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Optical investigation of Fermi-edge singularities in $Al_{0.35}Ga_{0.65}As/GaAs$ heterostructures

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Many-body effects of two-dimensional electrons in *n*-type modulation-doped $Al_xGa_{1-x}As/GaAs$ heterostructures have been studied by photoluminescence (PL), PL excitation (PLE) spectroscopy, and optically detected cyclotron resonance (ODCR). A Fermi-edge singularity (FES) is observed both in PL and PLE spectra when a gate voltage is applied. Strong enhancements occur for electrons at the Fermi edge (E_F) recombining both with holes bound at acceptors and holes at the GaAs valence-band edge. These assignments are supported by the spectral behavior of the ODCR signals. Our results show that the FES in optical spectra due to holes in the GaAs valence band is correlated in strength with the FES corresponding to holes bound at acceptors. The strong Fermi-edge enhancement in optical spectra in our structures is due to the presence of an unoccupied adjacent second electron subband near the Fermi edge.

Many-body effects such as the Fermi-edge singularity (FES) have previously been observed in PL spectra related to the two-dimensional (2D) electron gas in narrow $In_yGa_{1-y}As/InP$ quantum wells (QW's),[1] and in $Al_xGa_{1-x}As/GaAs$ modulation-doped QW's.[2–7] FES enhancements have been observed under a number of different conditions.[1,2,5] In the $In_yGa_{1-y}As/InP$ system, the PL observation of the FES has been attributed to composition fluctuations in the $In_yGa_{1-y}As$ layer, causing localization of confined holes.[1] The localization of holes ensures the k conservation in the optical transition. On the other hand, Chen *et al.*[2,8] have studied modulation-doped QW's in both the $Al_xGa_{1-x}As/GaAs$ and $Ga_{1-x}Al_xAs/In_yGa_{1-y}As/GaAs$ systems and concluded that the scattering between the Fermi sea and unoccupied adjacent electron subbands is responsible for the optical observation of the FES. The nearly resonant adjacent subband allows an efficient scattering path near $k=0$ for electrons at the Fermi edge E_F. Wagner, Ruiz, and Ploog[5] studied *p*-type $GaAs/Al_xGa_{1-x}As$ QW's and concluded that the observation of the FES is due to weakly localized electrons. To the best of our knowledge, there has been no report on the experimental observation of FES related to impurities up to now.

Recently, radiative recombination related to the 2D electron gas in $Al_xGa_{1-x}As/GaAs$ modulation-doped heterostructures has been reported.[9–14] In this Rapid Communication, we present a detailed optical investigation of many-body effects in a 500-Å asymmetric modulation-doped $Al_xGa_{1-x}As/GaAs$ heterostructure with a design similar to a high-electron-mobility transistor (HEMT), with an external electric field as a perturbation. Strong FES enhancements related to both holes bound at acceptors and holes in the valence band (VB) are observed.

The sample (HEM-1) used in this study is grown by molecular-beam epitaxy (MBE) on a semi-insulating GaAs substrate, followed by a 10-period AlAs/GaAs superlattice (SL), an undoped 50-nm GaAs layer, a 20-nm undoped $Al_{0.35}Ga_{0.65}As$ spacer layer, an 80-nm Si doped (10^{18} cm^{-3}) $Al_{0.35}Ga_{0.65}As$ layer, and finally a 5-nm GaAs cap layer. The two-dimensional electrons are confined in the notch potential at the interface between the undoped GaAs and the $Al_{0.35}Ga_{0.65}As$ spacer layer. A semitransparent metal gate consisting of 1-nm Cr and 5-nm Au was evaporated on top of the GaAs cap layer. To apply the electric field perpendicular to the interface between the GaAs and the $Al_xGa_{1-x}As$ layer, thin electrical wires were contacted on the metal gate and the GaAs substrate. In order to get a good bonding contact, 40-nm Au was used at the contact point on top of the semitransparent metal gate. The sample temperature could be continuously regulated down to 2.0 K. For the photoluminescence excitation (PLE) measurements, a tunable sapphire:Ti solid state laser was used as the excitation source. A double-grating monochromator and a GaAs photomultiplier were used to disperse and detect the PL signals. Optically detected cyclotron resonance (ODCR) experiments were carried out in a modified Bruker *X*-band electron-spin resonance spectrometer, equipped with a microwave cavity with optical access in all directions.[15]

Figure 1(a) shows PL spectra of the heterostructure at zero field with an excitation wavelength of 5145 Å at various excitation intensities. The energy positions of the transitions HB1 and HB2 (HB denotes *H* band) are found to be strongly dependent on the excitation intensity [Fig. 1(a)], since the potential across the active GaAs layer is dependent on the excitation intensity. The HB1 peak is interpreted as the recombination between electrons in the first subband and holes in the valence band, and HB2 as the corresponding recombination between the 2D electrons in the first subband and holes bound at acceptors in the active GaAs layer. A detailed study of the HB1 and HB2 transitions can be found in Refs. 12 and 14.

To modify the potential at the interface, a gate voltage was applied perpendicular to the growth direction. With negative gate voltages, the band bending across the active

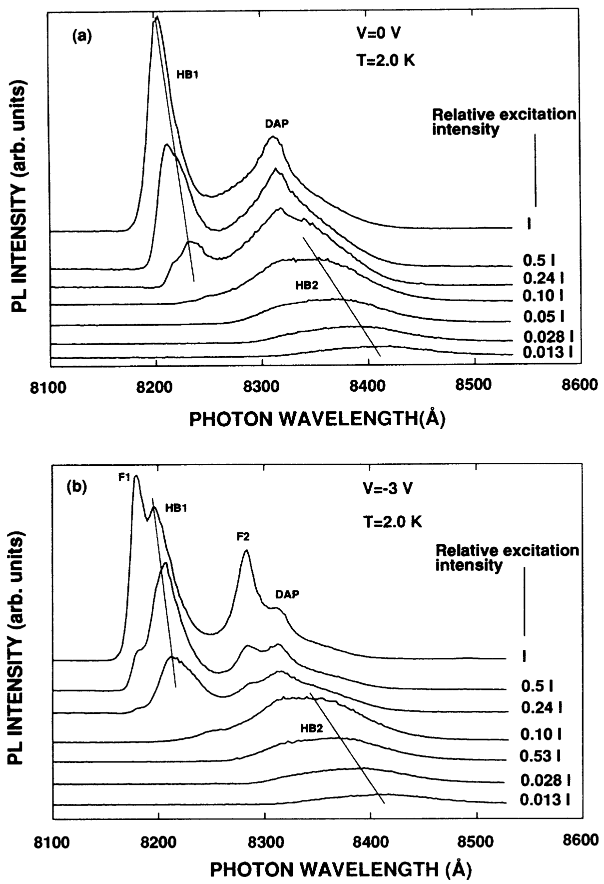

FIG. 1. PL spectra of HEM-1 measured at 2.0 K with different excitation intensities at (a) 0.0 V and (b) −3.0 V. The excitation wavelength is 5145 Å. The donor-acceptor pair (DAP) emission originates from the GaAs substrate.

GaAs layer is reduced, and the corresponding electron confinement in the notch potential decreases. Figure 1(b) shows the spectral changes at −3 V gate voltage with excitation conditions exactly as in Fig. 1(a). Comparing Figs. 1(a) and 1(b) we see that two new emissions, labeled $F1$ and $F2$, appear when the gate voltage is applied at high excitation intensity. To clearly demonstrate the influence of the gate voltage on the PL spectrum, Fig. 2 shows PL spectra with different applied electric fields. The HB1 transition shifts towards higher energy with increasing negative bias,[11] corresponding to the change in subband energy with the potential change. The intensities of the new emissions $F1$ and $F2$ with energy positions of 1.515 and 1.496 eV, respectively, increase with increasing negative gate voltage within a certain voltage region. At further increased negative gate voltages, the excitons related to the $n=2$ electron subband start to gain intensity to finally dominate the spectra (the top spectrum in Fig. 2).

Figure 3 shows the PLE spectra with detection at or close to the maximum of the HB1 emission. Two transitions related to the $n=2$ electron subband are labeled E' and E'' in Fig. 3.[13] The transition $F1$ observed in PL [see Figs. 1(b) and 2] appears also in the PLE spectra. The $F1$ transition oscillator strength is found to increase with

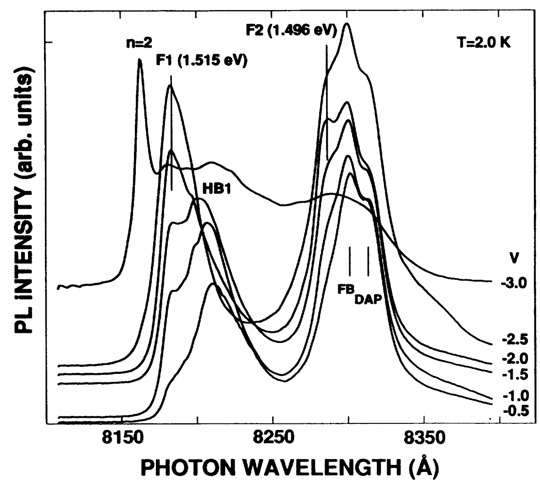

FIG. 2. PL spectra of HEM-1 measured at 2.0 K with different gate voltages. The excitation wavelength is 7900 Å. The free to bound (FB) and DAP emissions originate from the GaAs substrate. The spectra show clearly the varying intensity ratio between the HB1, $F1$, and $n=2$ exciton emissions as the Fermi level is altered by the applied field.

increasing gate voltage, similar to its behavior in PL spectra. To prove that the $F1$ emission originates from the active layer and not from the substrate, ODCR measurements of the $F1$ transition have been performed with varying angle (β) between the applied magnetic field and the sample growth direction. The cyclotron resonance peak clearly shifts towards higher magnetic fields, when the angle β increases, with a $\cos(\beta)$ dependence.[16] This fact demonstrates the 2D character for the $F1$ emission. The ODCR spectra for the peaks HB1 and $F2$ exhibit a similar 2D behavior.

To interpret the novel $F1$ transition at 1.515 eV Å as the FES related to $n=1$ subband electrons and holes in the GaAs valence band, we first have to rule out alterna-

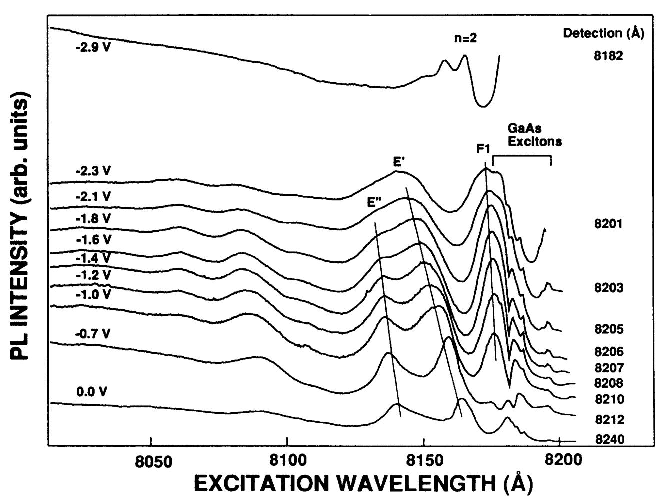

FIG. 3. PLE spectra of HEM-1 measured at 2.0 K with different gate voltages. The detection is set to a wavelength at or close to maximum intensity of HB1.

tive explanations: (1) The possibility of the free exciton in the bulk GaAs substrate can be excluded, since the ODCR of the $F1$ (and $F2$, HB1) emission shows 2D character. (2) The possibility of transitions related to different excited subbands can be ruled out purely from energy considerations. The observed energy separation between the $F1$ peak and the $n=2$ related E' peak (about 3 meV) is significantly less than expected for, e.g., the energy separation between the $n=2$ and $n=3$ states. The band structure of the heterojunction was calculated self-consistently to solve the Schrödinger equation (within the effective-mass approximation) and the Poisson equation. The exciton effects (within the single-particle approximation) were taken into account. The results show that the energy separation between the $n=2$ and $n=3$ electron subbands is larger than 9 meV in this structure. The possibility of $F1$ being related to any higher electron subband is therefore excluded. So we are left with the FES alternative. In previous studies of a one-side-doped 200-Å $Al_xGa_{1-x}As/GaAs$ QW by Chen et al.,[2] they concluded that when the separation between the Fermi energy and the unoccupied second electron subband is less than 5 meV, Fermi-edge enhancements in optical spectra occur because the nearly resonant adjacent subband allows an efficient scattering path near $k=0$ for electrons at the Fermi energy, thereby significantly increasing the optical oscillator strength for the correlated e-h pairs. According to the theoretical calculation by Mueller,[17] the Fermi-edge enhancements depend on the following: (1) the energy separation between the Fermi energy and the adjacent unoccupied electron subband; (2) the oscillator strength for optical transitions between 2D electrons and VB holes; (3) the Coulomb matrix element for electron-hole scattering between the occupied and adjacent unoccupied electron subbands. In our measurements, the separation between Fermi level and the second unoccupied electron subband can be reduced by the applied negative electric field, which in turn gives rise to an increased electron-hole scattering. Also the optical transition oscillator strength between electrons and holes will increase due to the reduced band bending across the active GaAs layer. These effects will result in an enhanced probability for the FES transition.

The second interesting feature is the $F2$ transition at 1.496 eV [Figs. 1(b) and 2]. Its intensity correlates with the $F1$ emission. We believe that the most plausible candidate would be a correspondence to the FES ($F1$) at 1.515 eV, but the hole in this case originates from an acceptor in the active GaAs layer. (The 500-Å active GaAs layer is known to contain about 1×10^{15} cm^{-3} residual C acceptors.) Its properties are then similar to HB2,[12] which is due to the transition between a hole bound at an acceptor and an electron in the first electron subband. The separation between the $F1$ and the $F2$ band is about 19 meV, i.e., similar to the separation between HB1 and HB2. The proposed interpretation of the $F2$ peak is also consistent with the 2D character evidenced in the ODCR experiments. An important consequence of this observation is that the hole localization cannot be the major factor for the optical observation of the FES, since the hole bound at acceptors and holes in the valence bands have very different degrees of localization. The FES related to holes in the VB or at acceptors should have a very different behavior, in particular as a function of temperature, if hole localization is mainly responsible for the optical observation of the FES. Our experimental results show that the two observed enhancements are correlated to each other. This fact indicates that the presence of an unoccupied electron subband near the Fermi edge is the main reason for the strong FES effects in optical spectra in this case.

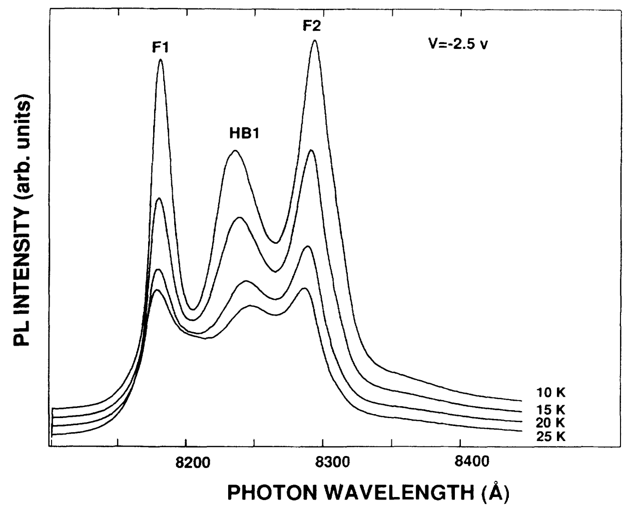

FIG. 4. The temperature dependences of the PL spectra measured on the HEM-1 sample at a gate voltage of −2.5 V. The emissions from bulk GaAs are much weaker above 10 K, so that emissions related to the 2D electron dominate the PL spectra.

The temperature dependences of the PL spectra are shown in Fig. 4. Both $F1$ and $F2$ emission intensities decrease faster than the HB1 intensity with increasing temperature. The intensity of the $F2$ peak clearly correlates with the intensity of the $F1$ peak. This fact is again consistent with the interpretation of the $F1$ and $F2$ peaks as being FES emissions. The fact that both PL bands $F1$ and $F2$ show similar ODCR spectra (negative peaks due to impact processes)[16] is also a strong support for this interpretation.

In summary we have presented an optical study of n-modulation-doped $Al_xGa_{1-x}As/GaAs$ heterostructures. Strong FES peaks related to both holes in the valence band and holes bound at acceptors are observed with applied gate voltages. The results indicate that the main reason for the observation of the FES in optical spectra is not the hole localization, rather the presence of an unoccupied adjacent electron subbands close to the Fermi edge, i.e., the nearly resonant adjacent subband allows an efficient scattering path near $k=0$ for electrons at the Fermi edge E_F in the context of electron-hole correlation.

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