Observation of sample-size-dependent transverse electric field in bismuth at low temperatures

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We measured the dependence of the transverse electric field $E_\perp$ on the temperature and dimensions of the bismuth sample. The observed increase of $E_\perp/E_\parallel$ with decreasing temperature at $T < 7\,^\circ$K and with decreasing sample thickness can be qualitatively explained within the framework of the theory of the diffusion size effect.

We describe the results of the measurement of the dependence of the longitudinal and transverse electric fields ($E_\parallel$ and $E_\perp$) produced when dc is made to flow through an elongated bismuth sample, on the temperature T and on the sample thickness d. The cross section of the initial sample was a parallelogram with a thickness (d) to width ratio 4–5 and with an acute angle ≈45°; the C_3 axis made an angle ≈56° with the sample axis, while the C_2 axis made an angle ≈40° with the sample axis. To measure simultaneously the longitudinal and transverse potential difference ($U_\parallel$ and $U_\perp$, respectively) we used two pairs of transverse potential contacts placed at a distance $h = 2$ cm from each other in the center of the sample. The external magnetic field was cancelled out with accuracy 0.05 Oe, and the magnetic field of the measurement current (0.3 A) was less than 0.1 Oe. The current leads were soldered with low-melting-point solder to the end faces, while the sharpened potential leads were welded to opposite faces of the sample. The misalignment of the pair of transverse contacts was $\Delta < 0.1$ cm. The sample thickness was successively decreased by etching in concentrated HNO_3, after which the measurements were repeated. To eliminate the influence of the structure of the surface on the properties of the sample,[1,2] all the data presented below describe the changes of the properties of a sample etched in the same manner. The ratio of $E_\perp^{\mathrm{meas}}$ and $E_\parallel$ is proportional to the ratio of the actually measured potential differences $U_\perp^{\mathrm{meas}}$ and $U_\parallel$, and can be represented in the form

$$\beta(T, d) = \frac{E_\perp^{\mathrm{meas}}}{E_\parallel} = \frac{U_\perp^{\mathrm{meas}}}{U_\parallel}\,\frac{h}{d} \approx \frac{E_\perp^{\mathrm{size}}}{E_\parallel} + \frac{E_\perp^{\mathrm{vol}}}{E_\parallel} + \frac{\Delta}{d}, \qquad (1)$$

where $E_\perp^{\mathrm{size}}(T, d)$ is the sought transverse field and $E_\perp^{\mathrm{vol}}$ does not depend on the dimensions and describes the contribution of the anisotropy of the volume conductivity. According to the data of[1,3], the ratios of the volume conductivities at $T = 5$–$7\,^\circ$K are $\sigma_{33}/\sigma_{11} = \sigma_{33}/\sigma_{22} = \mathrm{const}$, so that the second term does not depend on the temperature. The third term, which is determined by the misalignment of the transverse contacts, is constant.

The values of $E_\perp^{\mathrm{meas}}/E_\parallel$ calculated from the measurement results are shown as a function of T in Fig. 1. For convenience in plotting, curves pertaining to different d are shifted arbitrarily in a vertical direction, since the values of the constants are of no interest to us. The vertical segments on the experimental points indicate the limits of the random errors. At $T > 10\,^\circ$K, the curves are practically horizontal; at $T < 5\,^\circ$K the increment of the quantity $E_\perp^{\mathrm{meas}}/E_\parallel$, which is determined by the value of $[E_\perp^{\mathrm{meas}}/E_\parallel(T)]$, is larger than the thinner the sample. The characteristic temperatures of the kink on the $[E_\perp^{\mathrm{meas}}/E_\parallel(T)]$ curves determined from the points of intersection of the continuations of the horizontal and inclined sections of the curve shift towards higher temperatures with increasing d. Figure 2 shows the dependences of $E_\perp^{\mathrm{size}}/E_\parallel$ on the dimensions at 1.5 and 4 °K (curves 1 and 2): at 1.5 °K and $d = 0.09$ cm we have $E_\perp^{\mathrm{size}}/E_\parallel \approx 0.26$ (curves 3 and 4 show the dependence of the ratios $\rho_{300\,^\circ\mathrm{K}}/\rho_T$ on d at the same temperatures). It is important to note that these dependences were plotted with the quality and orientation of the sample unchanged.

We have thus shown that at liquid-helium temperatures there is produced in a bismuth sample a size-dependent transverse electric field that increases with decreasing temperature and sample thickness, and becomes comparable with the longitudinal field at $T < 4\,^\circ$K in a perfect sample $\lesssim$ 3 mm thick. The increase of the transverse field with decreasing sample thickness at 4.2 °K was observed also in[5], where the results of measurements performed on samples with three different dimensions were compared.

The often observed nonlinear dependence of the con-

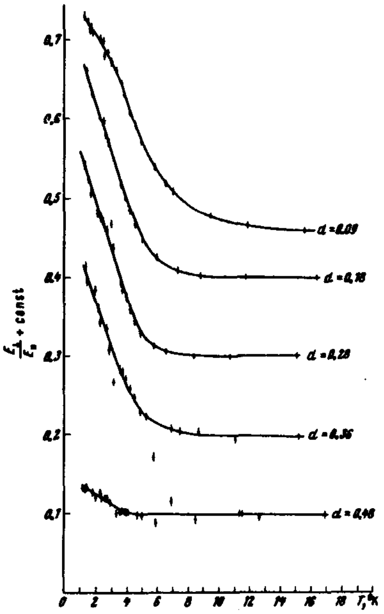

FIG. 1.

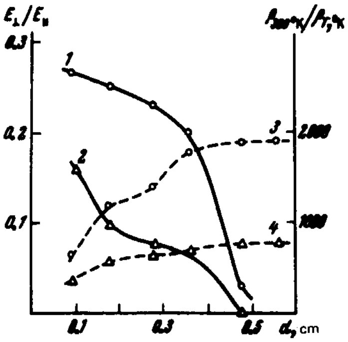

FIG. 2.

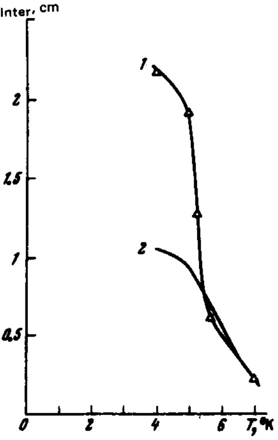

FIG. 3.

ductivity of bismuth samples (curves 3 and 4 in Fig. 2) on the thickness[1,2,4] is explained most fully within the framework of the diffusion size effect (DSE),[6-8] which takes into account the onset near the surface, over distances on the order of the electron diffusion length $l_g = \sqrt{l l_{\text{inter}}}$, of a layer with inhomogeneous carrier distribution, belonging to different valleys (l is the usual effective mean free path of the electrons in the volume and corresponds to the intravalley scattering of the carriers, and l_{inter} is mean free path for intervalley scattering). The formation of transverse electron concentration gradients near the surface, belonging to different valleys, should be accompanied by the onset of a compensating transverse electric field $E_\perp^{\text{size}}$, the magnitude of which at $d \lesssim l_g$ becomes comparable in order of magnitude, according to theoretical estimates,[8] with the field $E_\parallel$. The results of our experiments agree qualitatively with the prediction of the DSE theory. The condition $d \lesssim l_g$ can be satisfied either by lowering the temperature or by decreasing the thickness at a fixed temperature (Figs. 1 and 2). At high temperatures, where $d \gg l_g$, the ratio $E_\perp^{\text{size}}/E_\parallel$ is close to zero (horizontal sections of curves on Fig. 1). The contribution of this ratio to (1) becomes noticeable at $d \sim l_g$. From this we can estimate the effective electron mean free path in intervalley scattering in the volume, assuming that the kinks on the curves correspond to the temperatures at which $d \approx l_g \approx \sqrt{l l_{\text{inter}}}$. The value of l can be estimated numerically from the resistance at the minimal dimensions and temperature, where the conductivity is limited entirely by electron scattering from the sample surface: $l(T) = 1.7/T^2$ cm, which coincides with the estimates.[9] The calculated $l_{\text{inter}}(T)$ dependence is shown in Fig. 3 (curve 1), which gives also the function $l_{\text{eh}}(T)$ for electron-hole recombination,[10] calculated on the basis of measurement of the acoustomagnetic effect in bismuth (curve 2). At $T \gtrsim 5\,^\circ$K, the free path l_{inter} obtained by us agrees with the results of[10], and at lower temperatures, when the role of carrier scattering by lattice defects increases, it exceeds the values of l_{eh} given in[10]; this can be attributed to better quality of our samples ($\rho_{300^\circ K}/\rho_{4.2^\circ K} \approx 720$ as against $\lesssim 560$). The agreement of the value calculated from the size dependence with the results of[10] indicates apparently that electron-hole recombination is the fastest process in intervalley scattering of carriers.

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