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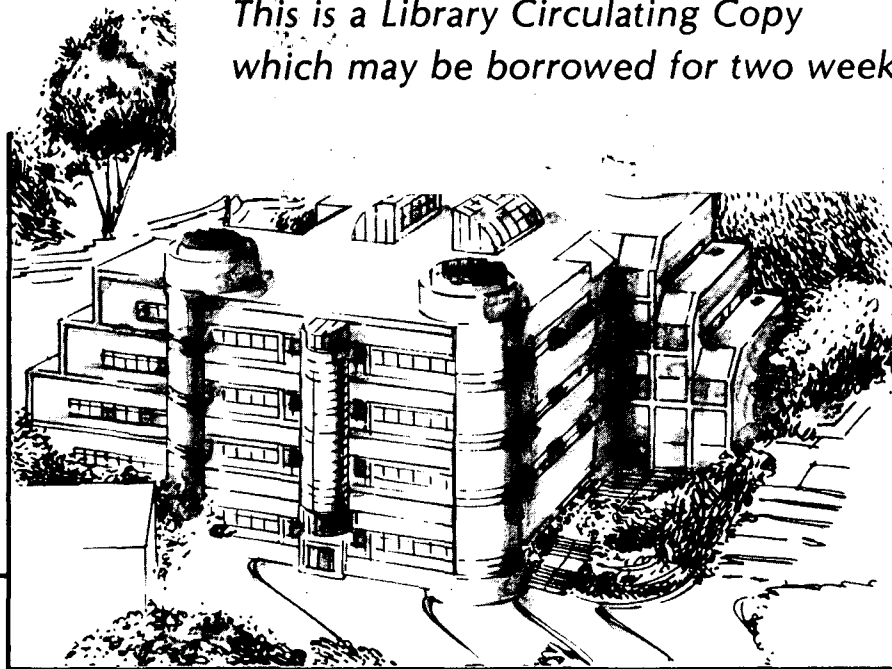Budapest, Hungary, August 22–26, 1988

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DISCLAIMER

PRESSURE DEPENDENCE OF THE DX CENTER IN $Al_{0.35}Ga_{0.65}As$:Te

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ABSTRACT

The pressure dependence of the DX center in $Al_{0.35}Ga_{0.65}As$:Te has been studied by Deep Level Transient Spectroscopy using a diamond anvil high pressure cell. The results confirm that the effects of pressure and increase in Al concentration on the DX center are qualitatively similar though quantitatively different. Specifically, the pressure coefficients of the activation energies for emission was found to change sign when the bandgap of AlGaAs changed from direct to indirect. On the other hand emission energy has been reported to be independent of Al concentration. Based on our results we conclude that the X conduction band minima also play a significant role in the DX center wavefunction.

INTRODUCTION

The properties of deep donors known as DX centers in AlGaAs alloys are known to depend on the Al concentration and on hydrostatic pressure.[1-5] A number of studies on the effect of alloying on the properties of the DX centers have been reported. It was found that the energy of the DX center followed the L conduction valleys as a function of Al concentration.[5] On the other hand the activation energy for emission (E_e) was independent of the alloy concentration.[4] These results have led to the proposal that the DX centers involved the L conduction band wavefunctions only.[6] So far there has been relatively few studies of the pressure dependence of the DX centers. Pressure was generally considered to produce the same effect on the DX centers as alloying by changing the relative ordering of the conduction band minima. Pressure,however, has an advantage over changing the Al concentration in that variations in the DX center properties due to different sample histories can be avoided and pressure does not change the amount of randomness introduced by alloying. In addition we have found that some DX center properties such as its capture and emission activation energies (E_c and E_e) are sensitive to its environment. For example,the values of E_e for DX centers in AlGaAs:Si and in GaAs:Si under pressure are 0.4 eV and 0.3 eV respectively.[7] The pressure

dependence of the DX center in AlGaAs:Si has been recently reported by Farmer et al.[8] In this paper we report the pressure dependence of the DX center in Te-doped AlGaAs. We found that the pressure coefficient of E_e changed sign when the bandgap switched from direct to indirect in contrast to alloying. Thus our results are inconsistent with the model proposed by Theis [6] and suggest instead that, at least in Te doped samples, the conduction band minima at the X point of the Brillouin zone also contribute to the DX centers.

EXPERIMENTAL DETAILS AND RESULTS

The samples used in this study were Schottky diodes fabricated from GaAlAs epilayers grown on GaAs substrate by liquid-phase-epitaxy and doped with 5×10^{16} cm^{-3} of Te. Ohmic contacts to the samples were prepared by evaporating Au-Ge alloy to the GaAs substrate followed by a 450 C anneal for one minute. Schottky barriers were formed by evaporating Al onto the epilayer. Samples were loaded into a diamond-anvil high pressure cell surrounded by epoxy and CaSO$_4$ as the pressure medium using a technique described by Erskine et al..[9] Sample pressure was determined by the standard ruby fluorescence technique. Several ruby chips were placed around the sample and the variation in the pressure determined from these ruby chips was typically ± 1 kbar.

Deep level transient spectroscopy (DLTS) were performed on the samples using a Boonton capacitance meter and a Princeton Applied Research dual-channel boxcar integrator. Some typical DLTS spectra obtained at atmospheric pressure and under pressure are shown in Figure 1. While the atmospheric pressure spectrum showed only one peak, some of the spectra under pressure showed two peaks which we have labelled as peaks A and B. At pressures above 6 kbar the peak B decreased rapidly in intensity and became unobservable. Comparing the value of E_e of these centers deduced from the DLTS spectra with those reported by Lang et al. we have identified the peak A with the DX center. At present the identification of peak B is still unknown. The emission rates (e_n) of the deep centers associated with A and B were deduced from the DLTS spectra. The capture rates (τ_c^{-1}) were measured by a standard majority-carrier pulse method at constant temperatures[10] analogous to the method of Lang.[3] Because of the nonexponential dependence of the signal on pulse width we have determined τ_c^{-1} from the 1/3-signal points rather than the 1/2-signal points used by Lang.

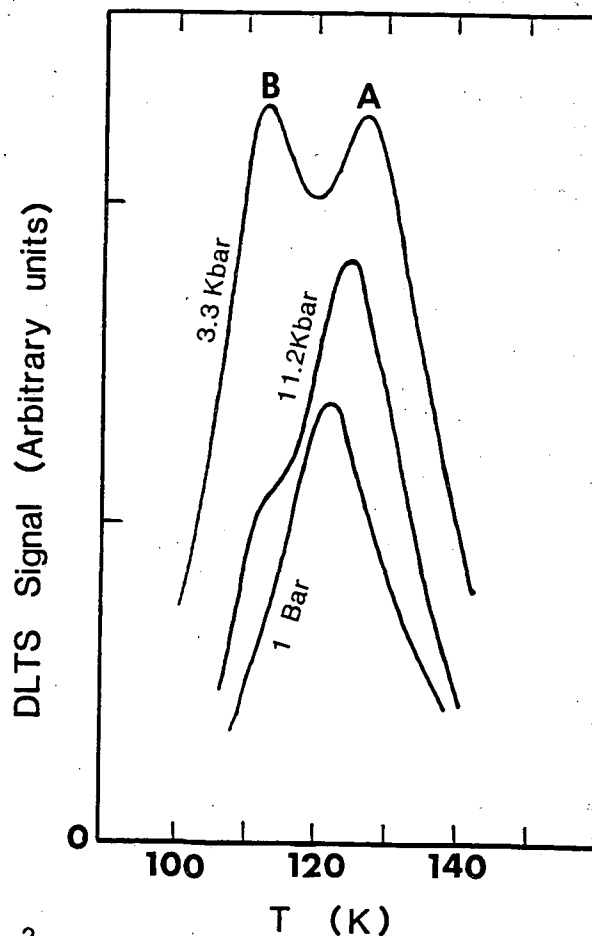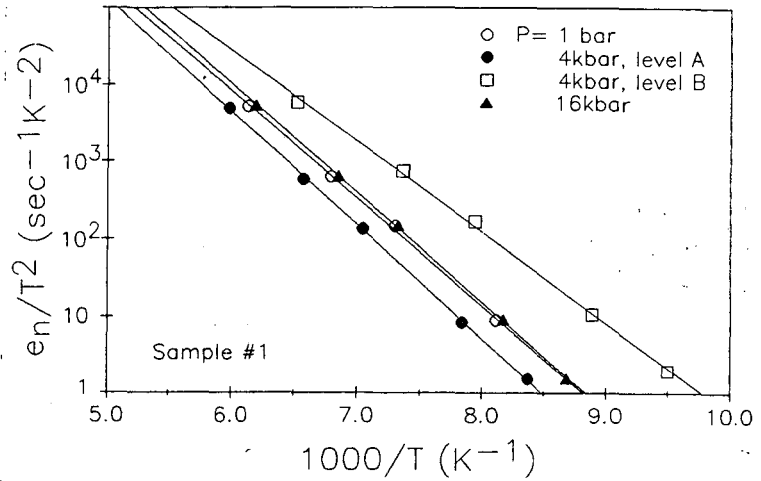In our samples both e_n and τ_c^{-1} were found to have activated temperature dependence:

Figure 1
Typical DLTS spectra in AlGaAs (35% of Al) doped with Te under different pressures. Window times: t_1=1 s, t_2=2 s. Filling pulse width:200 ms.

2

Figure 2
Arrhenius plot of the electron emission rate for levels A and B in sample # 1 at several pressures.

Legend:
○ P= 1 bar
● 4kbar, level A
□ 4kbar, level B
▲ 16kbar

Sample #1

Axes: e_n/T^2 (sec^{-1}K^{-2}) vs $1000/T$ (K^{-1})

$$e_n/T^2 = A_e \exp[-(E_e/kT)] \qquad (1)$$

$$(\tau_c)^{-1} = A_c \exp[-(E_c/kT)] \qquad (2)$$

where E_e and E_c are respectively the activation energies for emission and capture of the electron. Some plots of e_n/T^2 vs T^{-1} at different pressures are shown in Fig. 2. From these plots values of E_e and E_c in two different samples cut from the same wafer have been determined. As have been noted by Lang et al.[11] and also by Farmer et al.[8], the DLTS spectra of the DX center showed slight variations from sample to sample. In sample #1 we obtained the values of E_e=0.27$\pm$0.01 eV and E_c=0.235$\pm$0.01 eV at 1 bar. The corresponding values were 0.28 eV and 0.225 eV in sample #2. These values are to be compared with the values 0.28$\pm$0.03 eV and 0.18$\pm$0.02 eV reported by Lang [3]. In spite of the difference of about 0.01 eV in the absolute values of E_c and E_e in samples #1 and #2, their pressure dependences are quite similar as shown in Fig. 3. We have also observed a variation in the DLTS intensity of peak A and B as a function of pressure. These pressure dependences are shown in Fig. 4. The dependence of level A intensity is qualitatively similar to the alloy dependence reported by Lang et al.[11].

(a) ΔE_e (meV) vs Pressure (kbar)

$Ga_xAl_{1-x}As(x=0.35)$
● level A, sample #1
▲ level B, sample #1
○ level A, sample #2
△ level B, sample #2

(b) ΔE_c (meV) vs Pressure (kbar)

$Ga_xAl_{1-x}As(x=0.35)$
● level A, sample #1
▲ level B, sample #1
○ level A, sample #2
△ level B, sample #2

Figure 3
Pressure induced change in (a) the emission activation energy and (b) the capture activation energy in two samples of AlGaAs.
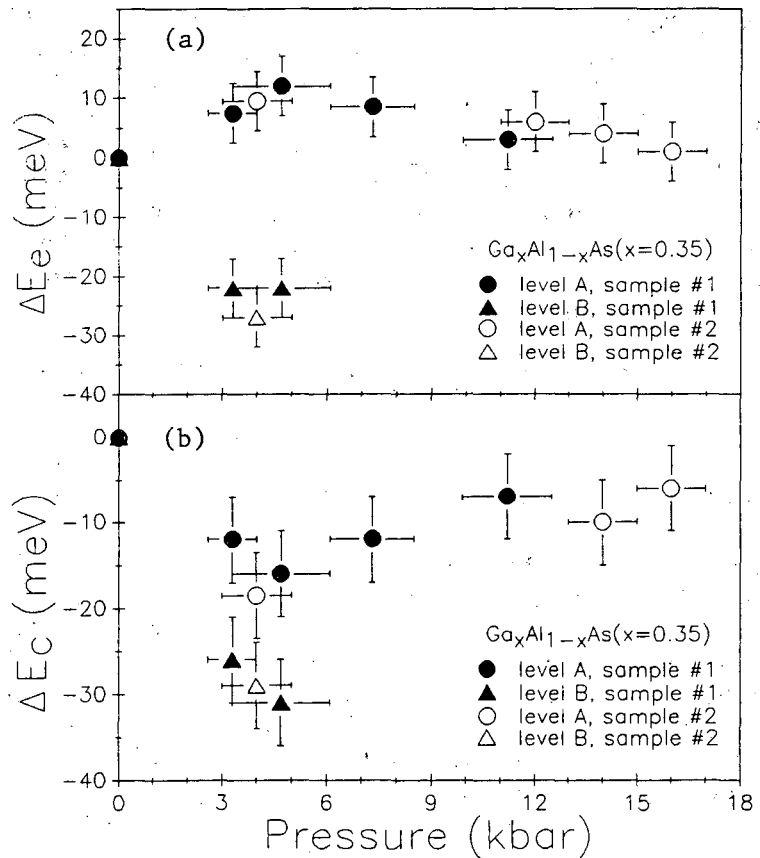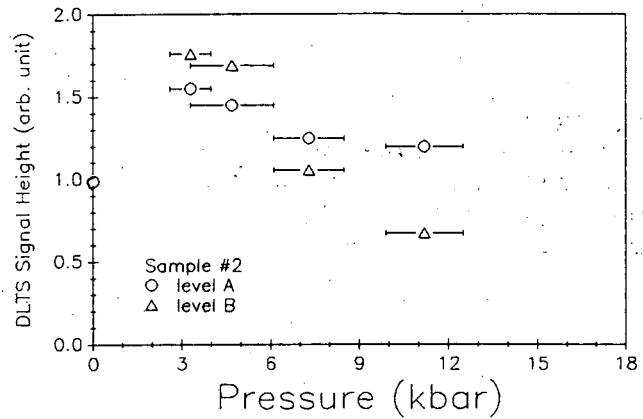
Figure 4
Pressure dependence of DLTS signal for level A and B in AlGaAs sample # 2.

DISCUSSIONS

The result of interest for this article is the change in the sign of the pressure coefficients of both E_e and E_c about 5 kbar. From these band edge pressure coefficients:[2] $dE_\Gamma/dP=11.8$ meV/kbar; $dE_L/dP=5.5$ meV/kbar and $dE_X/dP=-1.5$ meV in conjunction with the alloy dependence of the band edges given in Ref. 5. we estimate that 5 kbar is the pressure at which the band gap of $Al_{0.35}Ga_{0.65}As$ changes from direct to indirect. Changes in the dependence of E_c with Al concentration have been reported by Mooney et al.[4] in $Ga_{1-x}Al_xAs$:Si at x~0.4 where the bandgap changed from direct to indirect. However, no variations, beyond experimental uncertainty, was found in E_e with Al concentration. Our result is not inconsistent with the result of Mooney et al.[4] because changes smaller than 50 meV in the E_e of DX centers due to alloy variations may not observable due to sample to sample variation. On the other hand changes in E_e induced by pressure for a sample with a fixed Al concentration can be determined with the precision of a few meV.

Chand et al.[5] have studied the alloy dependence of the thermal ionization energy (E_t) of the DX center in AlGaAs:Si. They concluded that the DX center follows the L conduction band minima as a function of Al concentration. From our results we can deduce E_t and dE_t/dP by using the relationships:

$$E_t=E_e-E_c \quad \text{and} \quad (dE_t/dP)=(dE_e/dP)-(dE_c/dP) \tag{3}$$

We obtained (dE_t/dP) equal to 6 meV/kbar in the direct bandgap region and -2.8 meV/kbar in the indirect gap region. From the above band edge pressure coefficients the separation between the Γ and L conduction band minima changes under pressure at the rate of 6.3 meV/kbar. Thus in the direct bandgap region the pressure dependence of the DX center is consistent with the alloy dependence and both suggest that the DX center follows the L conduction band minima. In the indirect gap region the lowest conduction band minimum switches from Γ to X. If the DX center energy level continues to follow the L minima, we expect the difference between the pressure coefficients of E_t in the direct and indirect bandgap region to be given by $(dE_\Gamma/dP)-(dE_X/dP)=13.3$ meV/kbar. However, the experimental value for this difference is 8.8 meV/kbar. Thus our result suggests that the DX center *does not* follow exactly the L valleys in the indirect gap region. A close examination of the alloy dependence of the DX level in Fig. 5 of ref.5 also indicate a divergence between the DX level and the L valley at large Al concentration where the

4

bandgap becomes indirect. These results suggest that the X valleys also contribute to the DX center wavefunction in addition to the L valleys, and furthermore, that the X valley contribution becomes more important when the X valleys become lower than the valley. This conclusion is consistent with a theoretical calculation of the DX center performed by Chadi and Chang based on the model of the DX center as a doubly charged donor [12].

CONCLUSION

In conclusion we have presented new results on the pressure dependence of the DX center in GaAlAs:Te. We found that the pressure coefficients of the emission and capture activation energies changed sign when the bandgap switches from direct to indirect. Our results suggest that both the L and X conduction band valleys contribute significantly to the DX center wavefunction consistent with the latest model of the DX centers .

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