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DX Centers in Si-Doped AlAs

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DX centers in Si-doped AlAs were clearly observed for the first time. The activation energy was measured as 0.56eV from deep level transient spectroscopy (DLTS). The carrier concentration in the DX center revealed by DLTS was not proportional to the Si donor concentration. This result can be interpreted by the band structure that the DX center lies at 30 to 10meV above the X-conduction band minima, i.e., at 150 to 170meV below the L-conduction band minima.

I. Introduction

DX centers , i.e., deep donors, in n-$Al_xGa_{1-x}As$ imposes serious effects on the conductivities[1] and thus on device performance of such as high electron mobility transistor (HEMT). It is, therefore, an important subject to investigate the origin and the characteristics of the DX centers. It is well known that the DX center appears in $Al_xGa_{1-x}As$ with $0.22<x<0.8$. However, for further understanding of the behavior of the DX centers, investigations for wide variations of x are strongly required. Recently DX centers have been found also in n-GaAs.[2] On the other hand, for n-$Al_xGa_{1-x}As$ with higher Al content ($x>0.8$), it has not been clear whether the DX centers exist or not. In this paper, we report the existence of the DX center in n-AlAs and discuss its energy level.

II. Experimental Procedure

The samples for deep level transient spectroscopy (DLTS) and capacitance-voltage (C-V) measurements of an n-AlAs layer consisted of an n-GaAs buffer layer, an 1μm-thick n-AlAs, and a 300Å-thick n-GaAs cap layer, which were successively grown on an n^+-GaAs substrate by molecular beam epitaxy (MBE). The growth temperture T_g was 600°C or 700°C, the V/III ratio about 5, and the growth rate about 1μm/h. We have confirmed little oxidation of an n-AlAs layer. From Poisson's equation, the cap layer is found to be depleted at injection pulse of DLTS.

For DLTS and C-V measurements, Au was evaporated onto the epitaxial side to form Schottky contacts with diameter of 470~770μm. An injection pulse width was selected as 20msec to fill almost all (about 75% of) the deep traps with electrons. The repetition period was 60 to 200msec.

III. Experimental Results

3-1 DLTS Results

A DLTS spectrum for an n-AlAs layer is shown in Fig. 1. A signal by deep traps was observed around 200K. We will denote it as an E_1 trap. The activation energy and the capture cross section were 0.56eV and $1\times10^{-10}cm^2$, respectively. The full width at half maximum (FWHM) of the E_1 peak agrees with the theoretically calculated value assuming that the E_1 trap is a single level. This means that the emission transient follows an exponential function of time.

The dependence of the apparent E_1 concentration derived from DLTS, N_t, on the donor concentration N_d is shown in Fig. 2. Here, N_d was obtained from the C-V measurements

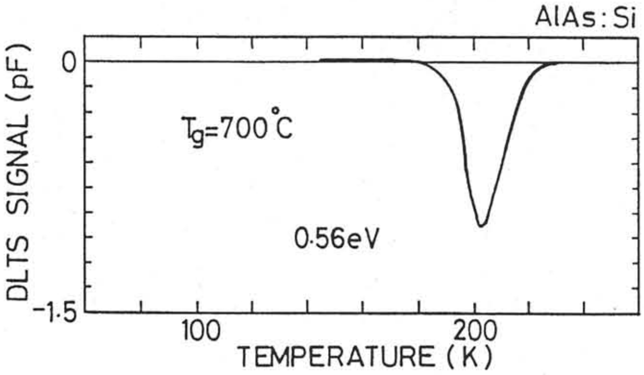

Fig. 1 DLTS spectrum for Si-doped AlAs. The E_1 trap (0.56eV) was observed.

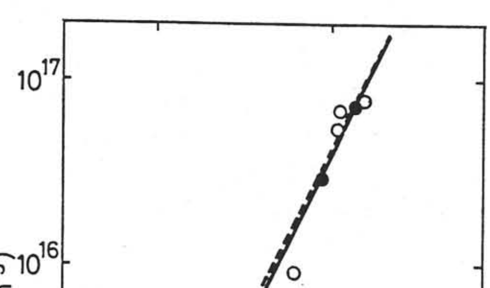

Fig. 2 Relationship between the apparent E_1 concentration from DLTS, N_t, and the donor concentration N_d. The growth temperature was 700°C for (○), 600°C for (●). The exprimental results can be best fitted by substituting $E_{DX}-E_X$=30meV in the case of (a) (solid line), 10meV in the case of (b) (broken line), respectively.

at room temperature. The N_t was independent of the growth temperature 600°C or 700°C, but strongly depends on N_d. It suggests that the origin of the E_1 trap is closely related to the Si donors. However, it is not proportinal to N_d, i.e., it decreases drastically with decreasing N_d. This correlation will be discussed later.

We also performed capture-DLTS. The spectrum is shown in Fig. 3. The positive peak around 195K originated from the E_1 trap. Its activation energy is about 0.5eV, which is as high as that of the emission energy.

3-2 Persistent Photoconductivity

We observed the persistent photoconductivity (PPC) effect. The electron concentration and conductivity increased by the irradiation of the light of GaAs light emitting diode and persisted for several hours at 77K after the removal of the light (see Table 1). However, the increase of the electron concentration was as low as $(0.14\sim5.6)\times10^{-3}$ of the Si donor concentration.

VI. Discussions

The above experimental results strongly suggest that the E_1 trap is the DX center, because the E_1 trap possesses the characteristics of the

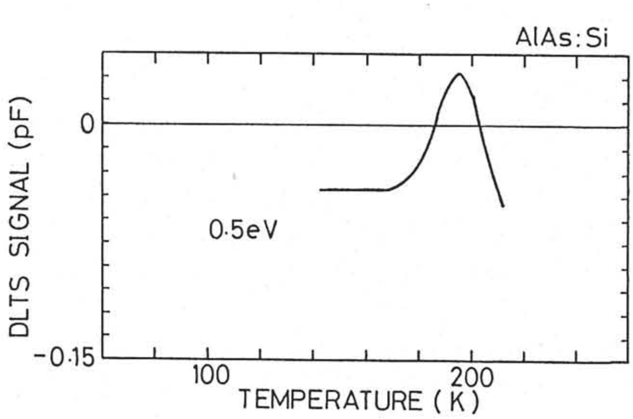

Fig. 3 Capture-DLTS spectrum of Si-doped AlAs.

DX center, i.e., (1) N_t strongly depends on N_d, (2) the capture energy is high, and (3) the PPC effect exists.

We consider a reason for the experimental results shown in Fig. 2 that N_t is not proportional to the Si donor concentration N_d. Since the N_t was estimated from the DLTS spectra, the N_t does not represent the true density of the DX center but the concentration of carriers trapped at the DX center when the injection pulse is applied. Therefore, if the DX center in n-AlAs lies above the Fermi level, the obtained N_t is much less than the true DX center concentration. The non-linear relationship between N_t and N_d shown in Fig. 2 can be interpreted by the energy level of the DX center. Figure 4 shows a schematic band structure of AlAs. The X-CB minima is the lowest and the L-CB minima is the second lowest. We consider two cases; (a) the Si donor forms only the DX center, (b) the Si donor forms the DX center and the shallow donor level.

In the case of (a), the true DX center concentration is equal to the Si donor concentration, $N_d=N_{DX}$. The following equation can be derived,

$$n_x=N_{DX}\cdot \{1-F(E_{DX})\}, \quad (1a)$$

$$N_t=N_{DX}\cdot F(E_{DX}), \quad (2)$$

where N_{DX} is the true DX center concentration, E_{DX} the energy level of the DX center. The F(E) is given by

$$F(E)=1/\{1+\exp((E-E_F)/kT)/g\}, \quad (3)$$

where E_F is the Fermi level and g is the degeneracy. The electron concentration in the X-CB, n_x, is given by

$$n_x=N_{cx}\cdot 2/\sqrt{\pi}\cdot FD(E_x), \quad (4)$$

where N_{cx} is the effective density of states in the X-CB, FD(E) the Fermi-Dirac integral, E_x energy at the X-CB minima. Relationship between N_t and N_d can be calculated by eqs. (1a)~(4), and the experimental results shown in Fig. 2

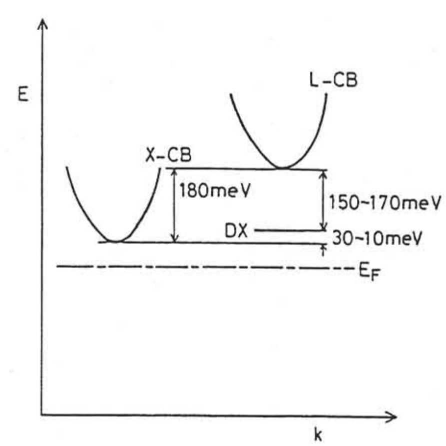

Fig. 4 Schematic band structure of AlAs.

Table 1 The change of carrier concentration (cm^{-3}) due to the persistent photoconductivity.

	n(RT)	n(77K, in the dark)	n(77K, after the removal of light)
#1	2.3×10^{17}	6.46×10^{15}	6.78×10^{15}
#2	6.2×10^{17}	3.35×10^{16}	3.70×10^{16}

can be best fitted by substituting $E_{DX}-E_X=30meV$. Since $E_L-E_X=180meV$[3], the DX center lies at 150meV below the L-CB minima.

In the case of (b), $N_d=N_{DX}+N_{SD}$, where N_{SD} is the shallow donor concentration. We replace Eq. (1a) with

$$n_X=N_{DX}\cdot(1-F(E_{DX})) +N_{SD}\cdot(1-F(E_{SD})). \quad (1b)$$

N_d and N_{SD} were measured as the concentration obtained from C-V measurements at RT, 77K ,respectively. The DX center concentration was determined by the difference between the donor concentrations obtained from C-V measurement at RT and at 77K. The experimental results can be best fitted by substituting $E_{DX}-E_X=10meV$. Therefore, the DX center lies at 170meV below the L-CB minima.

It was reported that the DX center follows the L-CB minima and lies about 160meV belows the L-CB minima in $Al_xGa_{1-x}As(x<0.22)$ as well as in $Al_xGa_{1-x}As(x>0.22)$.[4] Similarly our data for AlAs agrees well with that for $Al_xGa_{1-x}As$. Further consideration will be reported elsewhere.

V. Conclusion

We found the DX center in n-AlAs. Fundamental characterization gives the following results; (1) the activation energy and the capture cross section were 0.56eV and $1\times10^{-10}cm^2$, respectively, (2) the PPC effect can be observed, and (3) the DX centers lie at 30 to 10meV above the X-CB minima, i.e., at 150 to 170meV below the L-CB minima.

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