Temperature-dependent magnetic breakdown in aluminum

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A rapid growth and oscillations of the magnetoresistance were observed in aluminum in a field parallel to the [110] axis when the sample was cooled below 1 °K. The field at which the growth and oscillations set in depends on the temperature.

The behavior of the components of the magnetoresistance tensor of Al was investigated by us by examining the helicon characteristics.[1] We measured directly in the experiment the field dependence of the frequency and width of the first resonance of the standing waves in a single-crystal aluminum sample in a form of a plate measuring 8×7.4×0.5 mm. After cutting by the electric-spark method, the sample was annealed by the method of[2]1) to decrease its dislocation density.

The field dependence of the quantities indicated above was measured at four temperatures, 4.2, 1.4, 0.8, and 0.4 °K in a magnetic field up to 53 kHz produced by a superconducting solenoid with improved homogeneity, $\Delta B/B \lesssim 10^{-5}$ over the sample dimensions.

To register the helicon signal, we used a procedure with crossed coils,[1] used either in the "helicon-generator" regime[3] for continuous plotting of $f_{res}(B)$, or in a passive regime with excitation of the helicon by an external generator tuned with a small motor, so as to record the resonance as a function of the frequency at a fixed field. The field was fixed by transferring the solenoid into the "frozen" regime. The measurement results are shown in Figs. 1 and 2. The most effective is the behavior of the resonance with Δf (Fig. 1), which under our conditions, which correspond to the local limit, is proportional to a certain combination of the diagonal components of the magnetoresistance tensor. At 4.2 and 1.4 °K, the value of Δf is independent of the field, within the limits of the measurement errors (curve 1). At 0.8 and 0.4 °K (curves 2 and 3), starting with a certain temperature-dependent value of the field (see Fig. 1), a rapid rise is observed, followed by oscillations whose amplitude (shown by the arrows in Fig. 1) increases rapidly.

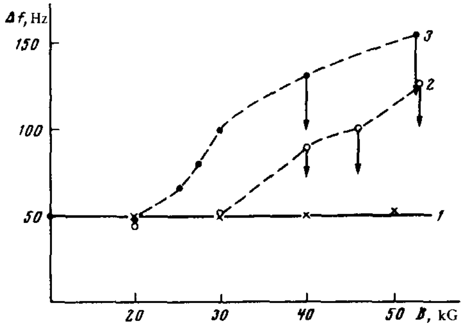

FIG. 1. Helicon-resonance width in aluminum sample vs. the magnetic field at various temperatures: 1—4.2 and 1.4 °K, 2—0.8 °K, 3—0.4 °K. **B** ∥ [110].

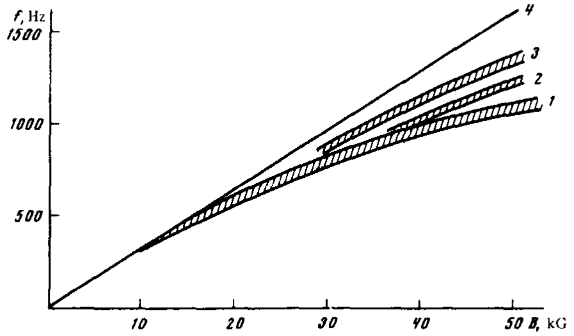

FIG. 2. Monotonic part of the plot of the helicon resonance frequency in aluminum sample against the magnetic field. The oscillation amplitude is also shown in arbitrary scale: 1—4.2 and 1.4 °K, 2—0.8 °K, 3—0.4 °K. **B** ∥ [110].

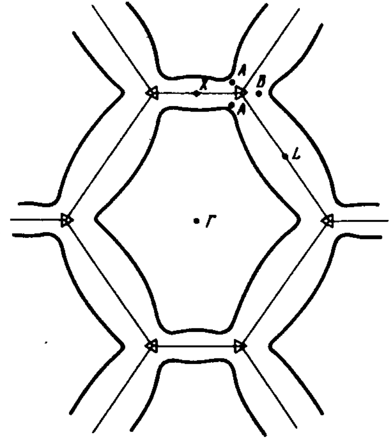

FIG. 3. Intersection of the Fermi surface of aluminum with the (110) plane drawn through the center of the Brillouin zone.

It should be noted that at the same time there are observed strong oscillations of the resonant frequency of the helicon,[3] which are superpositions of the oscillations from the γ orbits in the third zone of the Fermi surface of aluminum[4] and the short-period oscillations of the hole surface of the second zone. The latter can be observed in a field close to 50 GHz already at 1.4 °K, and at 0.4 °K their amplitude in the same field is comparable with the amplitude from the γ orbits.

The measurements of Δf at different points of the $f_{\mathrm{res}}(B)$ curve have shown that the short-period oscillations do not influence, within the limits of errors, the oscillations of the magnetoresistance. It was established that the magnetoresistance oscillates at a frequency corresponding to the γ orbit on a tube parallel to the field. The picture of the phenomenon, revealed by the results of the measurements of the resonance width, is supplemented by the results of the measurements of the monotonic part of the $f_{\mathrm{res}}(B)$ function, shown in Fig. 2. The straight line 4 in this figure represents the linear course of this function, calculated for the case of a field-independent Hall constant $R = 1.02\times10^{-12}\ \Omega-\mathrm{cm}/G$. Actually, the monotonic course of $f_{\mathrm{res}}(B)$ deviates strongly from the linear at 4.2 and 1.4 °K (curve 1). However, when the sample is cooled below 1 °K, the deviation from linearity decreases.

The described behavior of the galvanomagnetic characteristics of aluminum in a field parallel to [110], at the lowest investigated temperatures (growth and oscillations of the magnetoresistance, Hall constant that depends little on the field) is quite similar to that observed in the investigation of magnetic breakdown in aluminum[5] in a field parallel to the [100] axis. We therefore assume that in our experiments, too, magnetic breakdown is observed between the hole orbits of the second zone through the small electron orbit of the third zone, and the observed period of the magnetoresistance oscillations shows that the role of the small orbit is assumed in our case by the extremal γ orbit on the tube of the third zone (Fig. 3).

Calculations using the Ashcroft pseudopotential components[6] yield for the breakdown field at the points A (Fig. 3) a value 1.6×10^{6} G. At the points B, the breakdown field is larger by one more order of magnitude. It is possible that in fact the energy gaps at the points A and B are smaller, but the details of the situation seem to be determined by the smallness of the breakdown probability. Because of this smallness, the time of establishment of the interference amplitude of the wave function of the electron[7] is large. If the breakdown frequency ν_b on the γ orbit is defined as the reciprocal of this time, then we can interpret the temperature dependence of the breakdown, as observed by us, as the result of competition between the breakdown frequency ν_b and the frequency of the electron-phonon scattering on the orbit.[8] In terms of the frequencies of the various processes, the situation in our samples at various temperatures can be described, in our opinion, with the aid of the following inequalities:

$$T > 1\mathrm{K} \qquad \nu_c \gg \nu_p > \nu_b > \nu_d,\ \nu_i\ , \tag{1}$$

$$T \approx 0.8\mathrm{K} \qquad \nu_c \gg \nu_b > \nu_p > \nu_d,\ \nu_i\ , \tag{2}$$

$$T \approx 0.4\mathrm{K} \qquad \nu_c \gg \nu_b > \nu_d, \nu_i\ ,\ \nu_p\ , \tag{3}$$

where ν_c is the cyclotron frequency on the γ orbit, ν_p is the frequency of the electron-phonon scattering, and ν_d and ν_i are the frequencies for the scattering by dislocations and impurities. The inequalitites show that the high purity of the aluminum and low dislocation density in the sample, which were obtained by the aforementioned annealing, greatly facilitated the observation of the effect.

[1)] This annealing method was proposed by V.T. Petrashov to increase the amplitude of the de Haas-van Alphen effect.

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