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Fermi-edge singularity in heavily doped GaAs multiple quantum wells

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The absorption enhancement at the Fermi level of n-type modulation-doped multiple quantum wells is studied with photoluminescence excitation spectroscopy. We show that the limit of the pure Fermi-edge singularity (i.e., correlation between the sea of electrons and single holes), where no remnants of the band-edge exciton (correlation between single electrons and holes) are left, is only reached for the case of heavy doping ($n = 1.2\times10^{12}$ cm^{-2}). A direct comparison between experiments and available many-body theories is only valid in this limit. We find both quantitative as well as qualitative deviations from these theories. Previously neglected broadening mechanisms significantly reduce the enhancement effects. We report for the first time the dependence of the enhancement on the density of the photoexcited holes.

The optical properties of multiple-quantum-well structures (MQWS's) are largely influenced by correlation effects between charged carriers.[1,2] The correlation results from the rearrangements in the electron and hole systems in order to screen the Coulomb interaction. The result is a strong enhancement of the oscillator strength with respect to simple band-to-band transitions due to excitonic bound and continuum states. The band-edge exciton and the Fermi-edge singularity (FES) represent the limits of the correlation effects for low and high carrier densities, respectively. Band-edge excitons are formed by single electrons and holes. They have a hydrogenlike excitation spectrum. With increasing carrier density the excitons gradually unbind and the single-particle energies renormalize.[3] An enhancement of the oscillator strength, however, still prevails as a result of multiple scattering of electrons and holes close to the Fermi edge.[1,4] This so-called Fermi-edge singularity or Mahan exciton arises in n-type modulation-doped quantum wells (n-type MDQW's) from the correlation between a photoexcited hole and the sea of electrons in the wells.

The FES has been observed in $In_xGa_{1-x}As$/InP MQWS's,[5] in $In_xGa_{1-x}As/In_xAl_{1-x}As$-$n$-type MDQW's,[6] and $GaAs/Al_xGa_{1-x}As$ n-type MDQW's.[7-9] The holes need to be localized to detect the FES in the luminescence of highly excited, undoped MQWS's.[5] This restriction holds because a significant amount of holes, which have the same k vector as the electrons right at the Fermi level, are required in the recombination process. This localization is not needed in absorption[8] or photoluminescence excitation spectroscopy (PLE) (Ref. 6) of MDQW's. Only rather poor agreement, however, is found between the results in n-type MDQW's and many-body theories.[1,8] The predicted effect in undoped $GaAs/Al_xGa_{1-x}As$ MQWS's (Ref. 1) has not yet been observed.

We have studied a variety of n-type MDQW's and p-type MDQW's with different doping levels by PLE. We focus in this paper on the results in a heavily doped n-type MDQW. The correlation effects in this sample represent the limit of the pure Fermi-edge singularity. A direct comparison between experiment and the available many-body theories is only possible in this limit. Damping mechanisms neglected in the theories lead to strong reductions of the correlation enhancement even far away from the Fermi edge. We show for the first time that the FES strongly depends on the density of photoexcited holes.

The sample consists of ten GaAs wells with a width of 9 nm sandwiched between 35-nm-thick $Al_{0.34}Ga_{0.66}As$ barriers. The central 9 nm of each barrier is Si doped. The doping level has been determined by Hall measurements to be $n = 1.2\times10^{12}$ cm^{-2}. The lattice temperature can be tuned in a He cryostat between 5 and 300 K. For the photoexcitation we use a synchronously pumped dye laser with a repetition rate of 80 MHz and a temporal pulse width of 6 ps. This excitation source allows us to perform PLE at both low (10^9 cm^{-2}) and high (10^{12} cm^{-2}) densities of photoexcited electron-hole pairs. The highest possible excitation density is determined from a line-shape fit[10] to the luminescence spectrum of an undoped reference sample of the same well width to be $n = p = 1.4\times10^{12}$ cm^{-2}. The PLE signal is recorded time integrated by a photon counter coupled to a double monochromator. The detection wavelength can be chosen close to the maximum of the luminescence signal (1.549 eV) due to a large Stokes shift of the latter with respect to the absorption edge. The PLE spectrum is independent of the detection wavelength for heavily doped MDQW's.

The temperature dependence of the PLE spectra in the heavily doped sample for low excitation is depicted in Fig. 1. Two steps related to the transitions to the $n_z = 1$ (at 1.6 eV) and $n_z = 2$ subband (at 1.7 eV) in the conduction band are observed. Strong excitonic enhancement of the absorption is found at both steps. The temperature dependence of the spectra, however, shows that the character of the enhancement mechanisms is different. The peak at the $n_z = 2$ step broadens only slightly with increasing temperature, as is typical for a band-edge exciton resonance.[2] In contrast, the $n_z = 1$ peak[11] vanishes almost completely for increasing temperature. This behavior resembles the theoretically expected characteristics of the Fermi-edge singularity.[1,8]

The complete removal of the FES peak is only observed at this high doping level. In n- and p-type samples with

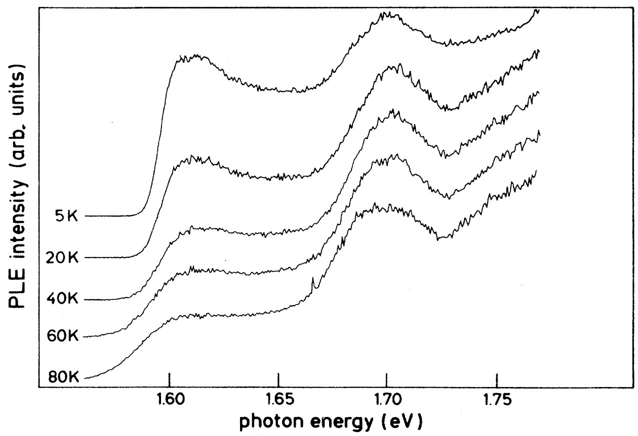

FIG. 1. Low-excitation PLE spectra as a function of lattice temperature. The curves are normalized to equal height above 1.72 eV.

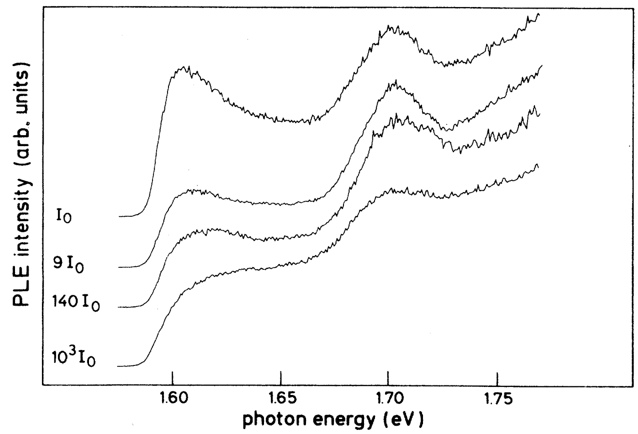

FIG. 2. PLE signal at various excitation levels ($10^3 I_0$ corresponds to a density of photoexcited carriers of 1.4×10^{12} cm^{-2}). The curves are normalized, except for $10^3 I_0$.

densities of 6×10^{11} cm^{-2} or less, a significant enhancement remains up to room temperature. Due to the smooth transition between the two extrema of the screening process, significant contributions with the character of the band-edge exciton are present in the spectra for MDQW's with lower doping. This is evident, e.g., in Fig. 5 of Ref. 8. A direct comparison of these spectra with calculations in the FES limit is thus questionable. Control measurements in these MDQW's and also undoped MQWS's prove that the observed behavior of the heavily doped n-type MDQW is not an artifact of the PLE method. We conclude that *the limit of the Fermi-edge singularity is reached only at high doping levels.*

The enhancement at the Fermi edge can also be removed completely when the density of photoexcited carriers is increased (Fig. 2). The absorption enhancement is already strongly affected for excitation densities which are 2 *orders of magnitude less* than the density of the electron gas (see spectrum for $9I_0$ in Fig. 2). In comparison to the lowest excitation (I_0), the number of electrons has not changed significantly, but the number of holes has increased by almost 1 order of magnitude. The strong reduction of the enhancement is thus caused by the comparatively low density of photoexcited holes. These measurements are the first which directly show the influence of the holes on the FES in n-type MDQW's. A significant decrease of the PLE signal is found even in the region of the first plateau above the FES peak. This reduction of the enhancement, which is also observed in the temperature dependence (Fig. 1), is not predicted by theory.[1,8]

We now extract the enhancement factor from our measurements and compare it to available many-body calculations. We first construct a simple model to describe the PLE spectrum without correlation enhancement. The theoretical spectrum is given by $D_0(E)[1-f_e(E)]$ where $D_0(E)$ is a step function starting at the band-gap energy E_g and $f_e(E)$ is the Fermi function of the electron gas. The temperature used in the Fermi function is adjusted to fit the slope of the experimental spectra at the Fermi level. The height of the plateau in the spectrum at 80 K is taken as a reference level for the step function for the following reason. The temperature dependence in Fig. 1 shows that the level of the first plateau decreases strongly when raising the temperature from 5 to 20 K. This decrease, however, levels off around 60 K and disappears for further increase of T. This effect is much less pronounced in MDQW's with lower doping and not found in undoped MQWS's. In the latter case, i.e., in the limit of band-edge excitons, the relative height of the $n_z=1$ and 2 steps is constant in this temperature regime. The relative decrease of the $n_z=1$ plateau in the MDQW, when the PLE spectrum is normalized to the region above the $n_z=2$ exciton, results from the reduction of the correlation at the Fermi edge. The remaining enhancement in the spectrum at $T=80$ K is negligible, which makes this spectrum suitable as a reference. The enhancement factor is then extracted from the difference between experiment and model (Fig. 3). A maximum enhancement factor of 2.4 is found at low temperature. The strong dependence of the enhancement on T not only at its peak but also at the plateau is evident.

Our experimental peak values are considerably smaller and the widths of the enhancement curves broader than expected from many-body calculations.[1,8] When we scale the results of Refs. 1 and 8 to the sheet electron density in our sample we find theoretical values of about 15 and 5, respectively, for the maximum of the enhancement. The width of the curves are E_0 and $1.5E_0$. The use of realistic quantum-well parameters in the theory[12] largely reduces the discrepancy for the peak values but not for the width of the enhancement. None of these theoretical models, however, describes the decrease of oscillator strength in the region of the plateau as it is found in our experiment. We will give evidence here that these deviations are due to the neglect of any homogeneous broadening mechanism in the theory.

Only little information is available on homogeneous broadening in MQWS's. Some properties of bulk materials,[13] however, can be applied. The damping due to carrier-carrier scattering was shown to have a minimum right at the Fermi energy but rapidly increases for energies above E_F.[13] Especially in the case of electron densities in excess of 10^{11} cm^{-2} nonequilibrium electrons, as are created in the absorption or PLE measurements, should be rapidly scattered out of their initial states. At low temperatures, this interaction with the electron gas should occur on the time scale of some 100 fs and thus lead to a significant state broadening. This damping increases with rising temperature due to the increasing scattering possibilities within the electron gas. Thermalization of excess photoexcited carriers was found to be extremely fast (<10 fs) in n-type MDQW's at room temperature.[14] The broadening of the hole levels should be small in the low excitation range. Hole-hole scattering is slow for densities of 10^9 cm^{-2} and the interaction with electrons is predominantly elastic due to the large mass difference. The broadening gets important for the hole states when the hole density is increased. It was shown in Monte Carlo simulations that at room-temperature relaxation for holes is faster than for electrons.[15]

Homogeneous broadening should drastically reduce the absorption enhancement, similar to the effect of the spread of the carrier distribution with increasing temperature. The latter process only affects the region close to the Fermi edge while the broadening increases with increasing energy above E_F. This is consistent with the observed temperature dependence of the first plateau, a feature that is not present in the theories[1,8,12] which do not include damping. Reducing the temperature freezes out the damping due to carrier-carrier scattering and the enhancement at the plateau recovers (Fig. 3). Further, the strong density dependence (see Fig. 2) of the FES is not expected from the available theories.[1,8,12] With increasing density the enhancement is removed gradually by phase-space filling. The density in the experiment, however, was only changed by a small fraction of the density in the electron gas (compare I_0 and $9I_0$). An effect due to the phase-space filling is not likely in this case. The density of photoexcited holes, however, was increased by almost 1 order of magnitude and reaches a level where carrier-carrier scattering gets important.

We conclude that the discrepancies between theory and experiment can be removed when damping is included in the calculations. This, however, is a complex problem, partly because little information is available on broadening effects in MQWS's. Finally, the observed importance of damping can explain the failure to resolve the FES in the luminescence of undoped MQWS's where the holes are not localized. These experiments are typically performed at conditions where the hole distribution is not degenerate. The carrier densities, however, are large enough for significant broadening of the hole states at k vectors corresponding to the k vector at the electron Fermi level. The effect of the FES is then, as shown above, suppressed.

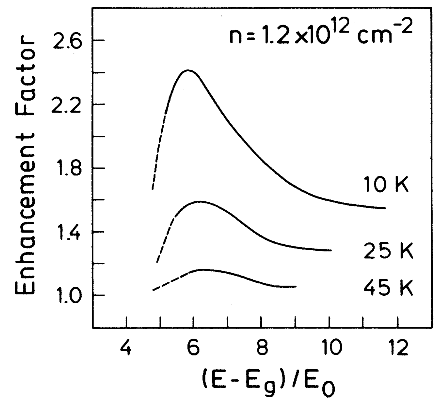

FIG. 3. Enhancement factor for low excitation density. The listed effective temperatures are extracted from the model (see text). An excitonic binding energy of $E_0 = 10$ meV is assumed.

In summary, the enhancement of the oscillator strength in n-type MDQW's is studied by PLE in the limit of the Fermi-edge singularity. This allows us to directly compare the experimental results to available many-body theories. Broadening mechanism due to carrier-carrier scattering are found to significantly reduce the enhancement. The FES is removed with increasing density of photoexcited holes due to damping rather than phase-space filling.

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