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FERMI-EDGE SINGULARITY IN EXCITONIC SPECTRA OF MODULATION DOPED AlGaAs/GaAs QUANTUM WELLS

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The dynamic response of an electron Fermi sea to the presence of optically generated holes gives rise to an enhanced interaction of correlated electron–hole pairs near the Fermi level, resulting in an enhanced oscillator strength for optical transitions, referred to as the Fermi-edge singularity. We studied this effect in modulation-doped quantum wells which provide confined dense Fermi sea, spatially separated from dopant atoms, easily accessible for investigations under low excitation conditions. The Fermi-edge singularity was observed in both photoluminescence and photoluminescence excitation experiments, although in the case of photoluminescence the samples had to be either co-doped with acceptors in the wells to provide necessary localization of holes or designed to allow for nearly resonant scattering between the electronic states near the Fermi energy and the next unoccupied subband of the 2D electron gas.

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The one-component plasmas, i.e., plasmas consisting predominantly of electrons or holes provide an easy way to study many-body interactions in semiconductors. Such situations are achieved by heavy doping of semiconductor materials beyond the metallic limit. Optical studies of the many-body phenomena involve the generation of additional electron–hole pairs, usually in concentrations much smaller than that of electron or hole plasma. For, let us say, n-type material the number of electrons remains practically unchanged in such situation, whereas the number of holes is determined by optical excitation. The holes then display some correlation effects, while the exchange effects are negligible unless very high excitation intensities are reached. Additional large contributions to the screening and renormalization effects arise from the interaction of the free carriers and the ionized impurities. A clear cut situation arises when the free carriers are spatially separated from the parent impurities. Such a separation can be realized in 2D modulation doped structures where the dopant atoms are localized in the barriers and the free carriers are spatially confined in a quantum well [1].

The many-body properties of 2D one-component plasmas are reflected in their optical spectra. In particular, the singularity of the optical spectra at the Fermi edge has been observed [2,3]. The Fermi-edge singularity (FES) or Mahan exciton [4] arises in n-type modulation doped quantum wells from the correlation between a photo-excited hole and the sea of electrons in the quantum well. Since the only electrons which can contribute to the screening of the positive hole charge are those close to the Fermi surface (no scattering can occur to the filled states with $k < k_F$) the strong enhancement of the oscillator strength of excitonic transitions close to the Fermi level is expected.

The investigated samples were high quality modulation doped $Al_{0.3}Ga_{0.7}As/GaAs/Al_{0.3}Ga_{0.7}As$ quantum wells grown by molecular beam epitaxy (MBE) on GaAs substrates. The samples consisted of the 100 Å wells sandwiched between 1300 Å thick, doped barriers. The sections of the length of 200 Å separated by 100 Å from the edge of the well were doped with Si to the concentration 10^{18} cm^{-3} (sample #162.96) and 10^{17} cm^{-3} (sample #163.96). The samples co-doped with Be acceptors in the well were also investigated.

Photoluminescence (PL) and photoluminescence excitation (PLE) measurements were performed in the temperature range 2–300 K using an argon laser or Ti-sapphire laser as the excitation source.

The optical absorption transitions in n-type modulation doped quantum wells (MDQW) are momentum conserving and due to the filling of the conduction band start at the energies higher than the band gap. On the other hand, the emission starts at the energy equal to the effective band gap (ε_g) and extends to higher energies as far as the spread of hole k-vector allows. Thus, there is always energy shift between PL and PLE spectra. In the parabolic approximation Fermi energy E_F is related to the low energy onsets of absorption (ε_F) and emission (ε_g) by: $E_F = (\varepsilon_F - \varepsilon_g)(1 + m_e/m_h)^{-1}$, where m_e/m_h is the effective mass ratio for the bands considered. Knowing the density of 2D electron gas in MDQW from the Shubnikov–de Haas (SdH) oscillations one can calculate the Fermi wave vector $k_F = (2\pi n_s)^{1/2}$ and the resulting Fermi energy $E_F = (\hbar\pi/m_e)n_s$. We have found an excellent agreement between the calculated and experimental values of E_F determined from PL and PLE spectra.

The low temperature PL spectrum for the sample #162.96 is shown in Fig. 1. The spectrum spreads over wide energy range and in contrast to undoped reference sample shows two well defined peaks separated by 81.6 meV. As the temperature increases, the Fermi level is broadened and the high energy peak gradually disappears although it is still visible at 77 K (see Fig. 2). A very improbable, non-thermalized electron distribution would have been needed to account for observed shape of PL spectrum if only vertical k-conserving transitions between electron and holes occurred. On the other hand, an abrupt cut-off at the Fermi energy shows that the carrier temperature must be low.

To account for apparently indirect transitions violating k-selection rule we invoke the following possible mechanism. At sufficiently small separation between

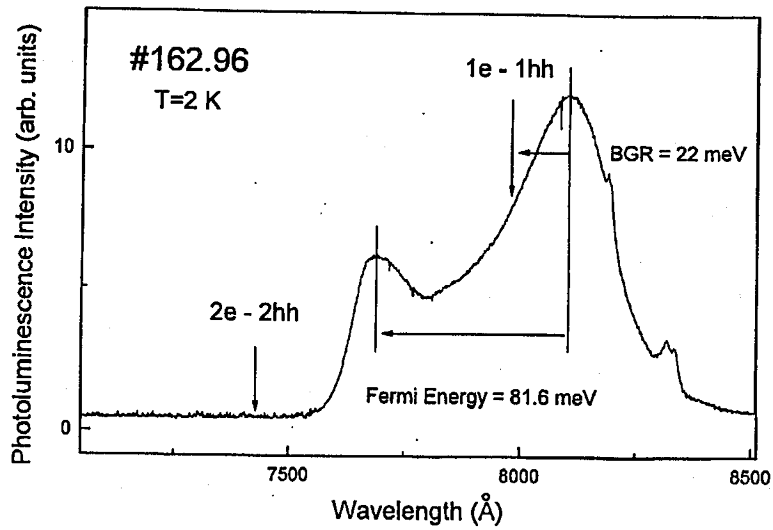

Fig. 1. PL spectrum from modulation doped quantum well of the thickness $L = 100$ Å. The spectrum shows the strong enhancement towards the Fermi energy E_F.

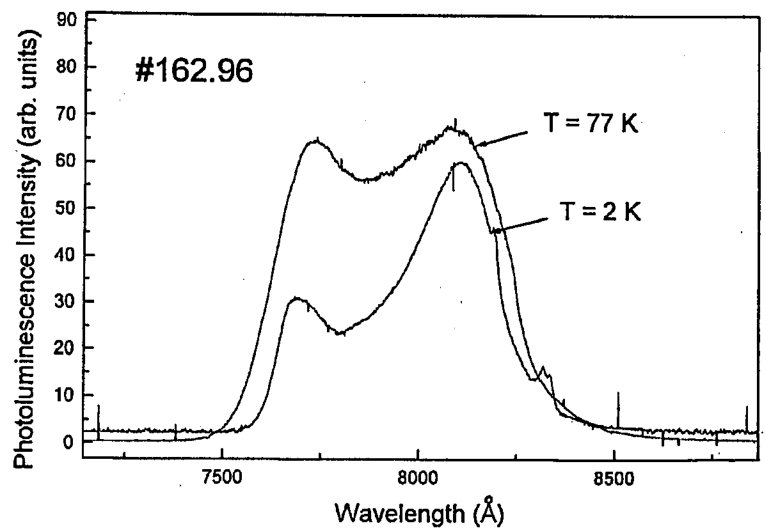

Fig. 2. Temperature dependence of PL spectrum for the 100 Å thick $Al_{0.3}Ga_{0.7}As/GaAs/Al_{0.3}Ga_{0.7}As$ MDQW.

E_F and the next electron subband ($n = 2$) an efficient scattering path near $k = 0$ is available for electrons at the Fermi energy. This can be observed in photoluminescence as an enhancement of many-body excitonic transitions at the high energy side of the emission line. Thus the access to an efficient scattering path for the electrons at the Fermi energy allows for observation of the Fermi-edge singularity in excitonic spectra despite the lack of localization mechanism of the holes (lack of acceptors or interface scattering providing momentum conservation). Although the separation of two peaks seen in PL spectrum shown in Fig. 1 is a simple function of 2D electron density n_s, the absolute position of the spectrum is not. It is indeed down shifted with respect to the undoped reference sample due to the band gap renormalization resulting from exchange interaction between electrons. The amount of band gap reduction has been estimated for 22 meV and is in agreement with local-density approximation (LDA) calculations [5]. In the narrower quantum wells for which the separation between $n = 1$ and $n = 2$ electronic subbands is higher the above described three-band mechanism [6] relying on the resonant transitions from the Fermi edge into the $n = 2$ exciton states is no longer operating and to observe Fermi edge enhancement of excitonic spectra we had to co-dope the samples with Be acceptors in the well. The localization of holes at the acceptors provided necessary spread of their wave vectors and k-conserving transitions were possible for $k \neq 0$, although in this case Fermi-edge singularity was much less pronounced.

In conclusion, we have observed the FES from n-type $Al_{0.3}Ga_{0.7}As/GaAs/Al_{0.3}Ga_{0.7}As$ MDQW. The dominant mechanism responsible for the FES in Be co-doped quantum wells has been shown to be the localization of holes at the acceptors. In the case of undoped quantum wells it is the resonant scattering of electrons near the Fermi edge and the next ($n = 2$) unoccupied subband which produces a sufficient $k = 0$ admixture in exciton wave function and enhances transitions from the high energy states despite the lack of localization mechanism of the holes. The results are of interest from the fundamental point of view. Such effects are also important for the modelling of optoelectronic device operation under high injection conditions.

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