# SINGULARITIES OF SHUBNIKOV - DE HAAS OSCILLATIONS IN A STRONG ELECTRIC FIELD

Yu. A. Bykovskii, V. F. Elesin, V. I. Kadushkin, and E. A. Protasov
Moscow Engineering Physics Institute
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Recently [1, 2], a nonlinear dependence of the transverse magnetoresistance $\rho_H$ on the electric field was observed in pure n-InSb. In this paper we report Shubnikov - Haas (SH) oscillations of the transverse magnetoresistance in a strong electric field.

We investigated experimentally n-InAs with carrier density $4.8 \times 10^{16}$ $cm^{-3}$ and mobility 35 500 $cm^2$/V-sec at liquid-helium temperature, i.e., under conditions when $\xi >> kT$ and $\hbar\Omega >> kT$, where $\xi$ is the Fermi level and $\Omega = eH/m^*C$ is the cyclotron frequency. The samples were rectangular and measured 1.5 x 0.2 x 0.4 cm. The current and the potential contacts were soldering the contacts, the samples were etched with CP-4. The magnetic field was excited by a sectionalized superconducting solenoid made of wire based on NbZr. The solenoid and the samples were in direct contact with the liquid helium.

The measurements were made by a null method using a PDS-021M x-y recorder. Special measures were undertaken to ensure constancy of the magnetic field during the entire time of plotting the current-voltage characteristics.

Figure 1 shows plots of $\rho_H(E)$ of one of the samples for the magnetic fields corresponding to the numbered points of the oscillation curve shown in the upper right corner. It is seen from the figure that the character of $\rho_H(E)$ changes significantly on going from $\rho_H$ at the maximum to $\rho_H$ at the minimum. A common feature of all the curves is the presence of a region where Ohm's law is satisfied (initial sections). The difference lies in the presence of

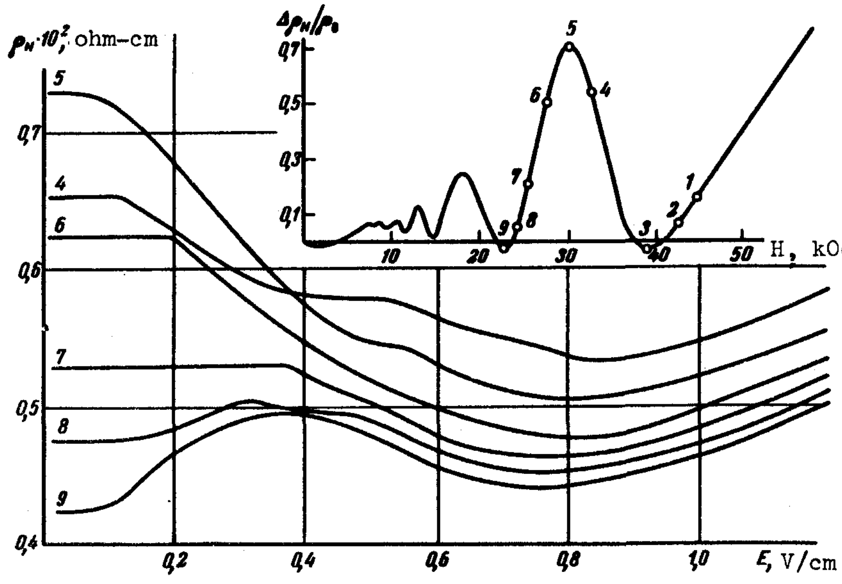


Fig. 1

sections in which $\rho_H(E)$ decreases at the maximum of the oscillation curve (0.05 - 0.55 V/cm for point 5) and of a growth with passage through a maximum for $\rho_H(E)$ at a value of H corresponding to the minimum of the oscillation curve (region 0.05 - 0.40 V/cm for the point 1). This anomalous behavior of $\rho_H(E)$ at the maximum and at the minimum, and also at the points close to them (see curves 4 and 8), was observed also for other extremal points of the oscillation curve.

The nonmonotonic dependence of the transverse conductivity on the electric field can be explained if it is recognized that heating of the electron gas leads to a broadening of the Landau levels and consequently to a decrease of the quantum corrections to the conductivity. The expression for the transverse conductivity is (cf., e.q., [3])

$$\sigma_{xx} = \frac{n_e e^2}{m^* \Omega^2 \tau_{ei}} \left[ 1 - \frac{5}{2\sqrt{2}} \left( \frac{\hbar\Omega}{\xi} \right)^{1/2} \frac{x}{\operatorname{sh} x} \cos\left( \frac{2\pi\xi}{\hbar\Omega} - \frac{\pi}{4} \right) \right], \tag{1}$$

where $x = 2\pi^2 kT/\hbar\Omega$ and $\tau_{ei}$ is the time of relaxation of the electron momentum on the impurities. The electron temperature $T_e$ for a semiconductor in crossed electric and magnetic fields was calculated in [4]:

$$T_e = T_0 \left[ 1 + \frac{1}{2} \left( \frac{cE}{sH} \right)^2 \left( 1 + \frac{\tau_{ak}}{\tau_{ei}} \right) \right], \tag{2}$$

where c and s are the velocities of the light and of the sound; $\tau_{ak}$ is the time of energy relaxation on the acoustic phonons.

It is seen from (1) that if

$$\cos\left( \frac{2\pi\xi}{\hbar\Omega} - \frac{\pi}{4} \right) = -1$$

(the magnetic field corresponds to the maximum of the SH oscillations), then $\sigma_{xx}$ decreases monotonically with increasing $T_e$ (and consequently E). On the other hand, if the magnetic

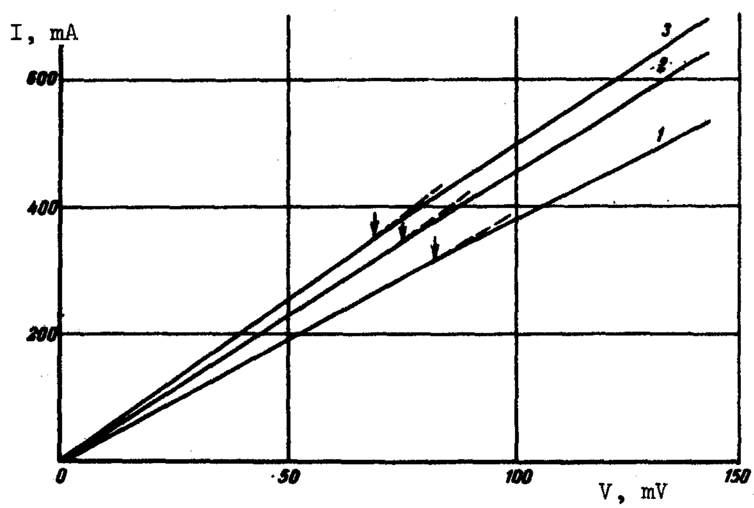


Fig. 2

field corresponds to a minimum of the oscillations

$$\cos\left(\frac{2\pi\xi}{\hbar\Omega} - \frac{\pi}{4}\right) = 1,$$

then $\sigma_{xx}$ increases with increasing electric field. Consequently, the change of the conductivity is due to the change of the oscillating part, since x becomes of the order of unity at relatively small $T_e$. (In our experiments $T_e \leq 40°$, i.e., $kT_e/\xi << 1$). An experimental reduction has shown that the monotonic part of $\sigma_{xx}$ remains practically independent of E up to electric fields 0.3 - 0.55 V/cm (for different curves).

Figure 2 shows the current-voltage characteristics corresponding to points 1, 2, and 3 on the oscillation curve (see Fig. 1) at different values of the magnetic field intensity. It is seen from the figure that the electric field at which the deviation from Ohm's law begins ($E_{cr}$) increases with increasing magnetic field intensity. It follows from (1) and (2) that apparently $E_{cr} \sim H^{3/2}$, which agrees qualitatively with experiment. Analogous results were obtained also for n-InSb.

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## ELECTRON NUCLEAR DOUBLE MAGNETOACOUSTIC RESONANCE AND $Cr^{3+}$ - $Al^{27}$ INTERACTION IN RUBY

V. A. Kolenishchev-Kutuzov, U. Kh. Kopvillem, and N. A. Shamukov
Kazan' Physicotechnical Institute, USSR Academy of Sciences
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Acoustic NMR was detected for the first time with the aid of the electron spin system. Lines of the acoustic NMR of $Al^{27}$ in a laser ruby single crystal were observed in the form of dips as a function of the frequency of the ultrasound against the background of the EPR line of the $Cr^{3+}$ ions. This new principle of detection of acoustic NMR increases the sensitivity of the acoustic measurements, makes it possible to investigate electron-nuclear interactions in crystals, and to clarify the dynamics of the occurrence of double resonances in multicomponent quantum systems.

As is well known [1], the electronic cross relaxation plays an important role in the redistribution of the energy absorbed by the $Cr^{3+}$ spins in the EPR process in $Al_2O_3$, and also in the establishment of the stationary population difference of the electronic spin system and of the intensity of the EPR signal. However, in view of the small specific heat of the $Cr^{3+}$ - $Cr^{3+}$ dipole-dipole system proceeds via a close coupling of this system with the Zeeman reservoir of the $Al^{27}$ spins. This gave rise to the idea of using this circumstance for the detection of acoustic NMR on $Al^{27}$: by saturating the acoustic NMR on the $Al^{27}$ nuclei, we block the channel through which energy flows out of the $Cr^{3+}$ - $Cr^{3+}$ dipole-dipole system, and