Current instability in bismuth single crystals in a transverse magnetic field

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(Submitted 13 May 1992; resubmitted 29 May 1992)
Pis'ma Zh. Eksp. Teor. Fiz. **55**, No. 12, 727–730 (25 June 1992)

When a current is passed through a high-quality bismuth crystal in a transverse magnetic field at liquid-helium temperature, monochromatic electromagnetic oscillations arise. The oscillation frequencies measured for samples of various thicknesses agree with the instability model proposed by Azbel'. Perturbations excited near an end of the sample are amplified.

The instabilities observed experimentally are usually difficult to study, and it is impossible to draw definite conclusions about their mechanisms, because of the complex frequency spectrum of the oscillations.[1] In the present study we have investigated an observed instability in a monochromatic part of the spectrum.

The experimental geometry is shown in Fig. 1. In the transverse plane, the width d and thickness b of the sample are about 1 cm. The length of the sample is about 10 cm. The longitudinal axis of the samples is parallel to the C_1 crystallographic axis. The temperature of the helium bath is $T = 1.3$ K. In these experiments we used high-quality bismuth single crystals with a resistivity ratio $\gamma = \rho_{300\mathrm{K}}/\rho_{4.2\mathrm{K}} = 900$. The carrier mean free path was comparable to the dimensions of the sample. When a current I of a few amperes was passed through the sample, and a transverse magnetic field $\vec{H}_\perp$ of about 1 Oe was applied along the C_3 axis, electromagnetic oscillations with frequencies ranging from tens to hundreds of hertz arose in the sample. The emf U which arose in the coils was amplified by a broad-band amplifier and was displayed on an oscilloscope O. Figure 1 shows a typical curve of U versus $\vec{H}_\perp$ at a fixed I for one of the samples, with $d = 1.5$ and $b = 0.9$ cm, measured by one of the coils. The observed values of U are on the oder of 10^{-6} V/turn. On the basis of the frequency characteristics, the region in which the instability occurs can be divided into regions of mono-

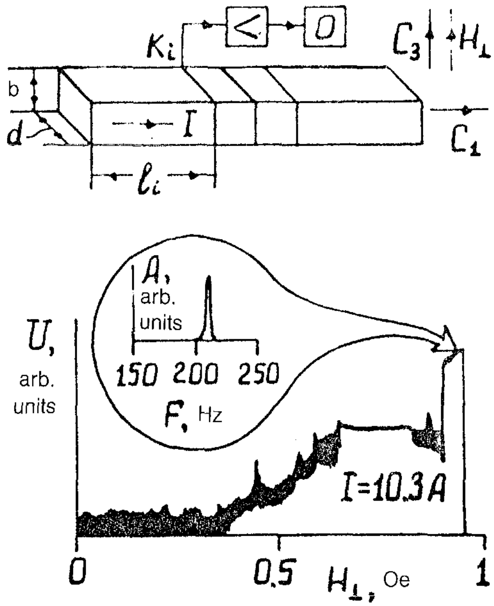

FIG. 1.

chromatic oscillations and of polychromatic oscillations (beats of different frequencies can be seen in this part of the plot). The inset in the circle in Fig. 1 shows the frequency spectrum of the oscillations found by a spectrum analyzer with a selectivity of 3 Hz. Here we see a monochromatic peak with a frequency $F_m = 210$ Hz. Since we were primarily interested in the characteristics of the monochromatic oscillations, we will be discussing only that region. The measurements show that for a given sample, and for fixed values of I and $\vec{H}_\perp$, the frequency and amplitude of the oscillations are independent of the position of the pickup coil (except near the ends of the sample, in regions with a length roughly equal to the transverse dimensions). They are also independent of the geometry of the current leads. On the other hand, they depend on the parameters I and $\vec{H}_\perp$. It was also found that F_m and A do not vary with the length of the sample, while they do depend on the transverse dimensions. An instability with the same frequency can be observed with the help of longitudinal potential contacts. The voltage oscillations have a magnitude of about 10% of the constant voltage drop. The measurements were carried out under current-source conditions.

Since the self-magnetic field of a current of several amperes contributes significantly to the magnetoresistance, and there is a substantial redistribution of the current along the cross section of the sample, it is natural to suggest the instability mechanism proposed by Azbel',[2] which involves oscillations in the current density in the cross section of a conductor. Estimates of the frequencies of the oscillations determined by the Hall velocity and a length scale on the order of the linear size of the cross section yield values which agree in order of magnitude with the observed values. Under the given experimental conditions, with a Hall angle on the order of one, the Hall velocity

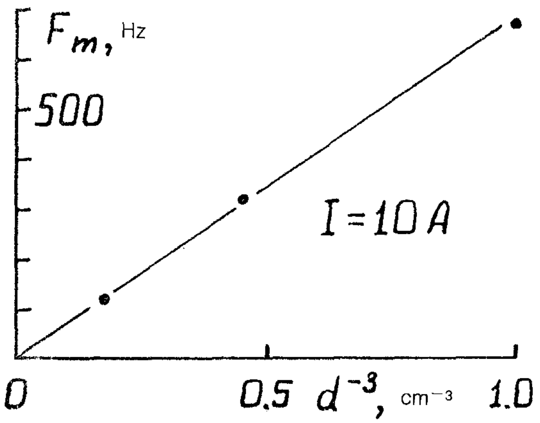

FIG. 2. Frequency of the instability versus the width of the sample for $d\cdot\vec{H}_\perp = 1.2$ cm·Oe.

should be on the order of the drift velocity. The latter is typically 10^2 cm/s at $I \simeq 10$ A and a carrier density of 10^{17} cm^{-3}. To see how well the model corresponds to the observations, we measured F_m as a function of the cross-sectional size of the samples. Since the self-field of the current and the applied field are comparable in magnitude, the distribution of magnetic fields in the sample is a complicated function of the relation between I and $\vec{H}_\perp$ and also of the cross-sectional dimensions. It is therefore difficult to interpret the results. To get around this difficulty, we varied the cross section of the sample in accordance with a similarity law. We selected values of I and $\vec{H}_\perp$ for each cross section in such a way that the change in the resultant magnetic field in the sample also obeyed a similarity law, in a sense: Smaller cross-sectional dimensions corresponded to proportionately smaller orbits of the charge carriers in the magnetic field. Under these conditions, the dependence of the Hall velocity (which is responsible for the frequency F_m) on the resultant magnetic field in the sample varies in proportion to $1/d$, as d is varied. Consequently, in order to satisfy the similarity law as we varied d, we left the current I constant and varied the value of $\vec{H}_\perp$, at which F_m was measured, in proprotion to $1/d$. Figure 2 shows the measured dependence of F_m on d ($d = 2b$). We see that this dependence is described well by $F_m \propto 1/d^3$. This result can be explained in the following way. The Hall velocity is proportional to the electric field and to the resultant transverse magnetic field. The electric field is proportional to $1/d$ at a constant current under size-effect conditions. The resultant transverse magnitude field is proportional to $1/d$ because of the particular measurement conditions. Since the "path length" traversed by the oscillations decreases in proportion to d, we should have $F_m \propto 1/d^3$, as observed.

Since the ratio of the length of the sample to its diameter is roughly 10, we are naturally interested in a synchronization of the oscillations in the different parts of the sample. We accordingly used a dual-trace oscilloscope to measure the phase relations between the emf signals at coils K_i. We conclude from the results that the observed oscillations take the form of a wave which is traveling away from the positive terminal of the current source toward the negative terminal (a change in the polarity of $\vec{H}_\perp$, in contrast with a reversal of I, did not affect the direction of the wave). The length of

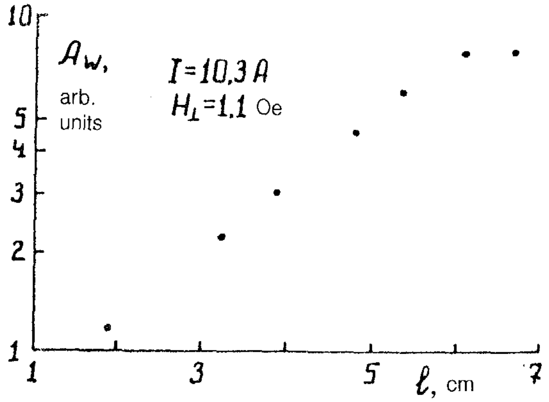

FIG. 3. Amplitude of the wave with a frequency of 210 Hz versus its range for a sample with $d = 1.5$ and $b = 0.9$ cm.

this wave is slightly greater than the transverse dimension. These results indicate that, first, the instability is associated with the hole component of the electron–hole plasma in the bismuth. In other words, the oscillations in different parts of the sample are synchronized in one direction because of the drift of the holes in the longitudinal electric field. Second, with a Hall angle of about one, the Hall velocity and the longitudinal drift velocity are approximately equal, explaining why the wavelength is approximately equal to the transverse dimension.

If, under conditions corresponding to the occurrence of the instability, we raise $\vec{H}_\perp$, without changing the current I, to a point at which the instability is essentially not seen, i.e., if we tune $\vec{H}_\perp$ to a point a few percent above the point at which the instability amplitude begins to decrease (Fig. 1), and if we use a coil to excite electromagnetic wave with a frequency close to the instability frequency near the end of the sample connected to the positive terminal of the current source, then the coils K_i also detect electromagnetic oscillations. Measurements of the phase relations of the emf signals at the various coils draw a picture similar to that found before the detuning of $\vec{H}_\perp$. The amplitude of the oscillations at first increases exponentially with distance from the end of the sample and then stabilizes, at a value equal to the amplitude of the instability before the detuning (Fig. 3). These observations can be explained on the basis that, as $\vec{H}_\perp$ is increased, the temporal growth of the instability, which begins from a low level of fluctuations, is comparatively slow. The instability does not have time to grow to a significant level over the time of propagation along the sample, which is related to the carrier drift in the longitudinal electric field. During excitation of oscillations near the end of the sample by means of a coil, the initial amplitude of the oscillations is set at a comparatively high level, and this amplitude increases exponentially in time. The superimposed carrier drift at a constant velocity along the sample apparently leads to the observed picture. If, instead of periodic oscillations, we introduce a perturbing pulse with a width of about 1 ms near the end of the sample, under the same conditions, then a train consisting of one or two oscillations is set up, according to measurements of the emf signals in the various coils. The frequency of the oscillations in this train is equal to the frequency of the instability. The train propagates along the sample at a constant velocity of 2.7×10^2 cm/s in the direction away from the positive terminal of the current source. The behavior of the amplitude of this train is similar to that of the amplitude of the periodic excitation. Changes in the pulse characteristics by amounts comparable to the values of these characteristics themselves do not affect the frequency of the train. This stability of the train frequency can apparently be explained on the basis that oscillations corresponding to a resonant frequency of electromagnetic oscillations in the sample are excited, and the motion of the train at a constant velocity is linked with the drift of holes.

I wish to thank V. T. Dolgopolov and I. B. Levinson for discussions.

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[2]M. Ya. Azbel', Pis'ma Zh. Eksp. Teor. Fiz. **10**, 550 (1969) [JETP Lett. **64**, 390 (1969)].

Translated by D. Parsons