

Measurements of the Density-Dependent Many-Body Electron Mass in Two Dimensional GaAs/AlGaAs Heterostructures

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We determine the density-dependent electron mass m^* in two-dimensional electron systems of GaAs/AlGaAs heterostructures by performing detailed low-temperature Shubnikov-de Haas measurements. Using very high-quality transistors with tunable electron densities we measure m^* in single, high mobility specimens over a wide range of r_s (6 to 0.8). Toward low densities we observe a rapid increase of m^* by as much as 40%. For $2 > r_s > 0.8$ the mass values fall $\sim 10\%$ below the band mass of GaAs. Numerical calculations are in qualitative agreement with our data but differ considerably in detail.

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In a crystal the mass of an electron often differs from its mass, m_0 , in free space. The electron mass in a semiconductor can deviate from m_0 by more than a factor of 10. The origin of this effect is interference of the electron wave function with the periodic array of the ions in the solid. Such “single particle” effects are well understood and readily calculated. However, there are other factors that affect the electron mass. In general, any excitation of the solid—such as phonons, spin waves, and plasmons—can impact the dispersion relation of the carrier [1], but only if such excitations come close to resonance. More intricate yet, the electron mass is modified by interactions with all neighboring conduction electrons. Naively one would think that interactions always enhance the carrier mass since they imply pushing against other electrons, making them apparently heavier. Yet, curiously, theory tells us that the mass can be reduced as well [2]. Such interactions are of complex “many particle” origin and bring us to the edge of the theoretical and numerical abilities in condensed matter theory.

The impact of electron-electron ($e-e$) interaction on carrier mass increases on lowering the dimensionality. Three dimensional (3D) electron systems are expected to show little effect, whereas 1D systems are highly affected. From an experimental point of view, 3D systems are most abundant and best characterized, whereas 1D systems are rare and suffer from many complications such as Peierls instabilities and their sensitivity to disorder. Two-dimensional electron systems (2DESs) provide an excellent compromise for the study of such many-body phenomena: 2DESs have been honed to extremely high quality [3] and the expected effects are moderately strong. In addition, the electron density in a 2DES is, in principle, continuously tunable, allowing the study of such phenomena within a single specimen over a wide range of densities. The strength of $e-e$ interaction is usually described by a dimensionless parameter r_s , which is defined as the ratio of Coulomb interaction to Fermi energy. In 2D,

r_s is inversely proportional to the square root of density, so a variable density translates into a tunable $e-e$ interaction.

Starting in the late 1960s [2], there have been many theoretical studies [4] of the impact of $e-e$ interaction on carrier mass using ever more powerful numerical tools. Experimentally, the silicon metal-oxide-semiconductor-field-effect-transistors (MOSFETs) had been the dominant implementation of a 2DES. Smith and Stiles [5] were the first to measure m^* as a function of r_s in such a device. However, subsequent work by Fang *et al.* [6] asserted that such mass measurements in MOSFETs were affected by several side effects. Yet, the Smith and Stiles [5] data remain the experimental reference point for this rapidly progressing area of theoretical investigation.

Recently, Coleridge *et al.* [7] have performed mass measurements on five fixed density GaAs/AlGaAs heterostructures, but only for $r_s < 1.7$. They observed a monotonically increasing m^* with increasing carrier density. With the recent interest in a transition from an electron liquid to an electron solid at very high r_s , several new studies have taken place [8,9]. They concentrate on phenomena associated with the anticipated phase transition but not with the electron liquid *per se*. Given the theoretical progress in the area of $e-e$ interactions and the availability of very high-quality 2DESs, a careful measurement of the effective 2D electron mass over a wide range of density seems to be of considerable importance to make contact between theory and experiment.

Toward this end we have measured m^* in a very high-quality, tunable density, GaAs/AlGaAs heterojunction-insulated gate field effect transistor (HIGFET) for $6 > r_s > 0.8$. We observe a strongly increasing mass towards low densities and a mass $\sim 10\%$ below the band mass for all $2 > r_s > 0.8$.

Our primary sample, HIGFET-1, was grown by molecular beam epitaxy onto a (001) GaAs substrate. The 2DES resides at the interface of 5 μm of GaAs and 5 nm of AlAs, topped with 4 μm of $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$. The latter acts as an

insulator separating the channel from the gate, which consists of a 25 nm thick heavily doped, conducting GaAs n^+ layer. The material was processed into a 600 μm square mesa using photolithography and contacted via Ni-Ge-Au annealed pads. An extra pad contacted the gate. Another sample, HIGFET-2, differs from HIGFET-1 in a thinner channel material (2 μm GaAs) and the lack of the thin AlAs layer. Both samples have a peak mobility of $\sim 1 \times 10^7 \text{ cm}^2/\text{Vs}$. The electron density of the 2DEG can be tuned by changing the gate voltage of the transistor. This provides a major advantage as compared to fixed density specimens since the strength of e - e interaction can be changed continuously.

Measurement of the specific heat would be the most direct way to determine the mass that includes e - e interactions. Such experiments are exceedingly challenging and have not yet been realized with high precision [10]. A mass determined by cyclotron resonance will not exhibit effects from e - e interactions according to Kohn's theorem [11]. Instead, we employ the Shubnikov-de Haas (SdH) effect and determine the effective mass from the reduction of the amplitude of these magnetoresistance oscillations with increasing temperature (see Fig. 1). For SdH measurements to provide reliable mass data, data collection has to be performed within appropriate parameter windows, and the interpretation of the data has to be conducted with considerable care and multiple cross-checks. In the following paragraphs we detail our procedure.

All measurements were performed in a dilution refrigerator over a temperature range from 100 to 400 mK. We used conventional low frequency ac lock-in techniques with excitation currents ranging from 1 to 100 nA, chosen to avoid sample heating. Data were taken in a single cooldown in order to have the most consistent quality from each sample. The temperature is based on a calibrated

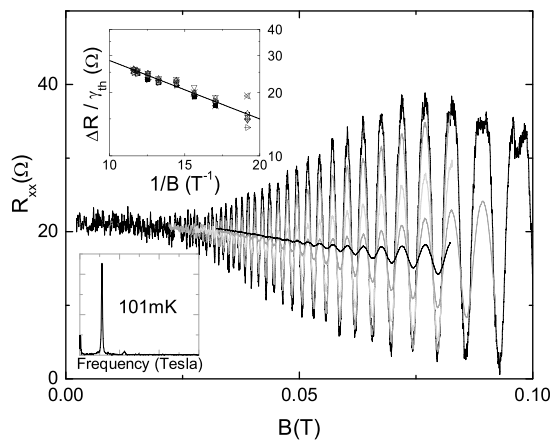


FIG. 1. SdH oscillations for $n = 5.4 \times 10^{10}/\text{cm}^2$ at $T = 101, 180, 260, 380$ mK. Lower inset: Fourier spectrum from the 101 mK data vs $1/B$. Upper inset: all Dingle plots for seven different T ranging from 100 to 400 mK data sets yield similar scattering time τ_q s.

ruthenium oxide thermometer mounted on the same silver sample holder. Magnetoresistance is negligible at low fields and the relatively high temperature ensures good thermal coupling between sample and thermometer. At each density, set by the gate voltage, we recorded a family of SdH traces at a range of temperatures. Data collection was limited to the moderate magnetic-field region such that the SdH oscillations were well developed but before the small spin splitting in GaAs was resolved. Therefore, in the region of our measurements, each minimum in the oscillations corresponds to a Landau level index i . The temperature was kept sufficiently high to avoid the quantum Hall regime, in which SdH oscillations are becoming nonsinusoidal.

SdH oscillations are a result of the comb of Landau levels sweeping through the Fermi level while the magnetic field is ramped. Hence, the oscillating part of the magnetoresistivity $\Delta\rho_{xx}$ can be written as a Fourier series [12,13]:

$$\Delta\rho_{xx}(\varepsilon) = \rho_0 \sum_p \gamma_{th} c_{\alpha,p} \exp\left(-\frac{p\pi}{\omega_c^* \tau_q}\right) \times \cos\left[2\pi p \left(\frac{\varepsilon}{\hbar\omega_c^*} - \frac{1}{2}\right)\right], \quad (1)$$

with $\omega_c^* = eB/m^*$, and $c_{\alpha,p}$ being a disorder coefficient [13]. The T dependence γ_{th} is given by

$$\gamma_{th} = \frac{2\pi^2 p k_B T / \hbar\omega_c^*}{\sinh(2\pi^2 p k_B T / \hbar\omega_c^*)}. \quad (2)$$

It is common practice to maintain only the fundamental term and neglect all higher order Fourier components. We will later explicitly check this assumption for our measurements. We derive the effective electron mass, m^* , by fitting, on a $\log(\Delta R/T)$ vs T plot, expression (2) to our T -dependent data from each index i , where R is resistance. We achieve excellent fits to all SdH data with a single mass value for each density in the whole temperature range $100 < T < 400$ mK [14]. Before discussing these results we performed several cross-checks to establish the reliability of our data reduction.

In recent literature there arose a concern as to whether the 3D SdH formalism applies correctly to 2D cases [15]. Significant deviations from the original Lifshitz and Kosevich (LK) formula were observed in de Haas-van Alphen effects of layered organic conductors [16] as well as in 2DEs of GaAs [17]. Such deviations can be traced back to a significant contribution from higher order Fourier components. When higher harmonics are negligible, the thermal reduction of the amplitude is well described by Eq. (2) [18,19].

In order to explore the variability of our mass data due to such possible deformations, we have used three different methods to derive m^* . (i) Data points depicted by solid black circles in Fig. 2(a) are m^* values fitted directly to

Eq. (2) with $p = 1$ only. Each point represents the average mass from several different Landau level indices, and this root-mean-square deviation dominates the error bars. (ii) Masses depicted as solid squares are derived from the same data, but after Fourier filtering them on a $1/B$ plot. A typical Fourier spectrum is shown in the lower inset of Fig. 1, demonstrating that higher harmonics are practically negligible. Accordingly, the filtered and unfiltered data differ only slightly from one another. (iii) We follow a revised version of the LK derivation for 2D Fermi liquids under strong $e-e$ interaction and electron-impurity scattering [20]. There, the thermal reduction of the first Fourier component of the SdH amplitude follows an exponential decay form instead of Eq. (2). The masses obtained from these fits are shown as crosses in Fig. 2(a). These m^* values are close to those from the Fourier filtered method. We conclude that our SdH data fall within the window over which an LK analysis can be applied and that our mass derivation is robust.

Another possible source of concern is density inhomogeneities. Such inhomogeneities were shown to considerably affect the determination of the scattering time via SdH [23], a subject we address later in this Letter. From the known density gradient across the wafer, we determine the

density gradient to be $\leq 0.07\%$ across our sample. The contribution of density inhomogeneities from surface roughness at the interface is estimated to be $\leq 0.1\%$ [24]. Our analytical calculations and many numerical simulations demonstrate that the thermal reduction factor is not affected by such density inhomogeneity and the m^* readings at any fixed field will not be influenced.

Data from HIGFET-2 are shown as stars in Fig. 2(a). Despite the differences between the two samples, their m^* coincide within the error bars. We also include data from four fixed density samples measured earlier by Coleridge *et al.* [7] at higher densities. These data are also consistent with our results. The m^* data from Si-MOSFETs are generally $\sim 20\%$ larger than GaAs data [5,8,9].

The effective mass versus density data of Fig. 2(a) follows a smooth but nonmonotonic curve. With increasing r_s at the low density part, there is a strong enhancement of m^* . At $r_s \sim 5$, m^* exceeds the GaAs band mass by $\sim 40\%$. In the high density region, m^* stays $\sim 10\%$ below the band mass for $2 \geq r_s \geq 0.8$. In this regime the nonparabolicity [25] of the GaAs conduction band actually further enhances the discrepancy between single particle mass and our measured mass. The dashed line shows the result of numerical calculation for the band mass at the Fermi energy due to 2D confinement plus band filling. Results from three different trial wave functions fall within the thickness of the line. The ratio of the measured m^* to the band mass, corrected for this nonparabolicity, is shown in Fig. 2(b) together with theoretical calculations. For clarity, we limit the data points to a subset of the data of Fig. 2(a).

Kwon, Ceperley, and Martin (KCM) [22] using a variational Monte Carlo method and Asgari *et al.* (A&al) [21] using a many-body local field approach have performed extensive theoretical calculations of the impact of $e-e$ interactions on the mass in 2D. The results of these numerics are plotted in Fig. 2(b) as a full solid line and as a dashed line, respectively. The KCM theory reproduces quite well the average mass values at low r_s , whereas the A&al(0) theory seems to depict the overall shape and the upturn at high r_s . However, both theories assume a zero-thickness 2DES. When adjusted for finite thickness, the A&al result follows the dotted line, A&al(f) [21]. No such adjustment is available for KCM and the coincidence of both curves must be considered accidental. In any case, these calculations seem to capture some aspects of the data but clearly do not describe the high r_s regime.

All numerical calculations have been performed for a 2D system in the absence of a magnetic field. Since our data were collected in small B fields and mostly in very high Landau levels we can regard our data as representing this limiting $B = 0$ case. However, Smith, MacDonald, and Gumbs [4] (SMG) have performed mass calculations in the presence of a B field based on the random-phase approximation (RPA). Their results are shown as a sequence of thin lines identified by the representative

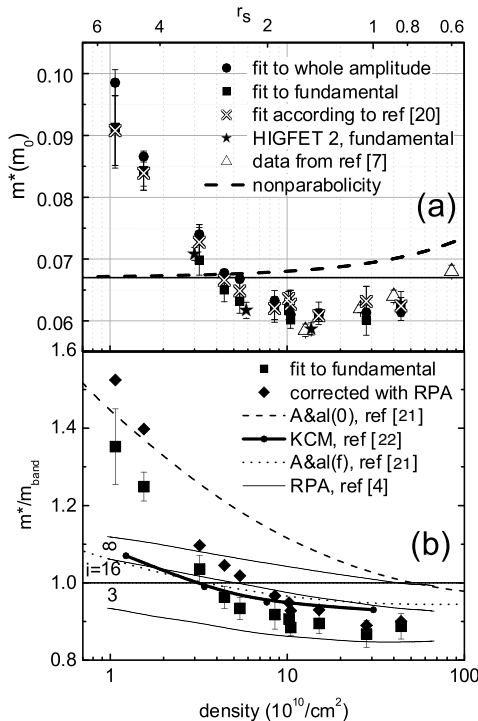


FIG. 2. Density dependence of 2D electron effective mass m^* (a) m^* from three different fitting methods, from a second specimen, and from another group [7]; see the legend. Mass enhancement due to nonparabolicity shown as a dashed line. (b) m^* s of “fundamental fit” in (a) corrected for nonparabolicity. Several theories are indicated as lines; see the legend and the text.

Landau index i . We note that $i = \infty$ is equivalent to $B = 0$ and can be directly compared to the other calculations, showing further the discrepancies between different theories. These $i = \infty$ results also differ considerably from our data. At the same time, the SMG calculation shows a considerable dependence of the mass value on the index which needs to be taken into account.

The experimental window dictated by temperature, sinusoidal line shape, and available B field results in a correlation between density n and available index i . Lower densities require the recording of low indices, whereas higher densities allow one to measure much higher indices. While the $i = \infty$ SMG results differ considerably from our data, it appears reasonable to use their fractional dependence of the mass on index, $m^*(i = \infty)/m^*(i)$, to correct our data for such an index dependence. The resulting m^* data are shown as filled diamonds in Fig. 2(b). The overall shape of the density-dependent mass is not much affected although the very low density masses are enhanced beyond the previous error bars, since such data were taken at relatively low i . On the other hand, the high density data are almost unaffected. While the correction suggested by the SMG work modifies somewhat the comparison between theory and experiment, the overall conclusions remain intact.

In addition to m^* , the envelope of the SdH oscillations provides us with a measure of the quantum scattering time τ_q at each temperature. Since τ_q enters the LK expression, Eq. (1), a temperature dependence of τ_q could affect the value of m^* . Before examining the data, we should stress that a T dependence of τ_q must be considered very weak and only on the scale of T/T_F , T_F being the Fermi temperature, since scattering by fixed imperfections is the only remaining mechanism and it is practically T independent in our temperature and density range. Nevertheless, we evaluated τ_q employing the semilog Dingle plot of the SdH amplitude normalized to $\rho_0\gamma_{th}$ [Eq. (1)] vs $1/B$. The upper inset of Fig. 1 shows such a typical Dingle plot for seven different temperatures. The slope of the data determines τ_q , which can be affected by density inhomogeneities [23]. However, here we pursue only a possible T dependence of τ_q . From extensive modeling we determine that it is unaffected by inhomogeneity of as much as 10%. Evaluating many Dingle plots, we find that over our T range, $\tau_q(T)$ varies by less than 1% for all $r_s < 4$; see also Ref. [8]. At the lowest two densities, our Dingle plots are ill defined. From numerical simulations we deduce that even there a T dependence of τ_q on the scale of T/T_F will at most generate a 3% error in m^* . Therefore, the effect of a T -dependent τ_q will have an insignificant impact on m^* in Fig. 2(a).

In conclusion, we have performed high precision measurements of the electronic effective mass in an ultra-high-quality, tunable, two-dimensional electron system over a

wide range of r_s , $6 > r_s > 0.8$. Performing various cross-checks and exploring several sources for error we convinced ourselves that our data provide an accurate measurement of the density-dependent impact of electron-electron interactions on the electron mass in a 2D system. Over wide stretches of density this mass renormalization can be negative. Various theoretical calculations reproduce sections of our data quite well, but none shows good agreement for the whole range of densities.

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