Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (30 September 1992)

Usp. Fiz. Nauk **163**, 105–108 (January 1993)

A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences was held on September 30, 1992 in the P. L. Kapitsa Institute of Physics Problems. Reports on the subject "Nanostructures in Physics and Electronics" were presented at the session:

1. *I. V. Kukushkin and V. B. Timofeev.* Magneto-optics of strongly correlated low-dimension electron systems.

2. *P. S. Kop'ev.* Quantum-size heterostructures based on A_3B_5 compounds (technology of preparation by the MBE method and physical properties).

3. *S. V. Gaponov.* New approaches in the formation of low-dimension objects.

4. *A. P. Arzamastsev, N. M. Grodnenskiĭ, Yu. V. Gulyaev, V. G. Mokerov, and A. K. Savchenko.* Technology of quantum-size systems based on heterojunctions of A_3B_5 compounds for nanoelectronics devices.

5. *Yu. V. Kopaev.* Quantum-wave optics.

6. *I. G. Neizvestnyĭ and V. N. Ovsyuk.* Physics and technology of semiconductor structures.

A brief summary of one report is published below.

I. V. Kukushkin and V. B. Timofeev. *Magneto-optics of strongly correlated low-dimension electron systems.*

1. The problem of the ground state of two-dimensional (2D) electrons in a strong transverse magnetic field is a central problem in the physics of low-dimension semiconductor systems. In the quantum limit, when the electrons fill the lowest level split off by the magnetic field (filling factors $\nu < 1$) and the temperatures are sufficiently low, Coulomb correlations result in the appearance of new states and new quantum objects associated with these states. The most striking of these objects are incompressible Fermi liquids (IFL) and the Wigner crystal.[1] The IFL states (Laughlin states[2]) correspond to fractional filling of the quantum states ($\nu = 1/q$, where q is an odd integer) and they are observed in magnetotransport experiments according to the fractional quantization of the Hall resistance (fractional QHE (Ref. 3)). Experiments of this kind have now established an entire hierarchy of IFL states, right up to filling factors $\nu \geqslant 1/7$.[4]

Theoretical calculations show, however, that in the quantum limit $\nu \leqslant 1/5$ long-range order and crystallization should arise in a system of interacting electrons (two-dimensional electron or Wigner crystals[5]). It was expected that in the presence of Coulomb correlations in the liquid phase (IFL states) the phase diagram of the crystal–liquid transition may turn out to be completely unusual. In the last few years efforts have been made to make progress in this extremely interesting field by using different experimental methods—low electron densities, strong magnetic fields, and quite low temperatures.

The most widely used tool for studying such systems in semiconductors is magnetotransport. In the ultraquantum region, $\nu \ll 1$, however, at very low temperatures this method encounters great, essentially insurmountable, difficulties due to the intensified effects of strong localization. However, strong localization does not affect magneto-optics as strongly. The object of this report is to demonstrate the possibilities of the magneto-optical method for studying the ground state of interacting electrons, including the IFL and Wigner-crystal states.

2. First, the preferred object of investigation should be semiconductor systems with pronounced asymmetry with respect to the electron-hole interaction. Such an object could be a single heterojunction, in which the two-dimensional electron channel is spatially separated by a region occupied by photoexcited holes (bound or free). In such objects Coulomb correlations in the two-dimensional electron channel will be masked least by the exciton effect. In symmetric systems, however, for example, in quantum wells, exciton effects will have a very strong effect.[6]

We investigated radiative recombination of 2D electrons and photoexcited holes localized in a δ-doped monolayer of acceptors (Be atoms) in specially prepared GaAs/AlGaAs heterostructures (HS).[7] The monolayer of acceptors was located, as a rule, quite far from the heteroboundary (at a distance $\geqslant 300$ Å). Under these conditions, the radiative recombination times of a 2D electron and a photoexcited hole of an acceptor are very long, of the order of 1 μsec. Due to the long radiative times the 2D electron system turned out to be minimally overheated with respect to the lattice, and in experiments temperatures down to 100 μK were reached in the system (with photoexcitation power of less than 1 μW). The electron temperature was monitored according to the width of the lines of the Shubnikov oscillations of the longitudinal magnetoresistance. Acceptors far from the interface perturbed only to a minimal degree the system of interacting 2D electrons in both the initial (before recombination) and final (after recombination) states. For this reason, the moment M_1 (center of gravity of the spectrum or line) of the first-order recombination spectrum as a function of the magnetic field (or filling factor) reflects directly the behavior of the ground-state energy of the 2D electron system. Breaks or cusps with both integer and fractional filling factors $\nu = p/q$ (where p is an integer and q is an odd integer) are observed in the experimentally measured dependences $M_1(\nu)$ (Fig. 1).[8] The breaks in the spectral dependences $M_1(\nu)$ and the derivative $dM(\nu)/d\nu$ (chemical potential) agree completely with the minima of magnetoresistance (see Fig. 1). The theory shows[9] that in certain model approximations, close to the conditions of optical experiments, the width of the breaks at fractional values of ν is directly related to the width of the Coulomb gap in the case of the fractional QHE as follows:

$$\Delta_q = \frac{\nu}{2q}\delta\frac{dM_1}{d\nu}.$$

The gap Δ_q separates the IFL ground-state from the continuous spectrum of quasiparticle excitations. The procedure described above was used to determine the Coulomb gaps for

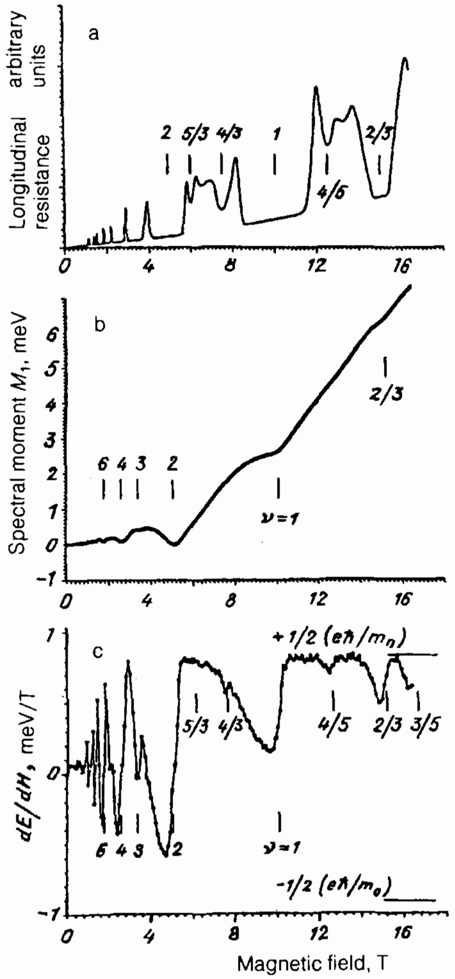

FIG. 1. Correspondence in the behavior of Shubnikov oscillations of the magnetoresistance (a), the first moment M_1 of the radiative recombination spectrum of 2D electrons (b), and the derivative $dM_1/d\nu$ (chemical potential) (c). The 2D electron density is $n_s = 2.4 \cdot 10^{11}$ cm^{-2} and $T = 100$ mK. Integer and fractional filling factors are indicated.

an entire hierarchy of IFL states, and their sensitivity to disorder in the system was also analyzed.

The magneto-optical method has the advantage that with its help the behavior of the corresponding gaps—cyclotron, spin, and quasiparticle in the fractional-QHE regime—can be traced experimentally as a function of the temperature. It was found that as the temperature increases, the gaps due directly to the electron-electron interaction suddenly collapse. In contrast to these gaps, the cyclotron gaps, whose width is not affected by the e–e interaction, decrease monotonically with increasing T, the decrease being described by corrections quadratic in the temperature.

3. A new line was discovered in the radiative recombination spectra of 2D electrons recombining with holes in the acceptor monolayer under conditions corresponding to Wigner crystallization.[10] This line appears in the spectra at critical values of the filling factor $\nu_c \leqslant 0.26$ and temperatures $T < 200$ mK. In an electric field the intensity of the new line increases at a certain threshold value of the field and near the threshold this increase is accompanied by intensification of the noise. This behavior is associated with depinning of the Wigner crystal.

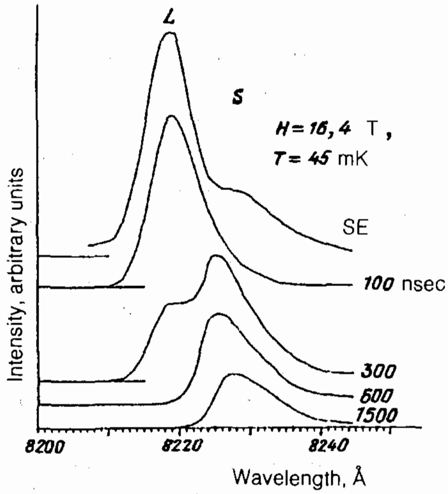

FIG. 2. Luminescence spectra for a sample with 2D electron density ns $= 5.3 \cdot 10^{10}$ cm^{-2} with steady-state excitation (SE) and pulsed excitation. The spectra were measured with delays indicated for each spectrum in nsec. $T = 45$ mK and $H = 16.4$ T.

The kinetics of radiative recombination in the Wigner-crystallization regime has been investigated for the first time with the help of the technique of pulsed excitation.[11] It was found that the radiative recombination times for electrons in the solid phase (including the state of a pinned Wigner crystal) are many orders of magnitude higher than the corresponding times for electrons in the liquid phase (including the IFL state). Figure 2 illustrates the changes occurring in the luminescence spectra, measured with different delay times under pulsed excitation. Obviously, for long delays $\Delta t > 500$ nsec only the line S, corresponding to recombination of electrons from the solid phase, remains in the spectra. Recombination occurs much more rapidly in the liquid phase (L). The radiative times τ in the solid phase increase exponentially with the magnetic field:

$$\tau = \tau_0 \exp(H/H_0) = \tau_0 \exp(A/\nu),$$

where τ_0 is the time at $H = 0$ and A is a numerical factor of

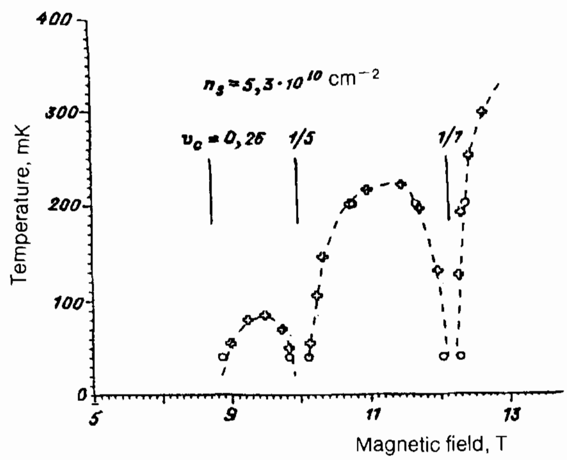

FIG. 3. Phase boundary of a Wigner crystal. The crosses correspond to measurements of the transition in a fixed field H and the circles correspond to measurements at fixed temperature T.

order unity. This behavior is a consequence of the strong localization of electrons in the 2D plane in the solid phase at low temperatures and in a strong magnetic field. The significant difference in radiative time scales made it possible to investigate independently the liquid and solid phases with pulsed photoexcitation, to distinguish states of the crystalline and disordered (glassy) solid phases, and to construct the phase diagram for a Wigner crystal (Fig. 3) in the T-versus-ν plane. The phase boundary starts at the critical values of the filling factor $\nu_c \leqslant 0.26$ and lies on the temperature scale below the classical melting point $T_c \approx 420$ mK, in agreement with the results of investigations of nonlinear magnetotransport[12] and rf absorption.[13] The unusual form of the phase boundary of the existence of the electron crystalline phase is associated with the fact that for fractional filling factors of 1/5 and 1/7 the Laughlin states (IFL states) are more stable.

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Translated by M. E. Alferieff