# Magneto-optics in GaAs-$Al_xGa_{1-x}As$ single heterojunctions

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We have investigated the radiative recombination of two-dimensional (2D) electrons with holes bound to acceptors from a δ layer, positioned at a well-defined distance from the interface, in *n*-type GaAs-$Al_xGa_{1-x}As$ single heterojunctions and have thereby characterized the system by photoluminescence and photoluminescence-excitation techniques. Using magnetotransport and magneto-optics we demonstrate that, under continuous free-carrier generation in $Al_xGa_{1-x}As$ by laser light, the decrease in the concentration of 2D electrons is accompanied by an enhanced mobility. The magneto-optical results show that the magnetic field dependence of the transition energies is strongly nonlinear just below filling factor 2, which we interpret as mainly due to *g*-factor enhancement. Finally we present the dependence of the electronic effective mass on the electron concentration, as measured from the Landau-level splitting.

## I. INTRODUCTION

Optical spectroscopy of two-dimensional (2D) electron systems has, until recently, concentrated on undoped quantum wells.[1] Of late, more of an interest has been taken in modulation-doped quantum wells[2,3] and this has extended to single heterojunctions (SH) in the last few years.[4] The interest in SH derives from the possibility of observing the energy spectrum of the electrons below the Fermi level.[4] This is in contrast to most of the usual measurements on SH, such as magnetconductivity,[5] magnetosusceptibility,[6] magnetocapacitance,[7] and spin and cyclotron resonance, which are only sensitive to the properties of the electrons close to the Fermi energy.

In this paper we describe luminescence measurements on *n*-type Be δ-doped GaAs-$As_xGa_{1-x}As$ SH, concentrating mainly on the radiative recombination of 2D electrons with photoexcited holes bound to the acceptors of the δ layer. Because the GaAs-$Al_xGa_{1-x}As$ heterojunctions are grown by molecular-beam epitaxy (MBE), a monolayer of acceptor atoms can be grown within the GaAs buffer layer at a well-defined distance ($z_0$) from the interface. The luminescence spectra consist of a convolution of the 2D electron-distribution function with that of the photoexcited holes. Owing to the δ doping, the energy distribution function of the holes, however, has been shown to be very small.[8] This acceptor δ-doped structure was especially prepared to optimize the intensity of the 2D electron luminescence, as the recombination is indirect in real space. By changing the value of $z_0$, the distance at which the acceptor atoms most effectively contribute to the radiative recombination intensity has been found, with typical values of $z_0=20$–25 mm.[8] High mobilities are still obtainable if the δ layer is sufficiently far away from the 2D channel, or if the acceptor concentration is low. In addition, it has been found that under continuous photoexcitation it is also possible to strongly decrease the 2D electron concentration ($n_s$) from that attained after saturation of the persistent photoconductivity, and that this effect depends on both the wavelength and intensity of the incoming laser light: A photon energy above a threshold value, equal to that of the band gap of the $Al_xGa_{1-x}As$, was found to be necessary for this effect to occur. Once this condition is fulfilled, the electron concentration decreases as the intensity of the incident light is increased.[9]

Using this new type of heterojunction and the technique of optically controlling the electron concentration, it was possible to investigate the properties of the 2D electron gas by comparing the results from a variety of measurements including Shubnikov–de Haas, photoluminescence (PL) and photoluminescence excitation (PLE).

## II. EXPERIMENTS

The samples under study were GaAs-$Al_xGa_{1-x}As$ SH ($x=2.8-0.32$) grown by MBE.[8] The Si-doped $Al_xGa_{1-x}As$ layers were 52.0–52.5 nm wide with donor concentrations $N_D$ ranging from $2\times10^{17}$ to $2\times10^{18}$ $cm^{-3}$. The spacer-layer width ranged from 17.5 to 23 nm, and those of the GaAs buffer layer from 50 to 2000 nm. In most of the samples studied here, a δ layer of acceptors (Be) was grown in the buffer layers at a well-defined distance from the interface. This distance varied from 5 to 30 nm. Owing to the low growth temperature of 580 °C to avoid diffusion, the acceptors were located within a few monolayers. The Be δ-doping concentration ($n_{sc}$) was about $2\times10^{10}$ $cm^{-2}$. All samples were grown under similar conditions, and the background *p*-type (carbon) doping level was estimated as $10^{14}$ $cm^{-3}$.

The electron concentration before illumination ranged between $3\times10^{10}$ and $6\times10^{11}$ $cm^{-2}$, depending on the sample and, after strong illumination by white light, increased to between $4\times10^{11}$ and $8\times10^{11}$ $cm^{-2}$. The typical 2D-electron mobility, measured in the dark after previous illumination, for an electron concentration of $5\times10^{11}$ $cm^{-2}$, was between $4\times10^5$ and $8\times10^5$ $cm^2/V\,s$ for $z_0>20$ nm, and was much smaller for $z_0<15$ nm.

The nonequilibrium carriers were either created using an $Ar^+$, $Kr^+$, or He-Ne laser, or with an $Ar^+$-pumped Styryl 9 dye laser with a linewidth of $\sim$0.1 meV. The optical spectra were recorded in the Faraday configuration and analyzed using a spectrometer with a spectral resolution of 0.1 meV. Measurements were taken in magnetic fields up to 13 T either using an optical cryostat or an optical fiber. PL spectra were obtained by exciting the sample above the GaAs band gap with light of fixed energy and scanning the spectrometer through the region of interest. PLE spectra involved setting the spectrometer at a fixed energy corresponding to a recombination transition and scanning the dye laser to higher energy. All Shubnikov–de Haas measurements were performed on Hall-bar samples.

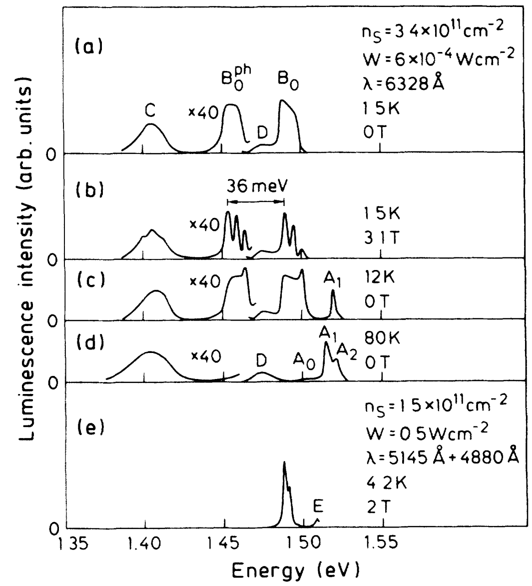


FIG. 1. Spectra of the radiative recombination of 2D electrons with photoexcited holes, showing all observed lines and their dependence on temperature and magnetic field.

## III. RESULTS AND DISCUSSION

### A. New channels of recombination

One sees in the luminescence spectra of these heterojunctions (Fig. 1) $A_i$ and $B_i$ lines corresponding to recombination of 2D electrons with free holes ($A$ lines) and holes bound to the acceptors ($B$ lines).[10] The index indicates the subband number. The $A$ lines are only observed in samples with 500 Å-wide buffer layers. At the lowest temperatures, in samples with low carrier concentrations, the $A$ lines are not observed due to the low oscillator strength of the $A_0$ line and because the first electron excited state is empty. Upon extending the wavelength scale and using low excitation powers, other additional luminescence lines can also be observed. These are labeled $B_0^{ph}$, $C$, and $D$ in Fig. 1. $B_0^{ph}$ is 36 meV lower in energy than the $B_0$ line and shows identical magnetic field and temperature dependence. That is, it splits into Landau levels in a perpendicular magnetic field [Fig. 1(b)], upon raising the temperature extra structure appears due to thermal population of the first-excited state [Fig. 1(c)], and it disappears from the spectrum altogether above 50 K [Fig. 1(d)], as does the $B_0$ line. We therefore identify it as a phonon replica. The $C$ line we tentatively assign to a deep impurity level (maganese, perhaps), and the $D$ line, which is only seen at low excitation powers, as an excited state of the $C$ line.

In some samples an additional line ($E$ line), Fig. 1(e), is observed whose intensity increases with magnetic field ($H$), as shown in Fig. 2(a), so that at 13 T it is 3 times more intense than the $B_0$ line. It is also temperature dependent, and, at 13 T, disappears above 15 K [Fig. 2(b)]; at 2 T, above 4 K. Its energy position extrapolated to $H=0$ [Fig. 2(c)] is 1.508 eV, which is close to the usual position of the $A_0$ line; however, its temperature dependence seems to rule out this assignment. This line demonstrates Landau-level splitting in a magnetic field, sensitive only to the normal component of the field, in a similar way to the $B$ line. This fact supports its identification as a transition involving an electron from

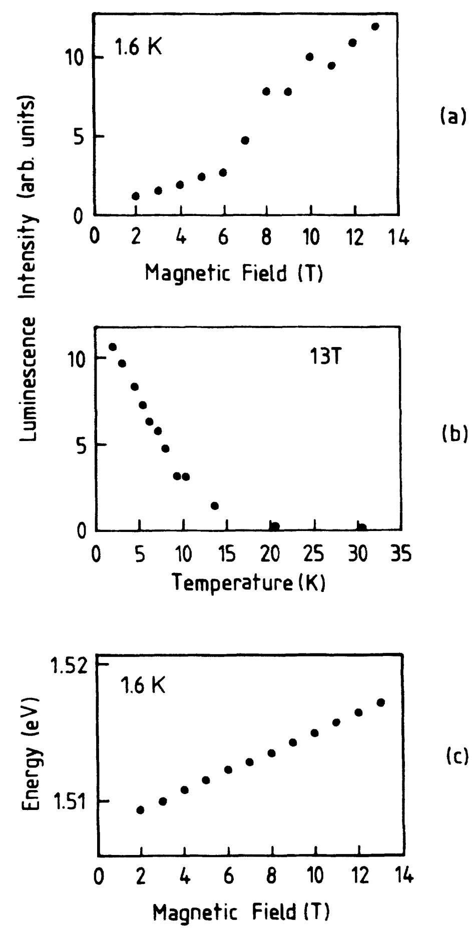


FIG. 2. Dependence of the intensity of the $E$ line on (a) magnetic field and (b) temperature. (c) Dependence of its spectral position on magnetic field.

the 2D channel. Our preliminary assignment of this transition is that it could be an $A^+$ center in which the hole degeneracy is lifted by the electric field near the interface. This center is strongly stabilized in a magnetic field. We also cannot exclude the possibility that these photoexcited holes are bound not to a neutral acceptor, but to the interface itself. A detailed presentation of the properties of the $E$ line will be the subject of a future publication.

### B. Photoluminescence-excitation spectra

The $B_0$ line, unfortunately, occurs at the same energy position as two bulk transitions: neutral donor to neutral acceptor ($D^0$-$A^0$) and bulk free electron to neutral acceptor ($e$-$A^0$), the intensities of which depend on the residual impurity concentration. Using PLE we have found that one can determine whether a peak in the PL spectrum is predominately a bulk or 2D transition. Figure 3(a) shows the usual PL spectrum, excited above the GaAs band gap, from a sample with two occupied 2D subbands. The luminescence spectrum obtained from exciting below the band gap but above the $B_0$ line energy gives us the bulk luminescence spectrum in this energy range, Fig. 3(b), since longer-wavelength light has a deeper penetration depth, and therefore the bulk signal dominates. As can be seen, the 2D luminescence extends down to 1.476 eV, while that from the bulk transitions cuts off at 1.483 eV. Therefore, via detection at low energy, one can obtain a clean PLE spectrum, Fig. 3(c), which seems to reflect the

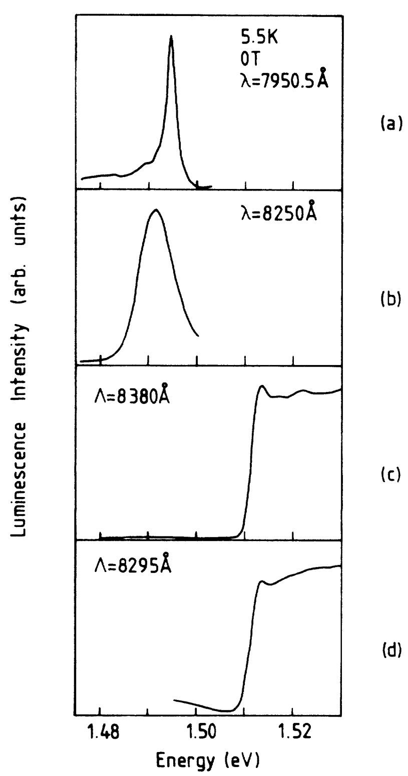


FIG. 3. Photoluminescence spectra (a) excited above ($\lambda = 7950.5$ Å) and (b) below ($\lambda = 8250$ Å) the GaAs band gap. (c) and (d) are photoluminescence excitation spectra detected in the $B_0$ line ($\Lambda = 8380$ Å $\equiv 1.4795$ eV) and in the $B_1$ line ($\Lambda = 8295$ Å $\equiv 1.4946$ eV), respectively.

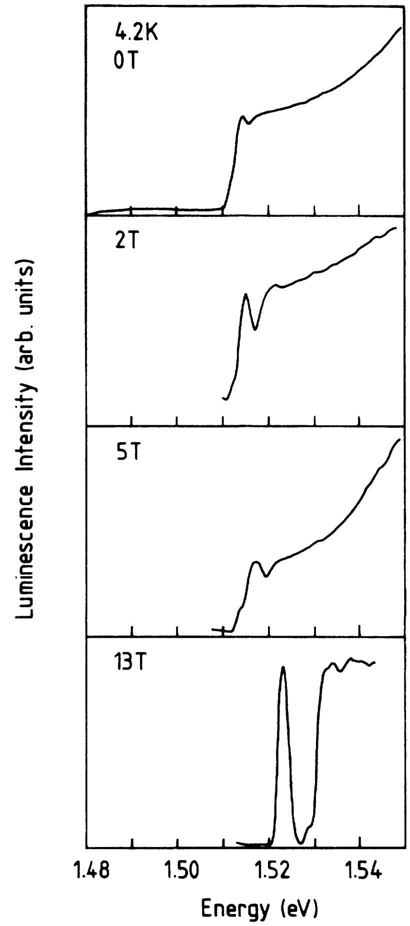


FIG. 4. Photoluminescence-excitation spectra at various magnetic fields with the spectrometer set either in the $B_0$ line (0 T) or in the $B_1$ line (2, 5, and 13 T).

absorption spectrum of the buffer layer although the 2D absorption onset would have a very similar appearance. Note the presence of a peak due to the bulk exciton at 1.515 eV. Detection at the position of the $B_1$ line (1.495 eV) results in a similar spectrum, Fig. 3(d), except that the absorption increases again at energies below the band gap due to the presence of bulk transitions coincident with the detection energy. In the case where the bulk transition intensity is dominant, this low-energy absorption becomes very intense and the onset at 1.515 eV becomes barely discernible.

In magnetic field the continuum edge shifts nearly linearly, while the excitonic peak shifts diamagnetically, and this is manifested in the increase in their separation with increasing field strength, as shown in Fig. 4. The increase of the absorption with energy above the onset is most probably due to the nonmonotonic dependency of the $B_0$ line luminescence intensity on the excitation power. (The dye laser intensity is gradually decreasing with increasing energy.)

### C. Increase in mobility by continuous photoexcitation

The Shubnikov–de Haas oscillations shown in Fig. 5(a) were recorded in the dark after strong illumination with

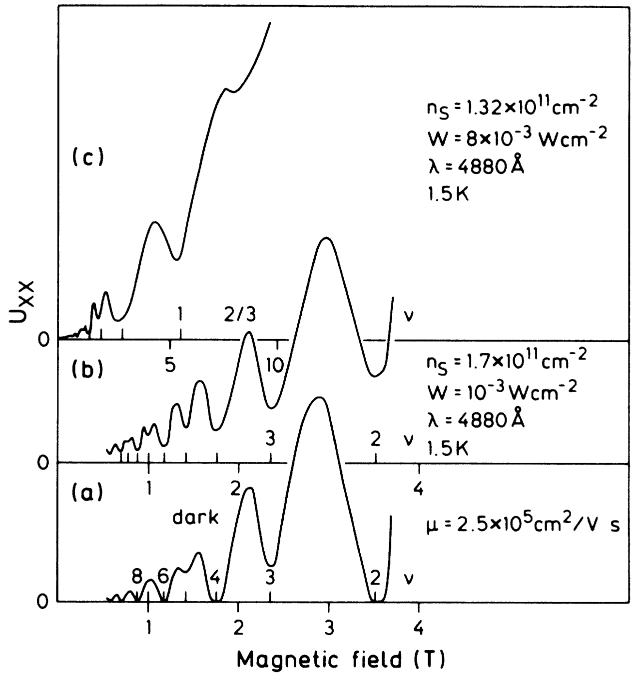


FIG. 5. Shubnikov–de Haas oscillations at 1.5 K measured (a) in the dark after previous illumination by white light, and (b) and (c) under continuous illumination by laser light.

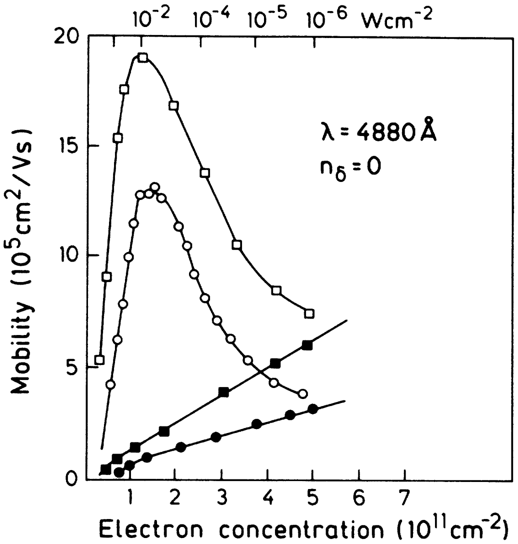


FIG. 6. Dependence of the mobility in two different samples (squares and circles) on the 2D electron concentration. The lower curves (solid symbols) are measured in the dark after previous illumination with white light, and the upper curves (open symbols) are measured under continuous illumination by laser light of wavelength λ = 4880 Å at various different powers.

white light. Those of Fig. 5(b) were measured under continuous illumination by laser light. Unfortunately, upon laser illumination the Shubnikov–de Haas oscillations can only be measured on a background of strong positive magnetoresistance due to parallel bulk photoconductivity. Figures 5(a) and 5(b), however, clearly show that at the same electron concentration the minima corresponding to filling factor $\nu = 5$, 7, and 9 are more pronounced under illumination than in the dark. Since minima at odd $\nu$ are only observed due to enhancement of the spin splitting,[11] and since this enhancement is very sensitive to the Landau-level width, these measurements confirm that the Landau-level broadening is minimal in these heterostructures and actually reduces upon photoexcitation, indicating an increased mobility.

The electron mobility, as determined from the square conductivity, of two different samples without Be δ doping, is plotted in Fig. 6 as a function of 2D electron concentration ($n_s$). Upon increasing $n_s$ by the persistent-photoconductivity effect, but measuring always in the dark, the mobility of both samples increases, as previously observed in similar samples.[12] On the other hand, under continuous illumination, even though the concentration of electrons reduces with increasing incident intensity[9] the mobility, in both samples, first increases and, only at higher intensities (and correspondingly lower $n_s$), decreases again. Bulk photoconductivity, of course, contributes to the values of the mobility measured. We have, however, been able to measure this contribution in the following way: As described previously,[9] we are able to reduce the carrier concentration in these samples down from the value obtained after saturation of the persistent photoconductivity to the original value which is realized at low temperatures, before the first illumination. This process can be monitored in the luminescence. The intensity of the line due to recombination of the 2D electrons with holes bound to residual acceptors (carbon) in the buffer layer[10] is plotted in Fig. 7(a) as a function of the incident light intensity. At the highest plotted incident intensities, the signal due to 2D recombination decreases, indicating a decreasing $n_s$. The square conductivity was measured simultaneously and is plotted in Fig. 7(b). At the incident light intensity at which the 2D

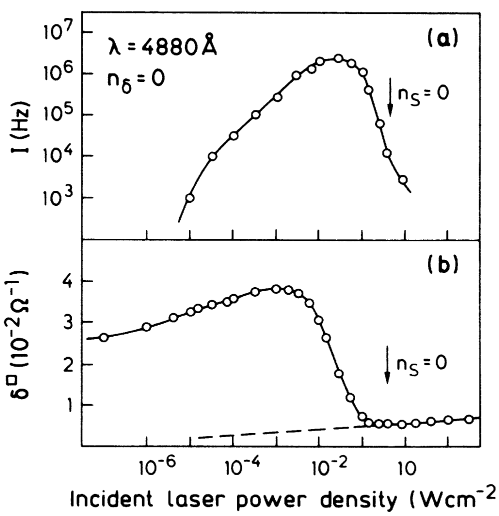


FIG. 7. (a) Intensity of the $B_0$ line and (b) the square conductivity as a function of illumination power at wavelength λ = 4880 Å.

luminescence line disappears from the spectrum, the square conductivity drops sharply to a value corresponding to the bulk contribution. From this measurement, we can, with certitude, claim that, over the electron-density range in which we observe this large enhancement in the mobility, the contribution from the bulk photoconductivity will be small.

This improvement in the system quality under illumination results from compensation of the charge of the ionized donors in the $Al_xGa_{1-x}As$ and, most importantly, in the spacer layer by the photoexcited electrons. The consequential suppression of charge fluctuations also contributes. Of course, when the carrier concentration becomes too small, then the usual effect of a decreasing mobility with decreasing $n_s$ dominates.[12] It should be noted that a similar enhancement of the mobility has also been observed in samples with Be δ doping.

An amplification of the fractional-quantum-Hall-effect (FQHE) activation energies should accompany this increase in mobility. Indeed, as can be seen in Fig. 5(c), features that may be due to the FQHE at $\nu=\frac{2}{3}$ have been observed in the Shubnikov–de Haas oscillations from photoexcited samples. From the tail of the luminescence line in a magnetic field, it was estimated that overheating does not exceed 0.1 K at $W=10^{-3}$ W cm$^{-2}$, thereby making these photoexcited structures viable systems for investigating the FQHE spectroscopically.

### D. Luminescence energy nonlinearities below filling factor 2

Upon application of a magnetic field, the $B_0$ line is observed to split into Landau levels. Only the lowest spin component of the 2D electrons is observed in the luminescence spectrum in finite magnetic field.[8] As previously reported, at odd filling factors ($\nu$) one observes the enhancement in the spin splitting as a reduction in the Landau-level splitting.[13] This behavior can again be seen in the magnetic field dependence of the second Landau level in Fig. 8(a). However, as this higher occupied Landau level is further depleted, at all odd filling factors except $\nu=1$ the Landau-level splitting increases again. Around $\nu=1$ the last remaining occupied Landau level first deviates drastically from its previous magnetic field dependence and then continues roughly parallel to its original direction [Fig. 8(a)]. The main contribution to this shift is again most probably $g$-factor enhancement, and thus gives a measure of the exchange energy [$\Delta g=8.4$ for Fig. 8(a)]. However, upon extrapolating this high-field dependence of the lowest Landau level back to $H=0$, one obtains a lower value of $E_0$, the energy position of the bottom of the subband. In the case plotted in Fig. 8(a), the low-field $E_0=1.4922$ eV and the high-field $E_0^*=1.4896$ eV, which represents a 2.6 meV increase in the Fermi energy, corresponding to an increase in electron density of $7\times10^{10}$ cm$^{-2}$. It has already been reported that a change in the 2D electron concentration results in a shift of $E_0$ rather than a shift of the Fermi level $E_F$.[9] Therefore, this high-field behavior may have, in part, an origin to the effects seen in cyclotron resonance by Richter *et al.*[14] and in transport by Haug *et al.*[15] In acceptor-doped samples the electrons avoid the repulsive Coulombic centers formed by the negatively ionized acceptors. The scatterer-induced states for acceptor-doped samples are higher in energy than the Landau-level states.[16] Thus, in the quantum limit, the electrons populate only pure Landau level states in the lowest spin-split Landau level, and no scatterer-induced states are occupied. This could mean that a spatial separation of the electrons away from the repulsive scatterers occurs and that the electrons are thus redistributed in "puddles" between the scatterers. This potential, which confines the electrons into "puddles," would then determine the electron density and, therefore, this redistribution would result in the increase in the local electron density that we observe. The size of the shift depends on the intensity of the incident light; the weaker this intensity, the greater the shift. This agrees with the above explanation, since the weaker the incident light, the more ionized acceptors are present.

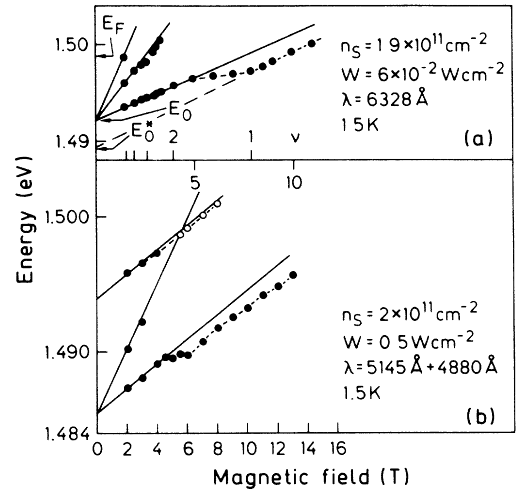


FIG. 8. Dependence of the spectral position of the luminescence lines on magnetic field and filling factor for two different samples. $E_F$ is the Fermi energy, and $E_0$ and $E_0^*$ the bottom of the subband determined from low- and high-field extrapolations, respectively. The open circles indicate the repopulated second subband.

It would seem reasonable to assume that this redistribution takes place in order to produce at $\nu=1$ a more uniform electron distribution, which must then include the electrons bound to the ionized acceptors. The magnetic length at $\nu=1$ is comparable to the average scattering length $(n_{sc})^{1/2}$. These acceptor-bound electrons would therefore account for the increased number of electrons suddenly felt at $\nu=1$ in the measurement. $n_{sc}=(N_0-n_s)\gamma$, where $\gamma$ is a constant of order 1 that gives the probability that the captured electron "belongs" to the 2D electron gas, and where $N_0$ corresponds to the electron density for which $n_{sc}=0$. The concentration increase (up to $N_0-n_s=7\times10^{10}$ cm$^{-2}$) is of the same order of magnitude as the estimated concentration of Be atoms present ($n_{sc}=2\times10^{10}$ cm$^{-2}$). Conversely, one could also argue that the increase in the electron concentration is up to 3.5 times the acceptor concentration and therefore contradicts the above uniform distribution explanation, indicating, instead, that the repulsion of the negatively charged, ionized acceptors is stronger than just that required to deplete an area equal to that occupied by an acceptor. This would result in the electrons experiencing a much deeper confinement potential and, consequently, would produce the higher local electron densities observed.

We also observe another interesting phenomenon in a sample where, at $H=0$, at the second subband is occupied. The $B_0$ line splits, as usual, into Landau levels in a magnetic field, Fig. 9, and at about $\nu=2$ ($H=4$ T) the higher subband depopulates, but then, surprisingly, at higher magnetic field it reappears in the luminescence spectrum ($H=6$ T). The explanation is partly given by the fan chart for this system [Fig. 8(b)]. The repopulation of the second subband occurs at the magnetic field value at which the second Landau level from the lower subband crosses this higher subband. This second Landau level should, however, be empty. It could be reoccupied due to the increases in electron density discussed just previously, which occur at the same magnetic fields. If this is what is happening, then the electrons in this repopulated second Landau level preferentially drop into the lower-energy second subband, and this is consequently observed in the luminescence.

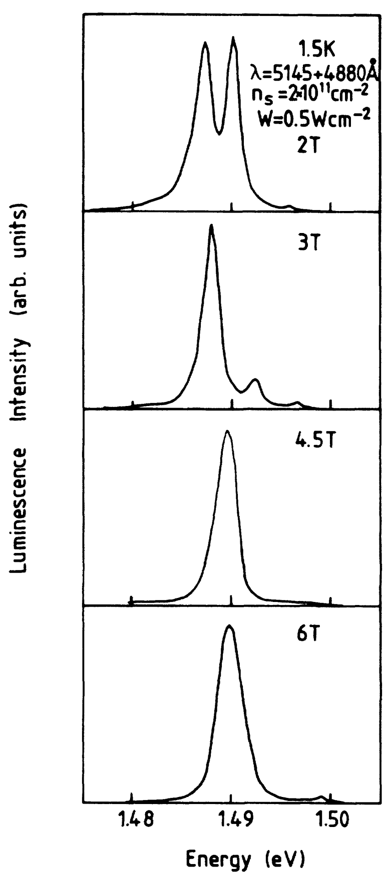


FIG. 9. Spectra of radiative recombination of 2D electrons with photoexcited holes bound to acceptor atoms in different magnetic fields at $n_s=2\times10^{11}$ cm$^{-2}$. The second subband transition ($B_1$ line) lies at about 1.496 eV at 2 T and at about 1.497 eV at 3 T, is absent at 4.5 T, and reappears at about 1.499 eV at 6 T.

### E. Electron-concentration dependence of the Landau-level splitting

In luminescence one observes the whole density of states below the Fermi level,[10] and when this splits into Landau levels in a magnetic field the behavior of all the occupied Landau levels can be monitored in the luminescence spectra. This gives us the unique possibility to measure the Landau-level splitting between occupied Landau levels, in contrast to cyclotron resonance, which can only measure the splitting between an occupied and an empty Landau level by making a transition across the Fermi level. We assume that the splitting of the two lowest Landau levels is $\Delta E=\hbar eH/m^*$, and then plot, in Fig. 10, this effective mass as a function of electron concentration as obtained from various samples with different concentrations. The dependence observed is a universal one and is not sample dependent. The concentration within each sample was varied by photoexcitation as described elsewhere.[9] The effective mass of the electrons is affected by exchange and correlation effects, and this results in the strong increase in $m^*$ (up to 30%) with decreasing $n_s$, as shown in Fig. 10. Such a dependence has recently been predicted theoretically for Si inversion layers,[17] and similar arguments should also be applicable to the GaAs-$Al_xGa_{1-x}$As system.

The results of Fig. 10 should be compared to cyclotron resonance measurements in the GaAs-$Al_xGa_{1-x}$As system,[18] which show an increase in the cyclotron mass with increasing electron concentration and overall smaller values (0.065–0.070) than those measured here. The in-

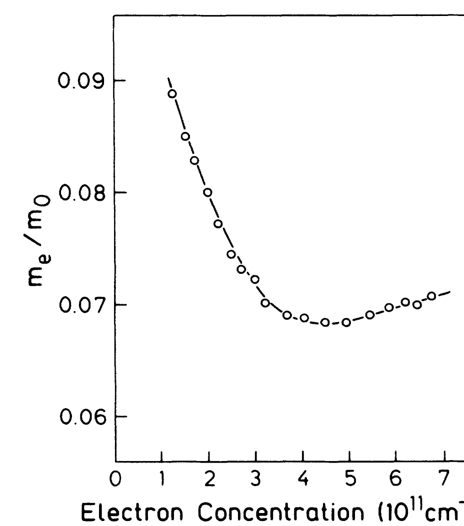


FIG. 10. Dependence of the electronic effective mass (determined from the Landau-level splitting as described in the text) on the 2D electron concentration.

crease is due to the effects of nonparabolicity, which increase with increasing $n_s$, and it is also the explanation of the rise seen in our results at higher $n_s$. Note that, in accordance with the Kohn theorem,[19] electron-electron interactions do not affect the cyclotron resonance frequency. The differences between the results of Ensslin *et al.*[18] and ours, we believe, can thus be explained as being due to the two techniques measuring different phenomena.

## IV. CONCLUSIONS

We have investigated the luminescence properties of $n$-type GaAs-$Al_xGa_{1-x}As$ single heterojunctions that have been δ-doped with Be in order to maximize the efficiency of the radiative recombination of the 2D electrons. This enables a direct investigation of the density of states of the 2D electrons. We have also been able to tune the 2D electron concentration optically, and have noticed that an increase in the electron mobility is associated with a reduction in electron density. This makes this system particularly appropriate for optical investigations of the integral and fractional quantum Hall effects.

Using the above method to vary the electron concentration, it has been possible to characterize the system in some detail using magnetophotoluminescence and magnetophotoluminescence-excitation techniques. In particular, we have observed a strong deviation in the energy position of the lowest Landau level away from a linear dependence on magnetic field below $\nu=2$. Finally, from the separation of two occupied Lantronic effective mass as a function of the 2D electron concentration.

*Note added in proof.* Our attention has been drawn to the theoretical work of P. A. Maksym[20] on the intersubband relaxation rate of photoexcited electrons. He finds that this rate is sensitive to both the number of available empty states in the lower subband and to the energy difference between the upper subband and $E_F$. His preliminary results appear, therefore, to provide a plausible explanation of the second subband repopulation phenomena described in Sec. III D.

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[1]For a recent extensive review, see C. Weisbuch in *Physics and Applications of Quantum Wells and Superlattices,* Vol. 170 of *NATO Advanced Study Institute, Series B: Physics,* edited by E. E. Mendez and K. v. Klitzing (Plenum, New York, 1987), p. 261.

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