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LOGARITHMIC TEMPERATURE DEPENDENCE OF THE CONDUCTIVITY OF THE TWO-DIMENSIONAL METAL

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We report on the first observation and studies of a weak delocalizing logarithmic temperature dependence of the conductivity, which *increases* the conductivity of the 2D metal as T *decreases* down to 16 mK. The prefactor of the logarithmic dependence is found to decrease gradually with density, to vanish at a critical density, $n_{c,2} \sim 2 \cdot 10^{12}$ cm^{-2}, and to have opposite sign further at $n > n_{c,2}$. The second critical density sets the upper limit on the range of existence of the 2D metal, whereas the conductivity at the critical point, $G_{c,2} \sim 120\, e^2/h$, sets an upper (low temperature) limit on its conductivity.

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Recently, a metal-insulator (M-I) transition and a metallic state have been observed in the strongly interacting two-dimensional (2D) carrier systems in Si-MOS structures [1], and confirmed later on n- Si-MOS [2], n- and p- Si/SiGe [3, 4], and p- GaAs/AlGaAs structures [5, 6]. This finding is in apparent contradiction to the commonly accepted one-parameter scaling theory (OPST) [7] for non-interacting particles, and has initiated a debate over the nature of the 2D metal [8 – 14].

Among the properties of the 2D metallic state, a striking exponential dependence of the resistance was found to exist over all range of the metallic densities, $n > n_{c,1} \sim 10^{11}$ cm^{-2}, at temperatures $T \ll E_F$ [12, 15]:

$$\rho = \rho_0 + \rho_1 \exp(-(T_0/T)^p), \qquad (1)$$

where $p \approx 1$, and T_0 is sample and density dependent. The above empirical law has obtained recently a theoretical interpretation [10, 16].

Since the above temperature dependence is reminiscent of the quasi-classical contribution of two scattering processes, there was not much evidence for a quantum origin of the phenomena in total. More over, it was earlier discussed [17], that the resistivity of the 2D gas may decrease $\propto (T/E_F)$ as T decreases, due to the temperature dependence of the screening length and, hence, of the random potential. Another classical reasoning invoked earlier [18] is related to valley multiplicity, which may result in additional inter-valley scattering of the electrons. The current studies were performed in order to verify whether or not the 2D metal has something in common with a quantum theoretical picture, being presently intensively studied.

We have made ac-measurements of the conductivity on two different, high mobility, n-Si-MOS structures at low dissipated power, with high precision, and at low

temperatures $T \ll E_F$. In this paper, we present experimental data which reveal, for the first time, a weak logarithmic temperature dependence of the conductivity persisting down to 16 mK, which gives a positive contribution to conductivity in the range from $G \approx 10$ up to $G = 120$ (conductivity through the paper is given in unites e^2/h, and resistivity $\rho = 1/G$). Our data confirm that the 2D metallic state, once formed by increasing the carrier density n above $n_{c,1}$, remains stable as $T \to 0$. We have found the upper critical density, $n_{c,2}$, at which the delocalizing logarithmic temperature dependence vanishes and further turns into the localizing one. It is not clear so far whether this point is an attractive focus or the critical point, anyhow it provides a finite conductivity value as temperature decreases or density increases.

We studied resistivity of two Si-MOS samples, with peak mobilities, $\mu =$ $= 41,000\,\mathrm{cm}^2/\mathrm{Vs}$ (Si-15a) at $T = 0.3\,\mathrm{K}$ and $\mu = 19,600$ (Si-43). Measurements were taken by a 4-terminal ac-technique in the temperature range from 0.28 K to 15 K, by precise sweeping the temperature during about 5 h, and 0.016 K to 3 K (for a few temperature points).

As described by Eq. (1), the exponential drop saturates at low temperatures. In order to reveal a weak quantum correction to the conductivity, and to separate it from the strong exponential dependence (1), measurements have to be performed at $T \ll T_0$, in the range of the apparent saturation of the exponential temperature dependence, Eq. (1). This can be achieved most effectively in the limit of high carrier density (high T_0, and high G) and low temperatures. The typical results measured in this extreme regime, are represented in Fig. 1 for a few carrier densities.

Full lines in Fig. 1 represent the empirical exponential function, $G \sim [\rho_0 +$ $+ \rho_1 \exp(-T_0/T)]^{-1}$, where the data were fitted with three parameters, ρ_1, ρ_2, and T_0 [12, 15]. This function saturates below a certain temperature, T^*, whereas the measured temperature dependence of G is crossing over to a weak dependence, which is linear in a $\ln T$ scale, $\delta G = C_T \ln(T/T^*)$.

For both samples, over a wide range of density, $\sim 1 \cdot 10^{11}$ to $\sim 20 \cdot 10^{11}$, this logarithmic dependence has a negative prefactor, i.e. it is delocalizing, thus driving the system to higher conductivity as temperature decreases. At relatively low G and low n (as shown in Fig. 1 a), the prefactor, $C_T = -0.4 \pm 0.1$, is of the order of the typical value u_v/π [19], where $u_v \sim (2-1)$ is due to the contribution of two valleys in (100) Si-MOS structures. At even lower density, close to $n_{c,1}$, the derivative $d\rho/dT$ remains positive down to 16 mK, however, the strong exponential dependence Eq. (1) does not allow to reveal a weak logarithmic dependence in the limited temperature range.

As density increases, the prefactor, C_T, gradually decreases and almost vanishes to zero at $n = 23.7 \times 10^{11}\ \mathrm{cm}^{-2}$, which corresponds to $G_{c,2} = 120.5$. Fig. 2 shows a typical density dependence of C_T for the sample Si-43. At $n = n_{c,2} \approx 25 \cdot 10^{11}\ \mathrm{cm}^{-2}$ the prefactor crosses the abscissa and further, at $n > n_{c,2}$, has opposite sign. The positive logarithmic prefactor indicates a weakly localized state in the limit of low-temperatures, whereas at $T > T^*$ the derivative $d\rho/dT$ remains positive. The similar dependence of C_T was found for the sample Si-15, with $G_{c,2} \approx 122$.

On the first sight, the positive sign of C_T is consistent with the recent calculations of the quantum corrections for a 2D non-interacting chiral system [13, 14] as well as consistent with the spin-orbit scattering model [19]. However, the strong reduction of the prefactor C_T with density has no correlation with the relevant spin-orbit and disorder

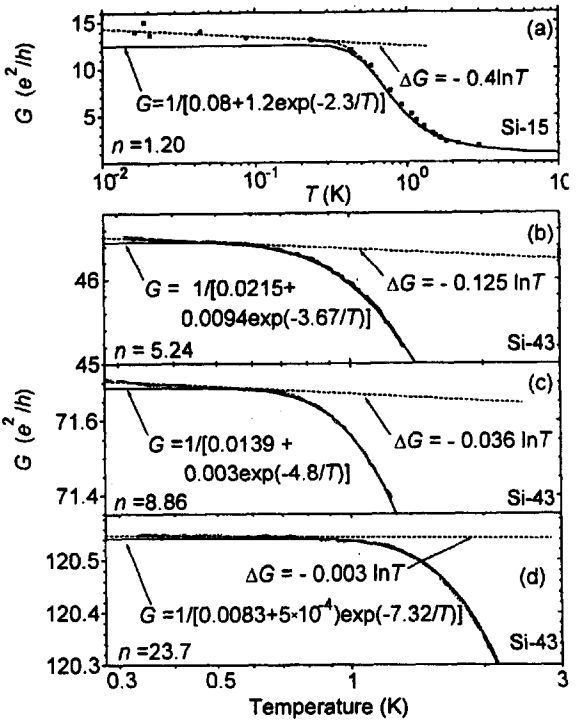

Fig.1. Temperature dependence of the conductivity in the low temperature limit, (a) for Si-15a at low electron density, and (b), (c) and (d) for Si-43 in a wide range of electron densities (indicated in units of 10^{11} cm^{-2}). To provide the required signal/noise ratio, every data point was averaged during 0.5 to 2 minutes. The continuous lines show the best fits by the exponential dependence Eq. (1), dashed lines show the logarithmic temperature dependence

parameters [13] $\Delta\tau$ and $k_F l$: both of them remain $\gg 1$ up to the density $n_{c,2}$ where C_T vanishes. Therefore, we presume, the observed weak delocalization is related to electron-electron interaction [20]. The existence of the 2D metallic state in the limited range of densities, from $n_{c,1} = 0.8$ to $n_{c,2} = 25 \cdot 10^{11}$ cm^{-2}, or correspondingly, from $r_s = 10$ to 1.8, is, evidently, in agreement with a consideration based on Coulombic interaction [20, 11].

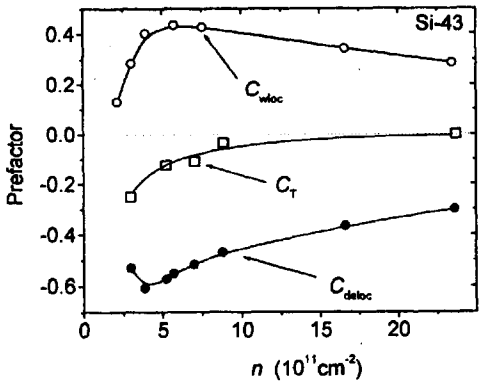

Fig.2. Density dependence of the logarithmic temperature prefactors: (i) the total prefactor of the zero field temperature dependence $C_T(n)$ (squares symbols), (ii) the prefactor for the localizing term $C_{wloc}(n)$ (open circles), and (iii) the purely delocalizing term, $C_{deloc}(n)$ (full circles)

The measurements performed on both samples have revealed qualitatively similar temperature and density dependence of the conductivity, shown in Figs. 1 and 2. However, the magnitude of the prefactor C_T was different, with the difference increasing from $\sim 10\%$ at high density, to a factor of 1.5 at low density, which is beyond the error limit. The

prefactor C_T may roughly be represented by a sum of two large prefactors having opposite signs (see e.g., Eq. (2.104) in Ref. [20]), both of which are disorder dependent:

$$C_T = C_{deloc} + C_{wloc}. \tag{2}$$

Here the positive C_{wloc} is due to the single-particle quantum interference ("backscattering"), and the negative C_{deloc} is an interaction contribution.

Motivated by this interpretation, we have also measured the negative magnetoresistance in the perpendicular magnetic field [21]. This effect is known to be due to the magnetic field suppression of the single-electron quantum interference. The analysis of the $R(H)$ data, thus yields the "localizing" term in the logarithmic temperature dependence [22], $C_{wloc} \ln T$ (where $C_{wloc} > 0$). The localizing prefactor shown in Fig. 2, reaches a peak value, $C_{wloc} \approx 0.4$ at density $n = 5 \cdot 10^{11}\,\mathrm{cm}^{-2}$; it decays sharply (by 2 times) as density decreases to $n_{c,1}$, and gradually decreases as density increases. The difference of the total and localizing corrections, $C_{deloc} = C_T - C_{wloc}$, shown in Fig. 2, represents thus an estimate for the purely delocalizing quantum correction [20]; it decays with density $\propto n^{-0.48}$ at $n > 3 \cdot 10^{11}\,\mathrm{cm}^{-2}$.

With these results, the overall temperature dependence of the resistivity given by Eq. (1) should be generalized as follows:

$$\rho = \begin{cases} \rho_0 + \rho_1 \exp(-(T_0/T)^p) & \text{at } T > T^*, \\ \rho_0 - \rho_0^2 C_T \ln(T/T^*) & \text{at } T < T^*, \end{cases} \tag{3}$$

where T^* is the sample and density dependent crossover temperature, varying from $T^* = 0$ at $n = n_{c,1} \approx 0.8 \cdot 10^{11}\,\mathrm{cm}^{-2}$ to $T^* \approx 1\,\mathrm{K}$ at $n = 10 \cdot 10^{11}\,\mathrm{cm}^{-2}$.

Eq. (3) corresponds to a non-universal, density dependent scaling function $\beta = d\ln G/d\ln L$ [16], raising with G proportionally $\ln(G/G_{c,1})$ at $T > T^*$ and at $G > G_{c,1} \sim 1$, and gradually falling with G roughly $\propto (C_T/G)$ at $T < T^*$ and at $G_{c,2} > G \gg 1$. Here, all parameters, $G_{c,1}$, $G_{c,2}$, T^*, and C_T are density dependent [15], and β equals to zero at two points, $n = n_{c,1}$ and $n_{c,2}$.

In summary, we have observed the persistence of the metallic state in the conductivity range up to $G = 120$, and down to temperatures as low as 16 mK. Experimentally, a weak logarithmic temperature dependence of the conductivity was found, which *increases the conductivity of the 2D metal as T decreases.* The pronounced logarithmic temperature dependence provides a strong evidence for the quantum origin of the 2D metallic state that emerges as temperature decreases. We have found the second critical density $n_{c,2}$, where the delocalizing logarithmic correction vanishes to zero, and hence, the conductivity stops growing, $d\ln G/d\ln L = 0$. The interpretation of this point either as an attractive stable focus point, or as the second critical point requires additional studies. In any case, the existence of this point provides a *non-zero value of the conductivity as T decreases to zero or as density grows.*

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