Optical Properties of a Dense 2-D Electron Gas

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We investigated the optical properties of two-dimensional electron gases in modulation-doped InGaAs/GaAs/AlGaAs single quantum wells. We discuss the results of interband optical spectroscopies on highly doped samples in which the Fermi level energy is near the bottom energy of the second electron subband. Photoluminescence spectra present unresolved emission band which as a strong evidences of second subband exciton transition as well as Fermi edge singularity. The coupling of the Fermi edge singularity and the second subband exciton is also investigated as a function of the temperature and the presence of the external magnetic field.

I. Introduction

Many-body effects in semiconductor quantum wells, such as fractional quantum Hall effect[1], band-gap renormalization[2] and Fermi edge singularity[3] are of great interest, both in theory and experiment. High mobility two-dimensional (2-D) electron gases are fundamental for device applications. Optical spectroscopy has shown to be a powerful tool to investigate these systems. In this work we used photoluminescence and excitation photoluminescence spectroscopy, including its dependence with temperature and longitudinal magnetic field, to study the properties of 2-D electron gas in modulation-doped InGaAs/GaAs/AlGaAs single quantum wells. The investigated structures were grown with the purpose of fabricating high electron mobility transistor devices (HEMT), taking advantage of the high mobility of the 2-D electron gas at the InGaAs channel.

The luminescence and absorption in modulation-doped quantum wells are complicated by the presence of the Fermi sea due to the 2D gas of electrons. Despite the strong screening and phase filling at high electron concentrations, the interaction between the many-electron system and a photogenerated hole induces an exciton-like effect, similar to the Mahan exciton for degenerated bulk semiconductors[4]. Many-body effects are also present at the edge of the Fermi sea. These effects are particularly enhanced for a heavy-hole mass. This can be achieved by the hole localization, for example, by local potential fluctuations due to the alloy potential. This effect results in the enhancement of the oscillator strength for optical transitions occurring close to the Fermi energy, known as Fermi edge singularity (FES).

The high-density of the 2-D electron gas in our samples marginally occupies the second subband of the quantum well. This occupation is critical for the optical properties of the structure. At low temperatures, when the Fermi level is only a few meV below the second subband, the FES is enhanced by the interaction between the 2D electron gas and the exciton associated to the second subband. However, when this subband starts to be occupied, the FES loses in importance and the second subband starts to luminesce. These two effects are extremely sensitive to the energy difference between the Fermi level and the second subband[5].

II. Experimental details

We show the results of measurements on two samples grown with the same structure and nominal parameters, but resulting in slightly different 2D electron gas densities. The structure consists of a 13nm GaAs/$In_{0.2}Ga_{0.8}As/Al_{0.25}Ga_{0.75}As$ pseudomorphic-strained single quantum well grown by molecular beam epitaxy (MBE). The $Al_{0.25}Ga_{0.75}As$ barrier has a planar Si doping concentration of 5×10^{12} cm^{-2} distant of 5nm from the $In_{0.2}Ga_{0.8}As$ layer. Shubnikov-de-Haas measurements[6] indicate that the 2D electron gas occupies only the ground electron level for both samples. Fig. 1 shows schematically the sample with the important parameters.

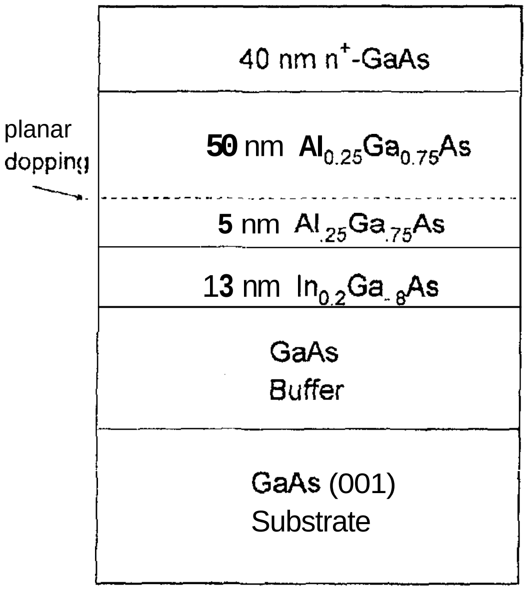

Figure 1: Schematic structure of InGaAs/GaAs/AlGaAs Modulation Doped Single Quantum Well samples.

Photoluminescence (PL) and photoluminescence excitation (PLE) experiments were performed with a Ti-Saphire laser pumped by an Ar+ laser as light source. The emission was analyzed using a 0.8 m double monochromator and a nitrogen cooled S1 photomultiplier coupled to a photon-counter system. The spectra were obtained at sample temperatures from 2 to 40K.

Magneto-luminescence (ML) experiments were measured in a superconductor-coil cryostat with an optical fiber system. The light source and the luminescence detection were the same as used in PL measurements.

III. Results and discussions

a. PL and PLE measurement

Fig. 2 shows the PL spectra at 2 K for samples #A and #B. PL spectra for both samples present two peaks. The first peak is easily associated to the transition involving the ground conduction and valence subbands (e1 - hh1). The second PL peak is present strongly asymmetric lineshapes, with a tail at the small-energy side for both samples. This peak may be attributed to either the FES or to the transition associated to the second conduction subband and the ground valence subband (e2 - hh1).

The forbidden e2 - hh1 transition for symmetric wells becomes allowed for the asymmetric case. In our samples only the AlGaAs barrier is doped with donors, enhancing the asymmetry in the InGaAs well. The PL peaks for sample #A are shifted to lower energies as compared to sample #B. The shift is attributed to the smaller 2-D electron gas density of sample #B which changes the potential profile of the sample, resulting in an increase of the interband transition energy.

We also observe a significant variation of the PL peak intensities. There is an inversion of the intensity ratio between the e1 - hh1 and e2 - hh1 transition peaks: the e2 - hh1 emission is dominant for sample #A and becomes relatively weak for sample #B. This changing may be related to the increasing of the e2 subband occupation in sample #A in comparison to sample #B. The luminescence intensity is proportional to the electronic subband occupation. Also, higher 2D electron gas concentration increase the asymmetry in the well. This

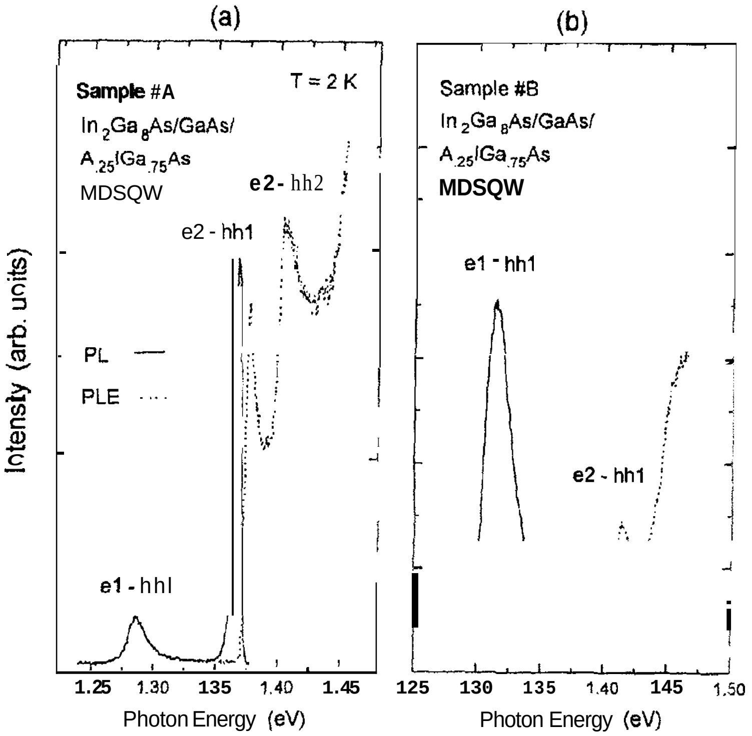

Figure 2: PL (continuous) and PLE (dotted) spectra at 2 K of a InGaAs/GaAs/AlGaAs MDSQW for (a) sample #A and (b) sample #B.

increases the oscillator strength for the e2-hh1 transition and decreases it for the e1-hh1 transition[7].

An alternative explanation is related to the FES, giving an additional emission band which may be present in this range. Chen et al[5] observed an enhancement of the FES emission band due to its coupling with the e2 - hh1 exciton which depends on the separation between the Fermi level and second electron subband. Since sample #A has a higher 2-D electron gas density than sample #B, the Fermi energy is closer to the second electron subband for sample #A. As a consequence, the coupling between the Fermi level and the second subband exciton should be stronger for this sample, resulting in an increase of the PL intensity, as observed in our **PL** spectra (Fig. 2). On the other way, the eventual occupation of the second conduction subband plays against the FES: as a consequence of the phase filling and screening effects, the exciton associated to the e2-hh1 transition is weakened, decreasing its interaction with the electrons at the Fermi edge.

The key factor in our experiments is the second subband occupation. The Shubnikov-de-Haas results show no occupation for this subband. However, the optical experimental results does not rule out this possibility. If the second subband is occupied, as the luminescence spectra seems to indicate, it is marginal and quite sensitive to the experimental conditions. Nevertheless, the two effects, FES and direct luminescence from the e2-hh1 transition, cannot be resolved in our samples. Both transitions are marginally separated in energy and within the peak broadening. In what follows, we give further evidences of the presence of both transitions in the second luminescence peak. The PLE spectrum (Fig. 2, dotted lines) for sample #A shows two peaks while sample #B shows only one. Since the PLE spectrum is related to the absorption at the excitation energy, the signal will start for photon energies just above the Fermi level, where the density of empty states at the conduction band is non-zero. The small Stoke shift may be related to the small occupation of the second subband.

Fig. 3 shows the (a) **PL** and the **(b) PLE** spectra as a function of the temperature for sample #A. We observe a slightly decreasing in the PL intensity ratio of the e2 - hh1 and e1 - 11111 peaks. Previous works on the subject have experimentally[3,7-9] and theoretically[10,11] shown that the Fermi edge singularity effect decreases as the temperature increases, being a very sensitive effect. On the other way, the e2-hh1 photoluminescence should be enhanced by the thermal occupation That may explain the observation of a strong second peak even at temperature as high as 40 K, when the FES should be already smeared out.

We observe that the PLE lineshape changes with temperature. At 2 K, the features correspond to well defined peaks, but as the temperature is increased the lineshape becomes less resolved and above 30 K it assumes a step-like shape. This behavior is explained by the occupation of the second conduction subband. The phase filling hampers the exciton formation and the PLE reflects the step-like density of state, characteristic of the 2-D system. The same features are observed in PLE spectra for excitons involving e2 electron and h112 hole subbands. This is expected, since the major effect is in the occupation of the second conduction subband. We should also mention that the quenching of the exciton state also plays against the FES.

Similar effects with the temperature are observed for sample #B.

b. Magneto-luminescence measurements

Typical 2 K magneto-luminescence spectra for sample #B are shown in Fig. 4 for different magnetic fields. As the magnetic field is increased, a series of peaks due to the Landau level inter-band transitions becomes well resolved. Without magnetic field the 2-D electron gas can occupy states with k varying continuously from 0 to kF, where kF is the wave vector corresponding to the Fermi level. In the presence of the magnetic field, the 2-D electron gas will then fill the discrete Landau levels up to Fermi level, which is pinned at a given Landau level. The PL peak corresponding to the lowest Lan-

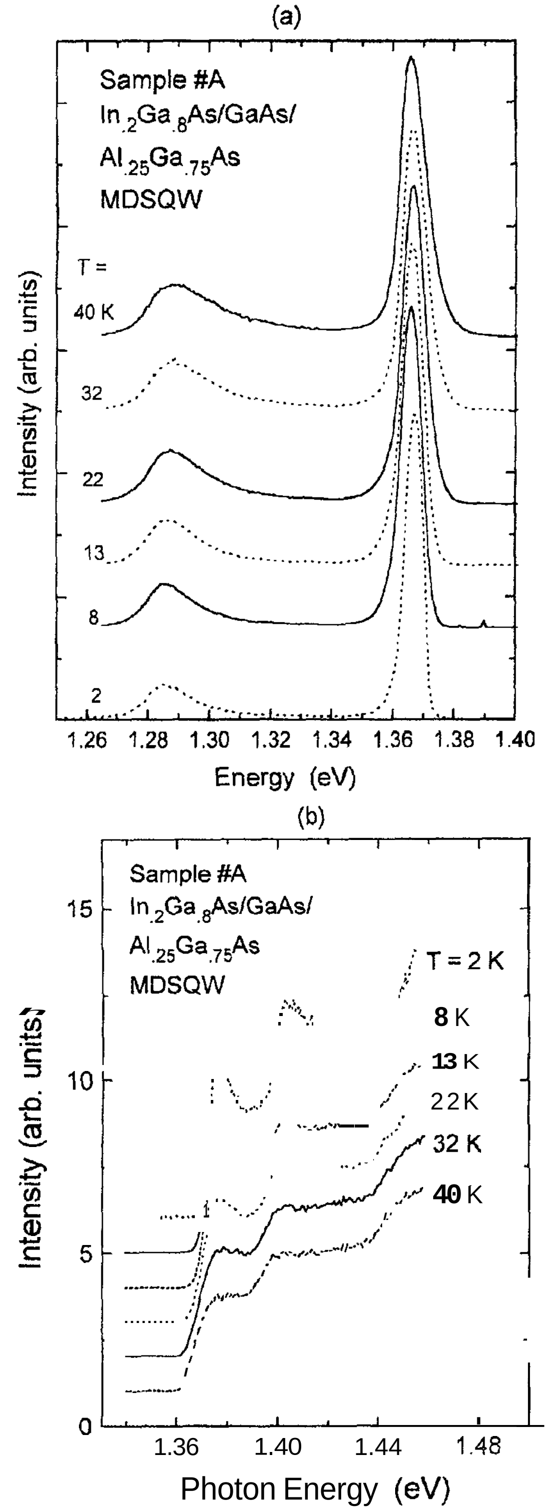

Figure 3: (a) PL and (b) PLE spectra of sample #A at different temperatures.

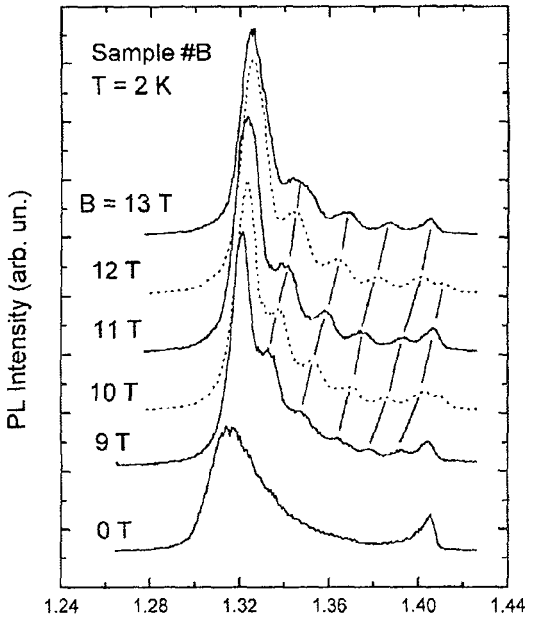

Figure 4: PL spectra at 2K for sample #R at different magnetic fields.

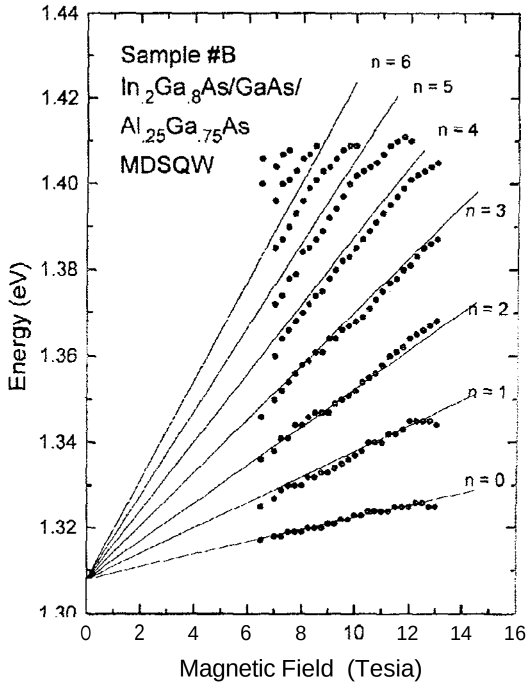

Figure 5: PL energy peak as a function of the magnetic field for sample #13.

dau level n = 0 is the strongest one, because most of the photo excited holes relaxes to the top of the ground state.

The magneto-luminescence peak positions are plotted as a function of the magnetic field in Fig. 5. We observe that the peak positions corresponding to small values of n reasonably follow a linear behavior. However, as n increases, the peaks are in a high energy region where the lowest e2 subband Landau level crosses the Landau levels associated to the e1 subband. In this region the strong mixing of states of the two subband Landau levels alter the simple linear behavior. The coupling effect is relevant in this case, as shown by Chen et al.[5]. The straight lines shown in Fig. 5 are given by: E $= (n+1/2)h\nu$ where $h\nu = eh/2\pi\mu c$, e is the electron charge, h is Planck's constant, c is the velocity of light and μ is the reduced effective mass of the electron-hole pair. The reduced mass calculated using bulk material parameters, 0.052 m_0, can only be used to explain the experimental data corresponding to $n = 1$. For $n > 1$, the best fitting is achieved with an effective mass of $\mu = 0.065\ m_0$. The reduced mass discrepancy for high value of n is consistent with the non-parabolicity of the conduction band and the mixing between the two transitions. For $n = 0$, we obtain $\mu = 0.04 m_0$, and this value is not yet understood at present.

For sample #A, the Landau level transitions show similar behavior but are not as well resolved as for sample #B.

IV. Conclusions

In conclusion, we studied the optical properties of high quality two-dimensional electron gases. A second peak at the PL spectrum was observed. Mixed effects due to the FES and the occupation of the second conduction subband were reported. At the present moment, it is not yet possible to resolve the origin of this transition. Most likely, the present situation shows a Fermi level quite close to the second subband. That allows the manifestation of both effects. At the same time, it prevents the resolution between them.

Acknowledgments

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