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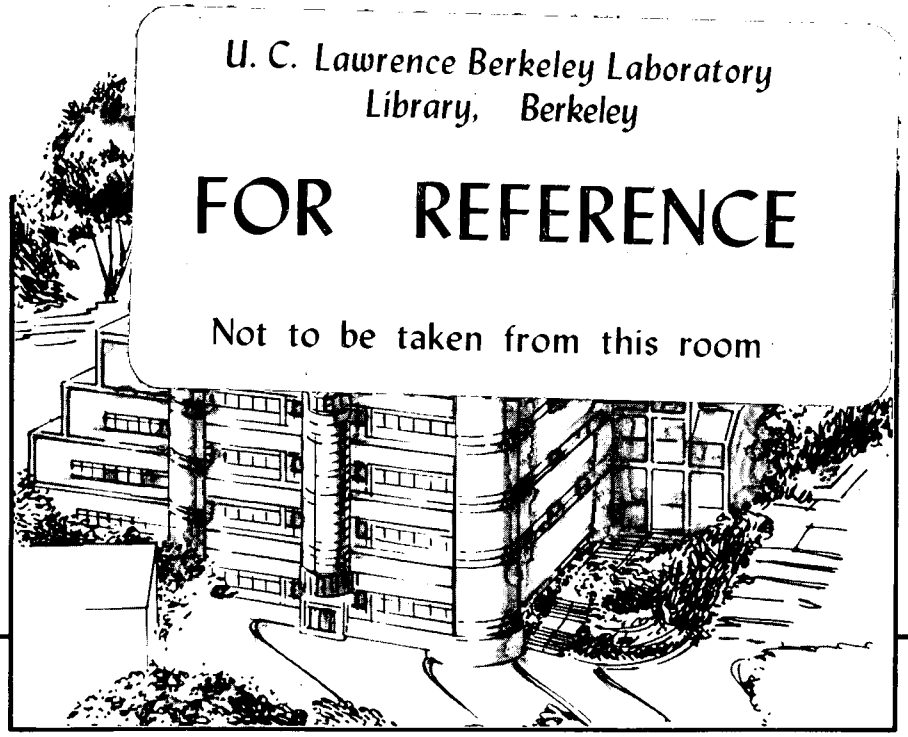

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Studies of Deep Level Transient Spectroscopy of DX Centers in GaAlAs:Te under Uniaxial Stress

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STUDIES OF DEEP LEVEL TRANSIENT SPECTROSCOPY OF DX CENTERS IN GaAlAs:Te UNDER UNIAXIAL STRESS

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ABSTRACT

DX centers in $Al_{0.38}Ga_{0.62}As$ doped with Te have been studied by Deep Level Transient Spectroscopy (DLTS) as a function of uniaxial stress. No splitting nor broadening of the DLTS peaks was observed. However, the peak positions and heights depend on the stress and its directions. The results have been analyzed by comparison with existing models and hydrostatic pressure measurements.

1. INTRODUCTION

Uniaxial stress has been applied to determine the symmetry of the A center in Si.[1] Uniaxial stress can produce splitting and shifts in the DLTS spectra of a deep center by altering its local environment and hence allow the symmetry of the defect to be determined. The DX center in III-V compound semiconductors has attracted much attention.[2] In a widely accepted model of this center proposed by Chadi and Chang[3] (to be referred to as the CC model), a donor atom or its nearest neighbor is displaced along one of the bonds. This lattice relaxation lowers the symmetry of the defect from T_d to C_{3v}. Under uniaxial stress the DX center DLTS peak is expected to split in a manner predicted by the theory of Kaplyanski[4]. In this paper we report the results of such a study of Te doped $Al_{0.38}Ga_{0.62}As$.

2. EXPERIMENTAL RESULTS

Our experiment has been performed on epi-layers of AlGaAs grown by liquid phase epitaxy on bulk GaAs crystals. The substrate was doped with 10^{18} cm^{-3} of Te and cut into rods with 1.2x1.2 mm^2 cross-sectional area and length of 6 mm. The rods were oriented by x-ray diffraction along one of these axes: [100], [110], or [111]. Epi-layers of $Al_{0.38}Ga_{0.62}As$ were grown on the (110) surface for the [111] and [100] rods and on the (111) surface for the [110] rods. In all case the thickness of the epi-layer was 3 μm and the concentration of Te was $3x10^{17}$ cm^{-3}. Aluminum dots of 0.8 mm diameter were evaporated onto the epi-layers to form Schottky barrier diodes. Uniaxial stress was applied with a stress rig described in detail elsewhere.[5] The stress apparatus was calibrated by measuring the of the oxygen thermal donor[5] in Si and the stress-induced birefringence in GaAs.[6] As an additional check, the polarized band-to-band photoluminescence from the GaAlAs epi-layer was measured as a function of stress. The splitting of the luminescence peak was found to be consistent with the valence bands deformation potentials of AlGaAs found in the literature.[7]

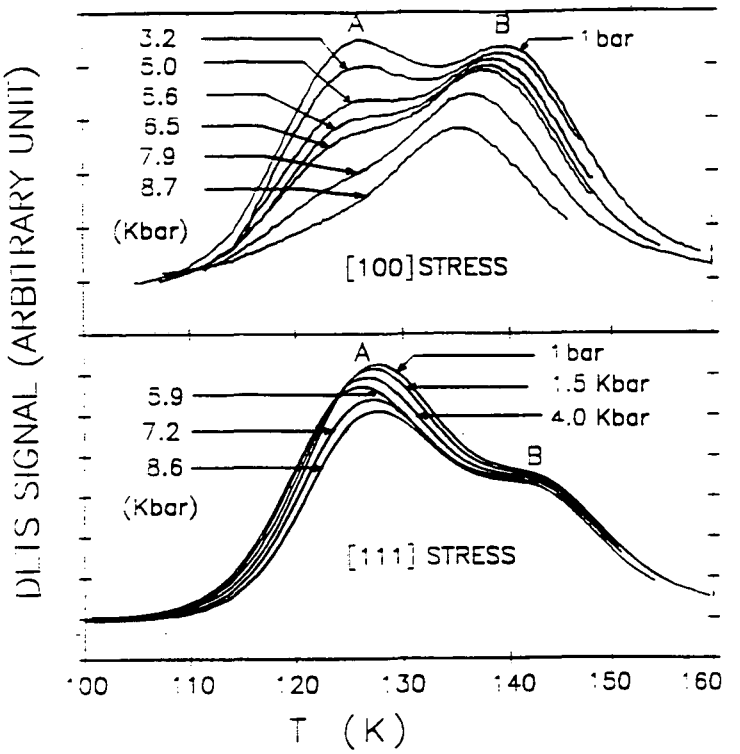

FIG. 1 DLTS spectra of DX centers in $Al_{0.38}Ga_{0.62}As$:Te as a function of uniaxial stress along the [100] and [111] directions. The time windows used are: 21 and 42 ms.

Filling pulses of 8 ms width were used in most of the measurements because at zero stress these pulses were found to saturate the DLTS signal.

Figure 1 shows the DLTS spectra measured for several different values of uniaxial stress applied along the [100] and [111] directions respectively. The [110] stress spectra are essentially linear combinations of the [100] and [111] spectra and will not be shown here. At zero stress, there are two peaks in the DLTS spectra. These peaks have comparable magnitudes and similar temperature dependence in their emission and capture rates. Their emission and capture behavior is in good agreement with our previous measurements on DX centers in GaAlAs:Te samples[8]. We have, therefore, identified both peaks as associated with the DX centers in our samples. The occurrence of multiple peaks in the DLTS spectra of DX centers has been explained in terms of the number of Al atoms in the vicinity of the DX center.[9] Since uniaxial stress produces only small shifts in the positions of both peaks, we have deconvoluted the DLTS spectra into a sum of two Gaussian functions. Gaussian functions are chosen because they produce the best fit to the experimental spectra both at zero stress and under large stress.[10] This deconvolution allowed us to determine more accurately the stress dependence of the peak positions and the widths of the DX center peaks. The stress dependence of the peak positions and the half widths of the two peaks determined in this way are shown in Fig. 2.

The main features of our results can be summarized as follows:

1. No splitting nor broadening of the DLTS peaks larger than the experimental uncertainty of about 1 K has been observed.

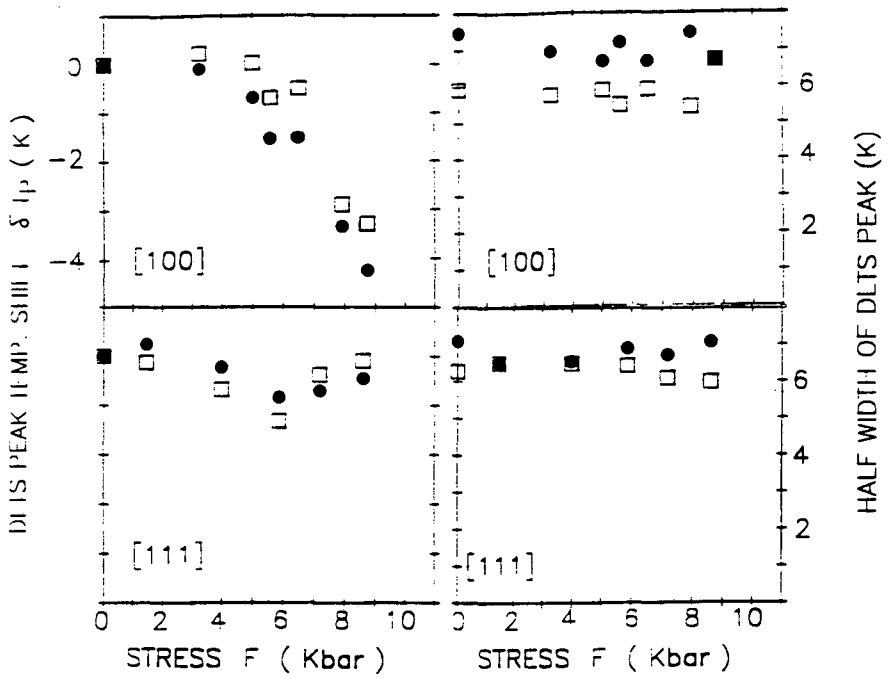

FIG. 2 Stress-induced peak temperature shifts and half widths of the two DLTS peaks A (open squares) and B (closed circles) in Fig. 1.

2. Uniaxial stress only causes shifts in the positions of the DLTS peaks. The stress dependences of the peak positions are different for the three stress directions.
3. Uniaxial stress decreases only slightly the peak amplitudes of the DLTS spectra except for [100] stress which produce large suppression of the low temperature peak at high stress. The amplitude of this peak was not recovered by increasing the filling pulse width, suggesting that this large decrease in peak amplitude is not caused entirely by an increase in capture barrier height under [100] stress.

3. DISCUSSIONS

Our results are difficult to understand in terms of L valley effective-mass theories of the DX center proposed by several authors.[11,12] The argument in support of this theory is that the DX level follows approximately the L valleys as a function of hydrostatic pressure or alloying with Al. To explain the characteristic properties of DX centers such as persistent photoconductivity, some authors (for example Bourgoin et al.[12]) suggested that electrons have to be excited into the L conduction band before they can be captured. into a DX center. As a result, the capture barrier height (E_C) is equal to the separation between the L conduction band and the conduction band minimum at g or X. Figure 3 shows the effect of uniaxial stress on the conduction band valleys in AlGaAs.[13] We note that a [111] stress causes the L valleys to split into a singlet and a triplet and at stress higher than 6 kbar the singlet L valley becomes the lowest conduction band minimum. According to the theory of Bourgoin et al.[12] E_C should vanish above 6 kbar. Such a drastic drop in E_C can be observed in the DLTS spectra by changing the filling pulse width. We have not observed any unusual change in the DLTS spectra for [111] stress above 6 kbar. Thus our [111] stress result shows conclusively that DX center properties are determined by the average conduction band structure and not by the L valleys only.

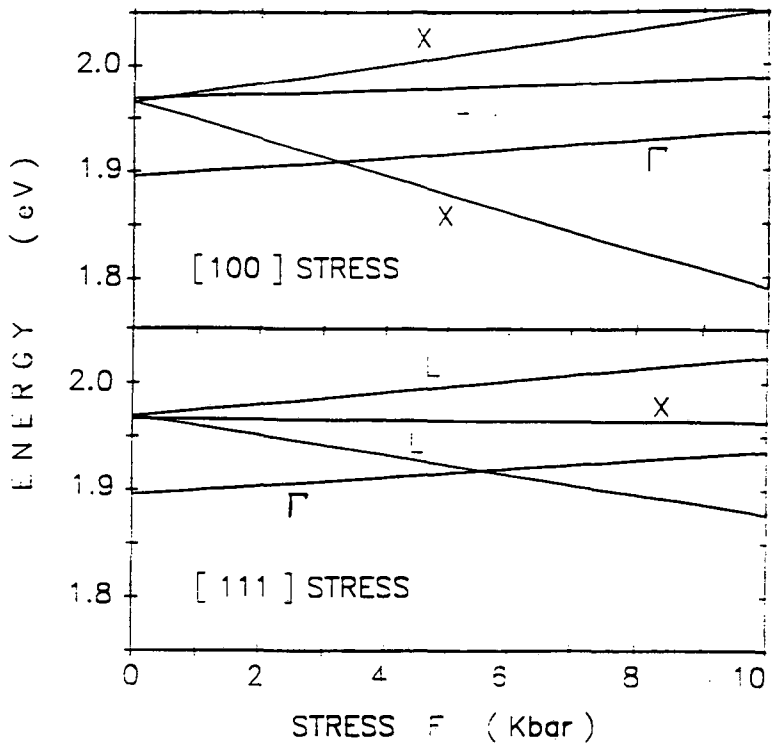

FIG. 3 Stress dependence of the conduction band minima in $Al_{0.38}Ga_{0.62}As$.

We have also interpreted our results in terms of large lattice relaxation models such as the CC model.[3] Within such models, we expect that uniaxial stresses along the [111] or [110] directions will split the DLTS peaks of the DX centers.[1] Surprisingly we did not observe any sign of splitting nor of broadening of the DLTS peaks. Another group has found similar results in Si doped AlGaAs at even higher uniaxial stress.[14] One possible explanation is that the stress-induced splitting of the DX center is too small to be resolved. Recently we have proposed another plausible explanation. We pointed out that there is one important difference between the A center in Si and the DX center. While the lattice displacement in the A center is independent of the charge state of the defect, the symmetry of the DX center depends on its charge state. Within the CC model, the symmetry of the DX center is lowered by lattice relaxation only when the defect is occupied by two electrons. [111] stress will split the degeneracy of the negatively charged state but not the positively charged state.[15] Since the lattice relaxation occurs during the capture phase of the DLTS spectra, one can infer that atomic displacement of the DX center occur in times of the order of a millisecond, i.e. the filling pulse duration. Thus unlike the A center, it is possible for DX centers to relax along the direction of lowest energy through the intermediate positively charged state during the DLTS experiment. Under this assumption, there is thermal equilibrium between defects with different directions of displacement and their populations are determined by Boltzmann statistics. Indeed a computer simulation of the DLTS spectra in AlGaAs based on this assumption shows no significant splitting nor broadening under uniaxial stress.[15]

Since there has been no theoretical calculation of the effect of uniaxial stress on the DX center within the CC model, we can give only a qualitative interpretation of our results.

First we note that an uniaxial stress can be decomposed into a hydrostatic component and a shear component. For a uniaxial stress of magnitude X, the hydrostatic pressure component is equal to X/3. Thus some of the effects of uniaxial stress on the DX center shown in Figs. 1 and 2 can be explained by the hydrostatic component of the applied stresses. Hydrostatic pressure has been shown to increases the emission barrier height (E_e) of the DX center when the conduction band minimum is at Γ and decreases E_e when the band minimum is at X.[8] This qualitatively explains the positive DLTS peak temperature shift at low stresses and the negative peak temperature shift for [100] stress above 4 kbars. However, the difference in behavior between [100] and [111] stress in Figs. 1 and 2 shows that the shear component of the stress also has an effect on the DX center. Our results differ from those of Wang et al.[14] who found that the effect of uniaxial stress on the DX center in Si doped AlGaAs could be explained by the hydrostatic component alone.

The difference in behavior of the DX center under large [100] and [111] stress can be understood in terms of the conduction band structure under the different stresses. As shown in Fig. 3 the conduction band minimum is at the X point of the Brillouin zone for large [100] stress while under large [111] stress the minimum is at L. As shown by hydrostatic pressure measurements, electrons emit from the DX level to the L valleys even when the conduction minima is at Γ.[8] Thus we expect no significant change in the emission barrier when [111] stress lowers one of the L valley below the Γ valley. On the other hand when [100] stress lowers the X valley below the Γ valley, we expect E_e to <u>decrease</u> with stress as found in hydrostatic pressure measurements. The pressure coefficient dE_e/dP is about -1 meV/kbar when the conduction minimum is at X.[8] This value of dE_e/dP is comparable to the corresponding pressure coefficient for the X minimum itself. For [100] stress the rate at which the singlet X minimum decreases in energy is about -18 meV/kbar. We can estimate the stress coefficient dE_e/dX from the results in Fig. 2 using the following relationship: $\delta E_e = \delta T_p(E_e/T_p)$ where T_p is the temperature of the DLTS peak. The value of dE_e/dX obtained in this way for [100] stress above 5 kbar is about -2 meV/kbar. The contribution to dE_e/dX from the hydrostatic pressure component is only about -0.3 meV/kbar. This shows that the lowering of the X valley below the Γ valley by a large [100] stress has the same effect of decreasing the emission barrier height of the DX center as found in hydrostatic pressure experiments. Finally, we note that when one of the L valleys becomes the lowest conduction band minimum at large [111] stress, E_e starts to <u>increase</u> very slightly with stress (see Fig. 1).

The stress dependence of the DLTS peak heights are more difficult to interpret within the CC model. We have attempted to determine the stress dependence of the capture barrier height E_c by varying the filling pulse width.[16] Quantitative interpretation of the results is complicated by the fact that there are two peaks in our spectra. For most stresses the weak dependence of the peak height on stress implied essentially a zero dE_c/dX within the experimental uncertainties. For large [100] stress there is a significant decrease in the peak height with increase in stress. However, only part of the decrease can be attributed to stress. Part of the decrease is probably caused by deformation of the sample because the peak heights are not completely recovered when the stress is released. Compared to the other stress directions, the [100] stress produces a much bigger decrease in peak height at high stress. This decrease is probably related to the lowering of the X valley relative to the Γ conduction band valley. A similar decrease in DLTS peak height has been observed in hydrostatic pressure experiments when the X

valleys became the conduction band minima.[8]

4. CONCLUSIONS

In conclusion we have performed a study of the DLTS spectra of DX centers in Te doped AlGaAs alloy as a function of uniaxial stress. Our results show convincingly that DX center properties are determined by the average conduction band energy and not by the L conduction valleys only. The absence of splitting of the DLTS peaks by uniaxial stress is found to be consistent with large relaxation models because of the dependence of lattice displacement on the charge state of the defect.

5. ACKNOWLEDGEMENTS

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