Electron solid at the Si surface in zero magnetic field?

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We report the observation of an electric field threshold conduction and saturation of the current-voltage characteristics which are accompanied by ac voltage generation in low-density two-dimensional electron layer at the Si surface in zero magnetic field. The observed effects seem to be inconsistent with single-particle conduction and support the formation of a pinned quantum electron solid in zero magnetic field.

At low temperatures and zero magnetic field, a low-density, two-dimensional ($2D$) electron system becomes an insulator due to the single-particle localization or formation of a pinned electron solid.[1] Both cases are characterized by activated temperature dependence of the resistance. However, nonlinear transport measurements can help to understand the nature of the ground state (see, for example, Ref. 2). Although both single-electron and many-body localization can be destroyed by an application of sufficiently high electric field,[3,4] the critical (threshold) electric fields E_{th} differ by several orders of magnitude for these two mechanisms. Another distinct feature of the electron solid transport is generation of ac voltage at very low dc currents.[2,5] In addition, the transport in the presence of the electron solid is often characterized by extremely long equilibration times.[2,5]

So far, the $2D$ electron solid in zero magnetic field has been observed only for electrons in helium[6,7]; the electron solid in this system is *classical* since the disordering

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thermal energy, $k_B T$, dominates the Fermi energy, $\varepsilon_F = \hbar^2 \pi n_s / m^*$, due to the rather low available electron concentration, $n_s < 10^9$ cm^{-2} (here m^* is the effective mass). Electron solid at a semiconductor surface was observed only *in a magnetic field* in GaAs/(AlGa)As heterostructures (see, for example, Refs. 5,7, and 8 and the bibliography cited there) and Si MOSFET's.[9–11] The presence of a magnetic field is known to help the formation of the electron solid[12] by quenching the vibrational motion of electrons. It was clearly shown[7] that zero-magnetic-field electron solid cannot exist in GaAs/(AlGa)As heterostructures. As for Si inversion layers, the situation in $H=0$ was not clear.

In this letter we report *zero-magnetic-field* nonlinear transport and noise measurements of a low-density $2D$ electron layer at the Si surface. The data clearly show that electric field has a threshold behavior, and that saturation of the current-voltage characteristics is accompanied by ac voltage generation. The results seem to be inconsistent with single-particle conduction and support the collective nature of the effect.

The results presented below were obtained with a Si MOSFET of the Corbino geometry with a source-drain spacing of 82 μm. The typical electron mobility of samples from this wafer was 2 m^2/Vs. We measured the I-V characteristics by applying a slowly swept (0.04–0.2 nA/min) dc source-drain current, I, and measuring the dc voltage, V, between the source and the drain. Simultaneously we detected the amplitude of the ac voltage generated in the sample in the frequency range 1-10^5 Hz.

Typical I-V characteristics, obtained upon increasing the current, are shown in Fig. 1. At a relatively high electron concentration, the I-V characteristics are linear. Nonlinearity appears at $n_s \approx 1.46 \times 10^{11}$ cm^{-2} (the lowest curve), accompanied by irregular pulses with a characteristic period >1 sec. Lowering n_s further leads to a saturation of the I-V characteristics; V_{sat} increased upon lowering n_s, which is at the same time nearly independent of the temperature at $T \leqslant 1$ K. Note that V_{sat} for the upper curve differs for negative and positive currents due to the influence of V on n_s, which becomes noticeable when $V > 50$ mV.

There is a clearly visible lag near $I=0$ in the two upper I-V curves: V becomes zero not at $I=0$ but at $I \simeq 0.1$–0.2 nA; this corresponds to a time delay $\Delta r \simeq 0.5$–1 min, which is much higher than the time constant of the DVM ($\simeq 3$ sec). The lag cannot be due to recharging of a shunting capacitance of the connecting wires (~ 100 pF) and of the sample (20 pF): even for infinite sample resistance, $\Delta r \sim 3$ s for $V_{th} \sim 100$ mV.

Figure 2a shows the voltage dependences of the differential resistance, dV/dI, normalized by the zero-current resistance, $R(0)$. These dependences were extracted from the I-V measurements at very slowly decreasing current (40 pA/min). At $|V|$ below the threshold value, the differential resistance remains almost constant, while after exceeding the threshold value, dV/dI decreases sharply (e.g., from 1.2 GΩ to 13 MΩ for the upper curve). Above $n_s \approx 1.4 \times 10^{11}$ cm^{-2}, the threshold behavior disappears (the lower curve). Almost at the same V_{th}, the broadband noise (ac voltage) abruptly appears (Fig. 2b) against the background of the instrumental noise (which is nearly independent of V). Upon increasing T or n_s, the excess noise disappears over all ranges of V and I.

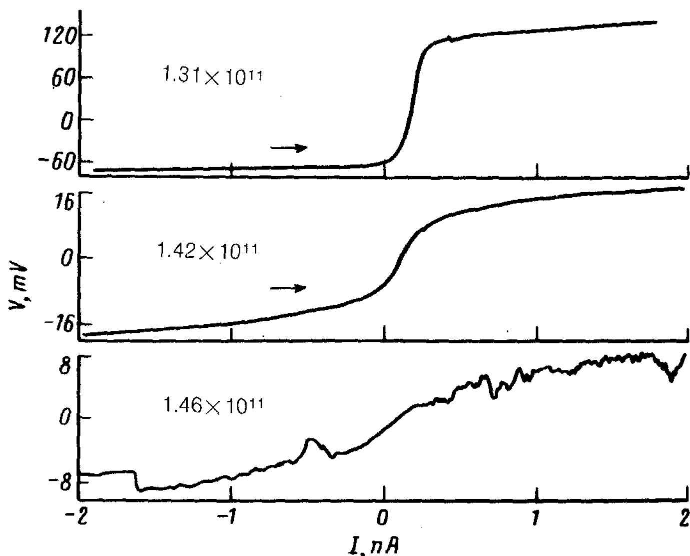

FIG. 1. I-V characteristics for three different n, at $T = 350$ mK. The numbers on the graphs show n, in units of cm^{-2}.

The observed nonlinearity can hardly be explained by the Joule heating or by electric field breakdown of the single-particle localization. Although the simple Joule heating can lead to zero or even negative dV/dI, the condition for saturation of the I-V characteristic[13] would require the specific temperature dependence of the resistance (for small power inputs, where the response is linear): $R(T) \propto (T - T_0)^{-1}$ (here T_0 is the temperature at $I = 0$). This dependence evidently cannot take place at least over a wide range of T_0 and $I \cdot V$. In addition, the almost constant differential resistance below the threshold, the abrupt appearance of the noise, and the long equilibration times near $I = 0$ are inconsistent with this mechanism of nonlinearity.

As for the destruction of a single-particle localization by an electric field, the field must be sufficiently high to supply an electron with an energy higher than the binding energy, W_b: $E_{th}^{1p} \sim W_b/el$; here e is the electron charge and l is the mean free path, which, according to the Ioffe-Regel criterion of the strong single-particle localization,[1] must be less than $(2\pi k_F)^{-1}$. W_b must be at least higher than $k_B T$, where T is the temperature at which the threshold still exists (~ 1.5 K). Therefore, the minimum value of E_{th}^{1p} is estimated to be $2\pi k_F k_B T/e = 2\pi k_B T(\pi n_s)^{1/2}/e \sim 10^2$ V/cm, which is two orders of magnitude higher than that observed experimentally, $E_{th} \approx 3$ and 6 V/cm (see Fig. 2a). Estimate of E_{th}^{1p} for strong single-particle localization on the basis of Ref. 3 also gives a too high threshold electric field: $E_{th}^{1p} \sim 2 \times 10^3$ V/cm for $n_s = 10^{11}$ cm^{-2}.

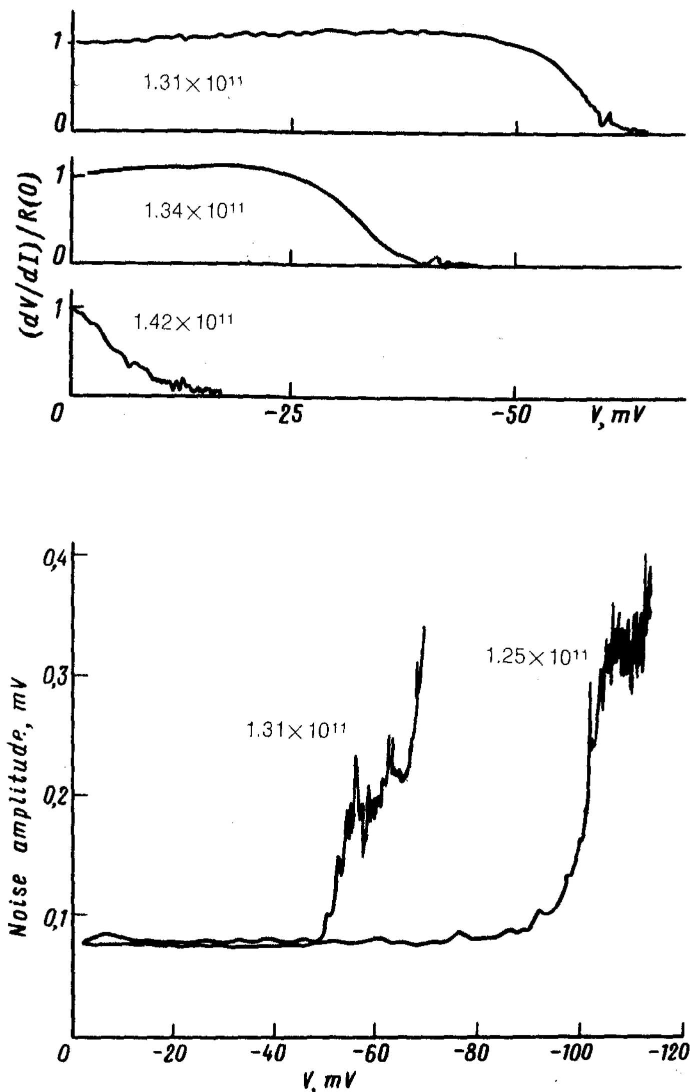

FIG. 2. Dc voltage dependences of the differential resistance (a) and noise amplitude (b) at $T = 350$ mK.

However, the low-electric-field threshold conduction is a characteristic feature of the electron solid transport. According to the two-fluid model,[2] the conduction at $E < E_{th}$ can exist due to single-particle excitations across the gap between the ground state (pinned electron solid) and the excited state (electron gas) and has an ohmic character. The electric field above E_{th} depins the electron solid and makes it slide.

This additional channel of conductivity reduces the resistance (see, e. g., Refs. 2 and 5) and can even lead to saturation of the I-V curves.[8,11] Since the I-V characteristics in Fig. 1 are similar to those mentioned above, we assume that in the zero-field case above the threshold the conductivity is also related to the sliding solid. The noise which appears simultaneously with the depinning of the solid and which accompanies its sliding is believed to be the consequence of the "jerking" of the electron solid across the random potential.[2,5] The very high equilibration times (>1 h) of the dc voltage near $I=0$ have also been observed for charge-density waves transport[2] and for Wigner solid[5]; according to Ref. 2, this "glassy" behavior suggests the absence of long-range order for a pinned electron solid.

Electron solid at the Si surface at low temperatures can be only a *quantum* solid, since for the available electron densities the Fermi energy exceeds the thermal energy ($\varepsilon_F \approx 7$ K per 10^{11} cm^{-2}). The cold melting of the electron solid is expected[1] at $n_c = \pi^{-1}(m^*e^2/r_c\varepsilon\hbar^2)^2$ (here ε is the dielectric constant and r_c is a dimensionless constant; estimates of its value vary over a wide range 4.5 (Ref. 14) to 33 (Ref. 15). For electrons at a Si surface, the higher effective mass and the lower mean dielectric constant increase the cold melting concentration by a factor of 20 in comparison with that for the GaAs heterostructures: $n_c \approx 10^{10}$–6×10^{11} cm^{-2}. This interval includes $n_c \approx 1.5\times10^{11}$ cm^{-2} observed in our experiments. More precise estimates[12] give $n_c \approx 8\times10^{10}$ cm^{-2} for an ideal crystal (in the absence of disorder) and $\approx 1.5\times10^{11}$ cm^{-2} for a concentration of pinning centers $n_p \sim n_s/10$.

In summary, we have observed nonlinear transport properties which support the formation of a pinned electron solid at the Si surface in zero magnetic field. The characteristic electron densities at which the effects exist are in agreement with theoretical predictions[12,14]; however, these values are much higher than those expected in, e.g., Ref. 15. Further experiments should shed more light on the nature of the ground state of $2D$ electrons at the Si surface in zero magnetic field.

[1]T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).
[2]G. Grüner, Rev. Mod. Phys. **60**, 1129 (1988).
[3]Y. C. Lee, C. S. Chu, and E. Castano, Phys. Rev. B **27**, 6136 (1983).
[4]P. A. Lee and T. M. Rice, Phys. Rev. B **19**, 3970 (1979).
[5]V. J. Goldman *et al.*, Phys. Rev. Lett. **65**, 2189 (1990).
[6]C. C. Grimes and G. Adams, Phys. Rev. Lett. **42**, 795 (1979).
[7]D. C. Glattli *et al.*, Surf. Sci. **229**, 334 (1990).
[8]F. I. B. Williams *et al.*, Phys. Rev. Lett. **66**, 3285 (1991).
[9]S. V. Kravchenko, J. A. Perenboom, and V. M. Pudalov, Phys. Rev. B 1991 (in press).
[10]S. V. Kravchenko, J. A. Perenboom, and V. M. Pudalov, in *Proceedings of the 9th Conference on Electronic Properties of 2D Systems,* Nara (Japan), 1991, p. 320; Surf. Sci., 1992 (in press).
[11]M. D'Iorio *et al.*, Surf. Sci. (in press) (1992).
[12]A. G. Eguiluz, A. A. Maradudin, and R. J. Elliott, Phys. Rev. B **27**, 4933 (1983).
[13]S. I. Zakharchenko and S. V. Kravchenko, Fiz. Tverd. Tela. **28**, 3531 (1986).
[14]P. M. Platzman and H. Fukuyama, Phys. Rev. B **10**, 3150 (1974).
[15]D. Ceperley, Phys. Rev. B **18**, 3126 (1978).

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