Saturable optical absorption of the deep Te-complex center in $Al_{0.4}Ga_{0.6}As$

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Direct measurements of optical absorption by a deep complex in Te-doped $Al_{0.4}Ga_{0.6}As$, referred to as the *DX* center, are reported. A novel double-waveguide configuration is employed to measure accurately the absorption coefficient α_{DX} of this center. The results are in agreement with earlier photoconductivity and photocapacitance measurements on this center, and are consistent with most aspects of an anomalously large lattice relaxation model which has been proposed to explain these earlier optical results. The photoconductivity results for this center predict a saturable absorption which is directly measured in this paper, and its temperature dependence is described. For a Te concentration of $\simeq 3\times 10^{17}$ cm^{-3}, the absorption reaches a maximum of ~ 18 cm^{-1} for $100 \leq T \leq 150$ K. At lower temperatures the absorption saturates; at higher temperatures it falls off due to thermal emission from the center. These effects are calculated using a simple rate equation. Also investigated is the dependence of α_{DX} on photon energy. The results are in good agreement with the magnitude of the absorption cross section as measured by photocapacitance, although the absorption peaks at somewhat higher energy.

I. INTRODUCTION

Recently a new type of defect center with a number of unusual properties has been observed in *n*-type $Al_xGa_{1-x}As$. For samples with Al composition in the range $0.25 \leq x \leq 0.7$, and Te doping of $\sim 10^{18}$ cm^{-3}, Nelson[1] observed that the photoconductivity was persistent at low temperatures; that is, for $T < 60$ K, photoconductivity was observed that continued for hours after the optical excitation was switched off. Using the so-called deep-level transient spectroscopy (DLTS) transient-capacitance technique,[2] Lang *et al.*[3-5] suggested that the center exhibited anomalously large lattice relaxation, as evidenced by the very shallow thermal depth of the center (0.1 eV) compared to the large optical depth (>1 eV). This center constitutes the dominant donor in Te-doped $Al_xGa_{1-x}As$, accounting for 80% –90% of the donors in the material.[3] Because this is a deep center, it is believed to be a complex resulting from the Te donor and some unidentified defect (presumably a native defect) and has been referred to as the "*DX* center."[4,5] Similar centers have been observed in $Al_xGa_{1-x}As$ doped with the donors Si, Se, and Sn.[1,3-5] A large-lattice-relaxation (LLR) model,[3,4] which will be summarized below, incorporates most of the experimental information that has been obtained on this center.

In this paper direct measurements of the optical properties of the *DX* center in $Al_{0.4}Ga_{0.6}As$ are reported over a wide range of temperatures, $10 \leq T \leq 300$ K. This investigation has been carried out for several reasons:

(i) Persistent photoconductivity has been observed in a number of other wide-band-gap semiconductors, such as $GaAs_{1-x}P_x$,[6] $Cd_{1-x}Zn_xTe$,[7] CdTe,[8,9] and GaSb.[10] Burkey *et al.*[7] have measured large lattice relaxation for defects in $Cd_{1-x}Zn_xTe$. It appears, therefore, that the unusual model proposed to explain these effects in $Al_xGa_{1-x}As$ may have widespread application for deep levels in semiconductors, and therefore warrants detailed investigation.

(ii) The photoconductivity and photocapacitance techniques that have been used to study this center are limited to the temperature range below 100 K. However, the optical properties of the *DX* center are of interest throughout the entire temperature range from 10 K to room temperature.

(iii) The presence of a saturable absorber in this ternary alloy, which is predicted by the photoconductivity, is significant from both a fundamental and device-oriented point of view. For example, it is well known that a saturable absorber could cause persistent intensity pulsations in GaAs double heterostructure (DH) lasers,[11-13] which would make them unsuitable for high-frequency applications to optical communications.

The LLR model proposed by Lang *et al.*[3-5] to describe the *DX* center is shown in Fig. 1. This is a configuration-coordinate diagram[14] showing the electronic plus defect coordinate energy for the conduction band (*C*), valence band (*V*), and the *DX*-center complex (*D*), whose configuration coordinate *Q* is displaced because of lattice relaxation when the center is occupied. The 0.1-eV difference in energy between the minima of the parabolas for *C* and *D* represents the defect activation energy in thermal equilibrium, as measured, for example, by the Hall effect. However, because of the large lattice relaxation, which must occur before the *DX* center can capture an electron, carriers in the

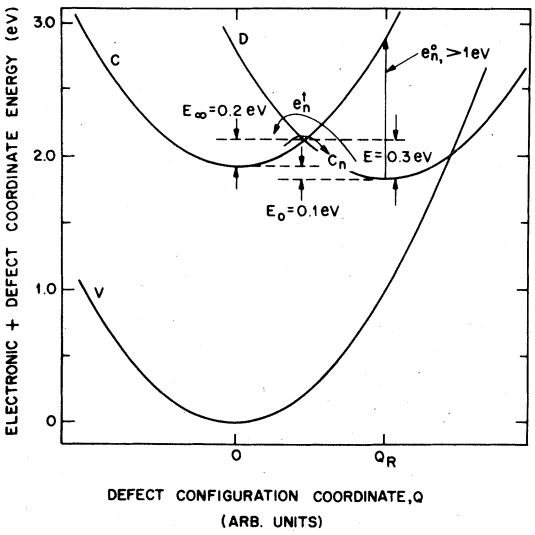


FIG. 1. Configuration coordinate diagram for the large-lattice-relaxation model of the *DX* center. e_n^o, e_n^t, and c_n are the rates for optical emission, thermal emission, and capture, respectively.

bottom of the conduction band may be trapped there. These conduction-band electrons originate from the ground state of the defect; they are optically excited into the conduction band with energies $h\nu \geq 1.0$ eV. Therefore, when these carriers have thermal energy less than 0.2 eV, persistent photoconductivity is observed. Along with displaying persistent photoconductivity, the center should behave as a saturable absorber, particularly at low temperature, while significant absorption should occur at room temperature.

The saturable absorption predicted to accompany persistent photoconductivity is directly measured for the first time in this work. An absolute determination of the *DX*-center absorption coefficient, α_{DX}, has been made as a function of temperature and photon energy. To measure α_{DX} accurately in the presence of other losses in the n-$Al_xGa_{1-x}As$ layer, and to confine the light for long absorption path lengths, a novel double-waveguide configuration was used. After briefly discussing the conceptual basis for absorption-coefficient variations in Sec. II, the double-waveguide technique and other experimental details are described in Sec. III. The results and discussion are given in Sec. IV. In addition to the direct measurement of the absorption saturation, the temperature dependence of α_{DX} can be accurately fit by a simple rate equation which is consistent with the configuration-coordinate diagram of Fig. 1, using parameters similar to those obtained from photoconductivity and photocapacitance studies. There is excellent agreement between the magnitude of the optical cross section measured by photocapacitance, and the cross section inferred from the absorption data presented here. There is, however, a slight discrepancy between the energy dependence of the cross section measured in these two ways. The significance of this is discussed in Sec. V along with our conclusion that this deep center probably plays no role in the presence of sustained pulsations in the GaAs DH laser.

II. THEORY

The photoconductive decay in Te-doped $Al_xGa_{1-x}As$ has been observed[1] to be thermally activated, with time constants that vary by many orders of magnitude over the temperature range investigated ($T \leq 100$ K). In particular, below ~60 K, the photoconductivity is persistent. This implies that the optical absorption due to *DX* centers should saturate, since the *DX* centers are emptied of electrons which are confined to the conduction band while the photoconductivity persists. The intensity of radiation transmitted through $Al_xGa_{1-x}As$ containing the *DX* center is expected to vary as

$$I_{DX} = I_i \exp[-(\alpha_{DX} + \alpha_0)L], \tag{1}$$

where α_{DX}, the *DX*-center absorption coefficient, is a function of the incident intensity I_i, α_0 includes all other losses, and L is the sample length. A linear relation between I_{DX} and I_i should result on a log-log plot, with y intercept given by $-(\alpha_{DX} + \alpha_0)/L$. If the *DX*-center absorption saturates ($\alpha_{DX} \to 0$), the y intercept should increase, with no change in slope. Thus a definite break in the linear relation between I_{DX} and I_i is an indication of absorption saturation, and the magnitude of the small-signal absorption coefficient, α_{DX}^0, is proportional to the change in y intercept. (α_{DX}^0 is the difference between the fully saturated and unsaturated *DX* absorption.) As the temperature is increased, it should be necessary to pump the center harder to reach saturation. This is expected because the rate of thermal escape of carriers from the conduction band, and subsequent recapture by the *DX*-center trap, is an increasing function of temperature.

It is possible to calculate the temperature dependence of α_{DX} using a simple rate equation. Three rates are involved in the time dependence of the concentration (n_{DX}) of occupied *DX* centers: e_n^o is the rate of optical emission from the center, e_n^t is the thermal emission rate, and c_n is the (bimolecular) recapture rate for carriers thermally excited from the conduction band and recaptured by a *DX* center. Then

$$\frac{dn_{DX}}{dt} = c_n n_c (N_{DX} - n_{DX}) - (e_n^t + e_n^o) n_{DX}, \tag{2}$$

where n_c is the concentration of carriers in the

conduction band, and N_{DX} is the total concentration of DX centers. Note that this rate equation is independent of any particular model; for the LLR model, the various rates are illustrated in Fig. 1. In steady state, Eq. 2 is set equal to zero, and can be solved for n_{DX}:

$$n_{DX}=\frac{c_n n_c}{(e_n^o+e_n^t)+c_n n_c}N_{DX}. \tag{3}$$

Consistent with the experimental result that the DX center is the dominant donor in Te-doped $Al_{0.4}Ga_{0.6}As$,[3] we assume that all of the carriers in the conduction band come from DX centers:

$$n_c=N_{DX}-n_{DX}. \tag{4}$$

Combining Eqs. (3) and (4) yields a quadratic for n_{DX}, which can be solved to give

$$n_{DX}=N_{DX}+\frac{e_n^o+e_n^t}{2c_n}\left[1-\left(1+\frac{4c_nN_{DX}}{e_n^o+e_n^t}\right)^{1/2}\right]. \tag{5}$$

The various rates in the problem are given by

$$e_n^o=\sigma_n^o\phi\,, \tag{6a}$$

$$e_n^t=aT^2e^{-E/kT}\,, \tag{6b}$$

and

$$c_nN_{DX}=(1/\tau)e^{-E_\infty/kT}\,, \tag{6c}$$

where σ_n^o is the cross section for optical absorption, ϕ is the incident-light flux, and the activation energies E and E_∞ are indicated in Fig. 1. Most of the parameters involved in Eqs. (6) are available in the literature, so n_{DX} can be evaluated quantitatively. The absorption coefficient α_{DX} is then given by

$$\alpha_{DX}=\sigma_n^o n_{DX}. \tag{7}$$

Consider the limiting cases:

(a). $T\to 0$. Then $c_nN_{DX}\to 0$ and $e_n^o\gg e_n^t$. Then

$$n_{DX}=N_{DX}+\frac{e_n^o}{2c_n}\left(-\frac{2c_nN_{DX}}{e_n^o}\right)=0\,, \tag{8}$$

so $\alpha_{DX}\to 0$ as expected.

(b). $T\to\infty$. $c_nN_{DX}\to 1/\tau$, and $e_n^o\ll e_n^t\to\infty$ (i.e., thermal emission dominates). Then

$$n_{DX}=N_{DX}+\frac{e_n^t}{2c_n}\left(-\frac{2c_nN_{DX}}{e_n^t}\right)=0\,, \tag{9}$$

and the absorption again vanishes. Absorption due to the DX center is therefore expected to be observable over only a limited range of temperature.

Note that the solution to the rate equation given above assumes steady-state conditions. The incident photon flux ϕ is therefore considered to be constant. If the light source is pulsed (with short pulse lengths), the dynamics of the problem are considerably more complicated. For example, absorption may begin to saturate during the occurrence of a single pulse. For this reason, quantitative measurements of α_{DX} have been made with optical sources that are essentially cw, as described in Sec. III.

III. EXPERIMENTAL

All samples studied in this work were prepared by liquid-phase epitaxy (LPE) using conventional techniques.[15] The layers were grown on {100} substrates at ~910 °C at a rate of approximately 12 μm/h. All layers were undoped except for those containing the DX center, which were prepared by adding sufficient Te to the melt to achieve an expected Te concentration of 10^{18} cm^{-3}. Capacitance measurements[16] made on similar single-layer samples grown at approximately the same time indicate, however, that the actual concentration of DX centers was ~3×10^{17} cm^{-3}. (The discrepancy between the Te added to the melt and the actual concentration of substitutional Te is not presently understood.)

The configuration of the double-waveguide sample used for many of the experiments reported here is shown in Fig. 2. The second layer grown contains the DX center; this is a 10-μm layer of $Al_{0.4}Ga_{0.6}As$ doped with Te as described above.

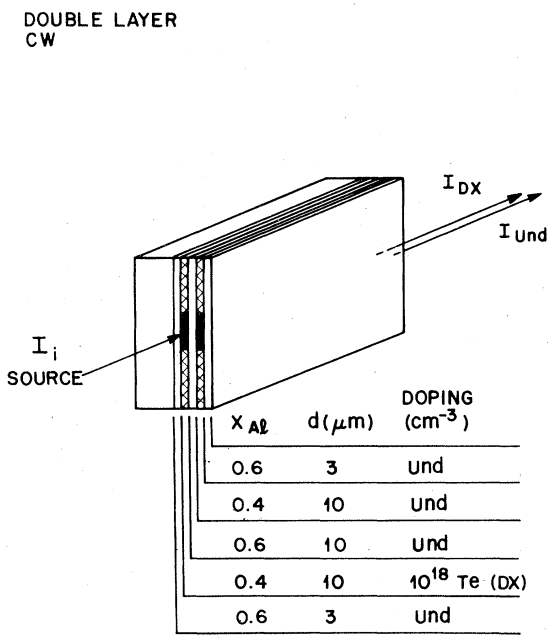


FIG. 2. Double-waveguide configuration used for measurements of the DX-center absorption α_{DX}. X_{Al} is the mole fraction of AlAs in each $Al_xGa_{1-x}As$ layer, d is the layer thickness. Layers are grown by LPE.

Undoped cladding layers of $Al_{0.6}Ga_{0.4}As$ were grown on each side of the *DX*-center waveguide, to confine the radiation which is coupled into the waveguide by focusing the incident radiation onto a cleaved face of the sample. The fourth layer is a second waveguide of $Al_{0.4}Ga_{0.6}As$, which is identical in every respect to the *DX*-center waveguide except that it is undoped. By measuring the transmission through the doped waveguide (I_{DX}) relative to the transmission through the undoped waveguide (I_{Und}), it is possible to correct for all losses which are common to both layers, and α_{DX} can be accurately measured. In cases where the absolute value of α_{DX} was not important, experiments were also performed on single-waveguide samples (similar to the first three layers shown in Fig. 2). For example, a single-waveguide sample was used for the measurements of the saturation of the optical absorption. A number of thick (100–200 μm) layers were also grown for direct absorption measurements using light incident normal to the layers, after removing the substrate with a selective etch.[17] However, these layers were found to have poor uniformity of Al composition, so that such direct measurements of α_{DX} were unsuccessful.

A block diagram of the experimental setup is shown in Fig. 3. The essential feature of the setup is the variable temperature cryotip refrigerator, with optical windows, mounted on a translation stage so that the sample can be scanned through the light path. The incident beam is focused to a spot ~10 μm in diameter with a 6×microscope objective, and coupled into the waveguide through a cleaved edge. An image converter is used to insure the correct optical alignment of the sample; then the maximum transmission through the waveguides is measured using phase-sensitive detection. Three different optical sources were used for these experiments. A Chromatix optical parametric oscillator (OPO), adjusted for oscillation at a suitable wavelength below the bandgap of the $Al_{0.4}Ga_{0.6}As$ waveguide, was used to vary the incident intensity over four or more orders of magnitude. This source was pulsed at a rate of 50 sec^{-1}, using 200-nsec pulses. However, because steady-state properties of the *DX* center were of primary interest, a cw YAlG:Nd laser and a Bausch and Lomb high-intensity monochromator were also used, chopped at the low frequency of 80 Hz (i.e., still essentially cw). Two different detectors were used, a cooled photomultiplier with S-1 response, and a Ge photodiode. Sample lengths of 1.2 and 5.0 mm were used.

IV. RESULTS AND DISCUSSION

A. Low-temperature saturation of the optical absorption

The intensity of radiation transmitted through a waveguide containing the *DX* center is shown in Fig. 4 for 100 and 120 K, as a function of incident intensity over four orders of magnitude. As described in Sec. II, the transmitted intensity is expected to vary according to Eq. (1), so that the y intercept increases as α_{DX} saturates. This is observed in Fig. 4. Furthermore, with increasing temperature the curve shifts to the right (increasing pump power), as expected. Thus the results shown in Fig. 4 confirm the absorption and saturation behavior anticipated from the persistence of the photoconductivity, and explainable in terms of the configuration coordinate model of Fig. 1. The value of the small-signal *DX* absorption coefficient, α^{o}_{DX}, can be estimated from the separation of the straight-line segments of the curve, as indicated in Fig. 4. However, it is felt that this method may not yield a reliable measure of α^{o}_{DX} because the optical source used was the pulsed OPO; therefore, steady-state results were not obtained. For this reason the dependence of α_{DX} on temperature and photon energy, to be described

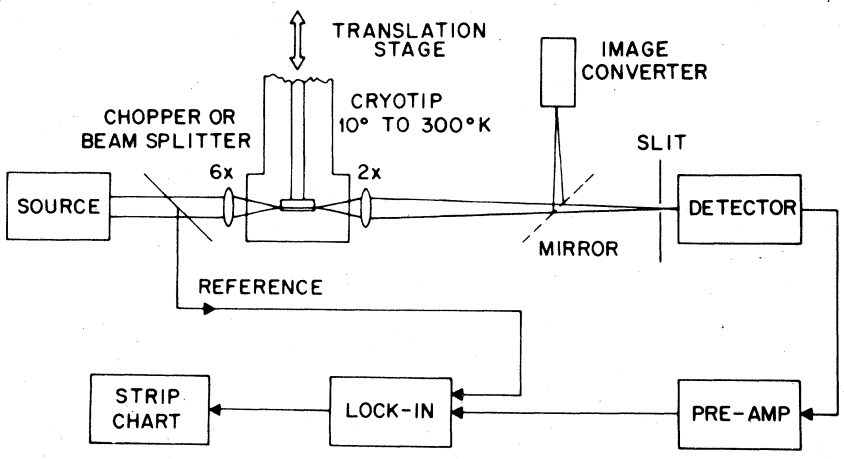


FIG. 3. Block diagram of experiment to measure α_{DX}. Light from the optical source is coupled into the waveguide by focusing onto a cleaved face of the sample mounted in a variable temperature cryotip Dewar.

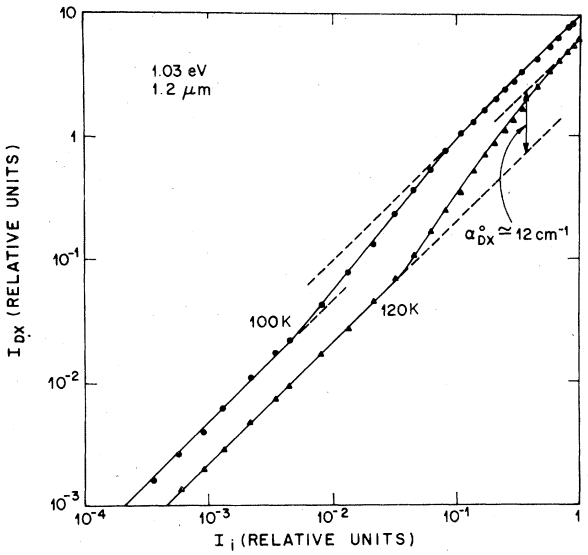


FIG. 4. *DX*-center transmission vs incident intensity. Deviation from linear relationship represents saturation of the optical absorption, which is temperature dependent. The separation of the straight line segments is a measure of α^{o}_{DX}, the small-signal *DX*-center absorption coefficient.

below, was determined with the double-waveguide sample pictured in Fig. 2.

B. Temperature dependence of the *DX*-center absorption

Transmission traces obtained from the double-waveguide sample are shown in Fig. 5. At 10 K the *DX* center is fully saturated, so the ratio of I_{DX} to I_{Und} corresponds to $\alpha_{DX}=0$. The inequality of the two peaks I_{DX} and I_{Und} at 10 K results from differences in coupling into the two waveguides (e.g., slight differences in layer thickness or imperfections at the cleaved edge of the sample), and demonstrates the advantage of the double-waveguide method. At 80 K the transmission through the *DX* waveguide decreases relative to that through the Und waveguide (which has remained relatively constant as a function of T); the new ratio of the two transmitted intensities yields $\alpha_{DX}(80\ \mathrm{K}) = 11.6\ \mathrm{cm}^{-1}$, using

$$\alpha_{DX}(T) = \frac{1}{L}\ln\left(\frac{I_{DX}(10\ \mathrm{K})/I_{\mathrm{Und}}(10\ \mathrm{K})}{I_{DX}(T)/I_{\mathrm{Und}}(T)}\right). \qquad (10)$$

In this manner, the temperature dependence of the *DX*-center absorption has been measured from 10 to 300 K.

The temperature dependence of α_{DX} has been calculated using Eqs. (5)–(7) and the parameters listed in Table I. Comparison is made in Fig. 6 with experimental values of α_{DX} at $\lambda = 1.06\ \mu$m measured with two different optical sources, the YAlG : Nd laser and the monochromator. This

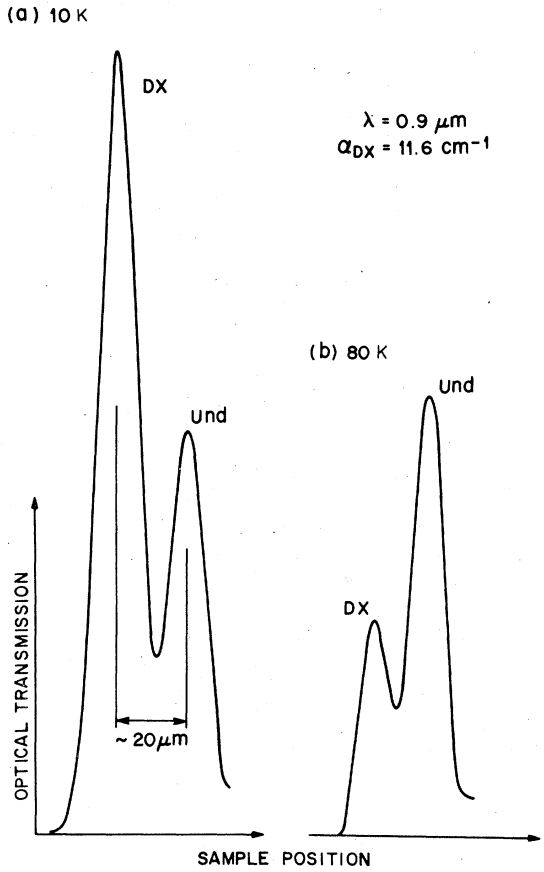


FIG. 5. Traces of the transmission through the two waveguides shown in Fig. 2 as the sample is scanned through the optical beam. The absorption is fully saturated at 10 K, so $\alpha_{DX}(10\ \mathrm{K}) = 0$.

figure shows only the temperature range $T \leq 150$ K, for which e_n^t is negligible. The intensity of the incident radiation from the two sources differs by two to three orders of magnitude, and excellent

TABLE I. Parameters used in rate equation to calculate temperature dependence of α_{DX}. Comparison is made with values measured by capacitance and photoconductivity.

	Values used in Eqs. (5)–(7)	Literature values	Reference
E (eV)	0.30	0.28 ± 0.03	4
E_∞ (eV)	0.15	0.18 ± 0.02	4
α (sec^{-1} K^{-2})	10^8	$10^{8\,a}$	3
τ (sec)	4.7×10^{-11}	4.7×10^{-11}	1
σ_n^0 (cm^2)[b]	5×10^{-17}	4×10^{-17}	4
N_{DX} (cm^{-3})	$3\times10^{17\,c}$	...	...

[a] This was evaluated at 200 K where $e_n^t = 10^5$ sec^{-1}, as measured by Lang in Ref. 3.
[b] Evaluated at 1.06 μm.
[c] Experimentally measured.

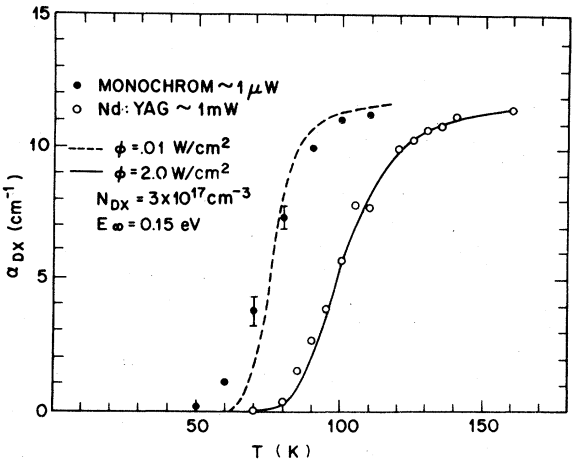


FIG. 6. Low-temperature saturation of α_{DX} for two different values of flux (ϕ) of the incident radiation. Solid and open points are experimental, solid and broken lines are calculated from the rate equation, and the parameters given in Table I.

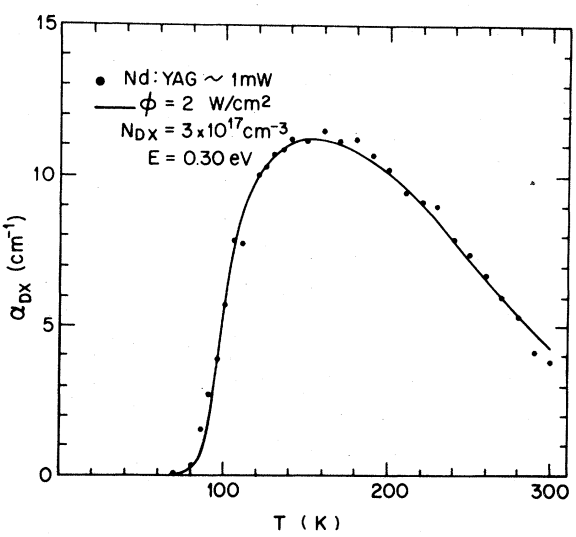


FIG. 7. Temperature dependence of α_{DX} over the entire range $0 \leq T \leq 300$ K. Solid line is calculated from the rate equation and parameters in Table I.

agreement is obtained between theory and experiment using values of light flux which differ by a factor of 200, as shown. To obtain this agreement, the starting values of parameters used for this calculation (the literature values in Table I) were varied to obtain a best fit. This best fit was obtained with $E_\infty = 0.15$ eV instead of the literature value $E_\infty = 0.18 \pm 0.02$ eV. Furthermore, an optical absorption cross section σ_n^o of approximately 5×10^{-17} cm^2 was assumed, with only a slight variation with temperature (i.e., $\sigma_n^o = 5 \times 10^{-17}$ cm^2 at low T, gradually decreasing to 4×10^{-17} cm^2 at $T = 90$ –100 K and constant at higher T). This nearly constant value of σ_n^o gave the best fit to the data over the entire temperature range, and is in excellent agreement with the value of 4×10^{-17} cm^2 measured by Lang between 44 and 78 K using the photocapacitance method. The experimentally determined DX-center concentration, $N_{DX} = 3 \times 10^{17}$ cm^{-3}, was also used to obtain this fit.

One important result is evident in Fig. 6. Very low values of light flux suffice to saturate the DX-center absorption at low temperature. At $\phi = 2.0$ W/cm^2 the "edge" of the absorption curve has already moved significantly to higher temperature from its position at 0.01 W/cm^2.

The rate equation also gives good agreement over the entire temperature range studied. Figure 7 shows the experimental and calculated results to 300 K for the YAlG:Nd laser source. At high temperature, α_{DX} decreases with increasing temperature because e_n^t becomes large. In this temperature range, $e_n^t \gg e_n^o$ for the incident-light flux used here, so the absorption coefficient is independent of flux. Thus considerably more intense radiation would be required to saturate the absorption at room temperature. To obtain the agreement shown in Fig. 7, $E_\infty = 0.15$ eV was used (as obtained for Fig. 6), and E was varied to give best fit. This procedure gave $E = 0.30$ eV. Note that $E_0 = E - E_\infty = 0.15$, which is within the experimental error of the values obtained by photocapacitance,[4] $E_0 = 0.10 \pm 0.05$ eV. The Hall coefficient measurements[1] also give $E_0 = 0.10$ eV. The agreement between these results is considered to be satisfactory.

Similar experimental results are shown in Fig. 8 for a series of monochromator wavelengths between 0.7 and 1.36 μm. A consistent family of curves has been determined, with α_{DX} increasing rapidly in the range $50 \leq T \leq 100$ K due to the thermal recapture described above, and then slowly decreasing at high temperature as the DX center is thermally depopulated. The experimental data points are shown explicitly; the solid curves are smooth extrapolations between data points, not rate-equation calculations.

C. Dependence of α_{DX} on photon energy

In addition to the temperature dependence shown in Fig. 8, the dependence of α_{DX} on photon energy ($h\nu$) is of interest. The data in Fig. 8 have therefore been replotted along isotherms in Figs. 9(a) and 9(b). These spectra show a broad increase of α_{DX} with increasing $h\nu$, with a tendency for a broad peak to occur between approximately 1.5 and 1.8 eV. As is evident from the form of the data in Fig. 8, these experiments were performed by coupling light of a given photon energy into the

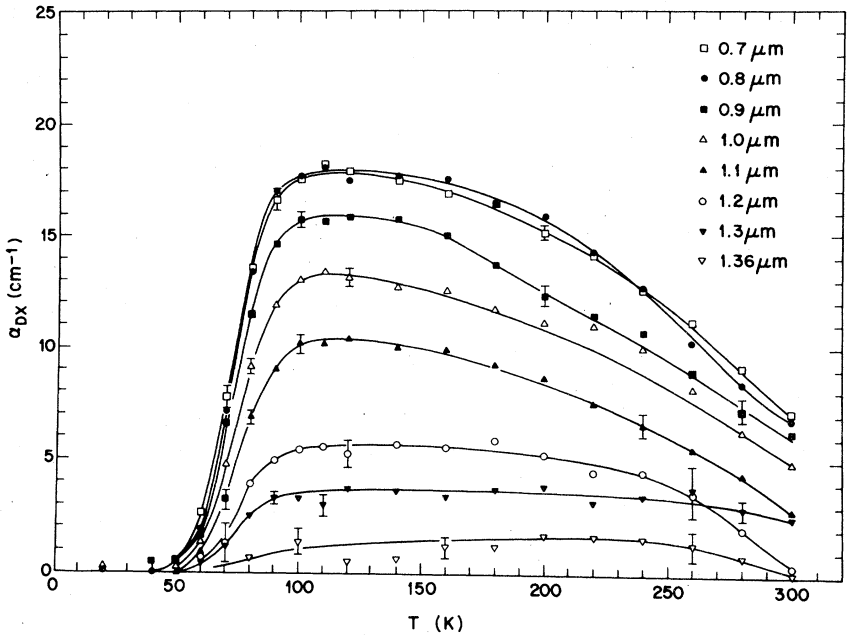


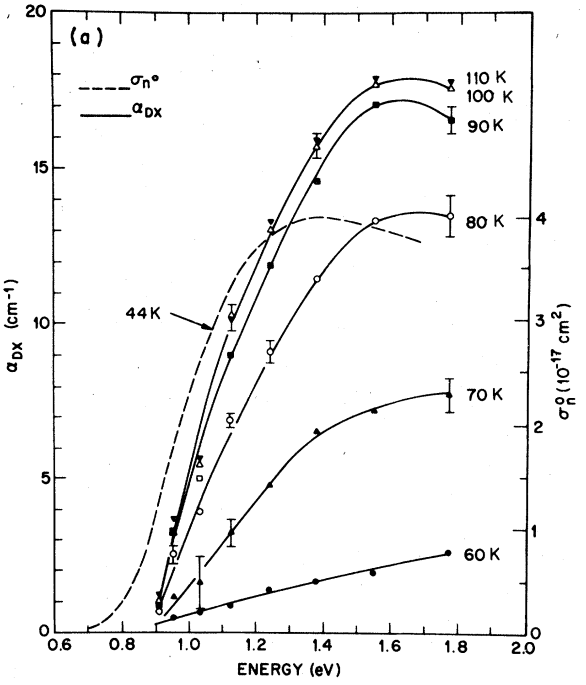
FIG. 8. Temperature dependence of α_{DX} for various values of incident radiation wavelength.

waveguides and varying the temperature. To confirm the validity of the spectral curves determined in this way, the experiment was also carried out by maintaining the sample at a constant temperature and varying the monochromator wavelength. These results are shown in Fig. 10. For the two temperatures investigated, the results are consistent with Fig. 9, although the absorption peak is somewhat more evident, and may occur at a slightly lower energy. The data in Fig. 10 are considered to be less reliable than those in Fig. 9 because of the difficulties inherent in the experiment; for each change in wavelength, all of the optics must be refocused because of the dispersion in the system.

Both sets of experiments show that the *DX*-center absorption peaks at an energy greater than 1.5 eV. Similar results have been obtained in recent photoconductivity measurements.[18] These results are consistent with attempts to measure the absorption directly in very thick layers (100–200 μm) of $Al_{0.4}Ga_{0.6}As$ using a Cary spectrophotometer. Because the layers were generally somewhat nonuniform, containing regions of lower Al composition, the *DX*-center absorption was superimposed on a broad absorption edge resulting from the average band gap of the low Al alloy. No definite *DX* absorption peak was observable, even though, with the 0–0.1-o.d. sensitivity slidewire of the Cary, such a peak should have been seen.

The photocapacitance measurements of the optical cross section reported by Lang *et al.*[4] show a peak at slightly lower energy, about 1.4 eV, with the low-energy absorption threshold occurring at ≈0.1 eV lower energy. These photocapacitance results are included on Fig. 9(a) as broken lines for comparison with the absorption data, since they should be proportional at constant T. At present the reason for this discrepancy is not understood. The absorption data reported here should, of course, be the most direct measurement. Photocapacitance experiments involve additional complications such as transparent (or partially transparent) electrodes and relatively large electric fields (up to 10^4–10^5 V/cm). Furthermore, photocapacitance probes a layer only ≈0.1 μm thick, whereas the absorption measurements reported here average over 10 μm. Finally, the presence of Si, a common contaminant for layers grown in quartz tubes, could also account for a shift of the absorption spectrum to higher energy. Si is also known to form a *DX* center,[5] with larger activation energies E and E_∞, and with a cross-section spectrum peaking about 0.4 eV to higher energy.

The calculations presented in Ref. 4, based on the LLR model, predict a small amount of broadening of the spectrum of the cross section as the temperature is increased, but measurements were limited in that work to $T < 80$ K. The data in Fig. 8 have been replotted for two temperatures in the region of maximum reliability, $T = 120$ and 240 K; the curves were normalized and plotted on semilog paper in Fig. 11. There may be an indication of broadening present in these spectra consistent with the curves calculated as in Ref. 4, shown by solid curves. However, data over several decades would be required to show this unambiguously because the broadening observed is within the noise limits of these measurements. It is clear, how-



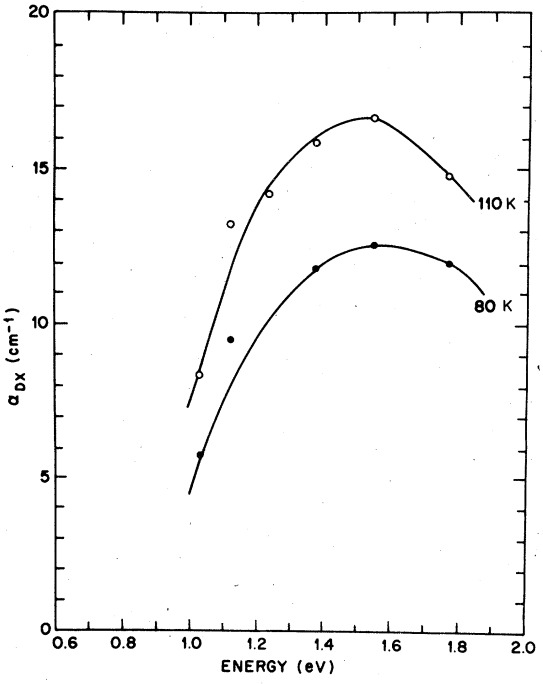


FIG. 10. Dependence of α_{DX} on photon energy, measured by varying the photon energy at a constant T, and refocusing the optics for maximum coupling into the waveguide. Reasonable agreement with Fig. 9 is obtained.

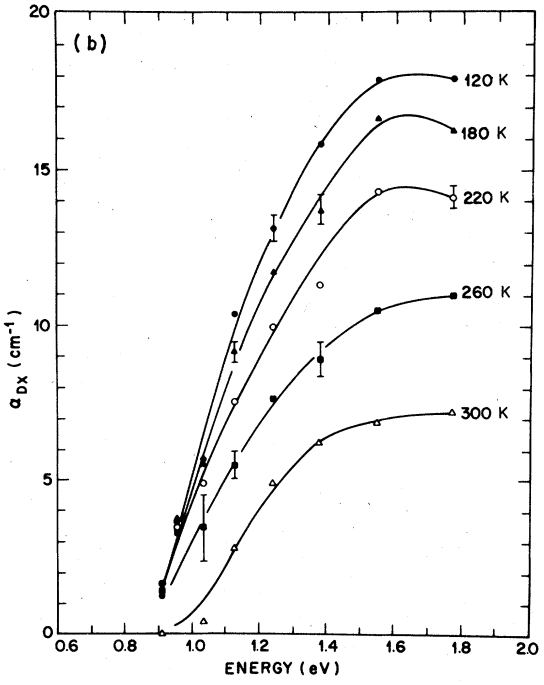


FIG. 9. Dependence of α_{DX} on photon energy, plotted from the data in Fig. 8. The broken line and right-hand scale in (a) indicate photocapacitance of the optical cross section, reported in Ref. 4, which should be proportional to α_{DX} at constant T.

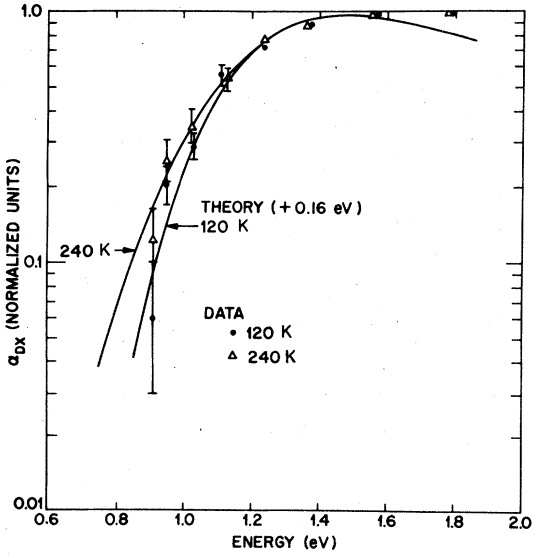


FIG. 11. Normalized absorption of the DX center vs photon energy at $T = 120$ K and 240 K. The solid lines are values of cross section calculated in Ref. 4, arbitrarily shifted 0.16 eV to higher energy.

ever, that the results shown in Fig. 11 are not inconsistent with the LLR model.

D. Polarization of the absorption

Because the shallow Te donor is involved in a center with a large optical activation energy, the *DX* center is believed to be a complex defect. For example, Lang *et al.*[4,5] have proposed that the *DX* center consists of a Te donor (on an As site) and an As vacancy (i.e., second nearest neighbors in the lattice). Such a center would have ⟨110⟩ axial symmetry. Although such a center would not produce polarization effects in the optical absorption if the defects were randomly distributed among the possible ⟨110⟩ orientations, site selectivity could occur during growth of epitaxial layers leading to optical polarization. Such effects have been observed in the rare-earth garnets.[19] Because of the waveguide configuration used for these experiments, such effects could easily be investigated by coupling incident polarized radiation into the waveguide with the electric field vector in the plane of the layer (TE mode) or perpendicular to it (TM mode). This was done for the double-waveguide sample at 70 K using radiation at $\lambda = 0.8\ \mu$m, conditions considered optimum for detection of differences in transmission for different polarization. The results indicated that the optical absorption was less than 1% polarized. We conclude that there is no significant site selectivity occurring during growth.

V. CONCLUSIONS

A detailed investigation has been carried out of the optical properties of an unusual, deep Te-complex center, referred to as the *DX* center, in $Al_{0.4}Ga_{0.6}As$. Saturation of the optical absorption, anticipated on the basis of the observed persistence of photoconductivity, has been measured. Excellent agreement has been obtained with absorption coefficient calculations using a simple rate equation which is consistent with the LLR model proposed to explain the capacitance and photoconductivity behavior of this center. This is the first direct demonstration of saturable absorption in a ternary layer used in GaAs/AlGaAs optoelectronic devices. The temperature dependence of the *DX*-center absorption can be accurately predicted by the rate equation, and the measurements yield a value of the optical absorption cross section that is in close agreement with that measured by photocapacitance.

The dependence of α_{DX} on photon energy has been measured using several different techniques. In all cases the absorption shows an increase with increasing energy, starting at ≈0.9 eV and reaching values as high as ≈18 cm^{-1} between about 1.5 and 1.8 eV. These spectra do not show a strong absorption peak, but rather appear as a broad "shoulder" or "tail" on the $Al_{0.4}Ga_{0.6}As$ absorption edge. This does not coincide with earlier photocapacitance measurements of the cross section, which show a broad peak in the spectral dependence at 1.4 eV. The reasons for this minor discrepancy are not presently understood. Attempts to measure the temperature broadening of the cross section, predicted by the lattice relaxation model, showed a definite tendency towards broadening, but were not unambiguous because of the weak absorption coefficients involved; α_{DX} would have to be measured over several decades, requiring sensitivity to small fractions of a cm^{-1}. No evidence was observed of polarization effects that might result from site selectivity during growth for this extended defect.

As a result of the measurements presented in this paper and additional investigations to be described elsewhere,[20] we believe the *DX* center cannot be responsible for the sustained pulsations at frequencies of 200 MHz to 2 GHz which are frequently observed in GaAs DH lasers. The room-temperature absorption coefficient for this center is small, less than 7 cm^{-1} at all wavelengths, and the cross section for absorption is also small, requiring a very large flux of optical radiation to saturate the center at room temperature. In addition, pulsations have been observed with little change in frequency over a wide range of temperatures, whereas the trap recapture rate changes by several orders of magnitude over the same temperature range.

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