolated localized electron states are expected to be associated with the dislocation cores.

In our recent paper [2], we revealed, by means of deep-level transient spectroscopy (DLTS), three deep-level traps associated with lattice-mismatch induced defects in two types of GaAs-based heterostructures: GaAs/GaAsSb and GaAs/InGaAs. In this communication we report new results of systematic investigation of kinetics for capture of charge carriers into the trap states. They give a new insight into the nature of the electronic states associated with two of the traps, which have been related to lattice-mismatch induced dislocations.

2. Samples

We investigated GaAs/InGaAs heterostructures, with the In content of 2%, grown by molecular beam epitaxy (MBE). The InGaAs layer of 1 μm thickness was grown on n^+-type GaAs buffer layer doped with Si. The InGaAs layer was Si doped to a thickness of 0.3 μm and its upper part was Be doped to p-type at the concentration of $10^{16}\,cm^{-3}$, so that an $n^+ - p$ junction was formed in the layer of the ternary compound. The junction

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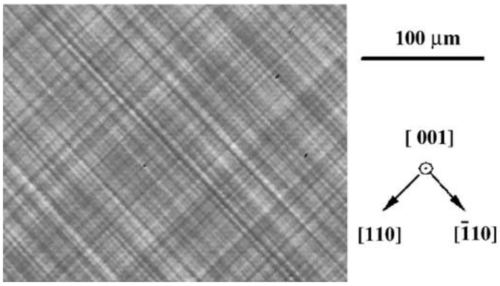

Fig. 1. Distribution of misfit dislocations at the interface of n^+–p GaAs/$In_{0.02}Ga_{0.98}As$ heterojunction revealed by means of EBIC technique in a scanning electron microscope.

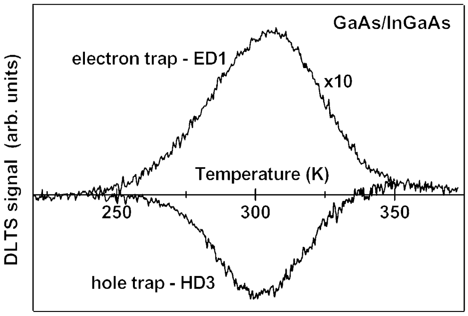

Fig. 2. DLTS spectra measured at a rate window of $48\,s^{-1}$ for the n^+–p GaAs/InGaAs heterojunction. The upper spectrum was recorded under reverse-bias conditions while the lower one was detected under forward-bias injection. Note the scale expansion for the upper spectrum.

position was shifted from the heterointerface towards the InGaAs side by 0.3 μm.

A difference in lattice constant between GaAs and the ternary compound, of about 0.2%, resulted in the generation of a two-dimensional network of misfit dislocations lying along two orthogonal ⟨1 1 0⟩ directions at the (0 0 1) interface. Such a dislocation network which has been revealed by means of an electron-beam induced current (EBIC) technique in a scanning electron microscope is shown in Fig. 1. Here, the misfit dislocations are visible as dark lines owing to enhanced recombination rate of electron–hole pairs generated by an electron beam.

3. DLTS results

The spectrum of lattice-mismatch induced defects has been studied by means of DLTS using p–n junctions formed in the epilayers. This allowed for investigation of both electron traps in the upper half of the band gap and hole traps in the lower half.

One electron trap, called ED1, has been revealed in the DLTS spectrum measured under typical bias conditions, i.e. under reverse quiescent bias, which was decreased to zero during the filling pulse, Fig. 2. This trap, with a deep level at $E_c - 0.64\,eV$ as determined from the slope of the Arrhenius plot shown in Fig. 3, has been attributed to threading dislocations in the layer of ternary compound close to the plane of p–n junction [2]. The ED1 trap had been, for the first time, revealed by means of DLTS in plastically deformed bulk GaAs at $E_c - 0.68\,eV$ and related to electron states associated with 60° dislocations [3]. The same trap was then found in several MOVPE-grown GaAs/InGaAs heterostructures by Watson et al. [4] and by Panepinto et al. [5], who ascribed the trap to misfit dislocations generated either at the interface [4] or in GaAs buffer layer close to the interface [5].

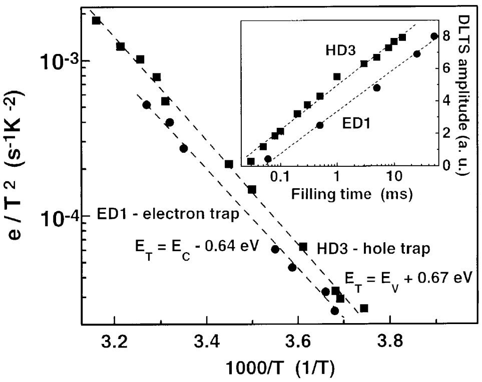

Fig. 3. Temperature dependence of the thermal emission rates (Arrhenius plots) for the traps revealed in the GaAs/InGaAs heterojunction. Energy positions of the trap levels, evaluated from the Arrhenius plots, are written in the figure. The inset shows DLTS peak amplitudes of ED1 and HD3 traps versus filling-pulse duration.

We have also identified the ED1 trap in GaAs/GaAsSb heterostructures with different Sb content (0–3%) and attributed it to threading dislocations present in the GaAsSb epilayer [2,6]. The activation energies for the electron emission from the ED1 traps, obtained for various heterostructures, decrease with an increase of the Sb or In content in the epitaxial layer similar to the manner in which the band-gap energy in the ternary compound decreases [2]. This relation implies that the energy level position of the trap with respect to the top of the valence band remains the same in each material, suggesting that the defect state is composed primarily of the valence band states. A similar dependence of the trap activation energy on the band gap energy has recently been found by Pal et al. [7] for the electron trap, attributed to threading dislocations in MBE-grown InGaAs layers with higher (10–30%) In mole fractions.

On the other hand, our DLTS measurements performed under injection conditions, i.e. under zero quiescent voltage and forward-bias filling pulse, revealed one hole trap (Fig. 2), called HD3, with a deep level at $E_v + 0.67\,eV$ (Fig. 3). We relate the trap, which has been detected only when the DLTS-active region comprises the interface, to defects associated with the lattice-mismatched interface, most probably to misfit dislocations lying at the interface. We revealed the same hole trap in the DLTS spectra of lattice-mismatched GaAs/GaAsSb heterostructures; however, the precise evaluation of its activation energy was strongly disturbed owing to the position of its DLTS line on the high-temperature slope of another line in those heterostructures [2]. Probably the hole trap recently found by Du et al. [8] in lattice-mismatched GaAs/InGaAs heterostructures with various In mole fractions and layer thicknesses is the same as HD3. That trap, labelled H4 by the authors, with the DLTS activation energy between 0.67 and 0.73 eV, has been related to misfit dislocations at the interface by comparing the DLTS spectra in various heterostructures with the distribution of dislocations revealed by means of transmission electron microscopy (TEM).

4. Capture kinetics

The principal argument for the assignment of the traps to dislocations was logarithmic kinetics for capture of charge carriers into the trap states. Such kinetics results from the Coulomb interaction between a charge carrier just being captured and other charges already captured at the dislocation line [9]. This interaction manifests itself in DLTS measurements in a linear dependence of the signal amplitude on the logarithm of the filling-pulse duration [3], as shown for the ED1 and HD3 traps over several orders of magnitude of that duration; see the inset of Fig. 3. In contrast, isolated point defects or impurities exhibit exponential capture kinetics.

Recently, Schröter et al. [10,11] proposed that electronic states associated with extended defects in semiconductors can be classified as *localized* or *bandlike* by taking into account the rate R_i, at which the states reach their internal electron equilibrium. The internal equilibration rate, when compared to the carrier emission rate from the defect R_e and the capture rate R_c, allows us to distinguish between *localized* states ($R_i \ll R_e$, R_c) and *bandlike* ones ($R_i \gg R_e$, R_c). The authors demonstrated, by computer simulation of DLTS spectra induced by the two types of states, that can be distinguished on the grounds of dependence of their DLTS-line shape on the filling time.

For *localized* states the DLTS-line maximum stays constant while changing the filling-pulse duration,

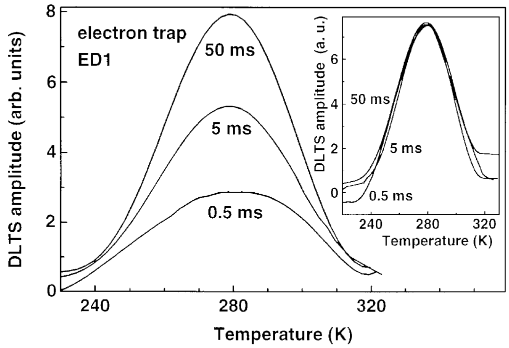

Fig. 4. DLTS line for the ED1 trap and its dependence on filling-pulse duration, whose values are written in the figure, measured at a rate window of $2\,s^{-1}$. In the inset, the line amplitude is normalized to the same height.

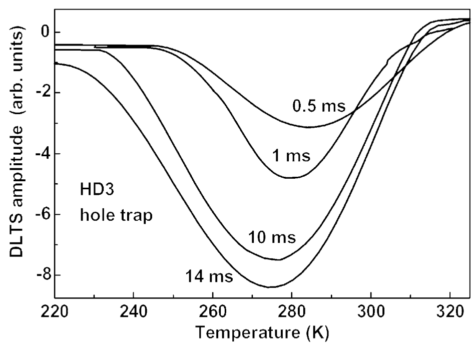

Fig. 5. DLTS line for the HD3 trap and its dependence on filling-pulse duration, written in the figure, measured at a rate window of $2\,s^{-1}$.

whereas the line amplitude exhibits a linear dependence on the logarithm of the filling time. Such behaviour has been found for the ED1 trap as shown in Fig. 4. This finding is in agreement with the results of Panepinto et al. [5] for the same electron trap, labelled EG4 in Ref. [5]. It has also been shown that the DLTS signal associated with 60° dislocations in plastically deformed Si can be described by this type of electronic states [10].

On the contrary, in the case of *bandlike* states, variation of filling-pulse duration results in broadened DLTS lines whose maximum shifts towards lower temperature on increasing that duration and whose high-temperature sides coincide. This is the case of the HD3 trap as demonstrated in Fig. 5. Possibly, the electronic states associated with misfit dislocations belong to *bandlike* states because of a higher regularity of those dislocations as compared with the threading ones. To this category of states belong also electronic states associated with dislocation rings bounding nanoscale $NiSi_2$ precipitates in silicon [11].

5. Conclusions

One electron trap and one hole trap have been found with the DLTS technique in lattice-mismatched GaAs/InGaAs heterostructures. The electron trap, called ED1, has been attributed to threading dislocations in the layer of ternary compound, whereas the hole trap, HD3, has been related to misfit dislocations lying at the heterostructure interface. A thorough analysis of the dependence of DLTS-line shape of the traps on the filling time allowed us to specify the type of electronic states related to both traps. We relate the ED1 electron trap to *localized* states and the HD3 hole trap to *bandlike* ones.

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