# Single-parameter scaling and conductance of 2D systems at the silicon surface

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The temperature dependence of the conductance of a 2D hole gas in field-effect silicon transistors is found to be determined solely by the conductance. This result is a compelling argument in support of the existence of a single-parameter scaling in systems with a strong spin-orbit coupling.

The question of whether a metal-insulator transition in disordered systems can be described in terms of a single-parameter scaling[1] has not yet been resolved. The existence of a single-parameter function $\beta(g) = d \ln g(L)/d \ln L$ (for 2D systems $g = R_{\square}^{-1} \hbar/e^2$, $R_{\square}$ is the surface resistivity, and $L$ is the size of the square-shaped sample), which describes the transition, was initially hypothesized[1] for a system of noninteracting electrons. The validity of this assumption is still being questioned.[2,3] The electron-electron interaction compounds this problem.[4,5] The method[6] used for experimental verification of the single-parameter scaling involves measuring the quantity $\beta_e = -d \ln g/d \ln T$. This method is based on some additional assumptions that there is a temperature-dependent length $L_T$, above which the conductance no longer depends[1] on $L$. The shape of the temperature dependence $L_T(T)$ in this case is determined solely by $g$.[6] If, for example, $L_T \sim T^{-\gamma}$ and $\gamma = \gamma(g)$, the function $\beta_e$ measured experimentally will depend exclusively on the conductance $g$: $\beta_e = \gamma(g)\beta(g)$.

Experiments carried out with different objects yielded different results. On the basis of measurements[6] using inversion electron channels of silicon field-effect transistors it was concluded that there is no single-parameter scaling. A single-parameter form of the function $\beta_e(g)$ was later observed for ultrathin $Bi_{14}Te_{11}S_{10}$ crystals[7] and surface conducting layers near the cleaved Ge surface and the intergrowth boundary between germanium bicrystals.[8]

In this letter we show that the temperature dependence of the conductance for various carrier densities in a 2D hole gas of field-effect silicon transistors can be described in terms of a single-parameter scaling[1] with the function $\beta_e(g)$, which is approximately equal to the function determined in Refs. 7 and 8. The results which we obtained confirm that the corrections to the conductance, which were predicted in Ref. 4 and which are due to the electron-electron interaction, are universally applicable in systems with a strong spin-orbit scattering. These results also make it possible to link the negative results of Ref. 6 with the corresponding weak scattering in the electron channels.

We have measured the function $\beta_e(g)$ using two field-effect silicon transistors with a $p$-type channel. The surface of the samples was oriented in the (100) and (111) planes and the thickness of the $SiO_2$ oxide layer was $\sim 1200$ Å. The maximum carrier mobility at liquid-helium temperature was $\mu \approx 1500$ cm$^2$/(V·s) for a sample with a (100) orientation and $\mu = 1100$ cm$^2$/(V·s) for a (111) orientation. The measurements were carried out with the help of an active alternating-current bridge at a frequency of 12 Hz using a four-point scheme. The quantity $\beta_e = -(\overline{T}/g)(\Delta g/\Delta T)$ was determined experimentally. In the measurements $\Delta T$ comprised approximately 5% of the mean value of the temperature, $\overline{T}$. The relative accuracy of the measurement of $\Delta g$ and $\Delta T$ was within 5%. The temperature interval was 4.2–1.3 K.

The value of $\beta_e$ changed as a result of changing two parameters—charge carrier density and temperature. The experimental results in Fig. 1 show, however, that $\beta_e$ is, in fact, a function of only a single parameter—the conduction. Here the function $\beta_e(g)$ is the same for samples of different orientations. The difference between the samples which is seen at $g \gtrsim 0.2$ [for the (100) orientation $\beta_e$ is greater than zero at $g \gtrsim 0.3$] apparently stems from the temperature dependence of the screening (see, e.g., Ref. 9). The experimental results of Refs. 7 and 8 are also shown in Fig. 1. The approximate equality of the function $\beta_e(g)$ for such a variety of objects shows, in our view, that the scaling theory is applicable to these systems. In contrast with the electrons, the holes in silicon are linked to systems with a strong spin-orbit coupling.[10] The conducting surface layers of germanium[11] and the electrons in $Bi_{14}Te_{11}S_{10}$ apparently possess the same property. The detection of single-parameter functional dependences $\beta_e(g)$ in these objects is in qualitative agreement with the predictions[4] that the quantum corrections associated with the electron-electron interaction are universally appli-

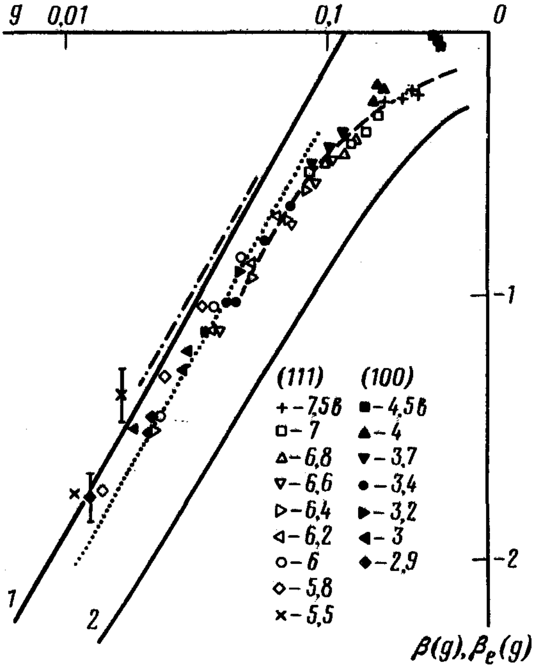

FIG. 1. The experimental values of $\beta_e(g)$ measured at various transistor gate voltages and at various temperatures, for the (111) and (100) orientations. The same signs correspond to the given charge-carrier concentration. Dot-dashed line and dotted line—the experimental functions $\beta_e(g)$ from Refs. 7 and 8, respectively.

cable in the presence of a strong spin-orbit coupling. The theory[4] of quantum corrections operates when $g \gg 1$. If the effects in the Cooper interaction channel are ignored, this theory yields $\beta(g) = -1/2\pi^2 g$. This functional dependence, which we extrapolated to the region $g \ll 1$ where the experiment was carried out, is represented by the dashed curve in Fig. 1. The solid curves 1 and 2 are respectively the results of numerical[13] and analytic[14] calculations of the function $\beta(g)$ for the noninteracting electrons in the absence of spin-orbit scattering. It should be noted that at $g \lesssim 1$ a direct comparison of $\beta_e(g)$ and $\beta(g)$ is difficult because of the presence of the proportionality coefficient $\gamma$ between them.[1)] In light of our study and taking into account the results of the theory of Ref. 4, it is thus natural to attribute the negative result of Ref. 6 to the observation that electron-electron interaction is not a universal occurrence in the system with a weak spin-orbit coupling such as the electron channels of silicon. The discrepancy between the results of the scaling theory and the experiment can thus be reconciled.

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[1)] For $g \gg 1$ we would expect $\gamma = \text{const} \approx 0.5$ for holes in silicon.[10,15]

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[1] E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. **42**, 673 (1979); **43**, 718 (1979).
[2] K. B. Efetov, Pis'ma Zh. Eksp. Teor. Fiz. **41**, 508 (1985) [JETP Lett. **41**, 619 (1985)].
[3] B. L. Al'tshuler, V. E. Kravtsov, and I. V. Lerner, Zh. Eksp. Teor. Fiz. **91**, 2276 (1986) [Sov. Phys. JETP **64**, 1352 (1986)].
[4] B. L. Altshuler and A. G. Aronov, Solid State Commun. **46**, 429 (1983).
[5] A. M. Finkel'shteĭn, Pis'ma Zh. Eksp. Teor. Fiz. **37**, 436 (1983) [JETP Lett. **37**, 517 (1983)].
[6] R. A. Davies, M. Pepper, and M. Kaveh, J. Phys. C: Solid State Phys. **16**, L285 (1983).
[7] H. H. Soonpaa and W. A. Schwalm, Phys. Lett. **100A**, 156 (1984).
[8] É. I. Zavaritskaya and I. I. Zvyagin, Pis'ma Zh. Eksp. Teor. Fiz. **41**, 393 (1985) [JETP Lett. **41**, 482 (1985)].
[9] A. Gold and V. T. Dolgopolov, Phys. Rev. B **33**, 1076 (1986).
[10] G. M. Gusev, Z. D. Kvon, and V. N. Ovsyuk, Zh. Eksp. Teor. Fiz. **88**, 2077 (1985) [Sov. Phys. JETP **61**, 1228 (1985)].
[11] B. M. Vul and É. I. Zavaritskaya, Zh. Eksp. Teor. Fiz. **76**, 1089 (1979) [Sov. Phys. JETP **49**, 551 (1979)].
[12] H. H. Soonpaa and W. A. Schwalm, Solid State Commun. **42**, 201 (1982).
[13] P. A. Lee, Phys. Rev. Lett. **42**, 1492 (1979).
[14] D. Vollhardt and P. Wölfle, Phys. Rev. Lett. **48**, 699 (1982).
[15] B. L. Altshuler, A. G. Aronov, and D. E. Khmelnitsky, J. Phys. C: Solid State Phys. **15**, 7367 (1982).

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