Spin-Independent Origin of the Strongly Enhanced Effective Mass in a Dilute 2D Electron System

A. A. Shashkin,* Maryam Rahimi, S. Anissimova, and S.V. Kravchenko
Physics Department, Northeastern University, Boston, Massachusetts 02115, USA

V.T. Dolgopolov
Institute of Solid State Physics, Chernogolovka, Moscow District 142432, Russia

T. M. Klapwijk
Department of Applied Physics, Delft University of Technology, 2628 CJ Delft, The Netherlands
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We accurately measure the effective mass in a dilute two-dimensional electron system in silicon by analyzing the temperature dependence of the Shubnikov–de Haas oscillations in the low-temperature limit. A sharp increase of the effective mass with decreasing electron density is observed. We find that the enhanced effective mass is independent of the degree of spin polarization, which points to a spin-independent origin of the mass enhancement and is in contradiction with existing theories.

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The ground state of an ideal, strongly interacting two-dimensional (2D) electron system is predicted to be a Wigner crystal [1]. The strength of the interactions is usually characterized by the ratio between the Coulomb energy and the Fermi energy, $r_s = E_c/E_F$. Assuming that the effective electron mass is equal to the band mass, the interaction parameter r_s in the single-valley case reduces to the Wigner-Seitz radius, $1/(\pi n_s)^{1/2} a_B$, and therefore increases as the electron density, n_s, decreases (here a_B is the Bohr radius in semiconductor). In the strongly interacting limit, no analytical theory has been developed to date. According to numeric simulations [2], Wigner crystallization is expected in a very dilute regime, when r_s reaches approximately 35. The refined numeric simulations [3] have predicted that prior to the crystallization, in the range of the interaction parameter $25 \lesssim r_s \lesssim 35$, the ground state of the system is a strongly correlated ferromagnetic Fermi liquid. At yet higher electron densities, at $r_s \sim 1$, the (weakly interacting) electron liquid is expected to be paramagnetic, with the effective mass, m, and Landé g factor renormalized by interactions. Enhancement of g and m within the Fermi liquid theory is due to spin exchange effects, with renormalization of the g factor being dominant compared to that of the effective mass [4]. In contrast, the dominant increase of m near the onset of Wigner crystallization follows from an alternative description of the strongly interacting electron system beyond the Fermi liquid approach, which also predicts the renormalization of m to be strongly sensitive to the polarization of spins [5,6].

In dilute silicon metal-oxide-semiconductor-field-effect-transistors (MOSFETs), a strong metallic temperature dependence of the resistance was observed a decade ago [7]. Although this anomaly was almost immediately attributed to strong electron-electron interactions, only after a strongly enhanced ratio of the spin and the cyclotron splittings was found at low n_s [8] has it become clear that the system behaves well beyond the weakly interacting Fermi liquid. Later, it was reported that the magnetic field required to produce complete spin polarization, $B_c \propto n_s/gm$, tends to vanish at a finite electron density $\approx 8 \times 10^{10}$ cm^{-2} [9,10]. These findings point to a sharp increase of the spin susceptibility and possible ferromagnetic instability in dilute silicon MOSFETs. In very dilute GaAs/AlGaAs heterostructures, a similar behavior has been observed in both the 2D hole [11] and electron [12] system. Recently, experimental results have indicated that in silicon MOSFETs it is the *effective mass,* rather than the *g factor,* that sharply increases at low electron densities [13]. The crucial point for understanding these properties of dilute 2D electron liquids is how the effective mass changes with the degree of spin polarization.

In this Letter, we report accurate measurements of the effective mass in a clean 2D electron system in silicon by analyzing temperature dependence of the weak-field Shubnikov–de Haas (SdH) oscillations in the low-temperature limit [14]. The effective mass is found to be strongly increased (by a factor of $\gtrsim 3$) at low electron densities. Using tilted magnetic fields, we find that the value of the effective mass does not depend on the degree of spin polarization, which points to a *spin-independent* origin of the effective mass enhancement. This is in clear contradiction with existing theories [4–6].

Measurements were made in a rotator-equipped Oxford dilution refrigerator with a base temperature of ≈ 30 mK on high-mobility (100)-silicon samples similar to those previously used in Ref. [15]. The resistance, R_{xx}, was measured by a standard four-terminal technique at a low frequency (0.4 Hz) to minimize the out-of-phase signal. Excitation current was kept low enough (0.1–0.2 nA) to

ensure that measurements were taken in the linear regime of response. Contact resistances in these samples were minimized by using a split-gate technique that allows one to maintain a high electron density in the vicinity of the contacts (about 1.5×10^{12} cm^{-2}) regardless of its value in the main part of the sample. Below, we show results obtained on a sample with a peak mobility close to 3 m^2/V s at $T = 0.1$ K.

A typical temperature dependence of the amplitude, A, of the weak-field (sinusoidal) SdH oscillations for the normalized resistance, R_{xx}/R_0 (where R_0 is the average resistance), is displayed in Fig. 1. To determine the effective mass, we use the method of Ref. [16], extending it to much lower electron densities and temperatures [17]. We fit the data for $A(T)$ using the formula

$$A(T) = A_0 \frac{2\pi^2 k_B T/\hbar\omega_c}{\sinh(2\pi^2 k_B T/\hbar\omega_c)}, \qquad A_0 = 4\exp(-2\pi^2 k_B T_D/\hbar\omega_c), \tag{1}$$

where $\omega_c = eB_\perp/mc$ is the cyclotron frequency and T_D is the Dingle temperature. As the latter is related to the level width through the expression $T_D = \hbar/2\pi k_B\tau$ (where τ is the elastic scattering time) [18], damping of the SdH oscillations with temperature may be influenced by temperature-dependent τ. We have verified that in the studied low-temperature limit for electron densities down to $\approx 1 \times 10^{11}$ cm^{-2}, possible corrections to the mass value caused by the temperature dependence of τ (and hence T_D) are within our experimental uncertainty which is estimated at about 10%. Note that the amplitude of the SdH oscillations follows the calculated curve down to the lowest achieved temperatures, which confirms that the electrons were in a good thermal contact with the bath and were not overheated.

In Fig. 2, we show the so-determined effective mass in units of the band mass, $m_b = 0.19m_e$ (where m_e is the free electron mass), as a function of electron density. The effective mass sharply increases with decreasing n_s. This is in good agreement with the data obtained by an alternative method based on measurements of B_c and of the slope of the metallic temperature dependence of conductivity in zero magnetic field, similar to those described in Refs. [9,13]. Using that method, we also determined that our g factor is practically density-independent and is equal to $g \approx 2.8$, which is close to $g = 2$ in bulk silicon. Note that the agreement between the results obtained using two independent methods as well as the fact that the experimental dependence $A(T)$ follows the theoretical curve justify applicability of Eq. (1) to this strongly interacting electron system [19].

A strong enhancement of m at low n_s may originate from spin effects [4–6]. With the aim of probing a possible contribution from the spin effects, we introduced a parallel magnetic field component, $B_\parallel$, to align the electrons' spins. As the thickness of the 2D electron system in Si MOSFETs is small compared to the magnetic length in accessible fields, the parallel field couples largely to the electrons' spins while the orbital effects are suppressed [20,21].

In Fig. 3, we show the main result of the paper: the behavior of the effective mass with the degree of spin polarization, $p = (B_\perp^2 + B_\parallel^2)^{1/2}/B_c$. Within our accuracy, the *effective mass m does not depend on p*. Therefore, the

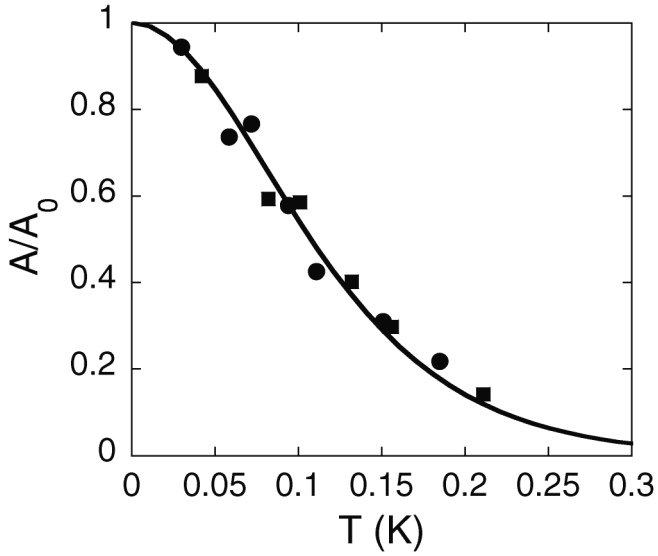

FIG. 1. Change of the amplitude of the weak-field SdH oscillations with temperature at $n_s = 1.17 \times 10^{11}$ cm^{-2} for oscillation numbers $\nu = hcn_s/eB_\perp = 10$ (dots) and $\nu = 14$ (squares). The value of T for the $\nu = 10$ data is divided by the factor of 1.4. The solid line is a fit using Eq. (1).

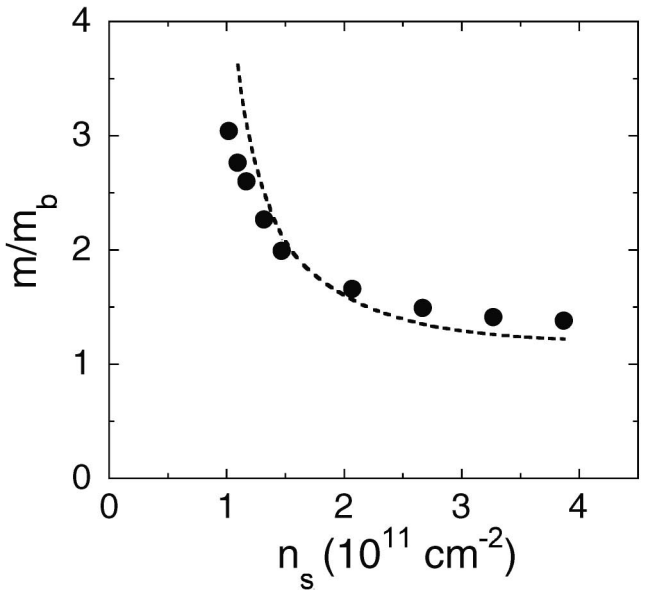

FIG. 2. Dependence of the effective mass on electron density in the spin-unpolarized system. Also shown by a dashed line are the data obtained using the method of Refs. [9,13].

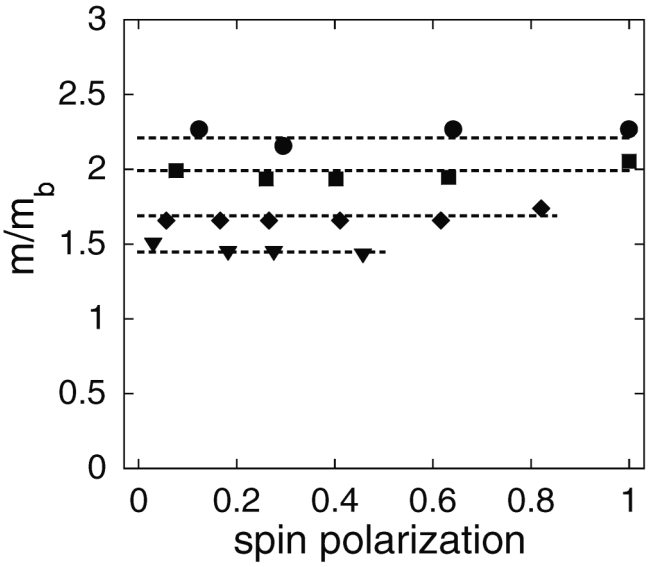

FIG. 3. The effective mass vs the degree of spin polarization for the following electron densities in units of 10^{11} cm^{-2}: 1.32 (dots), 1.47 (squares), 2.07 (diamonds), and 2.67 (triangles). The dashed lines are guides to the eye.

$m(n_s)$ dependence is robust, the origin of the mass enhancement has no relation to the electrons' spins and exchange effects [22].

In Fig. 4(a), we compare the extracted Dingle temperature, T_D, with that recalculated from the electron lifetime determined from zero-field mobility [13]. Although the elastic scattering time defining the Dingle temperature is in general different from the transport scattering time, the two $T_D(n_s)$ dependences are consistent with each other indicating dominant large-angle scattering [18]. This indicates that the Dingle temperature decreases with decreasing electron density, in agreement with the narrowing of the cyclotron resonance line observed at low n_s in Si MOSFETs [23]. In contrast, Fig. 4(b) shows that with an increasing degree of spin polarization, the Dingle temperature remains approximately constant, while the resistance increases by a factor of about 5. So, the straightforward correlation between the Dingle temperature and the elastic scattering time does not hold for fully spin-polarized electron system.

We now discuss the results obtained for the effective mass. We stress that in the present case, the interaction parameter, r_s, is larger by a factor of $2m/m_b$ than the Wigner-Seitz radius and reaches approximately 50, which is above the theoretical estimate for the onset of Wigner crystallization. As has already been mentioned, two approaches to calculate the renormalization of m and g have been formulated. The first one exploits the Fermi liquid model extending it to relatively large r_s. Its main outcome is that the renormalization of g is large compared to that of m [4]. In the limiting case of high r_s, one may expect a divergence of the g factor that corresponds to the Stoner

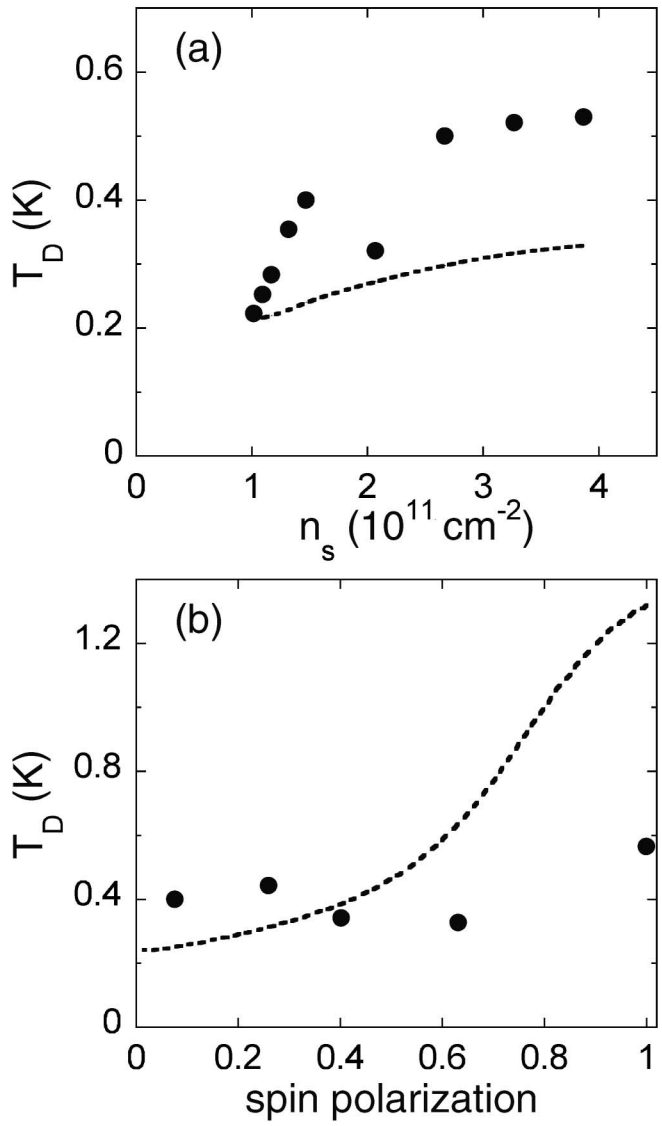

FIG. 4. Behavior of the Dingle temperature extracted from SdH oscillations (dots) and that calculated from the transport scattering time (dashed line) with electron density in the spin-unpolarized system (a) and with the degree of spin polarization (b). In (b) the electron density is equal to 1.47×10^{11} cm^{-2}.

instability. These predictions are in obvious contradiction to our data: (i) the dilute system behavior in the regime of the strongly enhanced susceptibility—close to the onset of spontaneous spin polarization and Wigner crystallization—is governed by the effective mass, rather than the g factor, through the interaction parameter r_s; and (ii) the insensitivity of the effective mass to spin effects also cannot be accounted for.

The other theoretical approach either employs analogy between a strongly interacting 2D electron system and He^3 [5] or applies Gutzwiller's variational method [24] to Si MOSFETs [6]. It predicts that near the crystallization point, the renormalization of m is dominant compared to that of g and that the effective mass diverges at the

transition. Although the sharp increase of the mass is in agreement with our findings, it is the expected dependence of m on the degree of spin polarization that is not confirmed by our data: the model of Ref. [5] predicts that the effective mass should increase with increasing spin polarization, whereas the prediction of the other model [6] is the opposite.

Thus, the existing theories fail to explain our finding that in a dilute 2D electron system the effective mass is strongly enhanced and does not depend on the degree of spin polarization. The fact that the spin exchange is not responsible for the observed mass enhancement reduces somewhat the chances for the occurrence of an intermediate phase—ferromagnetic Fermi liquid—that precedes electron crystallization. In principle, should the spin exchange be small, the spin effects may still come into play closer to the onset of Wigner crystallization where the Fermi energy may continue dropping as caused by mass enhancement.

In summary, we have found that in a dilute 2D electron system in silicon, the strongly enhanced effective mass is independent of the degree of spin polarization. This shows that the mechanism underlying the effective mass enhancement is not related to spin and exchange effects.

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*Permanent address: Institute of Solid State Physics, Chernogolovka, Moscow District 142432, Russia.

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