CRITICAL FLUCTUATIONS IN AN n-InSb ELECTRON PLASMA AT HELIUM TEMPERATURES

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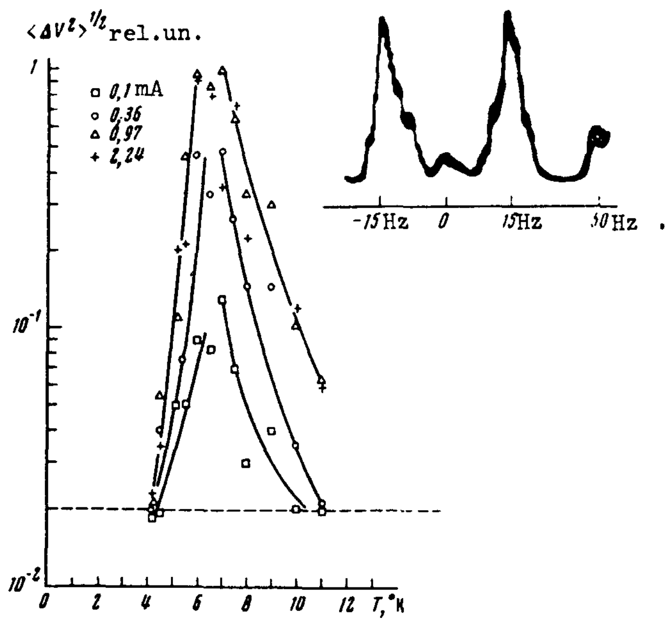
At temperatures $4.5 < T < 12°K$, a considerable low-frequency current noise was observed in n-InSb samples with electron density $n = (10^{13} - 10^{14})\ cm^{-3}$. The noise is distributed over the volume and, in view of the noticeable deviation of the electron gas from ideal at the chosen electrons temperatures and concentrations, it may indicate the existence of fluctuations of the critical type in a non-ideal electron gas.

The samples were cut from single-crystal n-InSb, mounted in a copper capsule on the end of a rod of stainless steel, and placed inside a transportable Dewar with liquid helium. This made it possible, by moving the rod in the helium vapor, to vary the sample temperature between 4.2 and 20°K. The temperature in the capsule was measured with a thermometer based on an Allen-Bradley resistor. Direct current was made to flow through the samples, and the balast resistance was 20 - 100 times larger than the sample resistance. An alternating noise voltage was applied to the input of a tuned U2-6 amplifier (bandwidth 2 Hz), and then to an S4-12 spectrum analyzer. The latter has made it possible to separate visually the noise signal measured in the 15 - 30 Hz range from the 50-Hz interference which was comparable with the signal in magnitude (see the figure).

The temperature dependence of $\langle \Delta V^2 \rangle^{1/2}_{20Hz}$ at 20 Hz is shown in the figure for a sample with $n = 2.6 \times 10^{13}\ cm^{-3}$. The maximum measured value of $\langle \Delta V^2 \rangle^{1/2}$ was of the order of 30 μV (at Δf = 2 Hz). Attention is called to the sharp increase of the noise when the temperature approaches $T_c \simeq 7°K$. The independence of T_c of the current flowing through the sample gives grounds for assuming that this temperature is characteristic also for the thermodynamic functions of the sample.

The observed noise depends non-monotonically not only on the sample temperature but also on the direct current I at a fixed temperature. At low



Noise voltage vs. sample temperature for different values of the direct current. The currents 0.1 and 0.36 mA correspond to the linear section of the current-voltage characteristic. The dashed line shows the noise level of the apparatus. The upper right corner shows the form of the oscillogram on the spectrum-analyzer screen.

currents, corresponding to the linear section of the current-voltage characteristic, $\langle\Delta V^2\rangle$ turns out to be proportional to I^2. We have assumed on this basis that the observed noise is a consequence of fluctuations of the conductivity of the sample. These fluctuations are not connected with the fluctuations of the contact resistance, since experiment has established a linear connection between $\langle\Delta V^2\rangle^{1/2}$ and the length of that section of the sample from which the noise voltage was picked off. In dc measurements, contact noise should not give such a dependence [1, 2].

The frequency spectrum of the noise was not investigated in detail, but it can be stated that with increasing frequency f the noise decreases sharply, and becomes smaller than the noise level of the apparatus already at 70 Hz for all values of T and I. In all cases when an estimate was made of the frequency dependence of the noise, the decrease of $\langle\Delta V^2\rangle_f$ with increasing f was not slower than f^{-4}.

In connection with the observation of such a low-frequency noise, it is of interest to mention here the long time (on the order of several msec) required for the conductivity to assume a steady state in n-InSb after turning on the current pulse at 4.2°K [3]; this time is much longer than the electron-energy relaxation time which was measured in the same experiment (~100 nsec). This occurred at $n = (2 - 8) \times 10^{13}$ cm^{-3} and remained unexplained.

Qualitatively, a similar dependence of the noise on T and I was observed by us also on another sample with $n = 2.7 \times 10^{14}$ cm^{-3}. The maximum absolute value of the mean-squared noise voltage was approximately one-quarter as large, and the temperature T_c was somewhat lower (~6.5°K).

The character of the temperature dependence and the larger value of the measured noise (for comparison we indicate that at sample resistances 10 - 100 Ω the Johnson noise is smaller by 4 - 5 orders of magnitude than the observed one) suggest that in this case critical fluctuations were produced, of the type usually occurring near second-order phase transition points and near the critical point of a liquid [4 - 6]. As a possible cause of the existence of the critical state in our case, we can indicate that the electron gas in the investigated samples was far from ideal.

In our samples, the total concentration of the donor and acceptor impurities was $N \gtrsim 10^{15}$ cm^{-3}, and the low electron density was due to the large compensation. Owing to the low effective mass of the electrons ($m^* = 0.014m_0$) and to the large dielectric constant of the crystal ($\kappa = 17$), the Bohr radius a in n-InSb is large, so that at $N \simeq 10^{15}$ cm^{-3} we have $Na^3 \gtrsim 1$. This inequality denotes that the individual centers do not form bound states for the electrons. But under the conditions of strong compensation ($n \ll N$), the inequality $na^3 \ll 1$ is automatically satisfied, and indicates that such an electron gas is not ideal at T = 0, owing to the interelectron interaction. The gas remains non-ideal also at non-zero (but not too high) temperatures. In the case of a non-degenerate gas, the non-ideality parameter r_s is given by [7]

$$r_s = e^2(4\pi n/3)^{1/3}/\kappa T. \quad (1)$$

At $n = 2.6 \times 10^{13}$ cm^{-3} and T > 4°K, the electron gas in InSb is non-degenerate, and it follows from (1) that $r_s \simeq 4.7/T°$, i.e., the electrons are noticeably non-ideal in the working temperature range.

To verify that this non-ideal behavior can lead to a growth of macroscopic (i.e., long-wave) fluctuations of the density, let us apply the phenomenological theory of fluctuations near the critical point in the Landau form [7]. Using the formula for the free-energy density F of a non-degenerate gas, in which the electron-electron interaction is taken into account in first approximation [8], and equating $\partial^2F/\partial n^2$ to zero, we obtain a relation between the critical concentration n_c and T_c

$$r_S(n_c, T_c) = 4/\sqrt{3}.$$

From (2) at $n = 2.6 \times 10^{13}$ cm^{-3} we obtain for T_c a value smaller than 7°K by an approximate factor of 3. Since the expression employed for F was obtained by series expansion in the non-ideality parameter and does not take into account the exchange corrections (which in our case are already comparable with the Debye corrections), no quantitative agreement was to be expected. This theoretical estimate, however, seems promising to us. We note that an analogous procedure gives the correct order of magnitude for T_c, for example, in the case of a Van der Waals gas.

It is still difficult to identify with assurance the state into which the electron gas goes over after crossing the critical point. Starting with Wigner's work, the possible existence at T = 0 of a non-ideal electron gas in a homogeneous neutralizing background in the form of an "electron crystal" (see references in [9]), produced by electrons localized as a result of their mutual Coulomb repulsion, has been considered a number of times. The properties of the non-degenerate electron gas at $r_s \simeq 1$ were less investigated. However, an investigation of this question by means of a computer experiment [10], using as an example a gas of classical ions in a neutralizing background, has shown that at $r_s \geq 2$ the dependence of the paired distribution function g_2 on the distance between the ions becomes oscillating, i.e., short-range order characteristic of a liquid is established in a gas of charged particles. A non-ideal electron gas, of course, differs from a non-ideal gas of classical ions, but for a degenerate gas calculation shows [9] the presence of oscillations of g_2 at $r_s \geq 4$, i.e., long before the formation of the Wigner crystal. One can therefore assume that the "self-localization" of the electrons, which is characteristic of an electronic crystal, occurs already prior to the formation of the latter, at lower values of the non-ideality parameter. "Crystallization" on the other hand produces only an ordered arrangement of the localization centers. A possible state of a non-ideal gas after passing through the critical point can then be assumed to be the "electron liquid" produced by "local" electrons[1)].

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SPONTANEOUS MAGNETIC MOMENT IN THE DIRECTION OF THE TRIGONAL AXIS IN $CoCO_3$

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According to the theory developed by Dzyaloshinskii [1] for the weak ferromagnetism of antiferromagnets, there can exist in rhombohedral crystals, besides the thoroughly investigated spontaneous ferromagnetic moment σ_D in the basal plane of the crystal, also a spontaneous moment σ_z directed along the threefold axis. The value of σ_z depends strongly on the direction of the antiferromagnetic vector $\vec{l}$ relative to the binary axes in the basal plane of the crystal. Such a moment was recently observed by Flanders in hematite (α-Fe_2O_3) [5]. We have observed in the present investigation the spontaneous moment σ_z in the rhombohedral antiferromagnet $CoCO_3$[1]. Its value turned out to be larger by approximately two orders of magnitude than in the case of hematite.

The existence of σ_z follows directly from the general form of the thermodynamic potential, which for rhombohedral crystals with symmetry D^6_{3d} can be written, following Dzyaloshinskii [1] in the form

$$\begin{aligned}\Phi = \frac{a}{2}\cos^2\theta + \frac{B}{2}m^2 - q\sin\theta(m_y\cos\phi - m_x\sin\phi) + \frac{D}{2}(\vec{\gamma}m)^2 - \\ - fm_z\sin^3\theta\cos 3\phi + d\cos\theta\sin^3\theta\sin 3\phi + e\sin^6\theta\cos 6\phi + \\ + \frac{g}{4}\cos^4\theta - \mathbf{m}\mathbf{H},\end{aligned} \tag{1}$$

where ϕ is the angle between the vector $\vec{l}$ and the C_2 axis, and θ is the angle between $\vec{l}$ and the C_3 axis.

Minimizing this potential at a specified angle ϕ we obtain for the magnetization along the z axis

$$\sigma_z = \frac{f}{B}\sin^3\theta\cos 3\phi\,. \tag{2}$$

From the results of magnetic measurements [2] it is known that if a field H > 2 kOe is applied in the basal plane, then the antiferromagnetic vector $\vec{l}$ is

[1]According to neutron diffraction data [3], in the absence of a magnetic field, the vector $\vec{l}$ in $CoCO_3$ is deflected from the basal plane by an angle β = 44 ± 4°. We do not know whether this angle changes with changing angle ϕ. However, from the isotropy of the magnetic properties of $CoCO_3$ in the plane it follows that the projection of the antiferromagnetic vector $\vec{l}$ on the basal plane is practically independent of the angle ϕ.