Scientific session of the Division of General Physics and Astronomy of the Academy of Sciences of the USSR (30 March 1991)

Usp. Fiz. Nauk 161, 201–205 (June 1991)

A scientific session of the Division of General Physics and Astronomy of the USSR Academy of Sciences was held on 30 January 1991 in the conference room of the P. L. Kapitsa Institute of Physics Problems of the Academy of Sciences of the USSR. The papers listed below were presented at this session.

1. N. M. Kreĭnes. Investigation of the dynamics of domain boundaries by the light-scattering method.

2. V. M. Pudalov. Wigner crystallization in a two-dimensional electron gas in semiconductors.

A brief summary of one of these papers is published below.

V. M. Pudalov. *Wigner Crystallization in a two-dimensional electron gas in semiconductors.* More than 50 years ago E. Wigner showed that as the electron density of a three-dimensional electron gas is reduced the Coulomb interaction among the electrons must bring about an energetically more favorable crystalline state (see the review in Ref. 1). An analogous possibility has been analyzed in Ref. 2 for a two-dimensional system of electrons, in which the energy of the Coulomb interaction is $\langle U \rangle = (\pi n_s)^{1/2} e^2/\varkappa$ (n_s is the two-dimensional density, e is the unit charge, and $\varkappa$ is the dielectric permittivity). Because of the intense study of two-dimensional electron systems, Wigner crystallization was observed first in an electron gas on the surface of liquid helium, and just in the last year in GaAs/(AlGa)As heterojunctions[3–8] and in Si metal-insulator-semiconductor (MIS) structures.[9,10]

The electron density in an electron gas on the surface of liquid He is low, $n_s < 10^9$ cm^{-2}, and the contribution of the zero-point oscillations, $\pi n_s \hbar^2/m^*$ to the kinetic energy $\langle W \rangle$ preventing the crystallization turns out to be less than the thermal energy $k_B T$ (here m^* is the effective mass of the electron: $m^* \approx 1 \cdot m_e$ for electrons on helium). Therefore, the pressure of an electron crystal on He is of a classical origin along the boundary $n_s = \pi(\varkappa k_B T/e^2)^2$ (the lower curve in the plane $H = 0$ in Fig. 1) at concentrations three orders of magnitude lower than that expected for quantum mechanical "cold melting" (the upper curve in Fig. 1). In GaAs/(AlGa)As heterojunctions, because of the small effective mass of the electrons, $m^* = 0.067 m_e$, the zero-point energy is higher than $k_B T$ and the melting/crystallization regime can be of a quantum-mechanical nature. However, the minimum electron density in heterojunctions, $n_s > 10^{10}$ cm^{-2}, is two orders of magnitude higher than the critical density for cold melting:

$$n_{sc} = 4/\pi a_B^2 \Gamma^2, \qquad (1)$$

where $a_B = \varkappa \hbar^2/m^* e^2$ is the Bohr radius and $\Gamma = \langle U \rangle / \langle W \rangle \approx 10^2$.

Therefore, an electron crystal in heterojunctions can hardly exist without a magnetic field, even for $T \to 0$. It has been predicted in a number of theoretical papers[11] that a magnetic field can induce crystallization in a low-density electron liquid at a density $\nu < \nu_c$ below a critical population ν_c of the lowest Landau level. The predicted value[11] of ν_c is between 1/3 and 1/10. In recent measurements of rf absorption,[3] photoluminescence,[4,5] and magnetoconductivity[5–8] in GaAs/(AlGa)As heterojunctions an electron crystal induced by a magnetic field was observed below or slightly above $\nu = 1/5$. In all cases the crystal disappeared at $\nu = 1/5$ and 2/9, being replaced by an incompressible electron liquid.[11] In silicon MIS structures the effective mass of the carriers is $m^* = 0.2 m_e$, which is three times that in GaAs/(AlGa)As heterojunctions, while the dielectric permittivity $\varkappa = 8$ is 1.6 lower than in the latter. As a result the value of n_{sc} is 20 times higher for Si and lies in a realistically attainable range of density. Small quantities of impurities and defects in real samples should promote crystallization because of the pinning of the electron lattice.[12] However, if their density is high, the Mott transition to the insulating state,[1] by shifting towards higher electron densities, can occur above the density n_{sc}.

An electron crystal can therefore form in Si under quantum-mechanical conditions even in zero magnetic field. The very low electron density, $n_s \ll 10^{11}$ cm^{-2} required for this to occur is quite attainable in Si MIS structures of extremely high quality.[9]

The magnetoresistance of Si MIS structures at temperatures 0.025–0.6 K was studied in the work reported in Refs. 9 and 10, and it was observed that as the density n_s was lowered the peaks in the resistance R_{xx} that are ordinarily seen in the quantum Hall effect at the points where the first and second Landau levels are half-filled ($\nu \approx 1.5$ and 2.5), increased exponentially by five to six orders of magnitude (Fig. 2). At the same time the Hall component R_{xy} of the resistance remained practically the same as for an ordinary electron gas,[9,13] indicating that essentially all the electrons remained delocalized. This conclusion is supported by measurements of the real and imaginary parts of the impedance of a gate/inversion-layer system.[13] All these investigations—of the magnetoresistance with dc and ac currents, and of the capacitance—clearly show that the insulating phase at half-integral level populations is related not only to the usual single-particle localization, but to the formation of a solid phase, pinned by inhomogeneities, in which the ground state is separated from the excited state by an energy gap.

It can be seen in Fig. 2 that the solid phase does not occur over the entire range of H, but only outside of the

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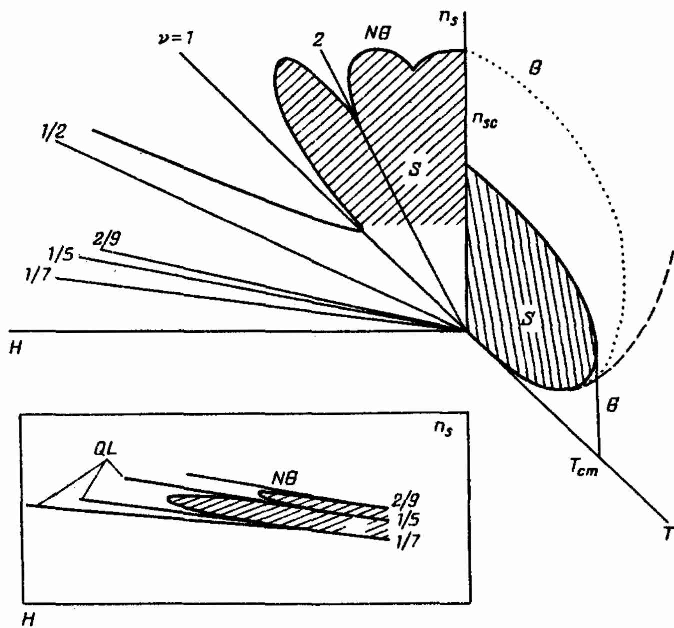

FIG. 1. Phase diagram of a solid electron state in coordinates T-n_s-H. Notation: S: solid phase; G: gas; NG:, nonideal gas (with strong e–e interaction); QL: incompressible quantum liquid. In the $H=0$ plane: the lower (dashed) curve represents the classical melting; the upper solid curve the quantum-mechanical "cold melting" of an ideal crystal; the upper dotted line represents the quantum-mechanical melting of the crystal. In the $T=0$ plane the straight lines emanating from the origin correspond to a constant population coefficient ν. The inset shows a portion of the diagram in the region of high fields.

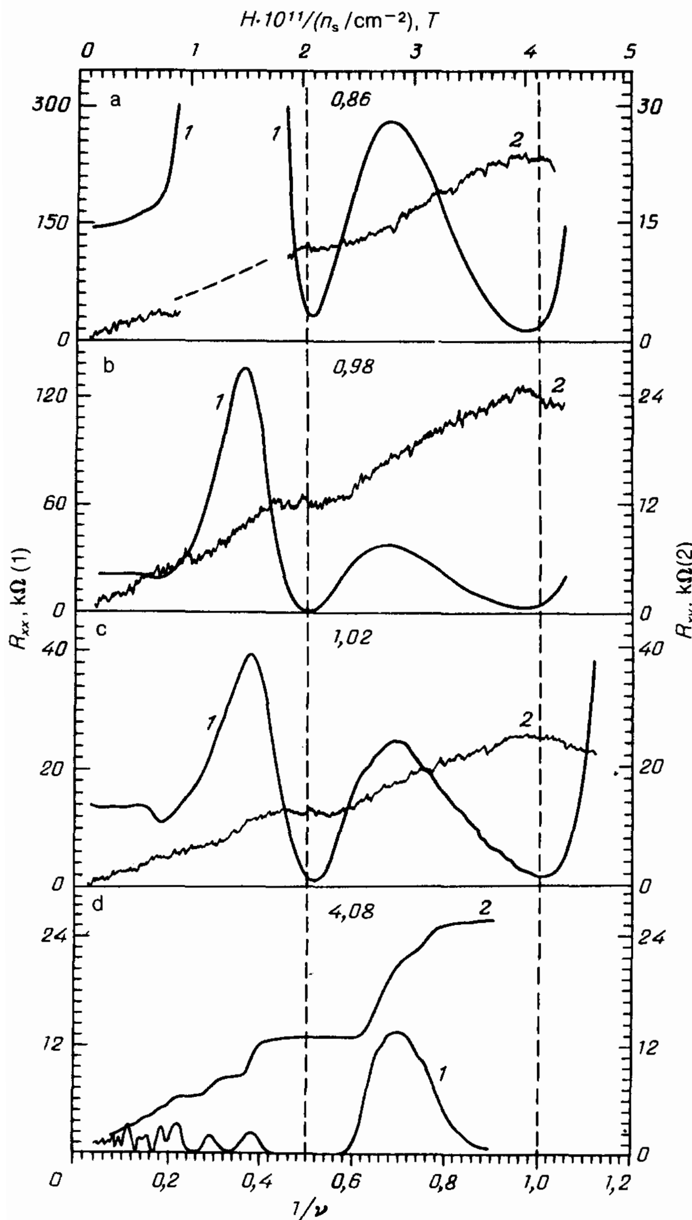

FIG. 2. Diagonal (1) and Hall (2) resistance of Si-MIS structures as functions of $\nu^{-1}\propto H$ for various electron densities. The numbers on the curves indicate n_s in units of 10^{11} cm^{-2}. Experimental conditions (Ref. 13): $T=240$ mK, measuring current 0.7 nA (a–c) and 2 nA (d).

regions of integral ν ($= 1$ and 2), where the minima in R_{xx} and the quantized values of R_{xy}, characteristic of the quantum Hall effect, are still present. This means that the energy gap that separates the ground state and the excited state vanishes at integral values of ν. The region of existence of the solid phase is also bounded at strong fields by the ordinary "magnetic freeze-out", which in silicon MIS structures occurs at $\nu < \simeq 1/2$ (the upward swing at the right-hand end of all the curves in Fig. 2), while in GaAs/(AlGa)As heterojunctions[8] it occurs at $\nu < \sim 1/5$. With a further decrease in the electron density the minima in R_{xx} disappear because of the propagation of the solid phase over the entire range of H.

At zero temperature the pinned solid phase must have insulating properties. At a finite temperature electron transport occurs in the solid phase by virtue of thermally activated transitions between the ground and excited states (In Si the latter is a gas with a strong e–e interaction[14]). This conclusion is supported by the exponential dependence of the peaks of R_{xx} on T^{-1} (Refs 8,10). If an electron field above a certain threshold value is applied the electron lattice is torn loose and then it is able to slip. This behavior shows up in the threshold observed in the current-voltage characteristics[8,10] and in the noise level.[8] Measurements[13] of R_{xy} (Fig. 2) are strong evidence for this conduction mechanism with a "slippage" of the solid phase.

In conclusion, it is interesting to compare the transport properties of the solid electron phase in GaAs/(AlGa)As with those in Si. In GaAs the solid phase occurs in the limit $H \to \infty$ on a background of the initial state of incompressible electron liquid, while in Si it occurs in a relatively weak, or even zero, magnetic field on the background of the initial state—a nonideal electron gas. At not too low electron densities the solid phase disappears in both cases at population factors that correspond to states with Hall resistance. The solid/gas and the solid/liquid boundaries, plotted with the data of Refs. 9 and 10, are shown nominally on the plane $T = 0$ on the phase diagram in Fig. 1. In both cases, $R_{xx} \to \infty$ as $T \to 0$, while the conductivity in the solid phase remains nonzero because of thermal activation or of exceeding the threshold electric field. At not too low temperatures $T > \sim 200$ mK, the pinning of the solid phase is not absolutely rigid in either of the two cases.

The generality of the observed physical phenomenon reflects the fundamental properties of two-dimensional electron systems.

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Translated by J. R. Anderson