Fermi-edge singularities in photoluminescence from modulation-doped GaAs quantum wells

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We have performed a detailed study of low-temperature photoluminescence (PL) from a pair of modulation-doped GaAs/$Al_xGa_{1-x}As$ multiple-quantum-well samples finding weak Fermi-edge singularities (FES's) associated with both heavy-hole and light-hole subbands. In contrast to previous experiments it appears that the presence of the FES's is not due to hole localization or the proximity of a second electronic subband. The many body enhancement above the single particle background is found to be comparable to that in systems with localized holes. The enhancement of the PL spectrum is significantly stronger than that of the absorption spectra from the same samples. Comparison with previously published data suggests that this asymmetry may be a general property of two-dimensional electron systems. [S0163-1829(97)00831-X]

The Fermi-edge singularity (FES) is a many-body enhancement of optical spectra that results from the response of a degenerate electron gas to the photocreation or annihilation of a positively charged hole. This phenomenon was first understood in simple metals where the absorption of an x-ray causes the excitation of an electron from a localized atomic core level to the Fermi level (μ) in the conduction band.[1,2]

Fermi-edge enhancement of optical spectra from a two-dimensional semiconductor system was first reported by Skolnick *et al.*[3] in photoluminescence (PL) from modulation-doped $In_xGa_{1-x}As$ quantum wells (QW's). The enhancement took the form of a large peak in the PL associated with recombination of electrons at the Fermi level. This peak was considerably stronger than the recombination due to electrons at the bottom of the conduction band, and the many-body enhancement above the single particle background was quite large (a factor of ~ 3). Over the past ten years it has become clear that the observation of the FES in PL is relatively rare, and the majority of studies have been performed using absorption or PL excitation (PLE) where the many-body enhancement above the single particle background is typically rather small. A significant outstanding problem is the lack of an understanding of the different strengths of the many-body enhancement observed in the various cases.

As in many subsequent reports a crucial factor which allowed the observation of the FES in PL in Ref. 3 was the localization of the valence band holes by a form of disorder, typically alloy fluctuations in $In_xGa_{1-x}As$ wells. This localization is important for two reasons. First, the conservation rules for optical processes require that electrons and holes have equal and opposite wave vectors (k). This requirement cannot be fulfilled for electrons at the Fermi energy ($k=k_F$) if the free holes are relaxed into states of lowest energy at the top of the valence band ($k=0$). Localized hole states, however, can be viewed as being constructed from states with a range of momenta, thus enabling PL from the vicinity of the Fermi level to be observed. Second, it has been predicted that for finite hole mass the FES in *both* PL and absorption will be smeared out over the effective bandwidth of the hole $(m_e/m_h)E_F$ leading to the destruction of the FES for even moderate Fermi energies.[4] Calculations of the absorption and emission spectra for the case of delocalized holes also predict that the FES should be washed out.[5,6] In contrast Bauer[7] argues that the FES should still be observable.

In general GaAs quantum wells will provide a cleaner system with less disorder, strain, and alloy fluctuations than $In_xGa_{1-x}As$ QW's and so the valence holes are expected to be delocalized. To our knowledge all published *absorption and PLE* spectra for modulation-doped GaAs QW's show Fermi-edge enhancement at low temperatures (see, for example, Refs. 8–14). This seems to be in contradiction with much of the above theoretical work since the holes involved in the absorption process are not obviously localized. We have previously reported FES's in the absorption spectra of the GaAs QW samples studied here, associated with both the heavy-hole (hh) and light-hole (lh) subbands.[15,16]

Despite extensive experimental studies of the optical properties of GaAs quantum wells (see Ref. 12 for a review) we are not aware of any conclusive report of the FES *in PL*, except in samples where the Fermi level lies close to an unoccupied electronic subband[17,18] (or where holes were localized by well width fluctuations[8] resulting in spectra similar to those in Ref. 3 for the $In_xGa_{1-x}As$ case). In the presence of a second subband the mechanism involved in the Fermi-edge enhancement is distinctly different to that in systems where no such additional subband is present;[17,18] our interest here is confined to systems where only the lowest conduction subband is of importance. FES's have also been reported in PL from GaAs/$Al_xGa_{1-x}As$ single heterojunction samples[19,20] but it seems to be largely unrecognized that the shallow confining potential at the heterointerface ensures

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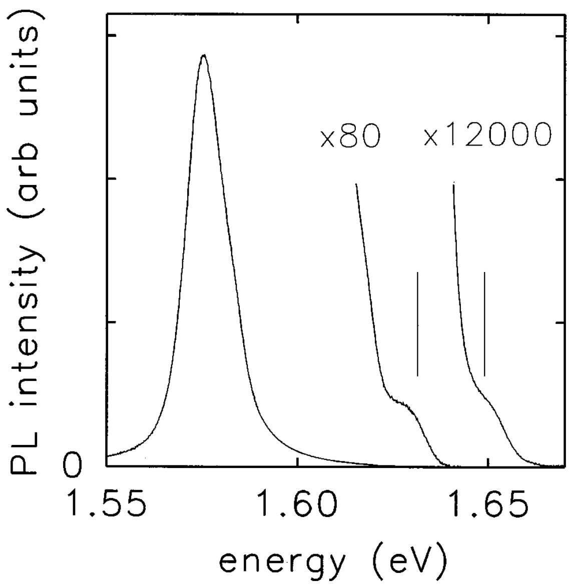

FIG. 1. PL from the $n_s = 13.5 \times 10^{11}$ cm^{-2} sample at 5 K showing weak hh and lh features associated with Fermi-edge singularities. Vertical lines mark the positions expected from the measured Stokes shifts. Note scale changes.

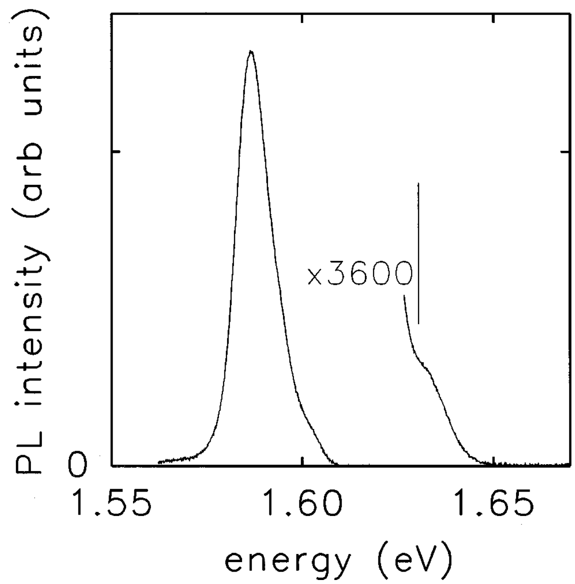

FIG. 2. PL from the $n_s = 7 \times 10^{11}$ cm^{-2} sample at 5 K showing a weak lh feature associated with a FES. A vertical line marks the position expected from the measured Stokes shift (Ref. 24). Note the scale change.

that an unoccupied subband lies close to the Fermi level. The absence of the FES in the large number of previous studies of free hole luminescence from doped GaAs QW's has been seen as evidence for the elimination of the FES by the finite hole mass.

We present here clear evidence for Fermi-edge enhancement of the PL spectrum from two modulation-doped GaAs QW samples. Enhancement is observed in the recombination of electrons at the Fermi level with both light and heavy holes. The form of the spectrum is clearly different to that when holes are localized but we show that the enhancement above the single particle background is comparable in the two cases. A weak feature similar to that reported here has been observed previously,[21] but in that case the possibility of hole localization was not addressed and the temperature dependence of the feature, which is crucial in identifying the FES, was not reported. Independent measurements of the carrier concentration are also important in assigning spectral features to the Fermi edge. Additionally in Ref. 21 the second electronic subband appears to lie only ~ 10 meV above the Fermi level in the occupied subband and it is difficult to rule out enhancement due to a weakened intersubband scattering process similar to that discussed in Refs. 17,18. In our narrow well samples the first and second electronic subbands are very well separated (by ~ 150 meV).

Our experiments were performed on a pair of MBE grown 50 period 60 Å GaAs/ 400 Å $Al_{0.3}Ga_{0.7}As$ multiple QW's. Each barrier is δ doped with Si 100 Å from the previously grown well. The larger distance (300 Å) before the next well is grown allows for some diffusion of the dopants. Standard transport measurements were used to obtain the carrier densities $n_s = 7 \times 10^{11}$ cm^{-2} and $n_s = 13.5 \times 10^{11}$ cm^{-2}. In addition, we have performed absorption measurements on samples that were chemically removed from their substrates,[22] yielding Stokes shifts between the PL peak and the half intensity point on the absorption edge[16] of 29 meV and 56 meV, respectively. These results are in good agreement with the Fermi energies derived from the transport measurements (24.5 meV and 47 meV) when dispersion of the hh subband ($E_{k=k_F} - E_{k=0} = 6$ meV and 9 meV) (Ref. 23) is taken into account.

PL was measured using a triple grating spectrometer and a cooled CCD detector. An appropriate choice of filtering on the triple spectrometer allowed weak features close to strong luminescence lines to be observed without saturation of the CCD. Excitation was provided by either an Ar^+ or tuneable Ti:sapphire laser.

Figure 1 shows PL from the $n_s = 13.5 \times 10^{11}$ cm^{-2} sample at 5 K. The main PL peak is at 1.5755 eV and there is a rapid fall off in PL intensity with weak additional structure (shown on an expanded scale) close to the energies expected for transitions from the conduction band Fermi level to the hh and lh valence bands (marked with vertical lines), i.e., the new features are shifted from the position of the main peak by the measured Stokes shifts.[24] Figure 2 shows similar weak structure for the $n_s = 7 \times 10^{11}$ cm^{-2} sample associated with transitions from the Fermi level to the lh band (again, the vertical line marks the calculated position of the feature[24]), but there is no observable structure for transitions to the hh band. Any feature associated with the hh band is obscured due to (i) the smaller Fermi energy in this sample which moves the weak hh feature closer to the strong, relatively broad, main PL peak, and (ii) the small feature in the spectrum at ~ 1.603 eV which appears to be due to a recombination of electrons and light holes near to $k = 0$. The fact that the "background" PL extrapolates to zero close to each of the features of interest is consistent with their occurrence at energies that correspond to the highest energy occupied conduction band states.

Figure 3 shows the temperature dependence of the hh feature for the $n_s = 13.5 \times 10^{11}$ cm^{-2} sample. Similar behavior is observed for the lh features for both samples. In all cases

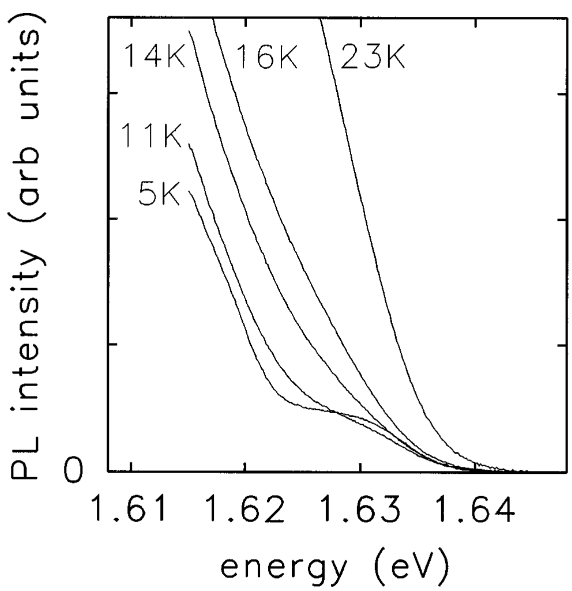

FIG. 3. Temperature dependence of the FES associated with the hh subband for the $n_s = 13.5\times10^{11}$ cm^{-2} sample. Similar temperature dependences are observed for the lh peaks in both samples.

the feature is washed out by increasing the temperature to $\sim$15–20 K: this temperature dependence is typical of the FES.[3,8,10,11,13] Note that the 11 K data shows that the enhancement is rapidly reduced, independent of the increase in PL intensity at higher energies due to the thermal smearing of the electron population close to the Fermi level.

We have also measured the effect of different excitation intensities and energies on these features. At low laser intensities each of the features is well defined (as shown in Figs. 1 and 2), but on increasing the laser power the peak weakens in a similar manner to that when the temperature is increased. There is no effect of changing the laser energy (below or above the $Al_xGa_{1-x}As$ band gap, using Ti:sapphire or Ar^+ excitation) except in so far as changes in the absorption coefficient of the sample may cause different amounts of heating for large laser powers.

As noted above, FES peaks that dominate the PL spectrum (i.e., which have strengths greater than the $k=0$ PL) have been observed previously in systems where the holes are localized. The nature of the singularity in the present case is clearly very different, e.g., in Ref. 3 the PL intensity at k_F is $\sim$3 times greater than at $k=0$, while in Fig. 1 the ratio is $\sim 1/500$. This indicates that the same localization mechanisms are not at work and it suggests that this may be the first observation of the FES in PL from systems with delocalized holes.

While the features observed here are very weak, the background PL in each case is much weaker still, and the enhancement above the single particle background appears to be quite large. To enable a comparison between spectra from samples with localized and delocalized holes, and to empirically quantify the Fermi-edge enhancement, we define $\zeta = I_{\mathrm{enhanced}}(\mu)/I_{\mathrm{unenhanced}}(\mu)$. We have fitted a decaying exponential background to the spectra near to the enhanced region to estimate $I_{\mathrm{unenhanced}}(\mu)$. If μ is defined as the energy at which the peak enhancement occurs then we obtain $\zeta\sim2$ for the $n_s = 7\times10^{11}$ cm^{-2} sample (lh peak) and $\zeta\sim3.5-4$ for the $n_s = 13.5\times10^{11}$ cm^{-2} sample (lh and hh peaks). We note that a similar enhancement ($\zeta\sim3$) can be defined for the data of Ref. 3 as in that case the high temperature data provides an estimate of $I_{\mathrm{unenhanced}}(\mu)$. PL data for $In_xGa_{1-x}As$ wells with low disorder[25] show a FES with weaker absolute magnitude but again the enhancement above an extrapolated ''background'' appears to be of order 2–3.[26] We suggest, therefore, that although the absolute strength of the FES observed here is small, the enhancement factor is comparable to that in systems with localized holes, and that the dominance of the spectrum by the FES in the case of localized holes[3] is a result of enhancement of an already large single particle background.

It is interesting to note that the values of ζ for the PL data in Figs. 1 and 2 are much larger than those estimated from absorption data for the same samples ($\zeta\sim$ 1.1).[16] In fact, for large n_s, the enhancement of the absorption edge is generally found to be small.[9–16] This asymmetry between the PL and absorption data is not expected theoretically, highlighting the need for further theoretical investigations of the role of the finite mass hole in *both* PL and absorption.

It might be argued that some form of localization is present which is necessary for the FES to be observed in the present samples. We believe that this is not the case for the following reasons. First, the qualitative differences between the spectra here and in Refs. 3,8 strongly suggest a different underlying mechanism. The PL at the position of the hh FES in Fig. 1 is $\sim$500 times weaker than the single particle background expected for localized holes (c.f. the dashed line in Fig. 1 of Ref. 3 which is for a sample with similar density but localized holes). Second, we have shown previously[15] in similar samples that the evolution with n_s of the energy position of the absorption threshold is characteristic of finite mass holes. It is highly unlikely that the absorption data from the present samples[15,16] could originate from excitation of localized holes and it is equally unlikely that the FES's in PL and absorption result from different mechanisms. Last, when the dispersion of the hh band is taken into account (as discussed above), the energy position of the FES is in each case consistent with the Stokes shift and the electron density from transport measurements, i.e., *the holes appear to have significant dispersion*.

For the FES to be observed in free hole PL it is necessary to find a hole with the correct wave vector ($k=k_F$) and it is clearly surprising that sufficient holes can be found near to k_F: in thermal equilibrium the population would be extremely small since $T\sim5$ K.[27] In other words it appears that the distribution of the valence holes is characteristic of a relatively high temperature; we estimate $T\sim50$ K for the hh's in the $n_s = 13.5\times10^{11}$ cm^{-2} sample. One factor that may well be responsible for the apparent long thermalization time for the holes at $k=k_F$ is that they have small excess energy (6, 9 meV for the hh's in the two samples) and so efficient energy loss mechanisms such as LO phonon scattering ($\delta E \gtrsim 36$ meV) are not available.[28]

In conclusion, we have observed Fermi-edge enhancement of PL involving both heavy and light holes which has a distinctly different form to that observed in the case of samples with localized holes. The qualitative differences in the spectra and the energy position of the features lead us to conclude that we have observed, for the first time, a FES in

PL from a system with delocalized holes. We suggest that the feature has not been observed previously due to low densities of valence holes at k_F rather than due to intrinsic weakness of the Fermi-edge enhancement. These results, together with previous observations of Fermi edge enhancement in absorption spectra, provide a significant theoretical challenge since, at present, there seems to be a widespead theoretical expectation that the FES should not be observed in systems with free holes.

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[24] The expected position of the lh FES is obtained by adding the lh-hh separation measured in absorption (Ref. 16) to the measured Stokes shift for the hhs.
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[26] The data in Ref. 21 also appear to be consistent with this value of ζ: in this case the feature that was attributed to the FES occurs in a regime close to the onset of an insulating phase and the importance of the localization of the valence holes is difficult to determine.
[27] Attempts to increase the population of holes using increased excitation power were unsuccessful because sample heating destroys the FES very quickly (see Fig. 3).
[28] Note that this is also true for light holes with $k \sim k_F$ since the lh-hh separation is $\sim$16–18 meV.