Fermi-energy-edge singularity in quantum wells containing more than one occupied subband

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A study of the Fermi-energy-edge singularity in asymmetric modulation-doped quantum wells is reported. It is shown that high densities of free carriers in filled $n=1$ electron subbands have no significant influence on the edge singularity in partly occupied $n=2$ subbands, demonstrating the weakness of intersubband Coulomb-scattering processes. The enhancement of oscillator strength at the Fermi energy is of very similar magnitude to that for excitonic transitions in undoped quantum wells.

Modulation-doped quantum wells (QW's) provide nearly ideal systems for the study of many-electron effects such as band-gap renormalization,[1,2] the Fermi-energy-edge singularity (FEES),[3-8] and shake-up processes.[9] The FEES is manifested at high electron density (n_s) as an enhancement of oscillator strength (the Mahan exciton[10]) for optical absorption [photoluminescence (PL)] transitions occurring just above (below) the electron Fermi level (E_F). In optical absorption, the FEES arises from the collective Coulomb interaction between the photocreated electron-hole pair and the Fermi sea of electrons.[10-14] One of the characteristic features of this many-body interaction is its very strong temperature dependence; at temperatures where the broadening ($\sim kT$) of the Fermi surface is of the order of the exciton binding energy, the spectral region of enhanced oscillator strength is strongly broadened and weakened.[11,13,14]

In the present paper, a study of the temperature dependence of the "excitonic" features occurring at E_F in both PL and PL-excitation (PLE) spectroscopy is reported in a series of asymmetric, modulation-doped $Al_yGa_{1-y}As$

($y=0.23$)-$In_xGa_{1-x}As$ ($x=0.07-0.11$)-GaAs strained-layer QW's.[15-17] The relatively wide QW's (150-250-Å width) cover the range from electron Fermi energy $\varepsilon_{Fn} = E_F - E_n$ greater than $E_2 - E_1$, the spacing between the first two ($n=1,2$) electron subbands, close to, but just less than $E_2 - E_1$, and much less than $E_2 - E_1$. This enables the effects on the oscillator strength at E_F, of high densities of carriers ($n_s \sim 10^{12}$ cm^{-2}) distributed between two subbands, to be studied.

The samples were grown[16] by molecular-beam epitaxy and consisted of the following layers grown on a semi-insulating GaAs substrate: 1-μm undoped GaAs, $In_xGa_{1-x}As$ quantum well (thickness d), undoped $Al_yGa_{1-y}As$ ($y=0.23$) spacer (thickness w_1), $Al_yGa_{1-y}As$ doped region (thickness w_2, doping level n_2), and GaAs capping layer (w_3,n_3). Details are given in Table I, together with (E_2-E_1) and E_F values determined from magneto-PL and Shubnikov–de Haas (SdH) studies.[18] PL and PLE were carried out from 2 to 50 K, in the low-intensity limit using ~ 10 mW/cm^2 of radiation from a Styryl 9 dye laser, and detected using a Ge photo-

TABLE I. Sample details.

Sample	d (Å)	w_1 (Å)	w_2 (Å)	n_2 (cm^{-3})	w_3 (Å)	n_3 (cm^{-3})	E_F-E_1 (meV)	E_2-E_1 (meV)	x
A	250	100	250	1.5×10^{18}	200	1×10^{14}	30.5	27.0	0.10(5)
B	200	40	400	1×10^{18}	100	2×10^{18}	34.0	34.5	0.07(5)
C	150	100	250	1.5×10^{18}	200	1×10^{14}	27.5	43.0	0.09(0)

diode or GaAs photomultiplier.

The PL spectrum (2 K) for sample A is shown in Fig. 1 (dotted curve). It consists of two bands, labeled E_{21} and E_{11}, arising from recombination of $n=2$ and 1 electrons, respectively, with holes in the $n=1$ valence subband. This sample with $d=250$ Å has $E_2-E_1=27.0$ meV, and $\varepsilon_{F1}=30.5$ meV, so that E_F resides 3.5 meV ($n=2$ density n_s^2 of 1×10^{11} cm^{-2}) above the bottom of the $n=2$ subband. E_{21} shows Landau-level (LL) splitting in magnetic field, characteristic of an ε_{F2} of 3.5 meV.[18]

The peak height for E_{21} transitions is 22 times greater than that for E_{11}. The principal reason is the much greater overlap for electrons in the $n=2$ subband with $n=1$ valence-band holes, than for those in $n=1$. The inset to Fig. 1 shows the band-edge profiles, and $n=2$ and 1 wave functions (ψ_2^e, ψ_1^e, and ψ_1^h), obtained from a self-consistent (Hartree) solution of Poisson's and Schrödinger's equation. The band-bending potential in these wide QW's causes a strong modification of the wave functions compared to $n_s=0$, and leads to very marked changes in the oscillator strengths for interband transitions.[2,15,17,19] ψ_1^e is well-confined towards the Al_y-$Ga_{1-y}As$-$In_xGa_{1-x}As$ interface whereas ψ_2^e is much more extended, but with larger amplitude towards the $In_xGa_{1-x}As$-GaAs interface. ψ_1^h is strongly confined towards the $In_xGa_{1-x}As$-GaAs interface. Using the wave functions shown in the inset to Fig. 1, a ratio (r_c) of 11 is calculated for the electron-hole overlap integrals squared for the E_{21} to E_{11} transitions, as compared to the experimental ratio (r_e) of intensities of 22.[20]

Such a calculation allows an estimate to be made for the magnitude of any excitonic enhancement of the E_{21} oscillator strength. Since E_{21} transitions occur close to the Fermi energy (<3 meV), a marked enhancement of oscillator strength is expected. For E_{11} transitions excitonic interactions are expected to be very weak. The E_{11} recombination peaks at the bottom of the band, since the
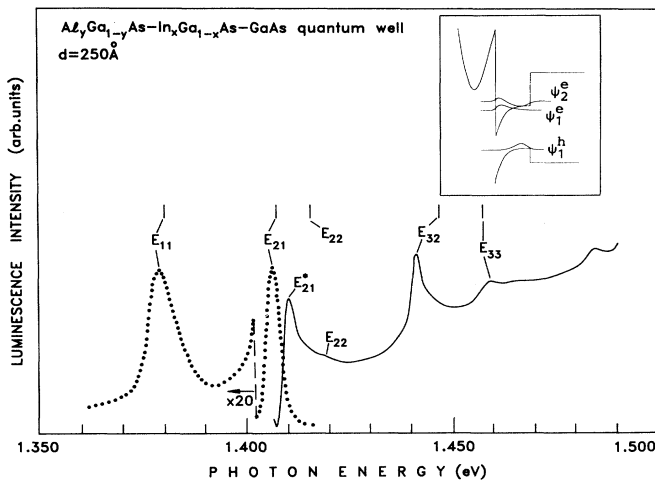

FIG. 1. PL (dotted) and PLE (solid line) spectra for sample A ($d=250$ Å) at 2 K. The PL spectrum is composed of E_{11} and E_{21} recombination bands. In PLE, E_{21}^*, E_{22}, E_{32}, and E_{33} absorption features are observed. The vertical lines above the spectrum are theoretical energies. Inset: self-consistent quantum well potential and wave functions.

only transitions allowed by wave-vector conservation arise for electrons at $E_1\approx0$ ($k=0$), as expected for a QW with weak disorder.[3,14] For the excitonic interaction to take place electron-hole scattering processes must occur into empty electron states. The only unoccupied electron states are above E_F, thus leading to very weak excitonic effects for the $k\approx0$ E_{11} transitions, which are also weak due to the small ψ_1^e,ψ_1^h overlap.

Comparison of the experimental ($r_e=22$) and theoretical ($r_c=11$) ratios leads to a value for the excitonic enhancement of E_{21} transitions of ~2 (±0.6).[20] This is a very reasonable value for the magnitude of excitonic effects, and is close to that found in absorption experiments on 250-Å undoped QW's having similar exciton linewidths (3.5 meV).[21] This conclusion is supported by the PLE, where possible complications due to population effects are eliminated. We have obtained similar values for the excitonic enhancement for E_{21} transitions in a variety of asymmetric QW's. We find no evidence for anomalous enhancements of oscillator strengths at E_F, as reported in finite magnetic fields,[17] so long as the dominant effects of the band-bending potential on the wave functions are taken into account.

The PLE spectrum for sample A is shown by the solid curve in Fig. 1. It consists of a sharp "excitonic" peak at E_F (labeled E_{21}^*) corresponding to transitions into empty states in the $n=2$ subband. Transitions between higher subbands are also observed. The vertical lines (marked E_{11}, E_{21}, etc.) are calculated transition energies (as in Figs. 3 and 4). They are in good agreement with experiment, further supporting the calculations of the oscillator strengths. The x values of the $In_xGa_{1-x}As$ are fitting parameters (see Table I) in the transition-energy calculations, after allowance of 15 meV for the band-gap renormalization at $n_s=9\times10^{11}$ cm^{-2}.[2] The excitonic peak at E_{21}^* is enhanced by a factor of ~2 relative to its continuum, in agreement with the deduction of ~2 enhancement from the comparison of the E_{21},E_{11} PL intensities.

The temperature dependence of the PL (E_{21} only) and PLE for sample A at 2, 21, and 38 K is shown in Figs. 2(a)–2(c). At 2 K [Fig. 2(a)] the PL shows the asymmetric line shape characteristic of an $\varepsilon_F=3.5$ meV. With increasing temperature [Figs. 2(b) and 2(c)] this broadens to higher energy showing the Boltzmann tail expected at 21 and 38 K, respectively. The PLE spectra for E_{21}^* show a very strong temperature dependence. The sharp E_{21}^* feature at 2 K (full width at half maximum 3.3 meV) is strongly broadened at 21 K (width 11 meV) and is visible only weakly at 38 K.

This behavior is characteristic of excitonic features at E_F (FEES) and arises when the thermal excitations ($\sim kT$) are of the same order as the Coulomb interaction energy between the photoexcited electron-hole pair and the Fermi sea of electrons.[11,13,14] The Coulomb interaction energy is expected to be of the order of the exciton binding energy, ~5 meV for the present wide $In_{0.1}$-$Ga_{0.9}As$ QW.[22] By contrast the exciton feature E_{32}, ~30 meV above E_F broadened only by LO phonon ionization processes, shows very little temperature dependence, in agreement with previous studies.[4-6] The present results show that a very strong temperature dependence of the ex-
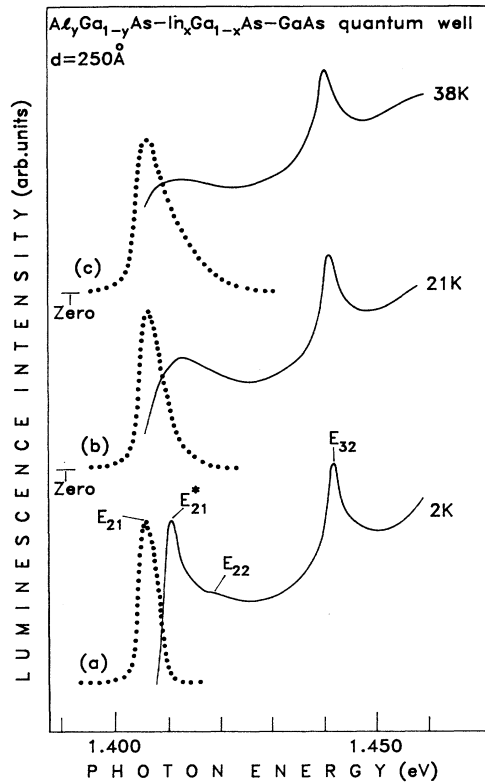
FIG. 2. Temperature dependence of PL (dotted) and PLE (solid line) spectra for sample A at 2, 21, and 38 K in (a), (b), and (c). The presence of 1×10^{11} cm^{-2} free carriers in the $n=2$ electron subband gives rise to the very strong temperature dependence of the E_{21}^{*} feature at E_F.
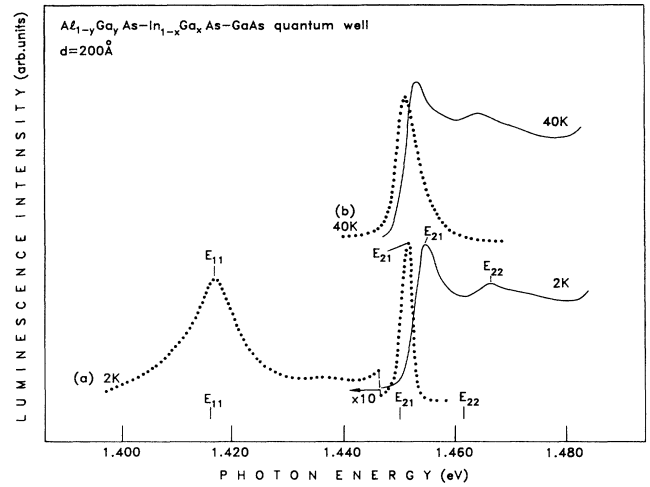

FIG. 3. PL (dotted) and PLE (solid line) spectra for sample B ($d=200$ Å) at 2 and 40 K [(a) and (b)]. In contrast to Fig. 2 the excitonic feature close to E_F (E_{21}) shows very little temperature dependence, due to the very small carrier density ($< 3 \times 10^{10}$ cm^{-2}) in the $n=2$ subband.

only carriers in the subband where the excitonic peak occurs contribute to the quenching of the enhancement at elevated temperature. The presence of carriers at *nearly the same energy* in the $n=1$ subband has little or no effect on the temperature dependence of the excitonic peak observed for transitions into the $n=2$ subband. This arises since the carriers at E_F in $n=1$ have a large wave vector
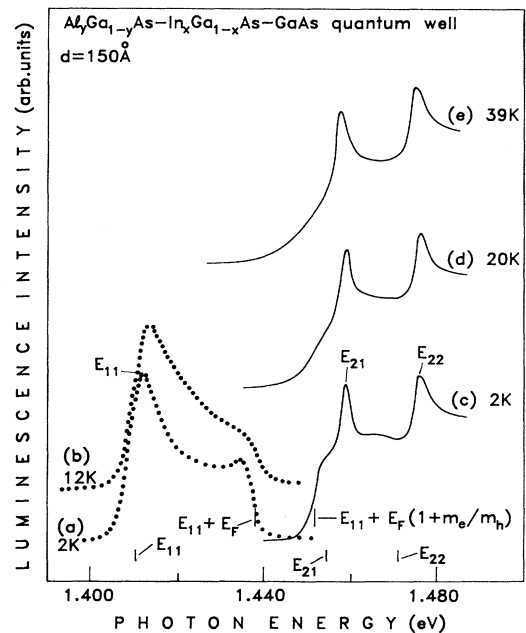
citonic feature at E_F is obtained even for a Fermi energy in the $n=2$ subband of only 3.5 meV, consistent with the results of Ref. 6 for a populated $n=1$ subband.

Figure 3(a) shows the 2-K PL and PLE for the 200-Å-wide sample B, where E_F resides close to the bottom of E_2 (within ± 1 meV, Table I). Both E_{21} and E_{11} PL is observed, although in this case no LL splitting, or narrowing, of E_{21} is observed in magnetic field, allowing an *upper* limit of ~ 1.0 meV to be placed on ε_{F2} ($n_s^2 \leq 3 \times 10^{10}$ cm^{-2}), in $n=2$. Even though the population of E_2 is small, E_{21} is observed with its full oscillator strength relative to E_{11}; increasing the laser power by an order of magnitude causes no detectable change in the value of r_e of 13. This compares with a calculated ratio of $r_c = 5.8$, and leads to a deduced value of 2.2 for the excitonic enhancement of the E_{21} peak, close to that found for sample A. The analysis is strongly supported by the fact that the decreasing trend in r_e with decreasing well width is well accounted for by the r_c calculations (i.e., $r_e = 22,13$ and $r_c = 11,5.8$ for the 250- and 200-Å QW's, respectively).

The PLE spectrum [Fig. 3(b)] at 40 K shows little change relative to its form at 2 K. A small decrease of the enhancement at E_{21} of ~ 0.7 is observed from 2 to 40 K in very marked contrast to sample A ($n_s^1 = 7.8 \times 10^{11}$ cm^{-2}, $n_s^2 = 1 \times 10^{11}$ cm^{-2}; sample B, $n_s^1 = 9.8 \times 10^{11}$ cm^{-2}, $n_s^2 \leq 3 \times 10^{10}$ cm^{-2}) where excitonic effects at E_{21} are barely visible at 40 K.[23] This demonstrates clearly that

FIG. 4. PL (dotted) and PLE (solid line) spectra for sample C ($d=150$ Å). PL from the $n=1$ electron subband only is observed ($E_F = 27.5$ meV, $E_2 - E_1 = 43$ meV). The very weak enhancement at $E_{11} + E_F(1 + m_e/m_h)$ observed in (a) (2 K) has been quenched by (b) 12 K.

$(k_F \sim 2.5 \times 10^6 \text{ cm}^{-1})$ and so will be coupled only weakly by the Coulomb interaction to the $n=2$ states at $k \approx 0$ which contribute to the observed transition. This contrasts with the $n=2$ electrons which can couple to the photo-excited electron-hole pair by a scattering process across E_F with almost no change in k. The intersubband coupling will also be reduced by the orthogonality of the $n=2,1$ wave functions.[24]

In Fig. 4(a) the 2-K PL spectrum for sample C ($d=150$ Å) is shown. E_F is 15.5 meV below E_2 (Table I), and only E_{11} PL is observed. This spectrum is taken with photomultiplier tube (PMT) detection which enhances features at E_F (1.437 eV) by a factor of 10 compared to PL at the bottom of the band, due to the decreasing PMT response to lower energy. The PL spectra in Figs. 1, 3, and 4 are taken with the Ge detector whose response is flat over the region of interest. The PL spectrum in Fig. 4(a) peaks at E_{11} and decreases towards E_F. A small enhancement is observed at E_F before decreasing abruptly to higher energy. This weak enhancement is ascribed to a FEES (a similar, very weak effect was seen in Ref. 15). The degree of disorder (or hole localization) is just sufficiently great to permit observation of an enhancement at E_F.[3,14] In accordance with the very weak enhancement, and hence very weak "binding energy," it is extremely temperature sensitive. Raising the temperature

to only 12 K [Fig. 4(b)] removes the enhancement, consistent with a binding energy of only ~ 1.5 meV. PLE spectra at 2, 20, and 39 K are shown in Figs. 4(c)–4(e), respectively. The onset of PLE is upshifted by $\Delta E = 12 \pm 0.5$ meV above E_F in PL, due to the requirement for k conservation in absorption.[2,6,7] $\Delta E = (m_e/m_h)E_F = 12.5$ meV for $m_e = 0.068 m_o$ and $m_h = 0.15 m_o$,[25] in good agreement with experiment. An excitonic peak is not observed in PLE at $E_{11} + E_F(1 + m_e/m_h)$, due to broadening by indirect transitions at large k_F^e.[6,12,14] With increasing temperature the E_{11} PL transitions show the expected broadening of the Fermi level, having a width of ~ 2 kT (8 meV) at 39 K [Fig. 4(e)].

In conclusion, the temperature dependence of the Fermi-energy-edge singularities in QW's containing more than one populated subband has been shown to be controlled by the carrier density in the subband in which the excitonic enhancement occurs. This is consistent with the relatively weak Coulomb coupling of states of widely differing wave vector. The strength of the excitonic enhancement at E_F in structures with low electron density in the $n=2$ subband is of similar magnitude to that found for excitonic transitions in undoped QW's.

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[20]r_c is a very sensitive function of well width and carrier density. For example, for $d=275$ Å, $E_F = 27.8$ meV, r_c is increased to 13.4 ($r_c = 11.3$ at $d=250$ Å, $E_F = 31.2$ meV), whereas for $E_F = 27.8$ meV and $d=250$ Å, $r_c = 8$. Thus, the r_c values should be considered to have an uncertainty of $\approx \pm 30\%$.

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