# Direct measurement of the effective-mass renormalization in n-type modulation-doped $Al_{0.23}Ga_{0.77}As/In_{0.08}Ga_{0.92}As/GaAs$ quantum wells

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We have made the first direct measurement of the electron effective-mass renormalization in n-type modulation-doped $Al_{0.23}Ga_{0.77}As/In_{0.08}Ga_{0.92}As/GaAs$ quantum wells. The technique takes advantage of the presence, in such asymmetric structures, of parity-allowed optical transitions between the two lowest conduction subbands and the lowest valence subband. We have found that the electron mass is enhanced by 17% in a well with a sheet carrier concentration of $1.25\times10^{12}$ cm$^{-2}$.

Many-body effects have recently been the subject of extensive study in two-dimensional (2D) systems.[1-8] In particular, band-gap renormalization has been measured directly in modulation-doped quantum wells[6] and somewhat less directly in high-intensity photoexcitation studies of undoped wells.[1-3] Up to the present time, however, the associated effective-mass renormalization has not been measured in a quantitative manner, although indirect evidence has been provided by the photoexcitation work. Here we report a method of determining this effect, by utilizing magnetoluminescence results from an n-type modulation-doped $Al_{0.23}Ga_{0.77}As/In_{0.08}Ga_{0.92}As/GaAs$ sample in which the Fermi energy is close to, but below, the second ($n_c=2$) conduction subband. The asymmetrical structure of the sample means that intersubband transitions with $\Delta n\neq1$ are allowed and, in particular, that transitions are observable between the lowest valence subband ($n_v=1$) and both the highly populated $n_c=1$ and the unpopulated $n_c=2$ conduction subbands. In our experiment the ground-state Landau-level splittings are observed in photoluminescence (PL) and the splittings in the higher subband transitions are observed in photoluminescence excitation (PLE). This allows a comparison of the reduced masses of transitions involving recombinations from both populated and unpopulated conduction-band states *to the same hole state,* thereby providing a direct measurement of the effective-mass renormalization due to the presence of the two-dimensional electron gas (2-DEG). The main advantage of this method over similar experiments using photogenerated plasmas[1-3] is that the carrier density can be determined independently via Shubnikov–de Haas measurements. A further advantage over the (Ga,Al)As/GaAs (Refs. 1 and 2) work is obtained because the quantum confinement and biaxially compressive strain present in the (In,Ga)As/GaAs material system give rise to a large separation between the valence-band $|\frac{3}{2},\pm\frac{3}{2}\rangle$ ground state and the $|\frac{1}{2},\pm\frac{1}{2}\rangle$ state,[9] so that there are no complications arising from valence-band structure and the fan diagrams obtained are quite simple to interpret. In addition, the technique described here allows a clear distinction to be made between the many-body mass renormalization effect and the effects of conduction-band nonparabolicity, which is not possible using conventional cyclotron resonance techniques which measure the effective mass at the Fermi energy.[10]

The sample used in this work had the following structure, grown by molecular-beam epitaxy on a semi-insulating GaAs substrate (alloy compositions were determined from calibrated flux rates): 1-$\mu$m undoped GaAs, 150-Å $In_{0.08}Ga_{0.92}As$ quantum well, 40-Å undoped $Al_{0.23}Ga_{0.77}As$ spacer, 350-Å Si-doped $Al_{0.23}Ga_{0.77}As$ ($n=1.5\times10^{18}$), 750-Å Si-doped GaAs capping layer ($n=2.0\times10^{18}$). From Shubnikov–de Haas (SdH) measurements we determined that the well sheet carrier density was $1.25\times10^{12}$ cm$^{-2}$.

A schematic diagram of the band structure in the vicinity of the quantum well is shown in Fig. 1. The energies of the lowest two conduction subbands and the lowest valence subband are indicated, together with the position of the Fermi level $E_F$, in our sample. Because $E_F$ lies just below the $n_c=2$ conduction subband, the PL observed under weak excitation is due predominantly to transitions between the $n_c=1$ and $n_v=1$ subbands, whereas the transition between the $n_c=2$ and $n_v=1$ subbands is seen primarily in absorption (or PLE in our experiment), as indicated in the figure.

PL and PLE data were obtained at 4.2 K with an Oxford Instruments 14.5-T vertical bore magnet in the Faraday configuration with the magnetic field perpendicular to the layers. An argon-ion-pumped Spectra Physics $Al_2O_3$:Ti laser was used as the source and the excitation radiation was delivered to the sample via an optical fiber. The luminescence was also collected by fiber, dispersed by a 0.85-m focal length Spex monochromator and detected using a North Coast Ge detector. A typical zero magnetic-field PL spectrum is shown in Fig. 2(a), in which the most prominent transition at 1.4189 eV is due to recombination between the $n_c=1$ and $n_v=1$ subbands. The $n_c=2$ to $n_v=1$ transition is barely discernible at 1.4616 eV, close to the Fermi energy $E_F$ indicating a very low carrier density in the $n_c=2$ subband. The lumines-

 

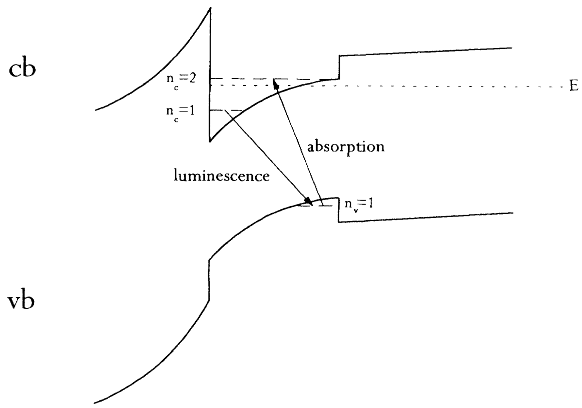


FIG. 1. A schematic diagram of the band structure of the $Al_{0.23}Ga_{0.77}As/In_{0.08}Ga_{0.92}As/GaAs$ quantum well, showing the energies of the lowest two conduction subbands ($n_c=1$ and 2) and the lowest valence subband ($n_v=1$). The Fermi energy lies just below the $n_c=2$ conduction subband, so that the transition between $n_c=1$ and $n_v=1$ subbands is seen in PL, whereas that between the $n_c=2$ and $n_v=1$ subbands is seen only in absorption (or PLE in our experiment), as indicated.

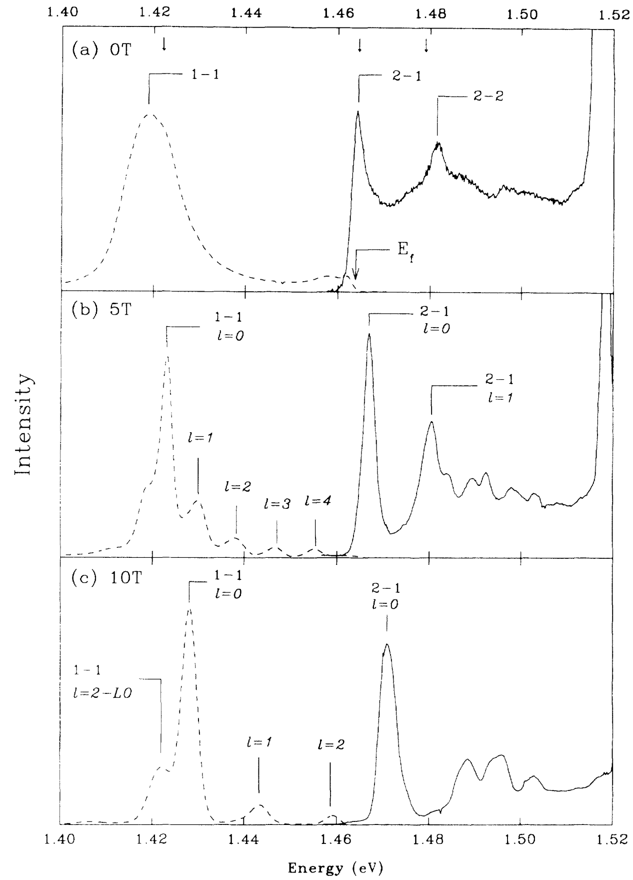


FIG. 2. Interband transition data obtained in zero magnetic field (a), and in magnetic fields of 5 T (b) and 10 T (c). The dashed lines indicate data obtained in PL and the solid lines indicate data obtained in PLE. Excitation power densities were approximately 20 mW cm$^{-2}$. The arrows in (a) indicate the calculated Fermi energy and interband transition energies. In (b) and (c), the development of the spectra into Landau-level transitions is clearly seen.

cence arises mainly from the recombination of doping electrons (with $k$ up to $k_F$) with photogenerated holes, and the presence of transitions involving electrons up to $E_F$ suggests that some hole localization occur in this sample. The weak transition at 1.4569 eV bears some resemblance to the Fermi-energy-edge singularities reported in the literature, which commonly occur in samples where $E_F$ is close to the $n_c=2$ subband.[11,12] However, resonantly pumped PL experiments, to be reported elsewhere, show that this transition is an LO-phonon satellite of deep levels in the GaAs barrier layer and we therefore ignore it here. Figure 2(a) also shows the zero-field PLE spectrum obtained by monitoring the $n_c=1$ to $n_v=1$ transition, in which both the $n_c=2$ to $n_v=1$ and the $n_c=2$ to $n_v=2$ peaks are clearly visible. To confirm our assignments and to deduce the carrier density in the $n_c=2$ subband, we have obtained a self-consistent solution of Poisson's and Schrödinger's equations, including band-gap renormalization in the local-density approximation. The Fermi-energy position and transition energies thus obtained are also indicated in Fig. 2(a). From the calculation we have established that the carrier density in the $n_c=2$ subband is less than 1% of the total well sheet carrier density and so can be neglected in the subsequent analysis.

Figures 2(b) and 2(c) show typical PL and PLE data obtained in magnetic fields of 5 and 10 T, respectively. The development of the spectra into Landau-level transitions, obeying the normal selection rule $\Delta l=0$, is clearly seen above fields of approximately 2 T. Additional weak structure associated with forbidden transitions ($\Delta l \neq 0$), present in the work of Lyo, Jones, and Klem[13] on similar samples, was not observed in our experiment. LO-phonon replicas of the transitions are also observable at lower energies. The PL transition energies for $n_c=1$ to $n_v=1$ and the PLE energies for $n_c=2$ to $n_v=1$ are plotted in Fig. 3, together with the $n_c=1$ subband Landau-level filling factors $\nu$ obtained from SdH. The lines are linear fits to the equation

$$E=(l+\tfrac{1}{2})\frac{\hbar eB}{\mu} ,$$

where $\mu$ is the reduced mass for the transition. Transitions are visible between Landau levels with quantum numbers up to $l=12$ for the $n_c=1$ to $n_v=1$ subband, and up to $l=5$ for $n_c=2$ to $n_v=1$. It is clear that there are substantial differences between the Landau fans of the two transitions, as well as small anomalies in the transitions at even filling factor. Considering the $n_c=1$ to $n_v=1$ transition first (open circles), we see that the lowest-order transition ($l=0$) extrapolates back to zero field at an energy that is considerably higher (1.418 eV) than that for the transitions with $l=1$ and above, whose intercepts rapidly converge to energies around 1.414 eV. This behavior is consistent with high-intensity photopumped experiments in GaAs undoped quantum

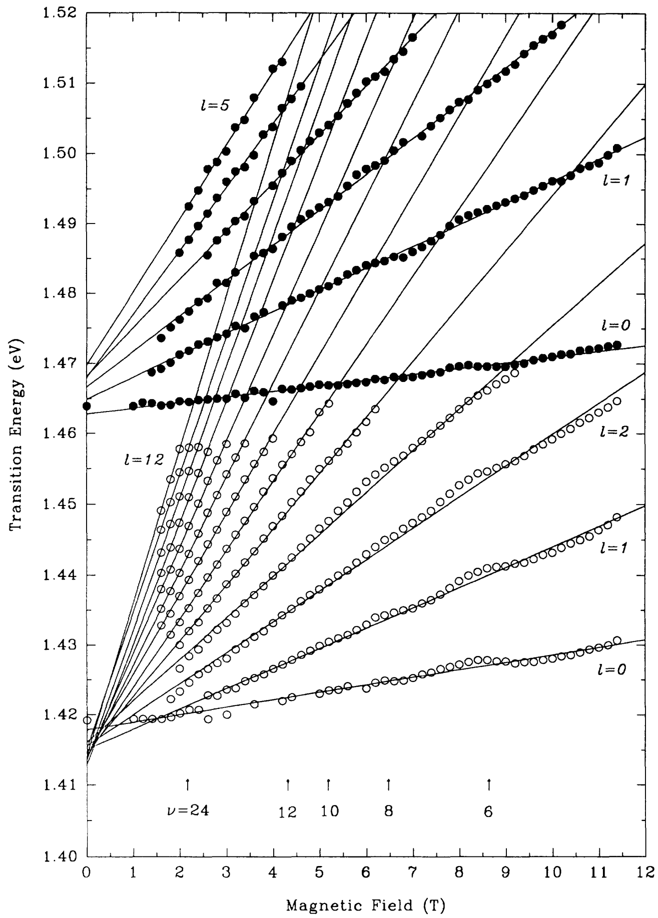


FIG. 3. Interband transition energies as a function of magnetic field. The open circles are data obtained from the $n_c=1$ to $n_v=1$ recombination and the filled circles from the transition between $n_c=2$ and $n_v=1$. Also shown are the Landau-level filling factors, indicated by the arrows, as obtained from Shubnikov–de Haas measurements.

wells[1,2,7] where the $l=0$ transition was perceived to have a different character from the transitions between higher-order Landau levels, which extrapolated to a single point 5–10 meV below $l=0$. In our data, the slopes of the linear fit give a reduced mass, $\mu_{1-1}$, of $0.0658\pm0.0013\, m_e$ for transitions with $l=2$ and above.

The $n_c=2$ to $n_v=1$ fan (filled circles in Fig. 3) has a behavior which is much more like that obtained from undoped wells.[9] The $l=0$ transition has a strongly excitonic character which gradually decreases as we move to higher $l$, the decreasing effect of Coulomb forces manifesting itself as a convergence of the zero-field intercepts at higher energy. Here the linear fit gives a reduced mass $\mu_{2-1}$ for transitions with $l=2$ and above of $0.0572\pm0.0011 m_e$, 13% less than that obtained from $n_c=1$ to $n_v=1$. Since both sets of transitions involve *the same hole states,* this difference can only be accounted for by a variation in the electron mass of similar magnitude. Quantitatively, we can use the fact that the hole mass is the same for each set of transitions to relate the electron effective masses in the $n_c=1$ and $n_c=2$ subbands ($m_e^1$ and $m_e^2$, respectively) to the measured reduced masses via the following expression:

$$\frac{1}{m_e^1}=\frac{1}{\mu_{1-1}}-\frac{1}{\mu_{2-1}}+\frac{1}{m_e^2} . \qquad (1)$$

The value of $m_e^2$ is obtained by linear extrapolation between the bulk GaAs value and the values measured directly for $In_xGa_{1-x}As/GaAs$ quantum wells with slightly higher indium concentration in Ref. 14, giving $m_e^2=0.064\pm0.001$. Using the experimentally determined $\mu_{1-1}$ and $\mu_{2-1}$, we obtain a value of $0.075\pm0.004 m_0$ for $m_e^1$ which represents a 17% increase in effective mass.

We attribute this effective-mass renormalization to many-body electron-electron scattering in the quantum-well region. It is well known that such processes give rise to a renormalization of the band structure due to exchange and correlation effects. Within the random-phase approximation the electron self-energy is the sum of two terms;[15] a screened exchange self-energy which is $k$-dependent and a $k$-independent Coulomb hole (CH) self-energy. In 2D plasmas the CH self-energy usually dominates the band-gap renormalization, but since it is $k$-independent it has no effect on the mass renormalization. However, the screened exchange interaction, which is zero in an empty band, does give rise to a change in the dispersion of the $n_c=1$ level. This change has been calculated in $Si/SiO_2$ inversion layers[16] to be approximately 16% for a sheet carrier density of $10^{12}$ cm$^{-2}$, which is consistent with our determination and also with estimates from the high excitation experiment of Maan *et al.*[1] in (Ga,Al)As/GaAs quantum wells.

From the data we are also able to deduce an in-plane $|\frac{3}{2},\pm\frac{3}{2}\rangle$ hole mass of $0.54\pm0.12 m_e$, which represents an increase over the previously reported values[17,18] for wells of similar width and composition which have been in the range $0.1-0.2 m_e$. This is clearly further evidence of hole localization.

Also apparent in Fig. 2 are deviations from linear behavior in both sets of transitions which occur at even filling factors. Such anomalies have been observed before in the $In_xGa_{1-x}As/InP$ system[19,20] and are due to changes in band-gap renormalization with filling factor. Ando[15] has shown that this behavior is mainly due to strong oscillations in the hole self-energy (for which only the Coulomb hole term is present), whose amplitude increases approximately linearly with field, consistent with our observations.

In conclusion, we have made a direct measurement of the effective-mass renormalization due to the one-component plasma in a modulation-doped $Al_{0.23}Ga_{0.77}As/In_{0.08}Ga_{0.92}As/GaAs$ quantum well. The electron mass was found to be enhanced by 17% by a 2DEG of density $1.25\times10^{12}$ cm$^{-2}$, in good agreement with theoretical estimates.

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