Spin Susceptibility and Effective Mass in a Variable Density Two-Dimensional Electron System

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The understanding of many-body Coulomb interaction in a two-dimensional system has been a fascinating yet challenging task for many years. Theoretical studies are hindered by the lack of effective tools in the strong coupling regime whereas the quality of present specimens limits the range of experimental investigations. We have fabricated a Heterojuction-Insulated Gate Field Effect Transistor (HIGFET) device in GaAs/AlGaAs with exceedingly high mobility, which enables us to probe the strong e-e interaction regime. We present measurements of a set of Fermi-liquid parameters, namely the spin susceptibility χ, the effective mass m*, and the effective g-factor g* over a wide range of low densities $2\times10^{9}cm^{-2} < n < 6.4\times10^{10}cm^{-2}$ ($2 < r_s < 12.4$).

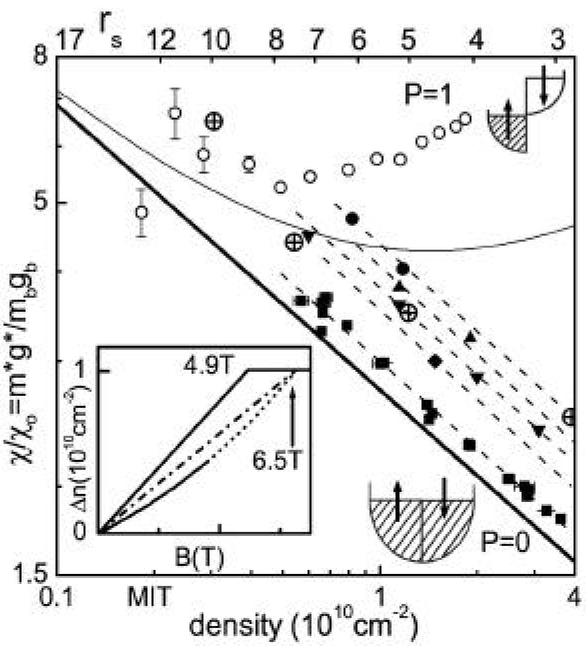

Fig. 1 Density dependence of $\chi\sim m^*g^*$ determined by two methods. Solid data points are from tilted-field experiment. Open circles show non-monotonic density dependence of m*g* derived from full polarization condition in in-plane field experiment. Inset shows the evolution of the net spin $\Delta n=Pn$ in an in-plane field for $n=1\times10^{10}cm^{-2}$ with interpolated regime (solid line) and extrapolated regime (dotted line). B_p=4.9T from in-plane field method and B_{ext}=6.5T from extrapolation of tilted-field method. A nominal $m^*g^*_{ext}$, slope of the dash-dotted line is derived from B_{ext} for all densities and plotted as a thin solid line in full figure. Thick solid line represents extrapolation of m*g* to P=0 limit. Crossed circles are theoretical calculations. See Ref [4] for details.

Two different methods are employed to measure the enhanced spin susceptibility $\chi/\chi_0 = m^*g^*/m_bg_b$, where $m_b=0.067m_e$, $g_b=0.44$ are the band values of mass and g-factor in GaAs and χ_0 the Pauli susceptibility determined by these values. Data from the tilted-field method (solid symbols in Fig. 1) exhibit an overall increase of χ/χ_0 with decreasing density. Data from the parallel-field method (open circles in Fig. 1), on the other hand, display a non-monotonic density dependence and are systematically larger in values than those from the tilted-field method. We can bring both results together with an empirical fitting equation $\chi/\chi_0 = (2.73+3.9Pn)n^{-0.4}$, which captures the density dependence as well as the polarization (P) dependence of χ. This increase of χ with P in an increasing in-plane magnetic field can account for the anomalous density dependence of g* reported recently in GaAs electron and hole systems [1-3]. Extrapolating the tilted-field data to the paramagnetic limit, we find that χ increases with decreasing density, showing an enhancement of 1.6 to 3.6 from $5\times10^{9}cm^{-2}$ to $4\times10^{10}cm^{-2}$. At the metal-insulator transition (MIT) density $2\times10^{9}cm^{-2}$, χ/χ_0 reaches approximately 5.5[4].

To identify in χ the individual contributions of the effective mass m* and the effective g-facotr g*, we determine m* using the temperature-dependent amplitude of Shubnikov-de Haas (SdH) oscillations in a very low perpendicular magnetic field. The enhanced effective g-factor g^*/g_b is then derived from $g^*/g_b = \chi m_b/\chi_0 m^*$, where χ is the paramagnetic susceptibility determined in the previous experiment. The results of m^*/m_b and g^*/g_b as a function of density are shown in Fig. 2 (a) and (b).

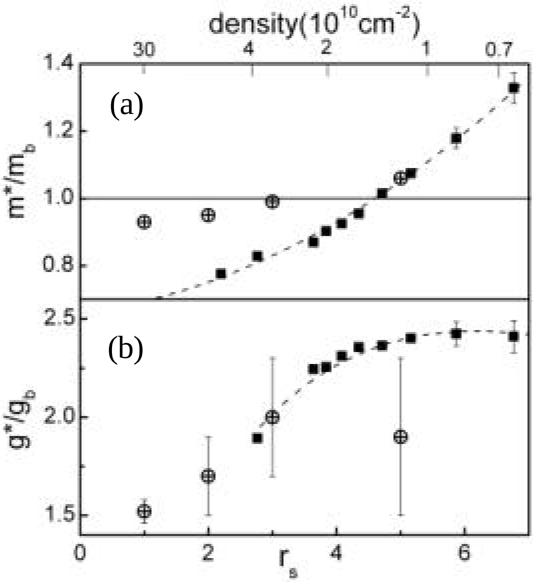

Fig. 2: (a) The enhanced effective mass m* as a function of density (top axis) and r_s (bottom axis). m* increases monotonically from $0.77m_b$ to $1.3m_b$ for $2.2 < r_s < 6.8$. Notice for $2.2 < r_s < 4.5$, m* is below the band mass m_b. Crossed circles are QMC calculations of Kwon et al [5].

(b) The enhanced effective g-factor g* derived from the extrapolated paramagnetic χ and m*. g* initially increases with increasing r_s but saturates at 2.4 g_b for $r_s > 5$. The saturation of g*, together with the continuing increase of m* in the high r_s regime, indicates the onset of a localized state. Crossed circles are again calculations from Ref [5]. Dashed lines are guide to the eye.

For $6.7\times10^9 cm^{-2} < n < 6.4\times10^{10} cm^{-2}$ ($2.2 < r_s < 6.8$), m* exhibits a monotonic increase with increasing r_s from $0.77m_b$ to $1.3m_b$. A large reduction of m* to below the band value occurs in the moderate r_s regime $2.2 < r_s < 4.5$. Existing many-body calculations in this regime produce m* values significantly larger than our experimental observations. The closest quantitative agreement with our data is achieved by the quantum Monte Carlo (QMC) calculations of Kwon et al [5], whose results are plotted in the figure as crossed circles. Corresponding g* values derived from measurements of m* and χ are shown in Fig.2 (b). g* exhibits an initial increase with increasing r_s but saturates at $2.4g_b$ for $r_s > 5$. We interpret the saturation of g* and the steady increase of m* as indications of a localized electron state, e.g. Wigner glass.

The controversial metal-insulator transition at a finite 2D density has attracted substantial attention of the community in recent years. The calculation of Zala et al identifies the many-body interaction correction to be responsible for the observed metallic behavior and provides a formula to extract the Fermi liquid parameter F_0^σ from the temperature dependent conductivity $\sigma(T)$. We have preformed such an analysis in our 2DES. A comparison between F_0^σ derived from g* measurement using $F_0^\sigma = 1/g^* - 1$, and those directly obtained from $\sigma(T)$ indicates the importance of small-angle scattering in the determination of F_0^σ using $\sigma(T)$.

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