

INTERBAND MAGNETO-SPECTROSCOPY OF A HIGH-DENSITY TWO-DIMENSIONAL ELECTRON GAS IN A STRONG IN-PLANE MAGNETIC FIELD

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We report results of temperature and field dependent studies of interband optical absorption and photoluminescence in a two-dimensional electron gas in a strong in-plane magnetic field (up to 45 T). We observe a field dependent shift of the Fermi energy with both the magnitude and sign of the shift varying with magnetic field. Simultaneous low temperature magneto-photoluminescence measurements reveal a monotonically increasing blue shift accompanied by a quenching of the intensity. A theoretical treatment based on a single particle picture and taking into account the diamagnetic shift as well as a shift due to an anisotropic effective mass cannot qualitatively reproduce our experimental results, indicating that many-body interactions may be important.

Keywords: Fermi-energy; 2DEG; in-plane magnetic field.

1. Introduction

The optical properties of a two-dimensional electron gas (2DEG) are significantly affected by many-body interactions. These effects, including the Fermi edge singularity (FES) and band gap renormalization, have been studied extensively, both at zero fields and in strong *perpendicular* magnetic fields (B 's).^{1,2,3} The strength of the many-body interaction is modified by the applied field due to magnetic confinement. In the perpendicular field, the electron motion in the plane of the quantum

well is quantized. As a result, the step-like 2D density of states transforms into a highly degenerate δ -function-like 0D density of states.

The case of a magnetic field directed *parallel* to the plane of the quantum well (Voigt geometry) has been less investigated. The in-plane motion remains quasi-free and the density of states still maintains its step-like form.

2. Experimental Scheme

The samples used in this experiments are Si modulation-doped $\text{In}_{0.19}\text{Ga}_{0.81}\text{As}/\text{Al}_{0.41}\text{Ga}_{0.59}\text{As}$ multiple quantum wells grown by molecular beam epitaxy. The layer structure consists of a semi-insulating GaAs substrate, a 50-period 2-nm $\text{Al}_{0.41}\text{Ga}_{0.59}\text{As}$ /2-nm GaAs superlattice buffer, a 30-nm $\text{Al}_{0.41}\text{Ga}_{0.59}\text{As}$ spacer, 20-period active layer: 10-nm $\text{Al}_{0.41}\text{Ga}_{0.59}\text{As}$ /Si- δ -doped $\text{Al}_{0.41}\text{Ga}_{0.59}\text{As}$ /20-nm $\text{Al}_{0.41}\text{Ga}_{0.59}\text{As}$ /7-nm $\text{In}_{0.19}\text{Ga}_{0.81}\text{As}$, followed by 30-nm $\text{Al}_{0.41}\text{Ga}_{0.59}\text{As}$ and a 10-nm GaAs capping layer. The electron density in the quantum well measured by Shubnikov-de Haas oscillations is $n_{\text{doping}} \sim 1.4 \times 10^{12} \text{cm}^{-2}$ at 1.5 K.

Magnetic fields, parallel to the QW plane, were applied up to 45 T (30 T) using superconducting-Bitter hybrid magnet (Bitter-type magnet). PL spectroscopy was performed through indirect excitation of the quantum wells by the 632-nm line of a He-Ne laser. White-light from a tungsten-lamp was used for absorption and all excitation and collection was done in the normal incidence to the sample surface.

3. Results and Discussions

Fig. 1 shows both (a) absorption and (b) PL spectra around the FES at magnetic fields up to 45 T at 4.2 K. In Fig. 1(a), the Fermi-edge E_F (indicated by the line with the arrow) shows an initial red shift with increasing magnetic field, followed by a blue shift with the crossover occurring at around 35 T. Fig. 1(b) shows the PL spectra and indicates that the band edge emission is suppressed consistent with the FES dominating the PL emission. The intensity of the PL reaches a maximum at 20 T and then shows quenching behavior (Fig. 1(b)) for higher fields. The inset figure in (b) shows the zero field PL spectra at 4.2, 40, and 60 K. The spectrum at 4.2 K is dominated by a strong enhancement at the Fermi edge¹, ~ 1.39 eV in the spectrum, with no definable band-edge feature. With increasing temperature, the band edge PL develops and subsequently decays. At 40 K, we clearly observe the coexistence of band-edge and the FES. The estimated Fermi energy in zero magnetic field is ≈ 60 meV above the band edge.

In Fig. 2 (a), we plot the position of the Fermi edge, extracted from the absorption data through a Fermi-dirac fit as a function of magnetic field for three different temperatures (4.2, 40, and 60 K). As the temperature is increased, the red shift of the absorption edge is significantly reduced. Also, the increase in temperature diminishes the quenching of the PL in concert with the disappearance of the FES. This is shown in the inset figure of Fig. 1(b).

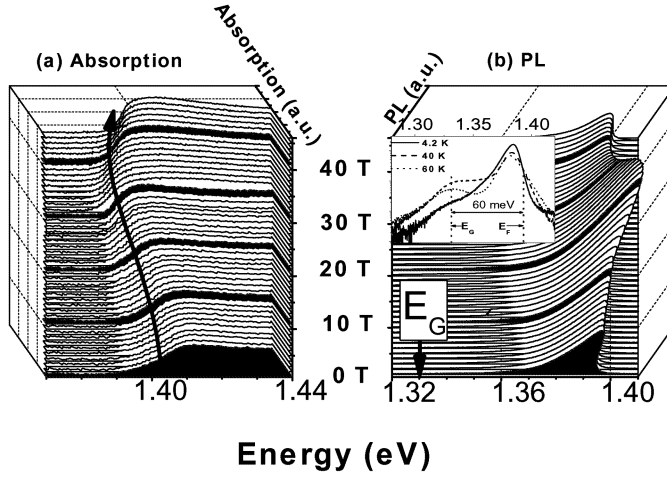


Fig. 1. Absorption (a) and PL spectra (b) with in-plane magnetic field up to 45 T at 4.2 K in n -doped $\text{In}_{0.19}\text{Ga}_{0.81}\text{As}$ quantum well. The arrow in (a) indicates the Fermi edge trace and in (b) the band edge E_G . The inset figure in (b) is PL spectra at 4.2 (solid), 40 (dashed), and 60 K (dotted). The dotted vertical lines indicate the rough positions of band edge (E_F) and Fermi edge (E_F) at 40 K whose difference is ~ 60 meV.

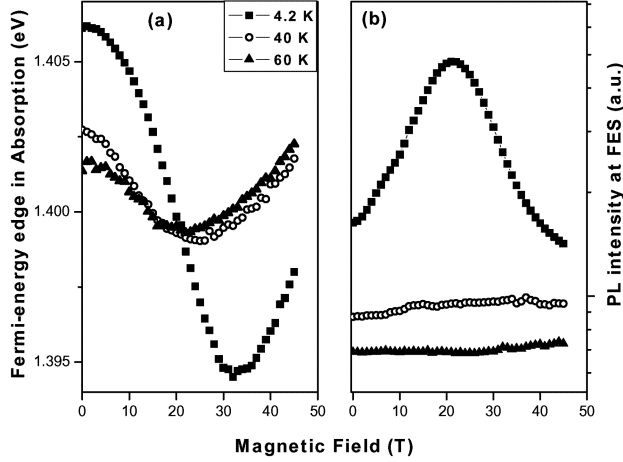


Fig. 2. (a) The Fermi edge obtained from fitting the absorption data in Fig.1(a) at three temperatures. (b) The PL strength at the FES at 4.2 (square), 40 (circle), and 60 K (triangle).

Both the spectral shift of E_F and the PL quenching behavior are consistent with a strongly enhanced FES at low temperature, and cannot be explained within a single particle picture. Our previous work has shown that a simplified, single particle model, including doping density and confinement but disregarding many-body effects and considering only the effect of the field on the electrons predicts

that there will be a parallel magnetic field induced shift in the Fermi energy given by:

$$E_f \approx E_f(0) + \frac{e^2 B^2 L^2}{60m^*c^2} \left(1 - 2\frac{E_f(0)}{\Delta E}\right). \quad (1)$$

The first term in the parantheses results from diamagnetic shift of the size-quantized energy levels and leads to a blue shift. The second term results from the increase to the in-plane effective mass perpendicular to the magnetic field.^{4,5} This anisotropic increase in the effective mass changes the density of states and lowers the Fermi level (red shift). The simple theory predicts an overall red shift when the ratio of the zero-field Fermi energy $E_F(0)$ to the energy separation between the first and second quantized levels in the conduction band of the quantum well ΔE , $E_F(0)/\Delta E$ is greater than $1/2$.⁶ However, the experimentally measured value of ΔE from far-infrared inter-subband resonance experiment is 173.6 meV and the $E_F(0)$ is estimated to be 60 meV, which gives $E_F(0)/\Delta E \approx 0.35$. Thus, the simple theory predicts a blue shift.

While the inclusion of the valence band holes might alter the sign of the shift, it is worth pointing out that the prefactor in front of the parantheses is too small at 30 T (about 3 meV) to give the correct magnitude independent of sign. Note however, that the simple theory predicts a much larger magnitude at 50 T and the turn over at these fields might result from these effects. It is clear however, that at low fields and low temperatures a more complete theory taking into account the many-body electron-electron interactions is needed. Transport measurements are currently underway to try and elucidate these effects.

4. Conclusion

Absorption and photoluminescence on 2DEGs in strong magnetic fields reveal an abnormally large red shift of the Fermi energy and simultaneous quenching of PL emission from the FES at low temperatures. These phenomena cannot be explained using a simple single-electron model of magneto-absorption. Results indicate that many-body interactions may play an important rule in this phenomena.

Acknowledgements

This work was supported by DARPA through Grant No. MDA972-00-1-0034 and NHMFL In-house Science Program.

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