Quantum oscillations of the magnetoresistance of bismuth in the phonon-generation regime

Yu. A. Bogod and R. G. Valeev

Physico-technical Institute of Low Temperatures, Ukrainian Academy of Sciences
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Oscillations of the transverse (E⊥H) magnetoresistance of bismuth were observed in the phonon-generation regime. The extrema of these oscillations coincide with the extrema of the Shubnikov–de Haas (SdH) oscillations. The amplitude of the oscillations in the phonon-generation regime has a temperature dependence that is anomalous for the SdH effect, namely, it increases on going from helium to hydrogen temperatures.

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At present it is customary[1] to relate the kink observed by Esaki[2] on the current-voltage characteristic (CVC) of bismuth at $E = E_c \approx sH/c$ [1)] with generation of phonons by the carriers that drift with supersonic vel-

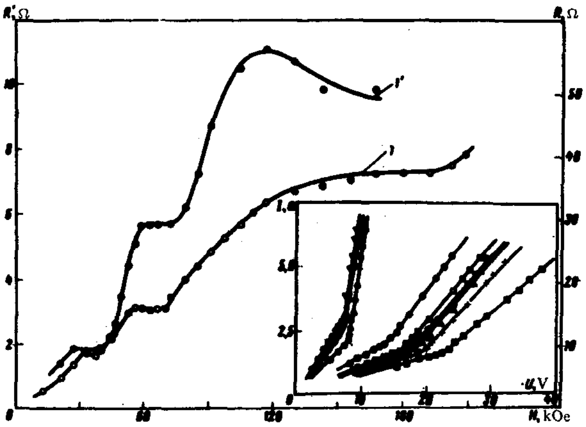

FIG. 1. MR of bismuth in the linear (curve 1, $T = 4.2\,^\circ$K) and nonlinear (curve 1′, $T = 20.4\,^\circ$K; $I = 6$ A) region of electric fields, $\nmid$ **H**, $C_3 = 16^\circ$. Insert: CVC at 20.4 °K in fields (kOe): 27(○), 33(◁), 40(●), 52.5(◑), 59(□), 66(◒), 72(▷), 79(×), and 91(■).

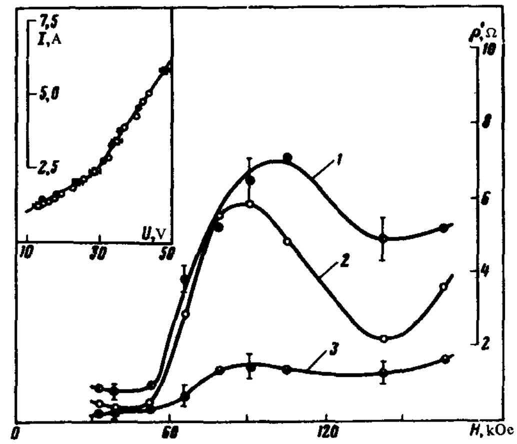

FIG. 3. Oscillations of the differential resistance in the nonlinear regime, $\nmid$ **H**, $C_3 = 8^\circ$: 1, 2, 3 corresponds to $T = 20.4$, 14, and 4.2 °K. Insert—CVC at $H = 79$ kOe and $T = 20.4\,^\circ$K: ●—first run of experiments, ○—second run.

ocity in the direction of **E**×**H**. The aggregate of the values of $E < E_c$ and $E > E_c$ will henceforth be called the linear and nonlinear regions of the electric fields, respectively. In our present study we measured the magnetoresistance (MR) in magnetic fields up to 200 kOe. The procedure for measuring the MR (R) in the linear region is described in detail in[5], and singularities in the measurements of MR in the nonlinear regime (R') were reported in[4,6]. We indicate only that the measuring current in our investigation at $E < E_c$ did not exceed 5×10^{-2} A, and at $E > E_c$ the current pulse was almost rectangular.

We present below the experimental results obtained with a single crystal having a cross section 1×1.2 mm (the sample preparation method was described in[4]) for two directions of the magnetic field in the C_2C_3 plane. The longitudinal axis of the sample was parallel to the

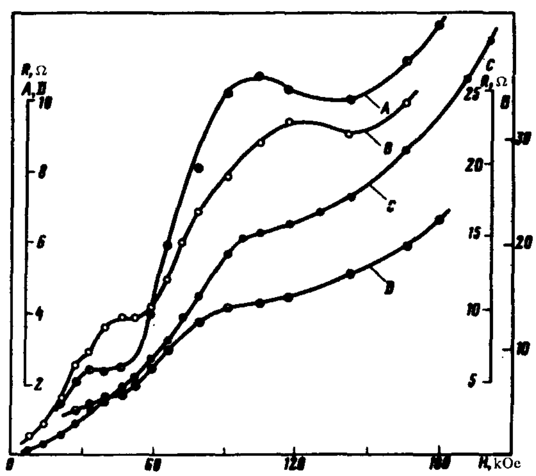

FIG. 2. Oscillations of MR in the case of $\nmid$ **H**, $C_3 = 8^\circ$. Curves B and C were obtained at $E < E_c$, $T = 4.2$ and 20.4 °K, respectively. Curves D and A were constructed at $E > E_c$, $I = 5$ A: D—$T = 4.2\,^\circ$K, A—$T = 20.4\,^\circ$K.

bisector direction C_1, and the distance between the potential contacts was 3.5 mm.

As seen from Fig. 1, all the singularities of the $R(H)$ dependence, i.e., the SdH oscillations, obtained at 4.2 °K, are duplicated in the nonlinear region. We emphasize that the $R'(H)$ curve corresponds to $T = 20.4\,^\circ$K. The insert shows the CVC of the sample at 20.4 °K (for magnetic fields close to 30 and 60 kOe), from which it follows, in particular, that in addition to the differential MR, namely $\rho' = (\partial U/\partial I)(H)$, the quantity E_c/H at $E > E_c$ is also a nonmonotonic function of the magnetic field. The oscillating character of $E_c/H = f(H)$ will be discussed in a separate article. Comparison of the curves shown in Fig. 2 indicates that, in contrast to the linear region (curves B and C), in the nonlinear regime the increase of the temperature from 4 to 20 °K is accompanied by an increase of the oscillation amplitude (D, A). The $\rho'(H)$ oscillations have the same regularity (Fig. 3), and the largest amplitude is realized at 14 °K. We wish to call attention in this connection to the following circumstance: Since the error of the oscillograms is usually about 10%, the errors in the determination of ρ' can be quite large. However, the good reproducibility of the results from one run of measurements to the other (see the insert in Fig. 3) allows us to regard as the main source of the errors the inaccuracy with which the signal is read, an inaccuracy connected with the thickness of the oscilloscope beam. Thus, the experimental results are quite reliable.

The fact that the extrema of the SdH oscillations coincide with the extrema of the functions $R'(H)$ and $\rho'(H)$ allow us to identify, with a great degree of reliability, the MR oscillations in the nonlinear region with the SdH effect. One cannot exclude the possibility that the nonmonotonic change of $(\partial U/\partial I)(H)$, observed by Esaki[2] at $E > E_c$ and $T = 2\,^\circ$K, and the oscillations observed by us in the nonlinear regime are of the same nature, but more definite conclusions can unfortunately not be drawn on the basis of the data of[2]. This type of oscillation undoubtedly included also the nonmonotonicities of $R'(H)$ and $\rho(H)$, observation of which at 4.2 and 20.4 °K were recently reported by the authors and by Onokienko.[4]

If it is assumed that, just as in the linear regime, the amplitude of the MR oscillations in the case of $E > E_c$ is proportional to $\{\exp(2\pi^2 k/\hbar\omega)(T + \hbar/\pi k \tau)\}$, then the collision broadening of the Landau levels at 4 °K should exceed the corresponding value in the hydrogen region. Favoring this assumption is also the increase (at given H) of R' and ρ' on going from 4.2 to 20.4 °K (see Fig. 3 and[3,4]), in contrast to the case $E < E_c$. All this allows us, in particular, to raise the question of the ratio of the total number of the "acoustic" (nonequilibrium) and "thermal" (equilibrium) phonons at helium and hydrogen temperatures. We note also that the results point to the possibility of investigating quantum effects in a wide temperature range, and by the same token increase greatly the value of this research method.

1)The approximate character of the equality was established experimentally by the authors of the present paper and Onokienko.[3,4]

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