Magnetoluminescence oscillations of a doped (Al,Ga)As/GaAs single heterojunction

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We have studied the photoluminescence spectra of a modulation doped (Al,Ga)As/GaAs single heterojunction in magnetic fields to 50 T at 4 K. When an external excitation is introduced to the system, photocreated electrons push the Fermi energy close to the second subband and lead to the formation of a hybridized eigenstate of the second subband ($E1$) exciton and the first subband ($E0$) two-dimensional electron state. The conduction-band hybridization enhances nonlinear behavior of magnetoexciton transitions in the optical process. At low fields, the $E1$ magnetoexciton transition is dominant, because the $E1$ hole wave-function overlap is larger than that of $E0$ hole. Beyond the $\nu=2$ quantum Hall state, where electron screening becomes negligible, electron-hole attraction is dominant, and holes tend to move to the interface. As a consequence, the photoluminescence oscillator strength switches from the magneto-exciton transition to the lowest-Landau-level subband transition above 13 T. [S0163-1829(98)03240-8]

The electrical and optical properties of quantum-well structures have been the subject of many investigations for a number of years. More recently, intensity and energy oscillations in the magnetophotoluminescence (MPL) of modulation-doped single heterojunction (MDSH) structures having one or two occupied subbands have been studied both experimentally and theoretically by several groups.[1–12] In photoluminescence (PL) studies, the presence of free carriers screen the photocreated electron-hole pairs and electron-phonon interactions. Coulomb interaction between the photocreated holes and the free carriers can lead to band-gap renormalization and Fermi-edge singularities. Many-body effects are particularly sensitive to magnetic fields as the density of states is strongly modified in two-dimensional electron-gas systems. MDSH's can be fabricated to possess ultrahigh mobility at low temperatures, and to have important applications as high electron mobility transistors. In particular, a study in a single-side-doped single quantum well showed that when the first subband ($E0$) Fermi energy lies in close proximity to the empty second subband ($E1$), the PL transition of the $E1$ subband exciton intensity oscillates with magnetic field.[4] In this case, the $E0$ subband free-carrier transition shows distinct Landau-level transitions, while the $E1$ subband exciton transition intensity oscillates with the same period as the Shubnikov–de Haas (SdH) oscillations. This study indicates that the strong modulation in magnetoexciton intensity requires negligible electron density in the $E1$ subband which is hybridized with the $E0$ state.

Unlike square quantum wells, a MDSH has a potential that changes with electron density in the well or with an external electric field. For optical measurements, when a light excitation is introduced to the sample, photoexcited electrons from the valance band can easily move to the well which makes the wedge-shaped potential well stiffer. Under these circumstances, photocreated electrons push the Fermi energy closer to the empty $E1$ subband in this potential. For this reason, an appropriately designed MDSH is a preferable system to study subband hybridization.

The MPL of MDSH's has also shown pronounced oscillations in the PL intensity of the hybrid exciton recombination, as well as its peak energy and width. Oscillations in the MPL intensity can be explained by many-body interaction between the $E1$ exciton and the Fermi edge resonance of Landau levels from the first subband ($E0$). The optical Shubnikov–de Haas effect resulting from many-body interaction was found to be most pronounced when the Fermi level lies within the extended states, i.e., at odd filling factors. Other theoretical studies argue that the main contribution to the oscillations arise from the electron-hole screening and valence-band self-energy.[5,7] Hawrylak and co-workers reported MPL results where no oscillations were observed in a MDSH structure; in their sample the holes were localized in an acceptor layer, and they contended that any oscillatory effects arise from the hole self-energy that is nearly canceled by the acceptor electron clouds.[8,9]

The sample studied here is an $Al_{0.33}Ga_{0.67}As/GaAs$ MDSH grown on a semi-insulating GaAs [001] substrate using an molecular-beam-epitaxy machine. It consists of an undoped 104-nm layer of GaAs, followed by an undoped $Al_{0.33}Ga_{0.67}As$ spacer layer of thickness 20 nm, a Si-doped

$Al_{0.33}Ga_{0.67}As$ layer of thickness 40 nm with a doping density of 1.5×10^{18} cm^{-3}, and an undoped GaAs capping layer of 17 nm. An optical fiber (diameter 0.6 mm) was used to couple the light into and out of the sample in 8-T and 20-T superconducting magnets and a 50-T pulsed magnet. MPL measurements were carried out at 4 K, with the sample mounted in a strain-free environment. The data were recorded using a $f/4$ 0.275-m spectrograph equipped with a cooled CCD detector. 1800 and 1200 l/mm gratings were used in the superconducting and pulsed magnets, respectively. The PL studies were conducted under the following conditions for all magnets: The laser excitation energy was 2.4 eV (514.5 nm); the power density on the sample did not exceed 1 mW/cm^2; and the spectral resolution was 0.05–0.08 meV. The pulsed-field spectra were recorded in a 2 ms time interval using a Pockel's cell shutter timed to coincide with the flat-top region at the peak of the magnetic field. Field values were monitored by a calibrated pick-up coil situated directly above the sample. We found two-dimensional electron density utilizing SdH oscillations which were performed simultaneously with PL in a 20-T superconducting magnet using a conventional four probe resistance measurement method.

The sample in this study has a mobility greater than 1.5×10^6 $cm^2/V\,s$, and had considerably less PL contribution from the bulk than previously reported.[11] We found that the oscillatory behavior of the MPL data and SdH measurements undertaken under the same illumination conditions had identical periodicity in inverse magnetic field. We have calculated the energy-band structure and wave functions of the system in a self-consistent manner under illumination and dark conditions. Comparison of our self-consistent calculation with SdH results indicated that under illumination, most of the electrons captured by the substrate are canceled by photocreated holes and the Fermi energy lies just below the $E1$ level. Due to the Coulomb interaction between two dimensional electron gas (2DEG) in $E0$ state and magnetoexcitons in $E1$ state, magnetoexciton transitions have nearly periodic oscillations in $1/B$ with an even filling factor. This phenomenon results from a sensitive response of the potential energy of a MDSH to the variation in distribution of the 2DEG.

Figure 1 displays typical PL spectra of the MDSH sample taken at 4 K as a function of magnetic field for $B//z$. At $B=0$, the spectrum consists of three peaks located at 1515.5, 1514.0, and 1510.5 meV. The middle peak is the most intense and is related to the radiative excitonic recombination of the $E1$ subband with photocreated holes close to the top of the valence band in the GaAs layer. The higher-energy peak of medium intensity is possibly due to the free exciton (FX) in bulk GaAs. The low-energy peak of weak intensity probably emanates from excitons bound to an ionized acceptor (A^{-}-X). The intensity of the FX peak and the A^{-}-X peak decrease with increasing magnetic field, and show a diamagnetic shift characteristic of excitonic transitions in the low-field regime. Energy scans were taken at 0.2 T intervals to 18 T. Intensity oscillations and small energy deviations (steps) from linear behavior for the $E1$ exciton transitions were observed over this magnetic-field range. These oscillations in PL energy and intensity are the key features in this paper.

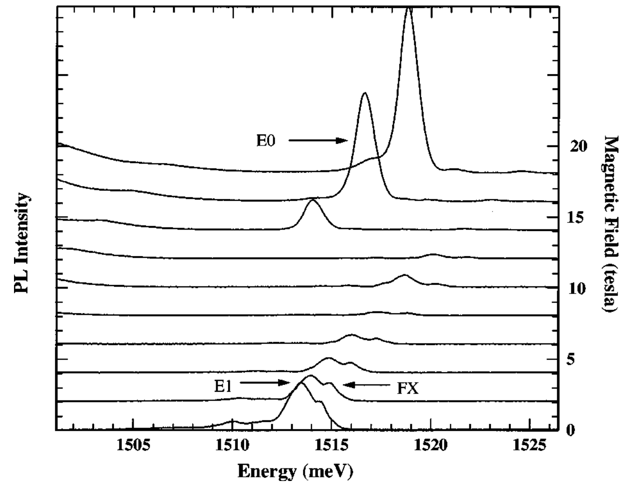

FIG. 1. PL spectra with $B\|z$ for the sample (GEN552) at $T=4$ K. The exciton ($E1$) transition abruptly loses its intensity at 12 T, and the free-electron-hole transition appears on the lower-energy side.

Before illuminating the sample with laser light, the electron density in the well is about 4.58×10^{11} cm^{-2}, and our theoretical calculation shows that the $E0$ and $E1$ energy levels and the Fermi energy lie at 47.7, 73.1, and 64.2 meV from the bottom of the well, respectively. The energy separation between the Fermi energy and the $E1$ subband is about 8.9 meV. After illuminating the sample, the electron density in the well increased to $5.82\times10^{11}cm^{-2}$, and the $E0$ and $E1$ energy levels change to 51.2 and 72.8 meV from the bottom of the well, respectively. Another interesting result of our calculation is that the Fermi energy is located at 0.67 meV below the empty $E1$ subband. Due to this close proximity of $E1$ and the Fermi energy, strong Coulomb interaction between 2DEG and the excitons influence the magnetoexciton emission.[4] The intensity modulation has the same period as the Shubnikov–de Haas oscillation; this is in good agreement with Ref. 4. In Fig. 2, we show the oscillatory nature of the intensity and energy with magnetic field. At low fields, below 13 T, the $E1$ magnetoexciton emission is

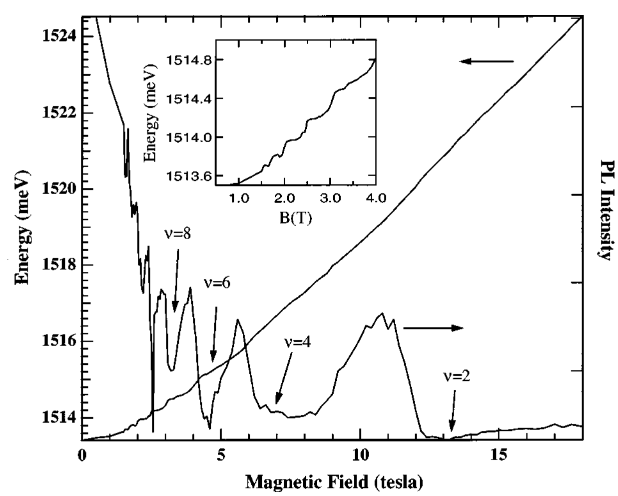

FIG. 2. Magnetic-field dependence of the PL energy and intensity of the magneto-optical transition at $T=4$ K. Both the PL intensity and energy show nonlinear behavior with magnetic field.

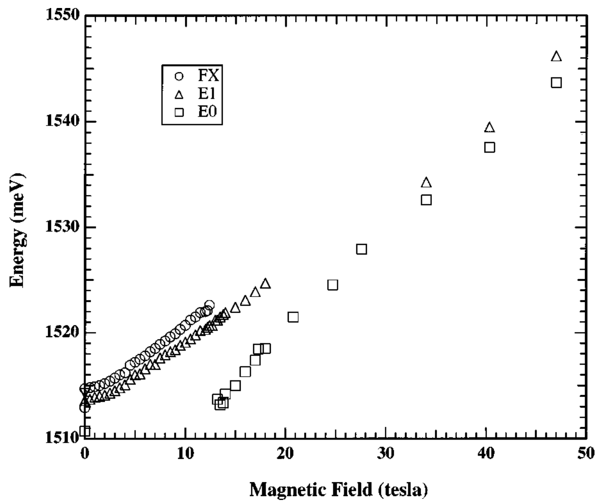

FIG. 3. PL energy vs magnetic field at $T=4$ K. At a high field above 30 T, the PL peak splits into two (triangles and squares). This splitting is possibly caused by the anticrossing of $E0$ and $E1$ transitions.

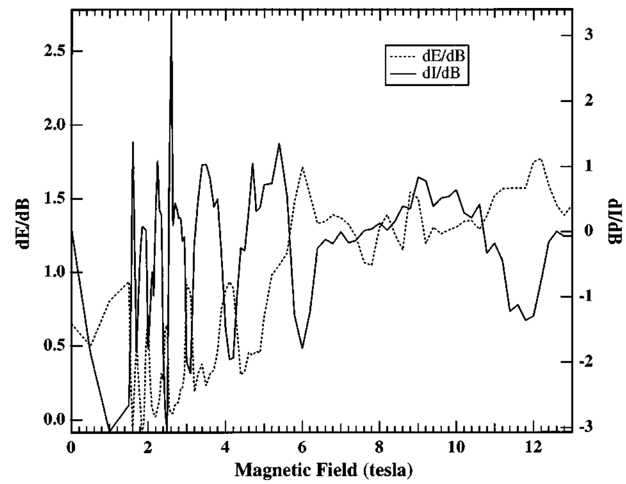

FIG. 4. Magnetic-field dependence of the dE/dB and dI/dB curves. These derivatives show opposite behavior, such that PL intensity minima correspond to PL energy maxima, and vice versa.

dominant and we could not see the $E0$ free-carrier transitions. In the region 12–14 T, the $E1$ level undergoes a rapid decrease in intensity and a new peak corresponding to the (0-0) inter-Landau transition for the $E0$ subband appears. This peak rapidly gains intensity with increasing field and at about 30 T shows splitting which is well resolved at the highest field (47 T). The complete plot is shown in Fig. 3.

For a single heterojunction, when laser excitation is applied to the system, the photocreated holes tend to move toward the GaAs flatband. This is caused by the Coulomb repulsion between the holes and Si donors which dominates over the attraction between screened electrons and the photocreated holes. In the wedge-shaped potential in a modulation-doped single heterojunction, the valence-band electrons and the photocreated holes are spatially separated. Consequently, the wave-function overlap between the $E1$ subband excitons and the photocreated holes is larger than that of electrons in the $E0$ subband and the photocreated holes. In a MDSH, photocreated holes need not to be localized in order to give rise to the optical transition of a hybridized excition. This is because the overlap of the $E1$ with the valence-edge hole state is large. Therefore, $E1$ excitons have a larger probability to recombine with the photocreated holes than the 2D electrons. As a result, the PL transition of 2D electrons in $E0$ subband below 13 T is not observed. When the magnetic field reaches the $\nu=2$ quantum Hall state, the Fermi energy stays in the localized state and the electron-hole screening is negligible. Due to the negligible screening strength, photocreated holes tend to move to the interface because the electron-hole attraction is dominant in the high-field limit. As a consequence, the PL recombination switches from the $E1$ exciton to the $E0$ free carriers above 13 T, which is around the $\nu=2$ quantum Hall state.

In the energy and intensity vs field plots (Fig. 2), the energy shows a steplike behavior, while the peak intensity shows an oscillatory behavior with the same period as the Shubnikov–de Haas oscillations which were simultaneously measured with PL. In Fig. 4, the derivative of intensity maxima (dI/dB) correspond to minima in the derivative of the energy (dE/dB) of the $E1$ exciton transition. This means that intensity minima occur when the Fermi energy is located in the extended states, whereas the energy maxima occur when the Fermi energy is located in the localized states. A Coulomb interaction between the 2D electron gas and the exciton state leads to the intensity modulation. When a Landau level of the 2D electron gas in the $E0$ subband crosses the $E1$ exciton state, due to a Coulomb interaction, corresponding eigenstates are hybridized. This enhances the interband matrix element for the overlapping transitions. When the Fermi energy crosses the $E0$ Landau levels, it changes the electron density in the $E0$ Landau levels that modulate Coulomb interactions between a 2D electron gas and an $E1$ exciton. This periodic change of the Coulomb interaction modulates the MPL intensity.[4]

The nonlinear behavior of the transition energy is more complicated. When the Fermi level sweeps through an extended state, the screening strength changes because the screening is proportional to number of electrons in the Fermi level. Repeating this process with changing magnetic fields modulates the screening effect, which leads to a nonlinear behavior of the transition energy in an optical process. Hawrylak, Polsford, and Ploog[9] reported that energy oscillations can be eliminated by acceptor doping in a single heterojunction, while the PL intensity continues to oscillate with magnetic field. With acceptor doping, hole screening is negligible because holes in the valence band are blocked by the doped acceptors, and electrons can ''see'' only the acceptors. A theoretical study[5] also has shown that energy variation occurs at the even numbers of integer quantum Hall states due to the screened exchange and Coulomb hole self-energy. However, it is suggested that the Coulomb hole of the hole term is dominant, since the electron exchange and correlation are effectively canceled, and insufficient photocreated holes exist to make the hole exchange term. We believe that it is primarily the Coulomb hole term that is responsible for the nonlinear optical behavior of the transition energy in 2D electron systems. In our system, a conduction-band hybridization occurs due to the close proximity of the Fermi energy and the $E1$ subband. As mentioned above, the magnetoexciton transition energy shows a steplike behavior, while the intensity has local maxima which is related to the fact that the Fermi energy stays in the localized states. Like the 2D electrons, $E1$ excitons see the screened holes because of the band hybridization due to the Coulomb interaction. Consequently, as the valence hole self-energy modulates with magnetic fields, the $E1$ exciton transition energy varies nonlinearly.

In conclusion, MPL oscillations in the energy and intensity of the magnetoexciton transition are observed that are periods in an inverse magnetic field and are nearly in phase with Shubnikov–de Haas measurements below 13 T, provided that the latter are obtained under comparable illumination conditions. Derivatives of the PL intensity and energy show that these oscillations occur in an opposite manner. Self-consistent calculations show that the second subband lies very close to the first subband. Conduction-band hybridization occurs due to the Coulomb interaction between the 2D electron gas in the $E0$ state and the $E1$ magnetoexciton, which leads to the modulations of magnetoexciton transition energy and intensity. We propose that the valence hole self-energy aroused by the Coulomb hole term is responsible for the nonlinear behavior of the transition energy, while the Coulomb interaction between two subbands is responsible for the intensity oscillations.

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