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NEW TYPE OF RESISTANCE OSCILLATIONS IN A MAGNETIC FIELD

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Submitted 4 April 1972
ZhETF Pis. Red. 15, No. 10, 592 - 596 (20 May 1972)

While investigating the dependence of the resistivity ρ of filamentary bismuth crystals (whiskers) on the magnetic field ($H < 3$ kOe at $T = 4.2°K$), we observed a new type of oscillatory behavior of $\rho(H)$.

The objects of the investigation were bismuth whiskers in the form of filaments and ribbons, of thickness on the order of 1 μ and length up to 0.5 mm, grown from the gas phase [1]. The purity of the initial bismuth was characterized by a ratio $\rho(330°K)/\rho(4.2°K) \approx 500$, corresponding to a mean free path $\lambda(4.2°K) \approx 1$ mm.

The samples were mounted by the clamped-contact method [2]. The plots of $\rho(H)$ and of the derivatives $\partial\rho/\partial J = f(H)$, obtained by a modulation technique, were produced with an automatic x-wire recorder.

The measurements were performed on 27 samples, of which 17 were in forms of small ribbons (the width exceeded the thickness by several times). The orientation of the sample axes could be deduced from the anisotropy of the resistance in the magnetic field and from the periods of the Shubnikov-de Haas oscillations. The axes of the ribbons and of several filamentary whiskers were in the basal plane.

The new type of oscillations was observed in 14 ribbon whiskers but in none of the filamentary whiskers.

Figure 1 shows one of the most striking $\rho(H)$ dependences for a sample with dimensions $\ell = 155$ μ, $\Delta \approx 8.5$ μ, and $d = 1.4$ μ (ℓ is the distance between the potential contacts, Δ the width, and d the thickness); the measuring current $\vec{I}$ was parallel to the magnetic field $\vec{H}$. The oscillation amplitude was usually of the order of several per cent of the monotonic part of the resistance, making the oscillations difficult to observe. The use of the modulation procedure greatly facilitated the registration of the oscillating part of the resistance. Figure 2 shows one of the simplest plots of $\partial\rho/\partial H = f(H)$ for a ribbon measuring $140 \times 2 \times 1$ μ and for $\vec{I} \parallel \vec{H}$.

In the general case the oscillatory $\partial\rho/\partial H = f(H)$ dependence is more complicated, as can be seen from Fig. 3, which shows the results for a ribbon with dimensions $133 \times 2 \times 0.5$ μ, $\vec{I} \perp \vec{H}$, and $\vec{H} \perp \vec{n}$ (where $\vec{n}$ is the normal to the plane of the ribbon).

The investigation of the influence of the number of factors on the unusual behavior of the resistance in the magnetic field has revealed the following distinguishing features:

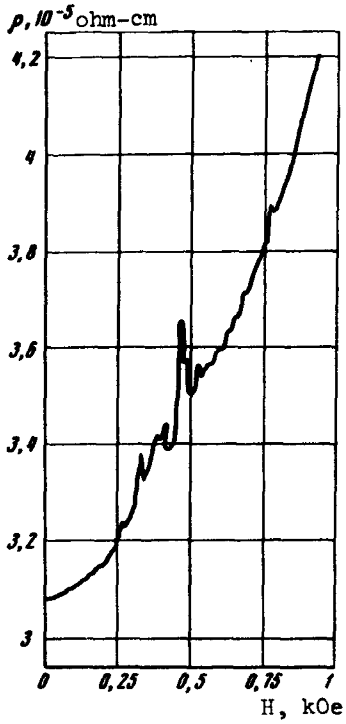

Fig. 1

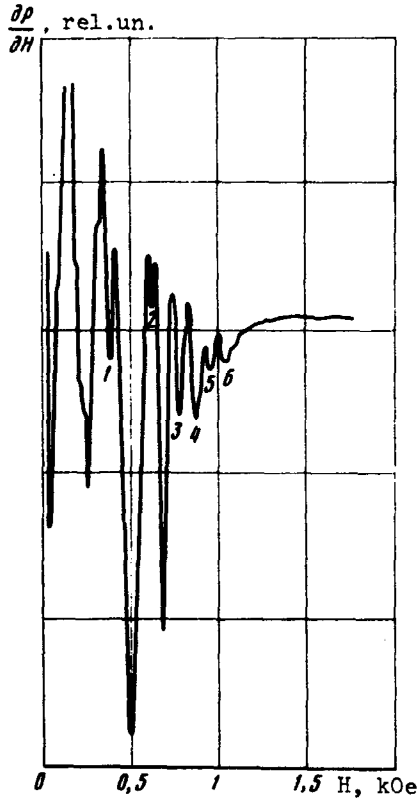

Fig. 2

1) The apparatus registered the appearance of oscillations starting with fields of several dozen Oe. The oscillation amplitude increases rapidly in a magnetic field, and then decreases just as rapidly until the oscillations vanish completely at a certain value H_d corresponding to the condition $r \simeq d$, where r is the radius of the electron orbit.

2) The Shubnikov-de Haas effect is observed in fields much stronger than the limiting value H_d, starting with approximately 10 kOe.

3) The oscillations are observed at any mutual orientation of the magnetic field, the measuring current I, and the normal n to the ribbon plane.

4) An analysis of the shapes of the ρ(H) and $\partial\rho/\partial H = f(H)$ curves makes it possible to conclude in the simplest cases that the oscillatory part of the resistance $\Delta\rho_{osc}(H)$ recalls a meander of rectangular steps.

5) The positions of the oscillation peaks and the limiting field H_d depend on the measuring current. With increasing current, H_d shifts towards weaker fields. A decrease of the current leads to stabilization of the peak position.

We have been unable so far to find a general law governing the positions of the oscillation peaks in a magnetic field. In strong fields one can note that the distance between the peaks decreases with increasing H before the effect vanishes. For example, in Fig. 2 the peak numbers 1, ..., 6 satisfy the condition $m \sim H^2$.

To establish the physical nature of the phenomenon described above, we start from the following: 1) the phenomenon is sensitive to the sample

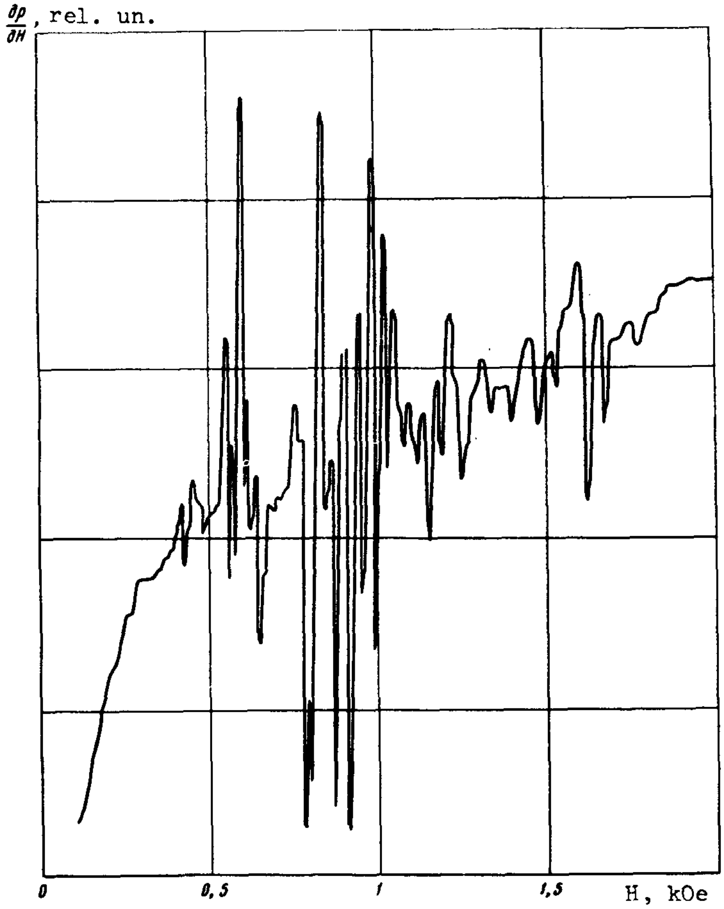

Fig. 3

dimensions. The limit of the existence of the effect corresponds to a magnetic field at which the radius of curvature r of the carriers in the bismuth becomes comparable with the sample thickness. 2) If $d < \lambda$ or r, then the principal role in the electron scattering processes is played by the surface. 3) For such perfect samples as whiskers, and for such metals as bismuth, the interaction of the electrons with the surface is close to specular.

Bearing this in mind, we propose that the new resistance oscillations are due to the presence in the metal of quantum surface levels produced in the magnetic field by specular interaction of the electrons with one surface of the sample (motion on truncated orbits of the Fermi surface).

Quantum surface levels of this type were observed by Khaikin in an investigation of the surface impedance of metals in weak magnetic fields [3]. The physical cause of the oscillations lies in the transitions between the quantum levels when the energy of the high-frequency field is equal to the energy difference between the levels. A theoretical interpretation of the results of [3] was given by Nee and Prange [4].

The surface-level spectrum for electrons interacting with two surfaces of the sample was considered earlier by Lifshitz and Kosevich in connection with a study of the oscillations of the magnetic moment in samples of limited dimensions [5].

The existence of quantum surface levels may give rise to oscillations of different thermodynamic characteristics of the metals, for example the magnetic moment, which can be observed also in effects of the de Haas-van Alphen type on truncated Fermi-surface orbits that are extremal with respect to area. The oscillations are connected in this case with the periodic change in the number of quantum levels with energy lower than the Fermi energy. According to [5], the amplitude of the oscillations should increase with increasing ratio d/r, and at d/2r > 1 the oscillations turn into the ordinary de Haas-van Alphen effect or the Shubnikov-de Haas effect on closed extremal orbits. No such behavior was observed in our experiments, and the oscillations vanish long before the Shubnikov-de Haas effect appears.

Besides these two principles for the "selection" of the quantum surface levels (the resonance principle and the passage of the Landau level through the Fermi level), there can exist also a "size-effect" principle: a real sample of limited dimensions can contain a finite number of Khaikin's quantum surface levels at a given value of H. Variation of the magnetic field changes this number and leads to a redistribution of the electrons among the levels, and consequently to a jump-like change in the density of states of the electrons near the Fermi surface.

The "size-effect" principle explains why the region where the oscillations exist is limited. Indeed, the dependence of the number of surface quantum levels m on the magnetic field is determined from the condition $z_m = d$, where z_m is the height of the arc of the truncated electron orbit. Since z_m cannot be larger than the diameter of the orbit, the conditions $2r = z_m = d$ determine simultaneously the maximum value of the number m and the limit of existence of the oscillations connected with the redistribution of the electrons over the levels in the plate: $m = f(H, d)$. Of course, in order for the oscillations to appear, the "size-effect" principle must be supplemented by an "extremal" one: it is necessary to choose among the truncated orbits only those that are boundaries of an extremal area in momentum space.

The complexity of the observed oscillatory picture is apparently connected with the fact that in bismuth there are four Fermi-surface ellipsoids. The influence of the measuring current can be attributed to the "deformation" of the Fermi surface under the influence of the electric field (the resistance of the sample is on the order of several ohms, the measurement currents at which the displacement of the peaks is noticeable is on the order of several milliamperes, and the mean free path is comparable with the distances between the current leads, making the electric-field energy comparable with the Fermi energy in the case of bismuth). Nor do we exclude the possibility that in the weak-field region ($d \ll r$) the observed oscillations contain also the quantum size effect in a magnetic field, predicted by Nedorezov [6], since all the conditions necessary for this purpose are satisfied.

In conclusion, we are sincerely grateful to L.A. Fal'kovskii for useful discussions and to G.A. Orekhanova for help with the experiment.

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