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# ELECTRON SOLID AT THE Si SURFACE IN ZERO MAGNETIC FIELD?

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We report observation of an electric field threshold conduction and saturation of voltage-current characteristics accompanying 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, [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 on helium [6,7]; the electron solid in that system is *classical* since the disordering thermal energy, $k_BT$, 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, [5,7,8] and references therein) and Si MOSFET's [9-11]. The presence of a magnetic field is known to aid in 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 on low-density $2D$ electron layer at the Si surface. The data shows clearly electric field threshold behavior and saturation of the current-voltage characteristics 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 $\mu$m. The typical electron mobility of samples from this wafer was 2 $m^2/Vs$. We measured $V(I)$ characteristics by applying a slowly (0.04 - 0.2 nA/min) swept dc source-drain current, $I$, and measuring the dc voltage, $V$, between source and drain. Simultaneously we detected the amplitude of ac voltage generated in the sample in the frequency range 1 to $10^5$ Hz.

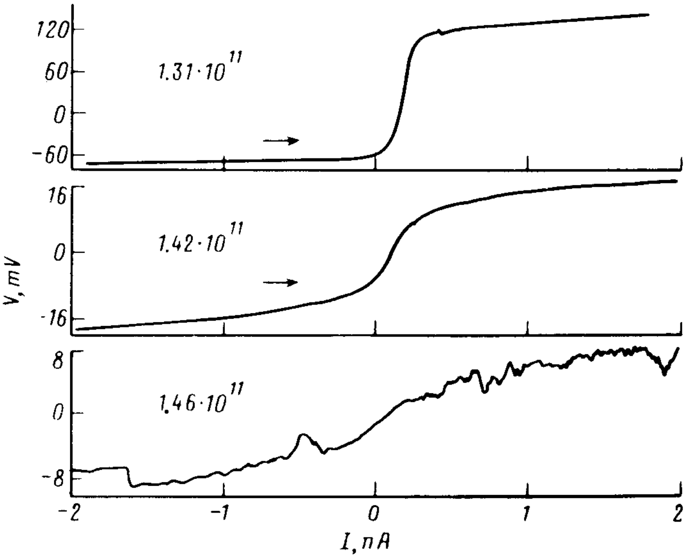

**Fig.1** $V(I)$ characteristics for three different $n_s$ at $T =$ 350 mK. The numbers on the graphs show $n_s$ in units of $cm^{-2}$.

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

There is a clearly visible lag near $I = 0$ in the two upper $V(I)$ curves: $V$ becomes zero not at $I = 0$ but at $I \simeq 0.1$ - 0.2 nA; this corresponds to a time delay $\Delta\tau \simeq 0.5$ - 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 ($\sim 100$ pF) and of the sample (20 pF): even for infinite sample resistance, $\Delta\tau \sim 3$ s for $V_{th} \sim 100$ mV.

Fig. 2 (a) represents the voltage dependencies of the differential resistance, $dV/dI$, normalized by the zero-current resistance, $R(0)$. These dependencies were extracted from $V(I)$ measurements at very slowly decreasing current (40 pA/min). At $|V|$ below some threshold value, the differential resistance remains almost constant while after exceeding the threshold value, $dV/dI$ decreases sharply (e.g. from 1.2 G$\Omega$ to 13 M$\Omega$ for the upper curve). Above $n_s \approx 1.4 \cdot 10^{11}$

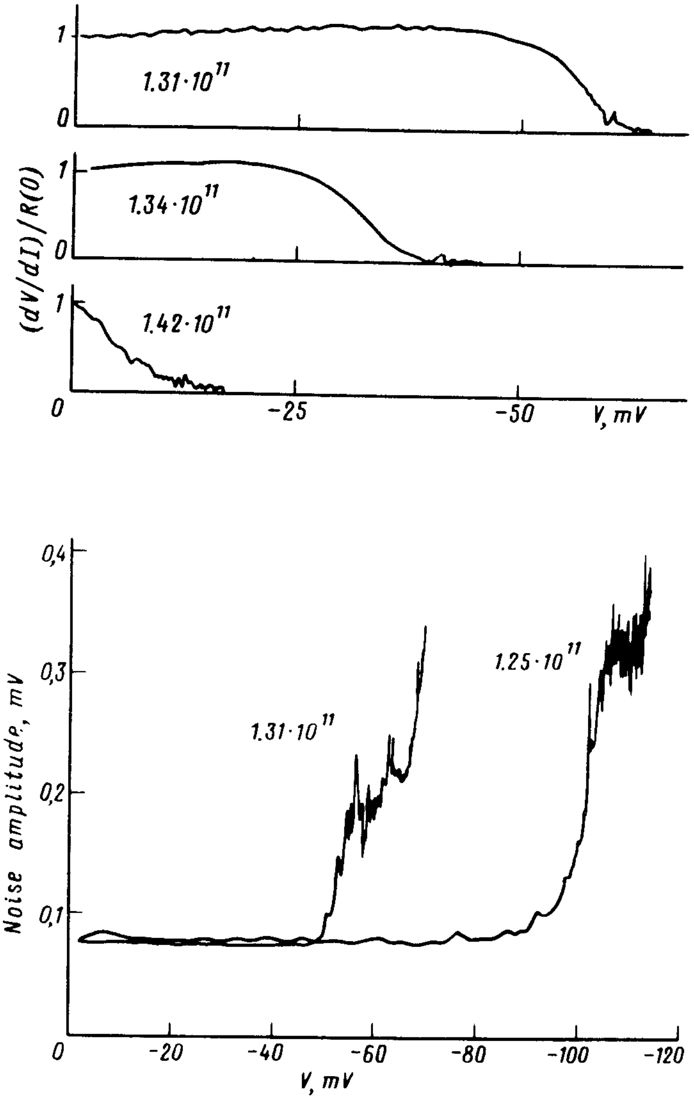

Fig.2 Dc voltage dependencies of the differential resistance (a) and noise amplitude (b) at $T = 350$ mK.

cm$^{-2}$, the threshold behavior disappears (the lower curve). Almost at the same $V_{th}$, the broadband noise (ac voltage) abruptly appears (Fig. 2 (b)) on the background of the instrumental noise (which is nearly independent of $V$). Upon increasing $T$ or $n_s$, the excess noise disappears over all range of $V$ and $I$.

The observed nonlinearity hardly could be explained by the Joule heating or by electric field destruction of the single-particle localization. Although the simple Joule heating can lead to zero or even negative $dV/dI$, the condition for saturation of $V(I)$ characteristic [13] would require the very specific temperature dependence of the resistance (for small power inputs, where 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 in a wide region 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 the de-Broghle length, $\lambda_{dB}$. $W_b$ must be at least higher than $k_BT$, where $T$ is the temperature at which the threshold still exists ($\sim$ 1.5 K). Therefore, the minimum value for $E_{th}^{1p}$ can be estimated as $k_BT/e\lambda_{dB} = 2\pi k_BT(\pi n_s)^{1/2}/e \sim 10^3$ V/cm which is more than by two orders of magnitude higher than the experimentally observed $E_{th} \approx 3$ and 6 V/cm (see Fig. 2 (a)). Estimate of $E_{th}^{1p}$ for strong single-particle localization on the basis of Ref. [3] also gives a too high threshold electric field: $E_{th}^{1p} \sim 2 \cdot 10^3$ V/cm for $n_s = 10^{11}$ cm$^{-2}$.

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 (pinned electron solid) and the excited (electron gas) states and has an Ohmic character. The electric field above $E_{th}$ depins the electron solid and makes it slide. This additional channel of conductivity diminishes the resistance (see e.g. [2,5]) and can even lead to saturation of the $I-V$ curves [8,11]. Since $I-V$ characteristics presented in Fig. 1 are very similar to those mentioned above, one can assume that in the zero-field case above the threshold, the conductivity is also related to the sliding solid. The noise appearing simultaneously with the depinning of the solid and accompanying its sliding is believed to be the consequence of the electron solid "jerking" 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 Si surface at low temperatures can be only *quantum* since for the available electron concentrations, 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 $n_c = \pi^{-1}(m^*e^2/r_c\epsilon\hbar^2)^2$ (here $\epsilon$ is the dielectric constant and $r_c$ is a dimensionless constant; estimates of its value vary over a wide range 4.5 [14] to 33 [15]). For electrons at a Si surface, the higher effective mass and the lower mean dielectric constant both increase the cold melting concentration by a factor of 20 in comparison with that for the GaAs-heterostructures: $n_c = 10^{10}$ to $6 \cdot 10^{11}$ cm$^{-2}$. This interval includes $n_c \approx 1.5 \cdot 10^{11}$ cm$^{-2}$ observed in our experiments. More precise estimates [12] give $n_c \approx 8 \cdot 10^{10}$ cm$^{-2}$ for an ideal crystal (in the absence of disorder) and $\approx 1.5 \cdot 10^{11}$ 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, they are far above than $n_c$ expected from e.g. Ref. [15]. Further experiments should shed further light on the nature of the ground state of 2D electrons at the Si surface in zero magnetic field.

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