“Current” states in tin

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It is shown that tin single crystals exposed to large-amplitude radio waves have at helium temperature a macroscopic magnetic moment even in a zero external magnetic field.

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It was observed earlier that bismuth single crystals placed in an RF electromagnetic field can exist in “current” states.[1] In a “current” state, a closed direct current flows over the surface of the sample even in the absence of an external magnetic field, and is the result of rectification of the high-frequency current. The rectified current produces a magnetic moment, the magnitude and direction of which are determined by the prior history of the sample.

As shown in[2], under the conditions of the anomalous skin effect the influence of the wave's own magnetic field on the trajectories of the effective electrons leads to rectification of the alternating current in the skin layer. The magnitude of the direct current is then determined by the value of the magnetic field in the interior of the sample. In the general case, the magnetic field is the sum of the external field and of the field produced by the rectified current. At large radio-wave amplitudes, the field of the rectified current is sufficient to maintain the rectification. This means that the sample will retain the macroscopic magnetic moment when the external magnetic field is turned off.

In this model there exists a natural scale for the amplitude $H_\sim$ of the field wave, namely the value h of the alternating magnetic field at which the electron path length in the skin layer is equal to the mean free path $l: h = pc\delta/el^2$. Here p is the Fermi momentum and δ is the depth of the skin layer. The value of the high-frequency field $H_\sim^c$ above which current states are observed is proportional to h, and in the simplest case of a quadratic dispersion law the proportionality coefficient depends neither on l nor on the carrier density n, nor on the frequency ω of the electromagnetic wave. Since $h \sim n^{1/9}$, current states are apparently not a property of semimetals only, and can be observed in normal metals. The carrier density in a normal metal exceeds the carrier density in bismuth by five orders of magnitude, so that to observe the current states in a metal with the same mean free path it is necessary to increase $H_\sim$ somewhat. However, an increase in the amplitude of the alternating field will not lead to an appreciable increase of the power released by the sample W, since $W \sim \delta(H_\sim^c)^2$ does not depend on the carrier density. The considerations advanced above have stimulated our experiments on tin.

The experiments were performed on two tin single crystals in the form of disks 17.8 mm in diameter, and 0.6 and 0.4 mm thick. The fourfold axis was normal to the plane of the disk. The samples were grown in a polished quartz mold and had an unetched mirror surface.

The same experimental setup as in[1] was used for the measurements. The high-frequency field was produced by an inductance coil, inside of which the investigated sample was placed. A small difference from the procedure of[1] was that in our experiments on tin the same inductance coil was used also to register the magnetic moment of the sample. The use of only one inductance coil made it possible to trace only the projection of the magnetic moment M of the sample on the axis of the coil, but facilitated the measurement of the amplitude of the high-frequency field. The value of $H_\sim$ was determined from the voltage on the inductance coil. The accuracy with which $H_\sim$ was determined was 10%.

In general outline, the results obtained with tin duplicate the results of the experiments on bismuth. At large RF field amplitudes, characteristic hysteresis loops were observed on the plot of $\partial M/\partial H_\sim$ against H (see Fig. 1). The derivative $\partial M/\partial H_\sim$ and the function $M(H)$ itself changed jumpwise simultaneously. The jump of $M(H)$ was verified by observing the jumplike changes of the magnetic moment on an oscilloscope screen, in analogy with the procedure used in[1]. The dimension of the loop A increases linearly with increasing $H_\sim$. The dependence of A on the direction of the external magnetic field relative to the crystallographic axes is shown in Fig. 2. The curves shown on this figure correspond to polarization of the high-frequency current along the [100] direction. A change of the polarization of the RF currents by an angle ±15° did not influence the form of the dependence of A on the direction of the external magnetic field.

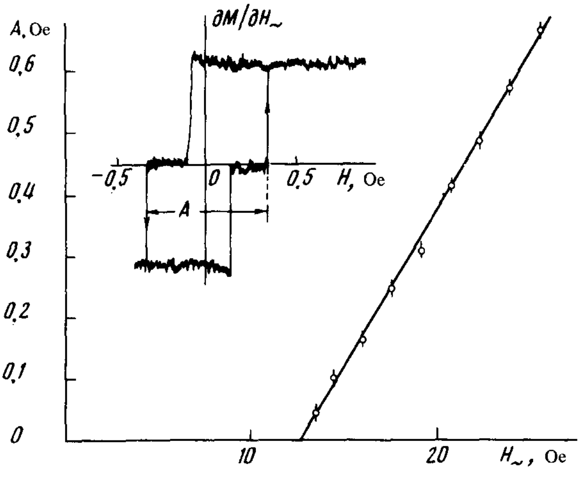

FIG. 1. Width of the hysteresis loop vs. the high-frequency field amplitude. Sample 0.6 mm thick, $T=4.15\,^\circ\mathrm{K}$, $H \parallel [100]$, the angle between H and $H_\sim$ is 10°, $\omega/2\pi=1.7$ MHz. A detailed plot of $\partial M/\partial H_\sim$ is shown for $H=25.4$ Oe.

The critical value of the amplitude of the high-frequency field was obtained by extrapolating the straight line $A(H_\sim)$ to zero dimension of the hysteresis loop. In contrast to bismuth, the same $H_\sim^c$ was obtained regardless of angle between the constant magnetic field, and the crystallographic axes of the sample at which the hysteresis curve was recorded. For the 0.6 mm sample, lowering the temperature from 4.15 to 3.73 °K decreased $H_\sim^c$ from 12.8 to 9.7 Oe, while the slope of the $A(H_\sim)$ line remained constant within 10%. For the thicker sample, the value of $H_\sim^c$ was smaller by a factor 1.5 than for the thinner one. The latter is apparently due to the difference in the sample quality. The hysteresis loop disappeared when the sample became superconductive, but the loop could be restored by increasing the amplitude of the RF field. This called for a field $H_\sim$ exceeding the field of the superconducting transition at the given temperature.

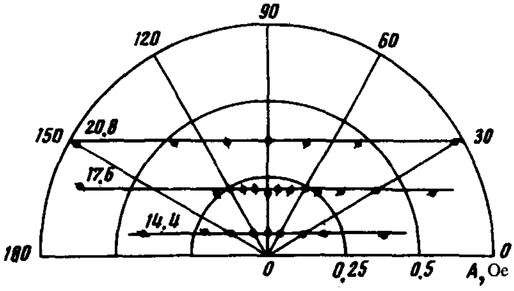

FIG. 2. Dependence of the dimension of the hysteresis loop on the direction of the external magnetic field. The angle is reckoned from the direction of the high-frequency current. $T=4.15$ °K, $H \parallel [100]$, $\omega/2\pi=1.7$ MHz, sample thickness 0.6 mm. The values of $H_\sim$ in oersteds are marked alongside the curves.

According to[2], a change of frequency should influence the value of $H_\sim^c$ exclusively via the change of the skin-layer depth. Therefore $H^c \sim h$ is proportional to $\omega^{-1/3}$. The results obtained with tin do not contradict such a dependence (see Fig. 3). The positions of the experimental points are described by an ω^{-k} curve with $k=0.38\pm0.05$. We note that a change of frequency did not influence the slope of the $A(H)$ line.

In the measurements on bismuth,[1] no dependence of the effect on the frequency was observed. What was measured in[1], however, is not $H_\sim^c$, but the dimension of the loop at $H_\sim \gg H_\sim^c$. As a check, we repeated the measurements on one of the bismuth single crystals. In the range from 275 kHz to 5 MHz, the frequency had no effect on $H_\sim^c$ of bismuth, whereas the depth of the skin layer in single crystals having the same quality varied in proportion to $\omega^{-1/3}$ in the same frequency range.

The very fact that current states are observed in tin offers evidence in favor of the explanation proposed in[2] for the cause of current states. Within the framework of the same model, we can explain also the dependence of the width of the hysteresis loop on the direction of the external magnetic field. For the explanation to hold it must be assumed that the main contribution to the rectified current is made not by the carriers of the small groups in tin, but by the carriers on the open part of the Fermi surface in the fourth zone. The only experimental fact that can be understood so far on the basis of the rectification mechanism proposed in[2] is the absence of a frequency dependence of $H_\sim^c$ in bismuth.

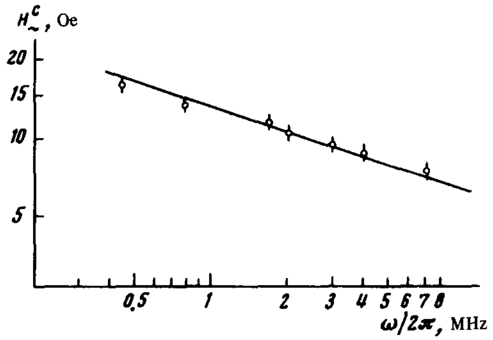

FIG. 3. Critical value of the alternating magnetic field vs. frequency. Sample thickness 0.6 mm, $H \parallel H \parallel [100]$, $T = 3.96$ °K. The line is a plot of $H_\sim^c \sim \omega^{-1/3}$.

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