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Critical behavior of the Pauli spin susceptibility in a strongly correlated 2D electron liquid *

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Abstract

Thermodynamic measurements reveal that the Pauli spin susceptibility in a strongly correlated low-disordered two-dimensional electron system in silicon becomes enhanced by almost an order of magnitude at low electron densities and has a critical behavior close to the metal-insulator transition point. This provides thermodynamic evidence for the existence of a phase transition.

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Phase transitions are often related to a change in the kinetic properties of electron systems. Recent transport experiments performed on clean two-dimensional (2D) silicon samples have indicated that this system possesses anomalous magnetic properties at low electron densities and undergoes an interaction-driven metal-insulator transition (MIT) at a critical electron density n_c [1, 2]. However, evidence for a phase transition cannot be conclusively based on results obtained by transport experiments: it must be sought in studies of the thermodynamic characteristics.

Here we report measurements of the thermodynamic magnetization and density of states in a low-disordered, strongly correlated 2D electron system in silicon. We have found that the spin susceptibility of band electrons (Pauli spin susceptibility) grows by almost an order of magnitude as the electron density is reduced, behaving critically near the MIT. This provides thermodynamic evidence for the existence of a phase transition. The nature of the low-density phase still remains unclear being masked by the insulating state caused by residual disorder in the electron system.

Measurements were made in an Oxford dilution refrigerator on low-disordered (100)-silicon samples with peak electron mobilities of 3 m^2/Vs at 0.1 K and oxide thickness 149 nm. These samples are remarkable by the absence of a band tail of localized electrons down to electron densities $n_s \approx 1 \times 10^{11}$ cm^{-2} [1, 2], which allows one to study properties of a *clean* 2D electron system without admixture of local moments. The second advantage of these samples is a very low contact resistance (in "conventional" silicon samples, high contact resistance becomes the main experimental obstacle in the low density/low temperature limit). To minimize contact resistance, thin gaps in the gate metalization have been introduced, which allows for maintaining high electron density near the contacts regardless of its value in the main part of the sample.

For measurements of the magnetization, the parallel magnetic field B was modulated with a small ac field B_{mod} in the range 0.01 – 0.03 T at a frequency $f = 0.45$ Hz, and the current between the gate and the 2D electron system was measured with high precision ($\sim 10^{-16}$ A) using a current-voltage converter and a lock-in amplifier. The imaginary (out-of-phase) current component is equal to $i = (2\pi f C B_{\text{mod}}/e)\, d\mu/dB$, where C is the capacitance of the sample and μ is the chemical potential. By applying the Maxwell relation $dM/dn_s = -d\mu/dB$, one can obtain the magnetization M from the measured i. A similar technique has been previously applied by Prus *et al.* [3] to a 2D electron system in silicon with high level of disorder [4].

For measurements of the thermodynamic density of states, a similar circuit was used with a distinction that the gate voltage was modulated and thus the imaginary current component was proportional to the capacitance. Thermodynamic density of states $dn_s/d\mu$ is related to magnetocapacitance via $1/C = 1/C_0 + 1/Ae^2(dn_s/d\mu)$, where C_0 is the geometric capacitance and A is the sample area.

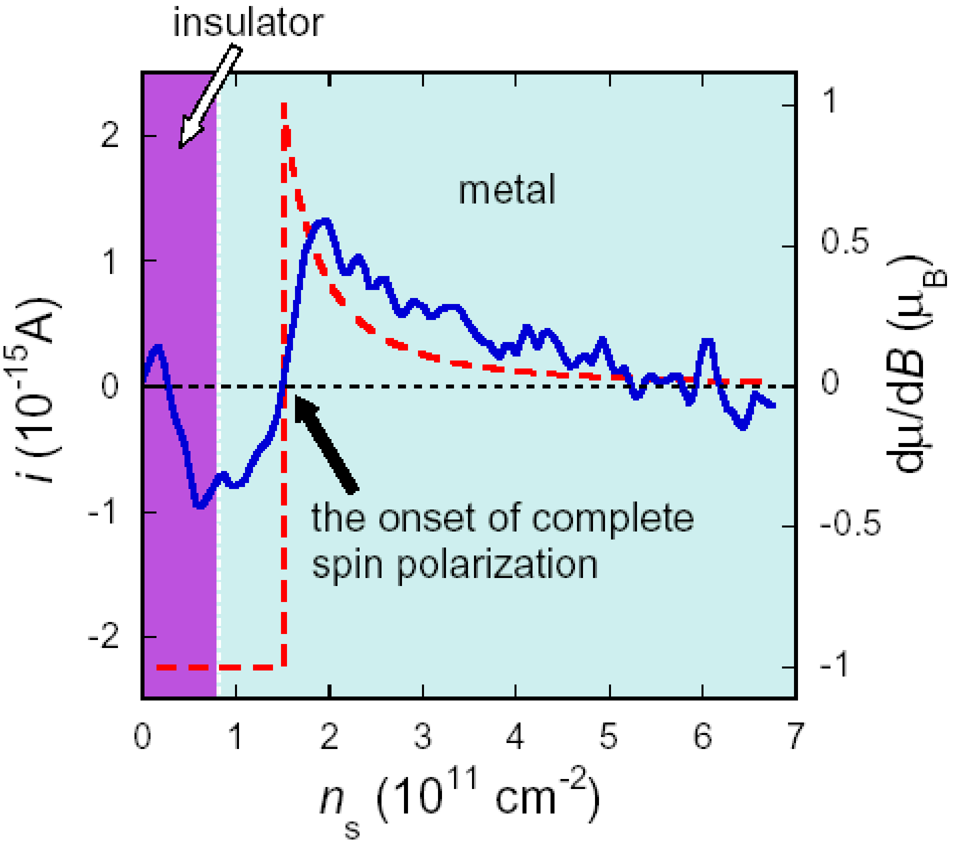

Figure 1: Imaginary current component in the magnetization experiment as a function of the electron density in a magnetic field of 5 T and $T = 0.4$ K (solid line). The dashed line shows the expected behavior, see text. The value $d\mu/dB$ is indicated in units of the Bohr magneton μ_B.

A typical experimental trace of $i(n_s)$ in a parallel magnetic field of 5 T is displayed by the solid line in Fig. 1. A nearly anti-symmetric jump about zero on the y-axis (marked by the black arrow) separates the high- and low-density regions in which the signal is positive and negative, respectively.

Such a behavior is expected based on simple considerations. At low densities, all the electrons are spin-polarized in a magnetic field, so $d\mu/dB = -\mu_B$ (at $n_s = 0$, the capacitance of the system vanishes and, therefore, the measured current approaches zero). At higher densities, when the electron system is partially spin-polarized, $d\mu/dB$ is determined by the Pauli spin susceptibility χ and is expected to decrease with increasing n_s since the interaction-renormalized χ decreases due to reduction in the strength of electron-electron interactions. Finally, in the high-density limit, the spin susceptibility approaches its unrenormalized value χ_0 and $d\mu/dB$ should approach zero. Importantly, the onset of complete spin polarization in the electron system is given by the condition $d\mu/dB = 0$. This allows determination of the polarization field $B_c(n_s)$, as well as $\chi(n_s)$.

In Fig. 2(a), we show a set of curves for the experimental $d\mu/dB$ versus electron density in different magnetic fields. Experimental results in the range of magnetic fields studied do not depend, within the experimental noise, on temperature below 0.6 K (down to 0.15 K which was the lowest temperature achieved in this experiment). The position of the jump, corresponding to the onset of full spin polarization of the electrons, shifts to higher densities with increasing magnetic field. In Fig. 2(b), we show how these curves, normalized by magnetic field magnitude, collapse at high electron densities (*i.e.*, in the partially-polarized regime) onto a single "master curve". The existence of such scaling verifies linearity of the magnetization with B confirming that we deal with Pauli spin susceptibility of band electrons and establishes a common zero level for the experimental traces. Integration of the master curve over n_s yields $\chi = M/B$, which is another method for determining the spin susceptibility.

The third method for measuring B_c and χ relies on analyzing the magnetocapacitance, C. Experimental traces $C(n_s)$ are shown in Fig. 3(a) for different magnetic fields. As the magnetic field is increased, a step-like feature emerges on the $C(n_s)$ curves and shifts to higher electron densities. In Fig. 3(b), we subtract the $C(n_s)$ curves for different magnetic fields from the reference curve at $B = 0$. The step-like behavior of the magnetocapacitance, evident in the figure, reflects the fact that the thermodynamic density of states should drop (by a factor of two for non-interacting electrons) when the electrons' spins become completely polarized due to the lifting of the spin degeneracy. By marking the onset of full spin polarization as indicated by arrows in the figure, we obtain $B_c(n_s)$.

In Fig. 4, we show the summary of the results obtained using all three methods described above. The dependence $B_c(n_s)$, determined from the magnetization and magnetocapacitance data, is represented in Fig. 4(a).

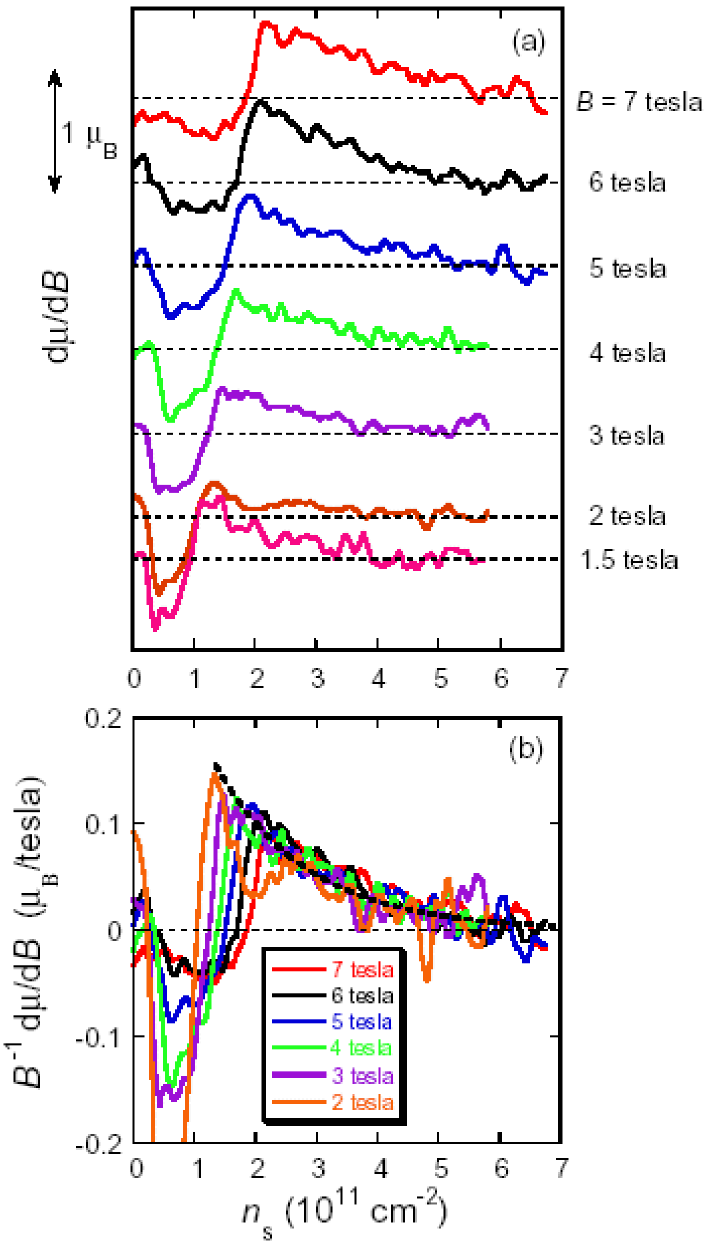

Figure 2: (a) The experimental $d\mu/dB$ as a function of electron density in different magnetic fields and $T = 0.4$ K. The curves are vertically shifted for clarity. (b) Scaling of the $d\mu/dB$ curves, normalized by magnetic field magnitude, at high electron densities. The dashed line represents the "master curve".

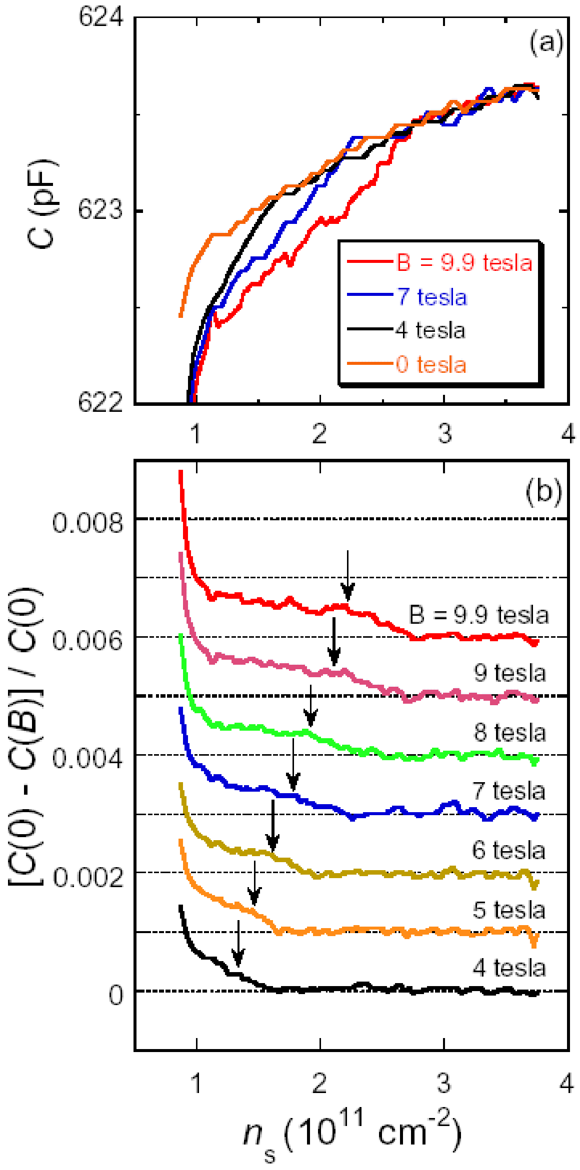

Figure 3: (a) Magnetocapacitance versus electron density for different magnetic fields. (b) Deviation of the $C(n_s)$ dependences for different magnetic fields from the $B = 0$ reference curve. The traces are vertically shifted for clarity. The onset of full spin polarization is indicated by arrows.

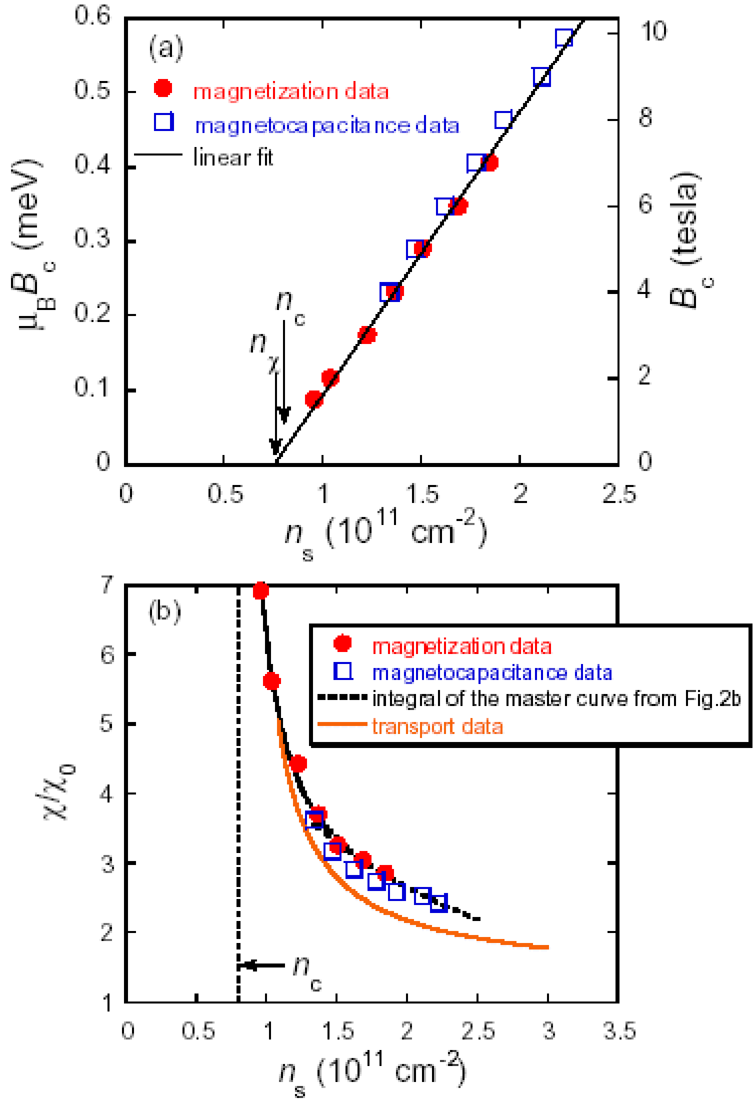

Figure 4: (a) Variation of the polarization field with electron density determined from the magnetization (circles) and magnetocapacitance (squares) data. The symbol size reflects the experimental uncertainty. The data for B_c are described by a linear fit which extrapolates to a density n_χ close to the critical density n_c for the metal-insulator transition. (b) Dependence of the Pauli spin susceptibility on electron density obtained by all three methods described in text. The dotted line is a guide to the eye. Also shown are the transport data of Ref. [6].

The two data sets coincide and are described well by a common linear fit which extrapolates to a density n_χ close to the critical density n_c for the MIT [5]. The expected curve for $d\mu/dB(n_s)$, shown as the dashed line in Fig. 1, has been calculated based on this fit and the relation $M = \mu_B n_s B/B_c$, where B/B_c is the degree of spin polarization. It describes the experiment reasonably well, although the value expected at low densities is different. The Pauli spin susceptibility versus n_s is plotted in Fig. 4(b). The agreement between the results obtained by all of the above methods is excellent. This establishes, in particular, that a possible influence of the diamagnetic shift is negligible in our experiment. There is also good agreement between these results and the data obtained by the transport experiments of Ref. [6], which adds credibility to the transport data; however, we note again that evidence for the phase transition can only be obtained from thermodynamic measurements. The magnetization data extend to lower densities than the transport data, and larger values of χ are reached, exceeding the "non-interacting" value χ_0 by almost an order of magnitude. (Note that the lowest accessible densities in our experiment are restricted by the condition that the jump in $d\mu/dB$ must be positioned in the metallic regime.) The Pauli spin susceptibility behaves critically close to the metal-insulator transition: $\chi \propto n_s/(n_s - n_\chi)$. This is in favor of the occurrence of a spontaneous spin polarization (either Wigner crystal or ferromagnetic liquid) at low n_s, although the origin of the low-density phase remains unclear because it is concealed by the insulating phase caused by residual disorder in the electron system.

In summary, the Pauli spin susceptibility has been determined by measurements of the thermodynamic magnetization and density of states in a low-disordered, strongly correlated 2D electron system in silicon. It is found to behave critically near the MIT, which gives thermodynamic evidence for a phase transition.

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References

[1] S.V. Kravchenko and M.P. Sarachik, Rep. Prog. Phys. **67**, 1 (2004).

[2] A.A. Shashkin, Physics-Uspekhi (in press); cond-mat/0405556.

[3] O. Prus, Y. Yaish, M. Reznikov, U. Sivan, and V. Pudalov, Phys. Rev. B **67**, 205407 (2003).

[4] In the sample used by Prus *et al.*, the band tail of localized electrons was present at all electron densities [3]. As a result, the measured magnetization was strongly nonlinear with magnetic field, and the extracted spin susceptibility had Curie temperature dependence characteristic of local moments (for more on this, see V.T. Dolgopolov and A. Gold, Phys. Rev. Lett. **89**, 129701 (2002) and Ref. [2]).

[5] The value n_c was determined from transport measurements (see Refs. [1, 2]).

[6] A.A. Shashkin, S.V. Kravchenko, V.T. Dolgopolov, and T.M. Klapwijk, Phys. Rev. Lett. **87**, 086801 (2001).