# Observation of circulating current components in bismuth in a magnetic field

I. N. Zhilyaev
*Institute of Problems of Microelectronics Technology and Especially Pure Materials, Academy of Sciences of the USSR*

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When a current is passed through a bismuth sample in a longitudinal magnetic field at liquid-helium temperatures, a circulating current component is observed in a transverse section of the sample. Measurements in a transverse field show that the effect stems from a system of magnetic domains in a transverse section.

The method used to prepare the samples for the present experiments and the measurement method are similar to those described in Ref. 1. When a current $I$ is passed through a sample in a longitudinal magnetic field $H_{\parallel}$, a change ($\Delta\Phi$) is detected in the magnetic flux linking a measuring coil wound around the central part of the sample. Figure 1 shows the experimental arrangement and the results of measurements of the effect in a sample with $\gamma = \rho_{293\text{K}}/\rho_{4.2\text{K}} = 900$; the results are plotted against $H_{\parallel}$ for the temperatures $T = 4.2$ K and $T = 1.3$ K for a current $I = 2$ A through the sample. Plotted along the ordinate axis is the specific magnetic flux $\Delta\phi = \Delta\Phi/Sn$ ($S = 1.1 \times 1.1$ cm$^2$ is the cross-sectional area of the sample, and $n = 1000$ is the number of turns in coil $K_1$), which represents the average magnetic

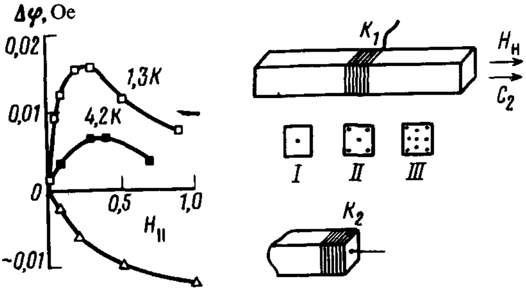

FIG. 1. The specific magnetic flux $\Delta\phi$ detected by coil $K_1$ versus the longitudinal magnetic field $H_{\parallel}$ according to measurements with a current $I = 2$ A flowing through the sample at the temperatures $T = 1.3$ K and $T = 4.2$ K. The lower curve is a plot of the Hall component of $\Delta\phi$ versus $H_{\parallel}$, according to measurements at $T = 4.2$ K by coil $K_2$ with $I = 2$ A.

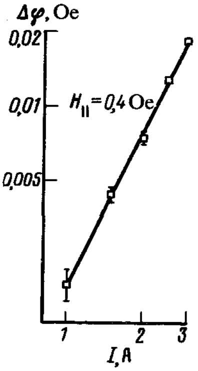

FIG. 2. The dependence $\Delta\phi(I)$ measured by coil $K_1$ at $T = 4.2$ K.

field over the cross section of the sample. The sketch of the sample is drawn to scale. The geomagnetic field is cancelled within 0.01 Oe. The effect increases with decreasing temperature. At $T = 1.3$ K with $I = 2$ A and low values of $H_{\parallel}$, we find $\Delta\phi / H_{\parallel} \simeq 0.2$. The effect changes sign when the direction of $H_{\parallel}$ is changed, but it does not change sign when the direction of $I$ is changed. Figure 2 shows the measurements of $\Delta\phi(I)$ at $T = 4.2$ K for $H = 0.4$ Oe (the logarithms of the corresponding quantities are plotted here). We see that the dependence is quadratic.

Since the measurements were carried out in a longitudinal magnetic field, which prevented the establishment of a uniform current distribution over the cross section of the sample, we were particularly concerned about the electrodes, which were made of copper wire 0.5 mm in diameter. To check the suitability of these electrodes for these measurements, we used the following method. The electrodes were first assembled from a single conductor to the sample: Conductors were soldered to the center of the end of the sample (arrangement I in Fig. 1; the dot shows the position at which the conductor is soldered), and measurements were taken. The number of conductors was then successively increased as shown by arrangements I, II, and III in Fig. 1, for the purpose of increasing the density (per unit area) of conductors at the end of the sample and for arranging a more uniform distribution of the current over the cross section of the sample. These measurements showed that at $T = 4.2$ K the magnitude of the effect does not depend on the electrode geometry; at $T = 1.3$ K the magnitude of the effect increases as we go from arrangement I to arrangement II (the maximum increase is $\simeq 25\%$), and as we go from II to III, there is essentially no change. The electrodes in arrangements II and III were thus judged suitable for our measurements at $T = 1.3$ K.

The observed effect can be explained on the basis of Refs. 2 and 3. As Pipkin and Rivlin showed, when a current is passed through a sample a compensating system of circulating currents should arise in its transverse section; these circulating currents constitute magnetic domains of a sort, for each of which the magnetic flux is proportional to $I^2$. The imposition of $H_{\parallel}$ in our experiments apparently disrupts the compensation by this system and gives rise to the observed effect. The mechanism proposed by Pipkin and Rivlin[2,3] for the formation of these domains runs as follows: The current flowing through the sample gives rise to an azimuthal magnetic field in the sample, which in turn gives rise to a Hall component of the current in the radial direction. If the conductor is isotropic, and its cross section is noncircular (e.g., square), the radial

Hall component in the directions toward the corners will not be directed normal to the surface. This circumstance will give rise to eight domains: two domains with currents in opposite directions but otherwise identical in each corner. In the case in which the sample has a circular cross section but is made of an anisotropic material (e.g., if there are two perpendicular extremal directions characterizing the anisotropy in the cross section of the sample), four domains should arise. The boundaries between these domains pass through the extremal directions of the anisotropy. The magnitude of the magnetic flux of the domains should be proportional to the radial Hall component, which in turn is proportional (at low currents) to the field $E$ and to the azimuthal magnetic field (which is proportional to $I$). The net result is a magnetic flux which is a quadratic function of $I$.

To check for the presence of Hall currents in bismuth under the present experimental conditions, and to estimate their magnitude, we measured the magnetic flux by means of coil $K_2$ in the same sample (Fig. 1). This coil was positioned near the end of the sample with an electrode in arrangement I; in this case, a radial current comparable in magnitude to the axial current flows near the end of the sample. In addition to the magnetic flux described above, which does not depend on the direction of $I$ and which is proportional to $I^2$, we found with coil $K_2$ a component of the magnetic flux which is due, we believe, to Hall currents: This component changes sign when the direction of $I$ is changed, and it is proportional to $I$. Figure 1 shows the $H_{\parallel}$ dependence of the Hall component according to measurements at 4.2 K and $I = 2$ A (lower curve) for one of the directions (the $H_{\parallel}$ dependence is odd). The sign of the Hall component corresponds to electrons. An estimate of the azimuthal field in the sample $\sim 1$ cm thick at $I = 2$ A yields 0.5–1 Oe. We see from Fig. 1 that the magnitude of the Hall component of the magnetic flux at $H_{\parallel} = 0.5$–$1$ Oe corresponds to a maximum magnitude of the effect at $I = 2$ A.

We believe that the presence of domains in a sample during current flow can also be tested in the following way. As we mentioned earlier at $I = 2$ A the azimuthal field in the sample is estimated to be 0.5–1 Oe. If a transverse magnetic field $H_{\perp}$ with a magnitude of about 1 Oe is imposed, it should cause a domain formed by an azimuthal field in the same direction as $H_{\perp}$ to occupy a larger area in the cross section of the sample, and the magnetic field of this domain should increase. As a result, the magnetic flux from it will increase, while the magnetic flux from the other domains should decrease. The resultant flux over the entire cross section, on the other hand, should be nonzero and should have the sign of the corresponding domain. In fact, we observe a flux of this sort, quadratic in $I$. Figure 3 shows the $\Delta\phi$ angular pattern measured with coil $K_1$ in a field $H_{\perp} = 1.2$ Oe at $T = 4.2$ K. We see that the observed maximum magnitude of the magnetic flux agrees with the maximum value of $\Delta\phi$ for the effect in $H_{\parallel}$ (Fig. 1). On the basis of this figure we conclude that four domains form in the sample during the current flow, indicating that the effect is unrelated to the shape of the sample (four corners should have given rise to eight domains). The effect is apparently related to the existence of two extremal directions of the anisotropy: along $C_3$ and perpendicular to $C_3$. Also shown in this figure is an angular diagram measured under the same conditions for a sample of circular cross section with a diameter of 0.9 cm, with $\gamma \simeq 800$, and with a longitudinal axis in the same orientation. We see that the

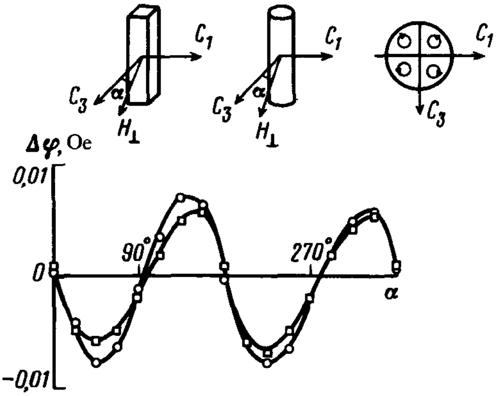

FIG. 3. The angular dependence of $\Delta\phi$ measured at $T = 4.2$ K in a transverse field $H_\perp = 1.2$ Oe in a sample with a square cross section (the squares) and in a sample with a circular cross section (the circles). Shown at the upper right is a sketch of the current directions in the domains.

results of these measurements are essentially the same as those for the sample with the square cross section. This agreement is further evidence that the effect stems from the anisotropy. Figure 3 is a sketch of the directions of the currents in the domains with respect to the crystallographic axes as found from these experiments. These particular directions apparently result from the circumstance that the electron Hall component is greater along $C_3$ than along $C_1$.

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[3] A. C. Pipkin and R. S. Rivlin, J. Math. Phys. **3**, 369 (1963).

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