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MAGNETO-PHOTOLUMINESCENCE STUDIES OF MANGANESE ACCEPTORS IN GaAs/AlGaAs MULTIPLE QUANTUM WELLS

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We have investigated the photoluminescence associated with residual manganese acceptors in *n*-type, modulation doped, GaAs/AlGaAs multiple quantum wells. In a magnetic field the luminescence breaks into discrete lines attributed to transitions between conduction band Landau levels and manganese acceptor states. The polarization of the luminescence was studied as function of magnetic field. A simple model based on the spin exchange interaction between the holes and the manganese ions successfully describes the polarization data.

INTRODUCTION

THE PHOTOLUMINESCENCE spectrum of *n*-type modulation doped GaAs/AlGaAs quantum wells is dominated by interband electron–hole recombination processes [1, 2] which have a maximum intensity around 12200 cm^{-1}. A weaker feature, observed at a lower energy (~ 12000 cm^{-1}), has been attributed to transitions between the conduction band and carbon acceptor states [3]. This feature was called an acceptor replica because it mirrored the band to band luminescence at zero field and in the presence of an applied magnetic field. In this paper, we report the observation of a deep acceptor replica which, in zero field, has a main peak at 11460 cm^{-1} and a weaker side-band at ~ 11800 cm^{-1}; both features are present in all of our MQW samples. The binding energy of the acceptor ground state is estimated to be ~ 105 meV (840 cm^{-1}). In a magnetic field both peaks break into sets of discrete lines, due to transitions from conduction band Landau levels to the impurity states. Previous work [4] on epitaxially grown bulk GaAs doped with manganese acceptor impurities displayed a feature around 11340 cm^{-1}, which likewise was attributed to conduction band to acceptor transitions. From these studies, the binding energy of the manganese acceptor was estimated to be 113 meV (911 cm^{-1}).

Manganese ions interact strongly with holes via a spin exchange interaction and, as a result, the luminescence associated with them is circularly polarized in the presence of a magnetic field [5]. We have studied the polarization of the deep acceptor magneto-luminescence as a function of magnetic field. The predicted field dependence, and the observed binding energy confirm that the luminescence features are associated with manganese acceptors in the GaAs quantum wells.

EXPERIMENTAL

The photoluminescence in the GaAs quantum wells was excited using either the 4880 Å line of an Ar^+ laser or the 6328 Å line of a helium–neon laser. The samples were placed in an immersion cryostat at a temperature of ~ 1.8 K. Magnetic fields up to 15 Tesla were applied perpendicular to the layers. The i.r. luminescence was focused on to the entrance slit of a SPEX double monochromator equipped with an RCA 31034A photomultiplier tube and a standard photon counting system was used to measure the peak positions and their shifts

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with magnetic field. The polarization of the luminescence at a particular field, was measured by setting the spectrometer at either 11460 or 11790 cm^{-1}, corresponding to the zero field luminescence peaks for the ground and excited states, respectively. A quarter wave plate, placed at a focus just before the spectrometer, was rotated at ~ 40 Hz. The modulated circularly polarized signal was synchronously detected using a lock-in amplifier system.

RESULTS AND DISCUSSION

In addition to the strong band to band luminescence, many GaAs quantum well samples exhibit other luminescent features at lower energies (between 100 and 1000 cm^{-1} below the intrinsic peak). The most prominent of these has been attributed to transitions between the conduction band and carbon acceptor states. A detailed magnetic-field study of the luminescence associated with these transitions has been described elsewhere [3]. In this paper we present the study of a deep acceptor replica observed in all our GaAs multiple quantum wells. In some samples the intensity of this replica is quite strong – comparable to that of the intrinsic luminescence. We shall concentrate on one of these samples, sample 9-17-79. The electron areal concentration $n = 5.6 \times 10^{11}$ cm^{-2}. The width of the wells and the barrier layers are: $d_{GaAs} = 245$ Å, $d_{AlGaAs} = 436$ Å. Figure 1 shows the zero field deep acceptor luminescence spectrum. The main feature has a peak around 11460 cm^{-1}. A weaker peak is observed at 11800 cm^{-1}. The feature at 11460 cm^{-1} is attributed to transitions between the conduction band and the deep acceptor. The weaker feature is observed only in samples with strong band to acceptor luminescence. It is thus attributed to transitions between the conduction band and an excited state of the deep acceptor. Luminescence associated with excited acceptor states has been observed previously in GaAs MQW's [3].

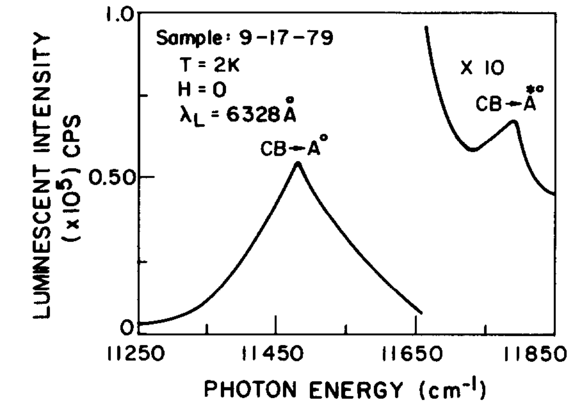

Fig. 1. Zero field photoluminescence spectrum of the band to manganese acceptor ground state (~ 11460 cm^{-1}) and its excited state (~ 11800 cm^{-1}). λ_L = 6328 Å; $T = 2$ K.

In the presence of a magnetic field the two replicas break into discrete lines due to transitions between conduction band Landau levels and the impurity states. Figure 2 shows a field scan taken with the spectrometer fixed at $E_s = 11460$ cm^{-1}. The first six Landau level ($l = 0, 1, \ldots, 5$) transitions to the acceptor ground state can easily be resolved. Similar spectra were recorded for the excited state. A summary plot of the energies of the Landau transitions as function of magnetic field

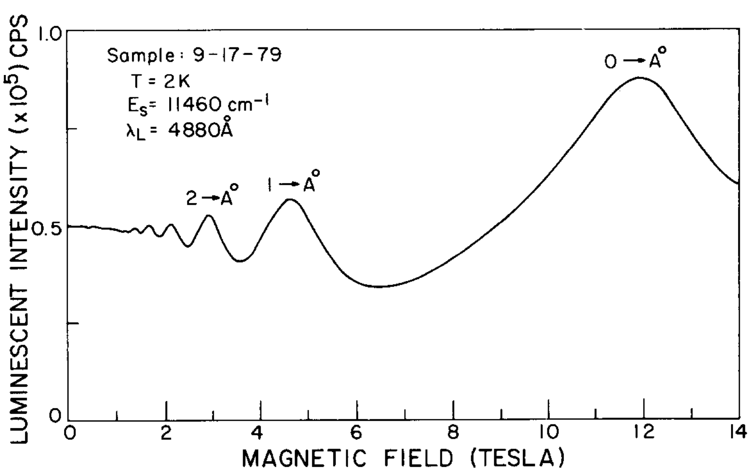

Fig. 2. Magnetic field scan of the photoluminescence at 11460 cm^{-1}. The intensity maxima are due to transitions from conduction band Landau levels to the manganese acceptor ground state ($l \rightarrow$ acceptor) for $l = 0, 1, \ldots, 5$). $\lambda_L = 4880$ Å; $T = 2$ K.

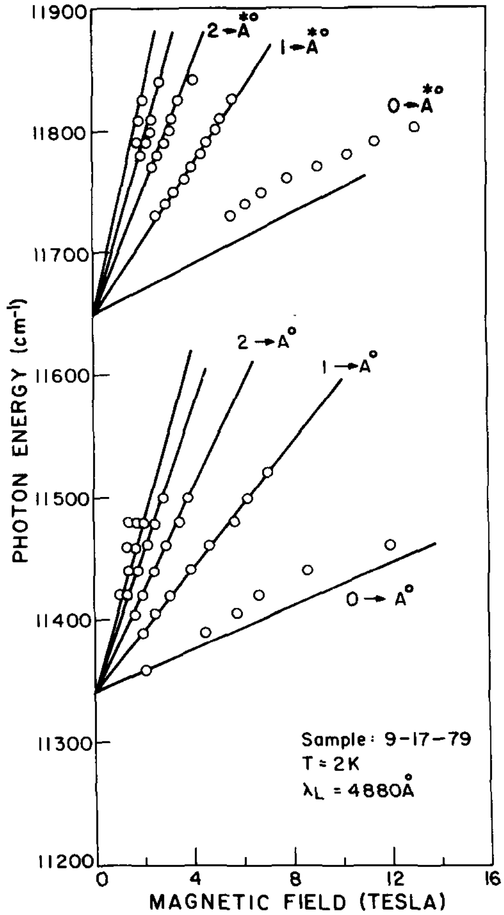

Fig. 3. Composite of the photoluminescence energy peaks as a function of magnetic field, obtained using field scans. The solid lines are drawn on the basis of a least-squares fit to the $l = 1$ transitions for both the ground and excited states. $\lambda_L = 4880$ Å; $T = 2$ K.

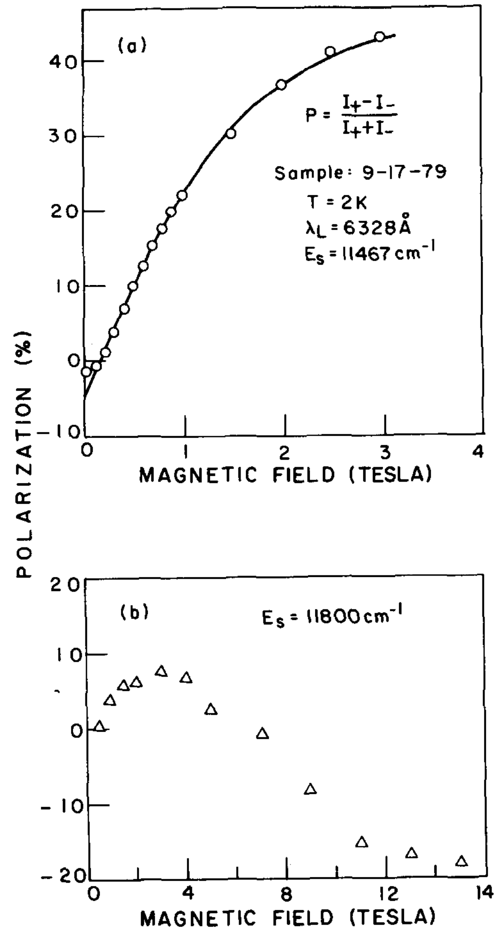

Fig. 4. (a) Polarization of the band to manganese acceptor ground state luminescence as function of magnetic field monitored at 11460 cm^{-1}. The curve is a theoretical fit to the data discussed in the text. (b) Polarization of the band to manganese acceptor excited state luminescence as function of field monitored at 11800 cm^{-1}; $T = 2$ K; $\lambda_L = 6328$ Å.

is shown in Fig. 3. Both the ground and the excited acceptor states exhibit associated Landau fans. The solid lines were drawn on the basis of a least-squares fit for the $(l = 1) \rightarrow$ acceptor transitions for which we have an adequate number of experimental points. The fit gives the intercept as well as the slope for that transition. The other lines ($l = 0, 2, 3, 4$) were drawn using the intercept as a common origin, and having a slope suitably scaled (with ratios 1:3:5:7:9). The origins of the Landau fans associated with the deep acceptor are at 11340 cm^{-1} (ground state) and at 11650 cm^{-1} (excited state). The interband Landau fan (not shown in Fig. 3) has its origin at 12180 cm^{-1}. The binding energy of the acceptor ground state, taken to be the difference between the origins of the intrinsic Landau fan and that associated with the acceptor ground state, is equal to 840 cm^{-1} (104 meV). In a similar way, the binding energy of the acceptor excited state is equal to 530 cm^{-1} (66 meV). Previous work [4] on bulk GaAs doped with manganese acceptors gives a binding energy of 911 cm^{-1} (113 meV). This acted as a basis for identifying the deep impurity to be a manganese acceptor. The polarization of the luminescence associated with the manganese acceptor, which is discussed below, confirms this interpretation.

In this section, we concentrate on the polarization study of the manganese acceptor replicas. Figure 4 shows the circular polarization measured as a function of magnetic field. (Here Fig. 4(a) refers to the ground acceptor state and Fig. 4(b) to the excited state). The polarization is larger in magnitude than that observed in the band to carbon acceptor luminescence and has the opposite sign.

The data are analyzed in terms of a simple model which includes the effects of the spin exchange interaction between the hole spin and that of the manganese spin. It is assumed that the spin exchange energy is larger than both k_BT and the magnetic energy of either an isolated hole ($\mu_B g_h^* H$) or a manganese ion ($\mu_B g_{Mn} H$). If $\mathbf{j}$ is the total angular momentum of the hole ($j = \frac{3}{2}$) and $\mathbf{S}$ the spin of the manganese ion ($S = \frac{5}{2}$), the state with the lowest spin exchange energy is that with $\mathscr{S} = 1$ where $\mathscr{S} = \mathbf{j} + \mathbf{S}$. This is the case if the spin exchange interaction has the same sign as it does for holes in II–VI compounds [6]. On the assumption that the spin exchange energy is large, the states with $\mathscr{S} > 1$ can be ignored. In the presence of a magnetic field applied in the z direction, the $\mathscr{S} = 1$ level splits into three components with $\mathscr{S}_z = -1$, 0 and 1. The energies are as follows:

$$E(\mathscr{S}_z = \pm 1) = \langle \mathscr{S} = 1, \mathscr{S}_z = \pm 1 | j_z b_1 - S_z b_2 | \mathscr{S} = 1, \mathscr{S}_z = \pm 1 \rangle E(\mathscr{S}_z = 0) = 0, \quad (1)$$

where $b_1 = \mu_B g_h^* H$ and $b_2 = \mu_B g_{Mn} H$, μ_B is the Bohr magneton, H is the magnetic field and g_h^* and g_{Mn} are the g-factors of the hole and the manganese ion, respectively. Using the Clebsch–Gordan coefficients for $\frac{5}{2} \oplus \frac{3}{2}$ we find:

$$E(\mathscr{S}_z = \pm 1) = \mp(\tfrac{3}{4} b_1 + \tfrac{7}{4} b_2) E(\mathscr{S}_z = 0) = 0. \quad (2)$$

The partition function Z is then:

$$Z = 1 + 2\cosh[\beta(\tfrac{3}{4} b_1 + \tfrac{7}{4} b_2)], \quad (3)$$

and

$$\langle j_z \rangle = -\frac{1}{\beta} \frac{\partial}{\partial b_1} [\log(Z)], \quad (4)$$

where $\beta = 1/k_BT$. The polarization P of the luminescence (assuming unpolarized electrons) is:

$$P = -\tfrac{2}{3} \langle j_z \rangle = \frac{\sinh[\beta(\tfrac{3}{4} b_1 + \tfrac{7}{4} b_2)]}{1 + 2\cosh[\beta(\tfrac{3}{4} b_1 + \tfrac{7}{4} b_2)]}. \quad (5)$$

The calculated polarization of the manganese acceptor ground state luminescence as a function of magnetic field is shown by the solid line in Fig. 4(a) together with the experimental data. The calculated curve is described by $P_{total} = P + P_0$ where the constant P_0 is the only fitting parameter. The non-zero value of P_0 (-4%) could be a result of stress on the sample. The quadratic dependence of the polarization on H at low field is also an indication of stress. The hole and manganese g-factor values of $g_{Mn} = 2$ and $g_h^* = -1.15$ were obtained from the literature [5].

The polarization of the luminescence associated with the manganese acceptor excited state as function of field is shown in Fig. 4(b). At high fields, the polarization changes sign as is expected when the magnetic energy of the hole becomes comparable to or larger in magnitude than the exchange energy. This indicates that the exchange energy for the manganese excited state is smaller than that for the ground state.

From these observations we deduce that the deep acceptor impurity is manganese. This result is confirmed (i) by the measured value of the binding energy obtained from Fig. 3 and (ii) by the excellent agreement shown in Fig. 4(a) between the observed field dependence of the circular polarization and the calculated values taken from equation (5). The latter is based upon a simple model that assumes exchange interaction between the hole spin and the ground spin state of a manganese impurity.

SUMMARY

We have studied the photoluminescence associated with residual acceptors in n-type, modulation doped GaAs/AlGaAs multiple quantum well heterostructures. The chemical species of the impurities was identified as manganese. This conclusion was based on their measured ground state binding energy in zero magnetic field; the value obtained was close to the accepted binding energy of manganese doped bulk GaAs. The impurity luminescence in all the MQW samples investigated, breaks into two sets of Landau fans. They are attributed to transitions between conduction band Landau levels and the ground and excited states, respectively, of the manganese acceptors. The observed circular polarization and its behaviour in a magnetic field further confirms the chemical species and the existence of a strong spin exchange interaction between the holes and manganese ions in III–V compounds.

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