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## Phosphorus Vacancy as a Deep Level in AlInP Layers

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Deep levels in AlInP layers, grown by metal-organic chemical vapor deposition (MOCVD) with various V/III mole ratios, have been carefully investigated by deep-level transient spectroscopy (DLTS). A deep level originating from phosphorus vacancy was observed with the activation energy of 0.65 eV. Examining this phosphorus-vacancy-related deep level provided a relatively simple means of understanding the phosphorus vacancy in AlInP, thus allowing us to determine an appropriate V/III mole ratio for growing AlInP.

KEYWORDS: AlInP, phosphorus vacancy, defect, deep level, DLTS, depth profile measurement

(Al<sub>1-x</sub>Ga<sub>x</sub>)<sub>0.5</sub>In<sub>0.5</sub>P alloys, lattice-matched to GaAs substrate, have been extensively used in visible light emitting laser diodes (LDs) and high-efficiency light-emitting diodes (LEDs).<sup>1-4</sup> As well known, phosphorus vacancies often exist in AlGaInP materials due to the high vapor pressure of phosphorus. These phosphorus vacancies conventionally form trapping centers or recombination centers, thus significantly reducing the efficiency of opto-electronic devices that use AlGaInP materials. To avoid phosphorus vacancy and ensure a satisfactory yield, a high V/III mole ratio is necessary when growing AlGaInP. Previous studies have used V/III mole ratios higher than several hundreds in growing AlGaInP alloys. However, the higher V/III mole ratio implies more costly manufacturing. Moreover, phosphorus vacancy is undetectable by general measurements, such as X-ray analysis or PL measurement. Therefore, how to measure phosphorus vacancy and choose a suitable V/III mole ratio are important tasks. This investigation uses deep level transient spectroscopy (DLTS)<sup>5</sup> to observe the deep levels in AlInP and, in doing so, obtains the information on phosphorus vacancy in AlInP. This information on phosphorus vacancy makes it possible to choose an appropriate V/III mole ratio for growing AlInP.

The samples investigated herein were prepared by organometal vapor phase epitaxy (OMVPE) in an Aixtron 200/4 system. The growth temperature is 760°C, the total pressure is 200 mbar, and the growth rate is 3 μm/h. For experimental purposes, the V/III mole ratio was varied from 40 to 200 in growing AlInP materials. Trimethylindium (TMIn), trimethylgallium (TMGa), trimethylaluminum (TMAI), and phosphin (PH<sub>3</sub>) are used as the source materials. Meanwhile, diethyltelluride (DETe) and bis(cyclopentadienyl)magnesium (Cp<sub>2</sub>Mg) are used for n-type and p-type doping, respectively. The sample construction adopted herein is p<sup>+</sup>-n junction structure. A 2-μm-thick Te-doped AlInP layer, followed by a 1 μm-thick Mg-doped AlInP layer and 0.1 μm-thick Mg-doped GaAs layer were successively grown on the (100)-oriented n<sup>+</sup> GaAs substrate. X-ray analysis indicated that the mismatch of samples was confined between 0 and 1000 ppm, which is the range generally required for growing material used in LEDs and LDs. The doping concentration in the Mg-doped AlInP and Mg-doped GaAs layers are around 2 × 10<sup>17</sup> cm<sup>-3</sup> and 1.5 × 10<sup>19</sup> cm<sup>-3</sup>, respectively. Besides, the concentration of Te-doped AlInP is around 3 × 10<sup>16</sup> cm<sup>-3</sup>.

The above concentrations were determined by C–V measurements and each sample produced nearly uniform doping distribution profiles. Ge/Au and Ti/Pt/Au, prepared by E-gun evaporation, were used as the ohmic contact metal on the n-type and p-type GaAs, respectively.

Figure 1 displays a typical DLTS spectrum, obtained from the sample grown with a V/III mole ratio of 80. Because the dopant concentration of Mg-doped AlInP significantly exceeds that of Te-doped AlInP, the depletion region is thought to exist in Te-doped AlInP. Therefore, the peaks in Fig. 1 are considerably due to the deep levels in Te-doped AlInP. According to Fig. 1, two deep levels, labeled L1 and L2, are observed, with the activation energy of 0.24 eV and 0.65 eV, respectively. The peak located at 195#K is the same as in previous studies by the present authors, and it has been confirmed to be a dopant-related defect.<sup>6,7</sup> Further information about deep levels in AlGaInP alloys with different dopings can be found elsewhere.<sup>8-13</sup> However, the other peak, which is located at 350#K in Fig. 1, has never been found before. Comparison with our previous studies<sup>6,7</sup> reveals that the major difference between these two experiments is the V/III mole ratio they are grown with. The previous studies used a higher V/III mole ratio than the present experiment with their ratio being around 160. Due to the high vapor pressure of phosphorus, phosphorus easily outgases from material during epi-

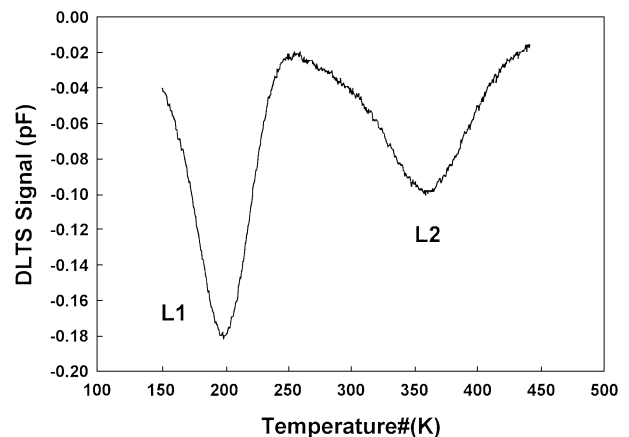


Fig. 1. DLTS spectrum obtained from AlInP with a V/III mole ratio of 80. The activation energy of trap L1 and L2 are 0.24 eV and 0.65 eV, respectively.

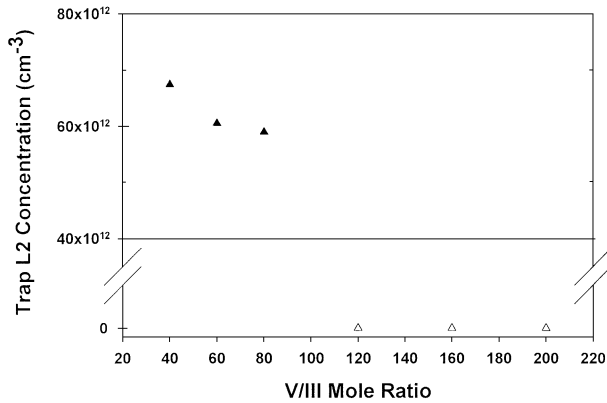


Fig. 2. Relation between trap L2 concentration (phosphorus vacancy concentration) and growing V/III mole ratio. The minimum trap concentration which can be detected by this DLTS system is  $4 \times 10^{13} \text{ cm}^{-3}$ .

taxy process. Therefore, the peak L2 is most probably caused by phosphorus vacancy. To further substantiate this assumption, a series of samples growing with different V/III mole ratios were examined. Fig. 2 illustrates the relation between the L2 concentration and V/III mole ratio. The L2 concentration obviously increases with decreasing V/III mole ratio. This result verifies that the L2 originates from phosphorus vacancy. The phosphorus vacancy increases greatly when the V/III mole ratio is lower than 120. When the samples grew with V/III mole ratios of 40, 60 and 80, the L2 concentration are  $5.89 \times 10^{13} \text{ cm}^{-3}$ ,  $6.05 \times 10^{13} \text{ cm}^{-3}$  and  $6.74 \times 10^{13} \text{ cm}^{-3}$ , respectively. Although the L2 concentration can not really present the actual concentration of phosphorus vacancy in AlInP, deep level L2 still provides a good means to understand the condition of phosphorus vacancy in AlInP. Meanwhile, the suitable V/III mole ratio can also be determined by experimenting with L2 concentration. The V/III mole ratio of 120 or 160 are thought of as a good V/III mole ratio for growing AlInP. On the other hand, to further understand the characteristics of the phosphorus vacancies in AlInP, it is necessary to measure the phosphorus vacancy L2 distribution profile. By increasing the carrier injection pulse height,  $V$ , from origin in increments ( $\delta V$ ) of 0.5 V or 1 V makes it possible to obtain a series of DLTS measurements. The equation used to calculate the distribution profile is

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

Where  $N_T$  denotes the defect concentration,  $\Delta C$  represents the initial height of the capacitance transient,  $C$  is the steady-state capacitance,  $V$  denotes the applied pulse height,  $n$  represents the net donor concentration, and  $W$  is the steady-state depletion layer width. Meanwhile, the DLTS active layer width can be expressed as

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

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

Where  $E_F$  denotes the Fermi level,  $E_T$  represents the trap energy level, and  $\lambda$  is the distance between the edge of the depletion layer and the point where the Fermi level crosses the trap level. Figure 3 displays the concentration profile of the

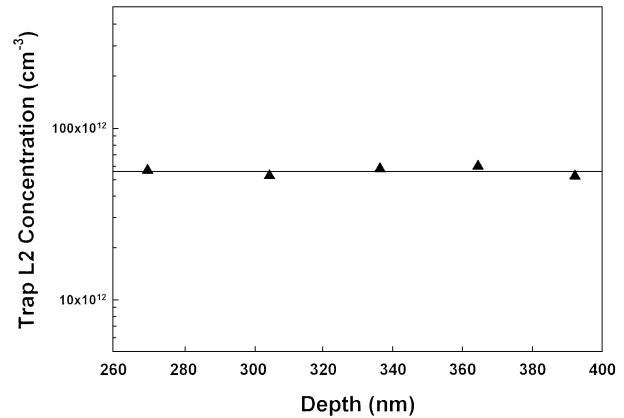


Fig. 3. The deep level L2 (phosphorus vacancy) distribution profile in AlInP.

deep level L2 in AlInP growing with a V/III mole ratio of 80, which presents a uniform distribution profile. Because the V/III mole ratio is constant during sample growing, it is expected that the phosphorus vacancy (L2) should also have a uniform distribution profile. Since the observation corresponds with expectations the deep level L2 in the Te-doped AlInP is again verified as a phosphorus-vacancy-related defect.

The high vapor pressure of phosphorus means that phosphorus vacancy often exists in AlInP. However, phosphorus vacancy can not be detected directly. This study, by analyzing the deep levels in AlInP with different growing V/III mole ratios, found a deep level which originates from phosphorus vacancy. Examining phosphorus-vacancy-related deep levels provided a relatively simple means of understanding the phosphorus vacancy in AlInP, thus allowing us to determine an appropriate V/III mole ratio for growing AlInP.

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