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Unexpected negative nonmonotonic magnetoresistance of the two-dimensional electrons in Si in parallel magnetic Field

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We report observation of the unexpected *negative and nonmonotonic* magnetoresistance of the 2D electrons in Si-MOSFET subjected to varying in-plane magnetic field, superimposed on a constant perpendicular field component. We show that this nonmonotonic magnetoresistance is irrelevant to the energy spectrum of mobile 2D electrons. We also observed variations of the density of mobile electrons with the in-plane field. We argue that both, variations of the negative magnetoresistance, and of the density of mobile electrons originate from the band of localized states. The latter ones coexist and interact with mobile electrons even at relatively high density, a factor of 1.5 higher than the critical density of the apparent metal-insulator transition.

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Properties of the dilute strongly interacting two-dimensional (2D) electron liquid, and, in particular, the apparent metal-insulator transition (MIT) in 2D remain challenging [1, 2]. One of the main problems here is to understand individual roles of two major driving forces, disorder and electron-electron (e-e) interactions. Purely interaction effects between mobile 2D electrons have been intensively studied both theoretically [3 – 9] and experimentally [10 – 14]; the role of disorder in these studies is limited to scattering of mobile electrons solely.

In contrast, the interplay of disorder and interactions, particularly, interaction between localized and mobile electrons is considered much rarely [15 – 17]; its experimental investigations are seldom. One might expect that the interplay should become more and more important as electron density decreases and approaches the critical density of the 2D MIT.

Usually, the presence of the localized states does not reveal itself in 2D transport, which is dominated by mobile electrons. The in-plane magnetic field, to the first approximation, does not couple to orbital motion, affecting only spins of mobile and localized electrons; for this reason, the in-plane field is a useful tool to study the localized states. Correspondingly, the influence of the localized states on the magnetotransport have been detected in Refs. [18 – 20] in strong in-plane field $g\mu B_{\|} \sim 2E_F$: under such conditions, the magnetoresistance (MR) and the field of its saturation have been found to depend on disorder (e.g., on sample mobility), and deviate from the behavior predicted for purely mobile electrons [5, 6].

In the current paper, we report observation of the negative and nonmonotonic MR in weak in-plane fields $g\mu B_{\|} \ll 2E_F$, which arises when a perpendicular component $B_{\perp}$ of the field is superimposed onto the in-plane component $B_{\|}$. Measurements have been made with a high-quality Si-MOS sample (peak mobility $2.4\,\mathrm{m}^2/\mathrm{Vs}$ at $T \approx 0.1\,\mathrm{K}$) in $^3\mathrm{He}/^4\mathrm{He}$ dilution refrigerator. The perpendicular and in-plane components of the magnetic field were independently controlled using the crossed-field set-up with two superconducting coils [10].

Figure 1 shows MR versus perpendicular field for dif-

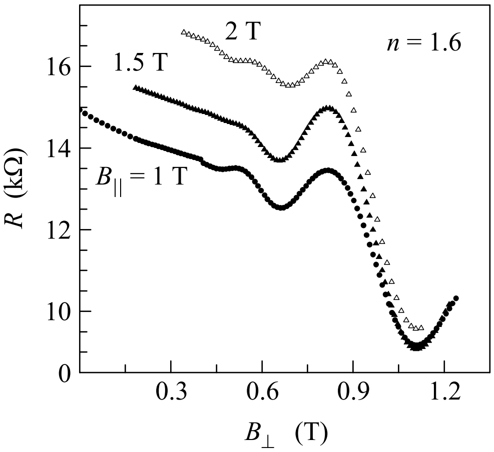

Fig.1. Shubnikov-de Haas oscillations in perpendicular field for three values of the in-plane field $B_{\|}$. Density is indicated in units of $10^{11}\,\mathrm{cm}^{-2}$

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ferent fixed $B_\parallel$ values. Starting the field of ~ 0.3 T (right after the weak localization suppression), on the top of the interaction-induced monotonic MR $\delta\rho_{xx}(B_\perp) \propto \propto -(\omega_c\tau)^2)$ [6], one can see conventional Shubnikov-de Haas (SdH) oscillations. Density values n quoted in the paper were determined from the period of these oscillations in perpendicular field. The oscillatory component $\rho_{xx}(B_\perp)$ is in a qualitative agreement with conventional theory of quantum oscillations.

In the purely in-plane field, for the density range studied $(1.1-2.2)\cdot 10^{11}\,\mathrm{cm}^{-2}$, the MR grows monotonically ($\propto B_\parallel^2$ in low fields) [11], in a qualitative agreement with the interaction-induced MR [5, 6]. However, when a fixed perpendicular field is applied and the in-plane field is swept, the MR varies in unexpected nonmonotonic fashion, as shown in Figs.2. First, the resistance decreases, passes through a minimum, and then starts rising as anticipated [5, 6]. For $n = 1.6\cdot 10^{11}\,\mathrm{cm}^{-2}$, the minimum occurs at $B_\parallel \approx 1.3$ T, as shown in Fig.2a. Second, the resistance exhibits weak oscillations; the oscillations are enlarged in Fig.2b by subtracting the monotonic background (fitted with the 2nd order polynomial). The field-positions of the two $\rho(B_\parallel)$ minima in Fig.2 depend on electron density and on $B_\perp$ field. We note that at higher densities and higher $k_Fl \gg 1$ values, these effects are not seen and the field dependence of $\rho_{xx}(B_\parallel)$ measured on these same samples becomes monotonic [11].

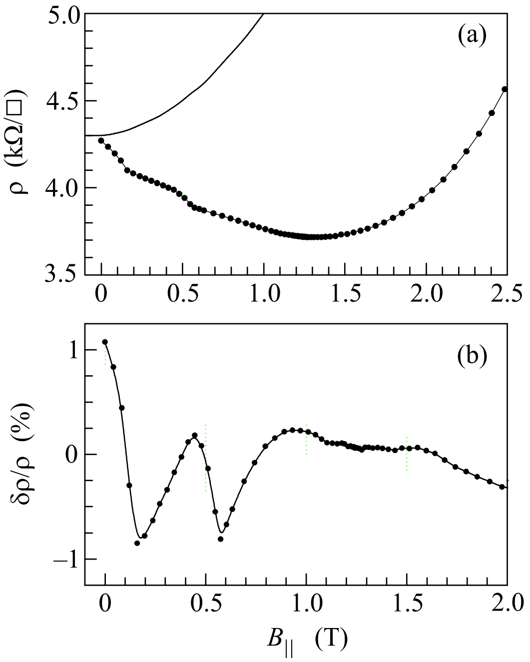

Fig.2. (a) Typical $\rho(B_\parallel)$ dependence in the presence of the $B_\perp$ field (dots); $\rho(B_\parallel)$ calculated according to Eqs. (1) and (2). (b) Oscillations $\delta\rho/\rho$ versus $B_\parallel$. Electron density $n = 1.6\cdot 10^{11}\,\mathrm{cm}^{-2}$, temperature $T = 0.2$ K, $B_\perp = 1.14$ T

The *monotonic* negative magnetoresistance versus $B_\parallel$ might be a result of the interaction-induced corrections to σ_{xx} [5, 6]:

$$\frac{\delta\rho_{xx}(B_\parallel)}{\rho_D} \approx -\left[1-(\omega_\perp\tau)^2\right]\frac{\delta\sigma^{ee}_{xx}(B_\parallel)}{\sigma_D}, \qquad (1)$$

where $\omega_\perp$ is the cyclotron frequency in the $B_\perp$-field, $\delta\sigma^{ee}_{xx}(B_\parallel)$ is *negative* and caused by magnetic field switching-off the spin-exchange processes in the triplet channel [5]:

$$\delta\sigma^{ee}_{xx} \approx \frac{k_BT\tau}{\hbar}\left[\frac{8F_0^a}{1+F_0^a}K_b(x)+K_d(x,F_0^a)\right], \qquad (2)$$

where the K_b and K_d are functions of $x = g^*\mu B_\parallel/k_BT$, as given in Refs. [5]. The line in Fig.2 shows the theoretical dependence calculated according to Eqs. (1) and (2), using the measured [10] value $F_0^a = -0.45$ for this density. The calculated dependence appears to be much stronger. Moreover, it describes a *positive* (rather than *negative*) MR, because for the given value $\omega_c\tau \equiv \mu B_\parallel = 0.76 < 1$, the square bracket in Eq. (1) is positive.

We conclude, therefore, that for low densities and low $k_Fl \sim 1$ values, the MR in $B_\parallel$ field is governed by mechanisms different from the purely interaction corrections [5, 6]; this conclusion is in accord with our earlier observations [19, 18]. In attempt to identify the origin of the $\rho(B_\parallel)$ oscillations, for each electron density, we have calculated the energy spectrum using the experimentally determined [10] renormalized m^* and g^*-factor values. Figure 3 represents an example of the calculated energy spectrum for one density and $B_\perp$ field value. In this plot, the energy levels vary as:

$$E_n\downarrow\uparrow = (n+\frac{1}{2})\hbar\omega_c^* \pm \frac{1}{2}g^*\mu\sqrt{B_\perp^2+B_\parallel^2}. \qquad (3)$$

For simplicity, we have neglected: (i) the quantum oscillations of the Fermi energy, (ii) $B_\perp$- and $B_\parallel$-field dependences of the effective mass and g-factor, and (iii) the valley splitting. We also presumed $E_F(0) = = n\pi\hbar^2/g_vm^*$, with m^* being the renormalized effective mass [10].

Considering the energy spectrum of mobile electrons, calculated with the above reasonably admitted assumptions, we find that it can not produce either the negative MR, or its oscillations. Indeed, the $B_\perp$ field of 1.14 T is chosen so that E_F lies in the middle of the energy gap; this is confirmed by Fig.1, where this field corresponds to the resistivity minimum. As $B_\parallel$ increases, the Fermi

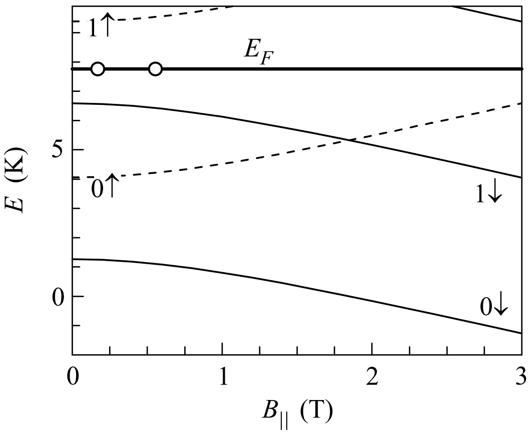

Fig.3. Energy spectrum of mobile 2D-electrons calculated for $n = 1.6 \cdot 10^{11}\,\mathrm{cm}^{-2}$, and $B_{\perp} = 1.14\,\mathrm{T}$, with the renormalized m^* and g^*-factor measured in Ref. [10]. Bold dots mark field positions of the measured MR minima. Bold line shows Fermi energy E_F, thin lines – energy levels for spin down (↓) and spin-up (↑) electrons. The levels are double-degenerate due to the two valley-spectrum

energy remains within the same energy gap until $\approx 4\,\mathrm{T}$ (see Fig.3); therefore, no oscillations can be anticipated until $B_{||} = 4\,\mathrm{T}$. In order to test, whether or not the presence of a *fixed* in-plane field causes unforeseen changes to the energy spectrum, we have made similar calculations of the energy spectra at varying $B_{\perp}$ field for each curves shown in Fig.1 (i.e. for $B_{||} = 1$, 1.5, and 2 T); the calculated spectra agree with the SdH oscillations. We conclude therefore, that the observed features in $R(B_{||})$ are not (solely) related with the energy spectrum of mobile 2D electrons.

In order to elucidate the origin of the unomalous oscillatory and negative MR (Fig.2), we plot in Fig.4 the typical density n of mobile electrons versus $B_{||}$ field, as determined from fitting the SdH oscillations [10] at fixed gate voltage value. The perpendicular field in these SdH measurements varied from 0.2 to 1 T to provide sufficiently high number of filled Landau levels (> 8) and a weak amplitude of the oscillations $\delta\rho/\rho \ll 1$. As Fig.4 shows, the density of mobile electrons *increases* slightly with the in-plane field; this does not correlate with either the energy spectrum (Fig.3) or with a weak monotonic dependence of the effective mass (and, hence, the Fermi energy) on $B_{||}$ [21, 22, 14] (note, that the frequency of SdH oscillations does not depend on m^* being dependent solely on the Landau levels degeneracy). Since the total charge in the Si-MOSFET (which is a plane capacitor) does not vary with $B_{||}$, we conclude, that there is a few % exchange of electrons between the reservoirs of 2D-mobile and localized states.

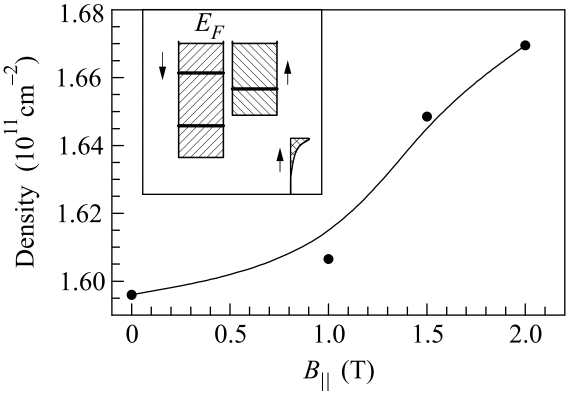

Fig.4. Typical dependence of the density of mobile electrons on the in-plane magnetic field, determined from the Shubnikov-de Haas oscillations period. Inset shows schematic energy diagram of the spin-up, spin-down and impurity bands, and direction of their motion with $B_{||}$ field. Energy spectrum corresponds to $B_{\perp} = 1.14\,\mathrm{T}$ and $B_{||} = 1\,\mathrm{T}$

The effects of exchange of electrons are natural in case the localized electrons fill the upper Hubbard band [15, 16]; the latter would float up towards the Fermi energy as density decreases. The upper Hubbard band is expected to be narrow [16], therefore, the in-plane magnetic field should quickly polarize it. The spin-polarization and motion of the band of localized states in the $B_{||}$ field may thus be the reason for the dependence of n on $B_{||}$ shown in Fig.4. The latter dependence, in its turn, explains semi-quantitatively the unexpected monotonic negative MR, $\Delta\rho$, as observed in $B_{||}$ field [see Fig.2a]: $\Delta\rho = (d\rho/dn)\Delta n(B_{||})$. With the experimentally determined value $d\rho(B = 0)/dn = 11.5k\Omega/\square$ per $10^{11}\,\mathrm{cm}^{-2}$ (for this same gate voltage) and $\Delta n(B_{||}) = 5 \cdot 10^{9}\,\mathrm{cm}^{-2}$ (see Fig.4), we anticipate the decrease in $\rho(B_{||}) = 0.6k\Omega/\square$ in the field range $B_{||} = 0 - 1.5\,\mathrm{T}$, which agrees well with the monotonic negative magnetoresistance, shown in Fig.2.

The nonmonotonic variation of the MR may also result from the peaked structure of the Hubbard band. The role of the $B_{\perp}$-field in this picture is to produce the ladder structure of the density of states in the band of mobile electrons, Eq. (1); this ladder moves with in-plane field relative to the peaked Hubbard band. Therefore, the nonmonotonic MR is not seen in purely in-plane field, though the localized band contributes a sample-dependent monotonic part to the in-plane field magnetoresistance [19, 11, 18]. An interesting question is whether or not the density of mobile electrons varies solely with $B_{||}$ or with $B_{\perp}$ field, however answering this question poses a difficult technical challenge.

To summarize, for the low-density 2D electron liquid in Si ($n \sim 10^{11}$ cm^{-2}, close to but noticeably larger than the critical density), we observed an unexpected negative and oscillatory magnetoresistance in the in-plane magnetic field, when a weak perpendicular component of the field is superimposed onto the in-plane field. Analysis of the features in MR shows that the negative MR and its oscillations are irrelevant to the energy spectrum of mobile electrons. We also observed a concomitant weak variation of the density of mobile electrons with $B_{||}$. The density variation is likely to cause the unexpected negative MR. We believe, the observed effects hint at the involvement of the localized states into the transport at low densities; the latter may supply the electrons to and from the band of extended states even at density as high as 60% larger than the critical density of the M-I transition. In other words, the observed effects evidence for the hybridization of mobile and localized carriers in the vicinity of 2D MIT. As electron density decreases and approaches the critical value of the MIT, the interaction between the localized and extended states is expected to grow. The interaction between the mobile and localized states, which is often ignored, may play an essential role in the overall phenomenon of the 2D MIT.

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