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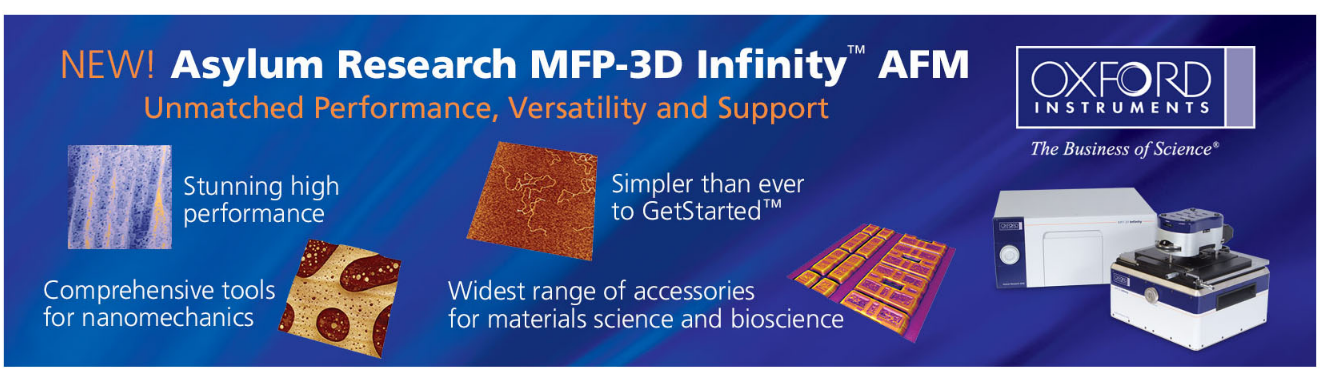

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Majority- and minority-carrier traps in Te-doped AlInP

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The properties of deep levels found in Te-doped AlInP grown by metal–organic chemical vapor deposition have been studied. By using *pn*-junction structure, both minority- and majority-carrier traps can be observed. Two deep levels are found in Te-doped AlInP: one majority-carrier trap and one minority-carrier trap. The activation energies of majority- and minority-carrier traps are 0.24 ± 0.05 and 0.25 ± 0.03 eV, respectively. The majority-carrier trap is uniformly distributed, indicating that this level belongs to some kind of bulk defect. © *1999 American Institute of Physics.* [S0003-6951(99)05202-X]

$(Al_{1-x}Ga_x)_{0.5}In_{0.5}P$ alloys, lattice matched to GaAs substrates, have been widely used in visible light-emitting laser diodes (LDs) and high-efficiency light-emitting diodes (LEDs).[1–4] As is well known, deep levels in these optoelectron devices significantly reduce the efficiency. Therefore, investigation of the deep levels in AlGaInP materials is important. The deep levels in Si-, Zn-, and Se-doped AlGaInP have been widely investigated,[5–8] but information on the deep levels in Te-doped AlInP is very limited. Te-doped AlInP has been conventionally used as *n*-type cladding layers in LDs and LEDs. In addition, the quality of cladding layers heavily influences device performance. In order to elevate device performance, it is desirable to study the deep levels in Te-doped AlInP. Deep-level transient spectroscopy (DLTS)[9] and capacitance–voltage (*C–V*) measurements are employed to characterize deep levels and doping concentrations, respectively, in the present experiments. The Schottky diode structure is frequently used in DLTS measurements owing to its relative ease of sample preparation, but this structure can only measure the majority-carrier traps. However, the minority-carrier traps may play a more important role in the operation of LDs and LEDs. Therefore, the *pn*-junction structure is adopted in this study, because such a structure allows us to observe both minority- and majority-carrier traps. The aim of our study is to obtain a characterization of the deep levels, both minority-carrier traps and majority-carrier traps, present in Te-doped AlInP.

The samples investigated herein are prepared by organic–metal vapor phase epitaxy (OMVPE) in an Aixtron 200/4 system. The growth temperature is 760 °C, the V/III mole ratio is approximately 160, the total pressure is 200 mbar, and the growth rate is 3 μm/h. Trimethyindium (TMIn), trimethylgallium (TMGa), trimethyaluminum (TMAl), and phosphin (PH_3) are used as the source materials. Diethyltelluride (DETe) and bis(cyclopentadienyl)magnesium (Cp_2Mg) are used for *n*- and *p*-type doping, respectively. A 2 μm Te-doped AlInP ($n=6\times10^{15}$ cm^{-3}) layer, followed by a 1 μm Mg-doped AlInP ($p=2\times10^{17}$ cm^{-3})layer and 0.1 μm Mg-doped GaAs ($p=1.5\times10^{19}$ cm^{-3}) layer were successively grown on the (100)-oriented n^+-GaAs substrate. The quality of the AlInP layer had been examined by x-ray diffraction and the mismatch of the AlInP layer is around 559.2 ppm. Generally, the mismatch of the material used for LDs and LEDs is said to be confined within the range from 0 to 1000 ppm. Alternately, the above doping concentration is determined by *C–V* measurements and nearly uniform doping distribution profiles are obtained. Ge/Au and Ti/Pt/Au, prepared by E-gun evaporation, were used as the Ohmic contact metal on the *n*-type AlInP and the *p*-type GaAs, respectively.

The DLTS measurements are based on altering the space-charge region to investigate the properties of deep levels. First, a steady-state reverse bias is applied to the *pn* junction to establish a space-charge region. Because the doping concentration of Mg-doped AlInP markedly exceeds that of Te-doped AlInP, most of the space-charge region exists in Te-doped AlInP. A carrier injection pulse toward zero bias then momentarily decreases the space-charge region width, making the majority carriers available for capture by deep levels. On the other hand, if a carrier injection pulse exceeds the zero bias, minority carriers are injected from Mg-doped AlInP. This behavior makes minority carriers available for capture by traps. Figure 1 shows a typical DLTS spectrum obtained from Te-doped AlInP under a no-minority-carrier-injection condition. This situation implies that the carrier injection pulse does not exceed the zero bias. Therefore, only majority carriers exist and can be captured by deep levels. According to Fig. 1, one majority-carrier trap exists in the DLTS spectrum. The emission activation energy E_a of this level deduced from the Arrhenius plots is 0.24 ± 0.05 eV and the average deep-level concentration is around 7×10^{13} cm^{-3}. In order to obtain further information about this deep level, measuring the spatial distribution of defects is necessary. The carrier injection pulse height V is increased from the origin in increments (δV) of 0.5 or 1 V and then a series of DLTS measurements is obtained. The equation used to calculate the distribution profile is[10]

$$\delta(\Delta C/C)=(\epsilon/qW^2n)[N_T(x_c)/n]\delta V,$$

where N_T is the defect concentration, ΔC is the initial height of the capacitance transient, C is the steady-state capacitance,

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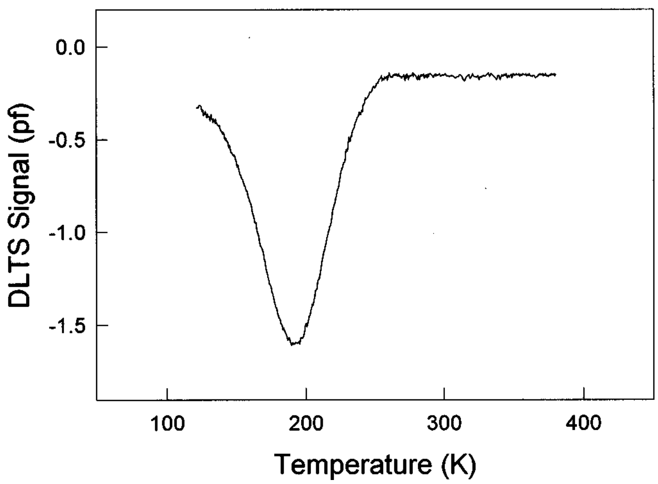

FIG. 1. DLTS spectrum obtained from Te-doped AlInP under the no-minority-carrier-injection condition. Only majority carriers exist in the material.

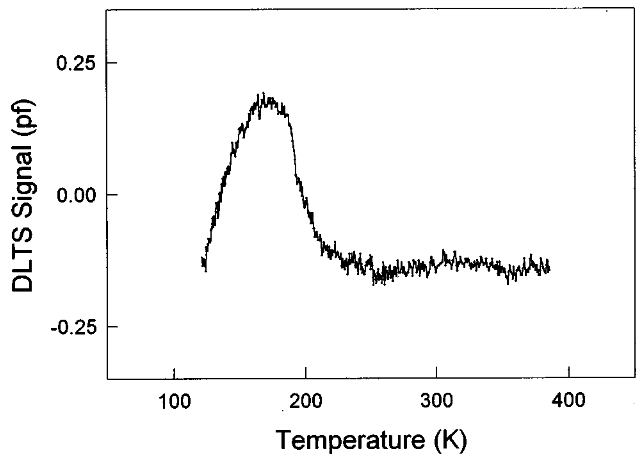

FIG. 3. DLTS spectrum obtained from Te-doped AlInP under the minority-carrier-injection condition. Both minority and majority carriers exist in the material.

V is applied pulse height, n is the net donor concentration, W is the steady-state depletion width, while the DLTS active layer width is given by

$$x_c = W - \lambda = W - [2\epsilon(E_F - E_T)/nq]^{1/2},$$

$$W = A\epsilon/C,$$

where E_F is the Fermi level and E_T is the trap energy level. λ is the distance between the edge of depletion layer and the point where the Fermi level crosses the trap level. Figure 2 shows the majority-carrier trap concentration distribution in Te-doped AlInP. Obviously, this majority-carrier trap is uniformly distributed. From this aspect, this majority-carrier trap should belong to some kind of bulk defect, not interface defects.

Besides measuring under the no-minority-carrier-injection conditions, we can also obtain information of minority-carrier traps in the material under a minority-carrier-injection condition, the carrier injection pulse exceeding zero bias condition. Figure 3 shows a typical DLTS spectrum under the minority-carrier-injection condition. One peak also appears in Fig. 3. However, the peak in Fig. 3 does not coincide with the DLTS theory curve, indicating that the peak is not composed of only one trap. Thus, we can infer that Te-doped AlInP contains at least two traps. Comparing Fig. 1 with Fig. 3 reveals that both peaks are located near 195 K. Because both minority and majority carriers exist in the material under the minority-carrier-injection condition, we think that Fig. 3 should be composed of two deep levels: one minority-carrier trap and one majority-carrier trap. The minority-carrier trap, not having been processed previously, begins the trapping activity as the minority-carrier-injection condition. On the other hand, the majority-carrier trap proceeds with the trapping activity regardless of minority-carrier injection or not. Both minority-carrier and majority-carrier traps compose the peak profile in Fig. 3. To confirm our assumption, the data in the Fig. 1 data are subtracted from data of Fig. 3 to obtain Fig. 4. According to the DLTS curve fitting theory, the peak in Fig. 4 is verified as a single minority-carrier trap and this result confirms the credibility of our assumption. The emission activation energy E_a and the average deep-level concentration of this minority-carrier trap are 0.25 ± 0.03 eV and 1×10^{14} cm^{-3}, respectively. The values of the activation energy of minority- and majority-carrier traps again verify that the behaviors of trapping minority and majority carriers are not attributed to merely one deep level. Because the energy gap of AlInP at room temperature is around 2.3 eV, the values of the activation energy

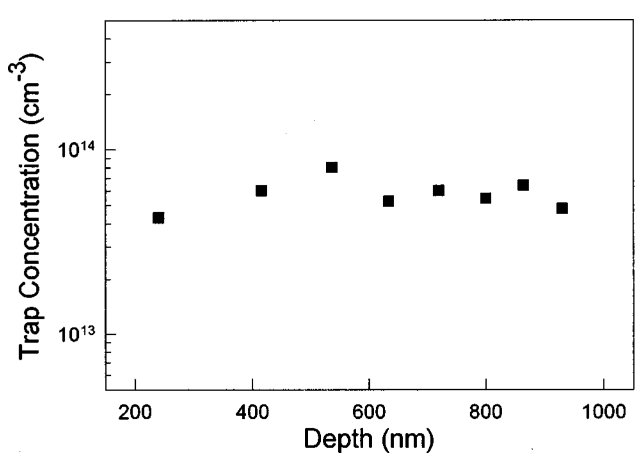

FIG. 2. The distribution profile of majority-carrier traps in Te-doped AlInP.

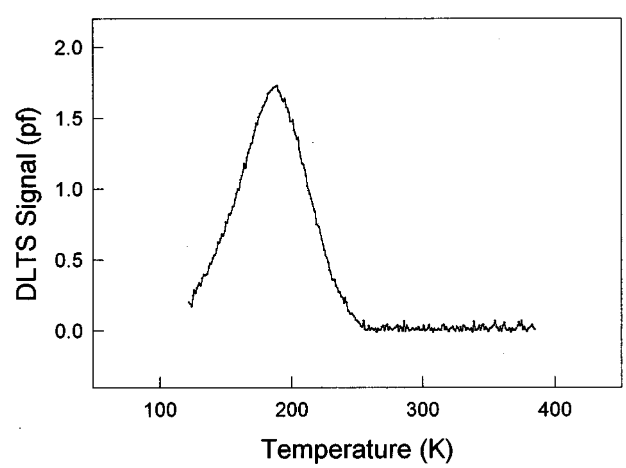

FIG. 4. DLTS spectrum obtained from the combination of Figs. 1 and 4.

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of minority- and majority-carrier traps are so much smaller than the value of the energy gap. If the trapping behavior is merely due to one deep level, it should be a recombination center, not a trapping center. However, an effective recombination center is normally located near the midgap of the band gap, not the band edge. Comparing our results with previous studies in Si-, Zn-, and Se-doped AlInP reveals some similar characteristics. Most previous studies, including Si- and Zn-doped AlInP research, simply found one majority-carrier trap and the defects are verified as uniformly distributed. Besides, the activation energies of the defects, which are 0.48 and 0.42 eV in Si- and Zn-doped AlInP, are small. In spite of the two majority-carrier traps found in Se-doped AlInP, one of these two defects also presents uniformly distributed and small activation energy, 0.29 eV. From the above discussion, we believe that the majority-carrier trap found in Te-doped AlInP should be the same kind of the defect as in previous studies. Because all the majority-carrier traps found in Si- and Zn-doped AlInP, and some majority-carrier traps in Se-doped AlInP have been verified as dopant-related deep levels, we can further infer that the majority-carrier trap obtained in Te-doped AlInP is also a dopant-related deep level. However, direct evidence is still necessary along with precise experiments.

In conclusion, this work has investigated the deep-level properties of AlInP doped with Te. By using a *pn*-junction structure, both minority- and majority-carrier traps can be observed. According to our results, two deep levels are found in Te-doped AlInP: one minority-carrier trap and one majority-carrier trap. The majority-carrier trap has been verified as a uniform distribution in AlInP and its activation energy is small. Compared with previous studies, we can infer that the majority-carrier trap originates from Te-related defects. The origin of the minority-carrier trap still remains unclear. Further work is necessary to determine the structure of the deep levels obtained in Te-doped AlInP.

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