Phase transition of order 2 1/2 in zinc

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The anisotropy of the magnetoresistance $\rho(H)$ in the free state and under uniaxial elastic tension was measured in filamentary zinc crystals ~1 μm thick. The measurements were performed at $T=4.2$K in fields up to 80 kOe. An abrupt change in the anisotropy of $\rho(H)$ was observed at an elongation $\Delta l/l_0 \approx 0.35\%$ along the [2$\bar{3}$11] axis. This change is attributed to a change in the topology of the Fermi surface of zinc—the bridges along the [0001] axis are broken, as are several bridges in the (0001) plane.

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The energy spectrum $\epsilon=\epsilon(\bar{p})$ of the conduction electrons in a metal has singular critical points ϵ_c at which the equal-energy surfaces change their topology. It was shown by I. M. Lifshitz[1] that if the Fermi energy of the electron ϵ_F goes through a critical value ϵ_c when any one parameter is continuously varied, then this should be accompanied by a sharp anomaly in the density of states of the conduction electrons and by corresponding sharp anomalies in the thermodynamic and kinetic properties of the metal. As proposed by Lifshitz,[1] these anomalies are customarily called "transitions of order $2\frac{1}{2}$". They are not connected with the change of the lattice symmetry and are electronic transitions without a jumplike change in the total number of the conduction electrons. The theory has shown that the critical values $\epsilon_F=\epsilon_c$ can be reached, in particular, when the metal is subjected to strains of various types, both isotropic and anisotropic, by impurities, and also by a magnetic field.[2]

The new unusual relations in the properties of metals, predicted in[1], have stimulated intensive experimental searches for phase transitions of order $2\frac{1}{2}$. The problem lies, first, in observing the topological changes themselves in the Fermi surface (FS) (revealed, for example, by the vanishing or the appearance of new frequencies of quantum oscillations or by the change of the magnetoresistance) and, second, in the experimental proof that this change has the character of a phase transition, i.e., it is accompanied by various anomalies of the properties of the metal.

The first to be developed was the procedure for obtaining appreciable hydrostatic pressures, which ensured the success of practically all the investigations aimed at observing the transitions of order $2\frac{1}{2}$.[3] It was soon demonstrated that, at least in the case of Zn and Cd[4] and Bi,[5,6] the topological changes of the FS can be obtained at realistically attainable strains, and their signs are different in the case of Zn and Cd. The first topological transition from a closed to an open FS at pressures on the order of 10 kbar was registered for Cd.[7] A vanishing of the electron ellipsoids at pressures of the same order was next observed in Bi with Sb impurities.[8,9] Transitions induced by a magnetic field were observed in Bi[10] and Te.[11] Lazarev *et al.*[12] advanced the hypothesis that the nonmonotonic pressure dependence of the superconducting-transition temperature T_c of thallium can be due to a change in the FS. This assumption was theoretically verified in[13], but from the experimental point of view the question of the existence of a phase transition of order $2\frac{1}{2}$ remains open, since no topological changes in the FS of thallium were observed directly.

The results obtained in many studies have indicated that for most metals the critical point ϵ_c cannot be reached by the existing procedure of producing hydrostatic pressures. It was proposed[14] to use filamentary crystals (whiskers) of metals for the observation and study of transitions of order $2\frac{1}{2}$. It is well known that these objects can be subjected to large reversible elastic strains. However, the realization of the unique properties of whiskers has encountered great methodological difficulties, involving the development of whisker mounts suitable for simultaneous mechanical and electrical tests. Moreover, the physical properties of the whiskers at low temperatures, which differ substantially from those of bulky samples, have not been investigated. By now these difficulties have been overcome and we have proceeded to the study of the influence of uniaxial tension on the geometry of the FS of metals.

The first measurement object was chosen to be zinc, whose open FS have a number of thin necks. We have hoped to "break" these necks during the course of the dilatation. The results of the measurements are given below.

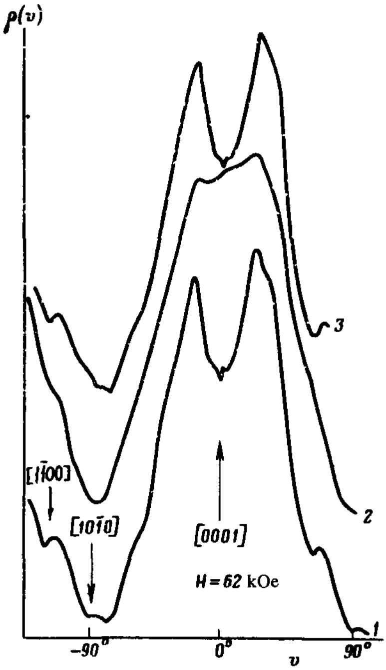

FIG. 1.

The objects of the measurements were plate-like Zn whiskers ~1 μm thick and ~2—3 mm long. The variation of the FS topology was observed by measuring the anisotropy of the resistance, which in the presence of a strong magnetic field is due to the existence of open FS sections.[15] The mechanical and electrical mount for the whiskers was produced with the aid of "Epotek-20" epoxy resin. The tension was produced by a specially constructed rigid linkage with an approximate ratio 1/3000. The measurements were performed at $T=4.2$ K in magnetic fields up to 80 kOe.

Figure 1 shows the resistance in a magnetic field $H=62$ kOe against the field rotation angle in a plane perpendicular to the measuring current, for a whisker having an orientation along the [2$\bar{3}$11] axis (the orientation was determined from a comparison of the anisotropy of $\rho_H(\theta)$ of the whisker and the bulky sample with allowance for the size effect in the plate). The minima of the resistance in the (0001) plane are connected with the open sections of the FS in the [0001] direction ("vertical arms of the monster"), while in the $\{10\bar{1}0\}$ plane they are connected with the "horizontal necks" of the same "monster."[15] The first rosette is given for zero tension, the second is for a 1% rapid elongation of the sample $\Delta l/l_0$, and the third is obtained after the monster is removed. For convenience, the curves are shifted relative to one another. In the case of tension, two minima of $\rho_H(\theta)$ vanish. This vanishing can be interpreted as the breaking of a number of necks of the "monster": along the [0001] axis and in the (0001) plane. The fact that the minimum at $\overline{\mathbf{H}} \parallel (10\bar{1}0)$ is preserved indicates that only one of the three nonequivalent necks of the "monster" in the (0001) plane is broken. Figure 2 shows the dependence of the resistance of the tension for two characteristic minima of the "rosette" of Fig. 1. The sizes of the points correspond to the measurement accuracy. It is seen that for the direction $\overline{\mathbf{H}} \parallel (0001)$ the curve has the form of a transition that sets in at $\Delta l/l_0 \approx 0.35\%$. It is typical that the change of the magnetoresistance occurs on the $\epsilon < \epsilon_c$ side, in agreement with the theory of[1].

Similar investigations carried out by us on Bi and Sb whiskers reveal only large quantitative changes in the FS of these metals. Thus, at $\Delta l/l_0 = 1\%$ certain sections of the FS of Sb decrease to approximately one-half, while those of Bi increase by five times. By way ofillustration, Fig. 3 shows a plot of the Shubnikov—de Haas effect in Bi elongated 0.3 and 0.6% along the binary axis,

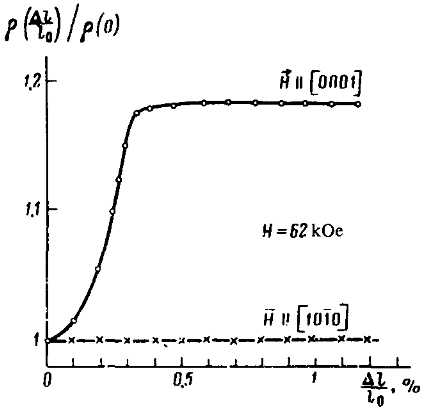

FIG. 2.

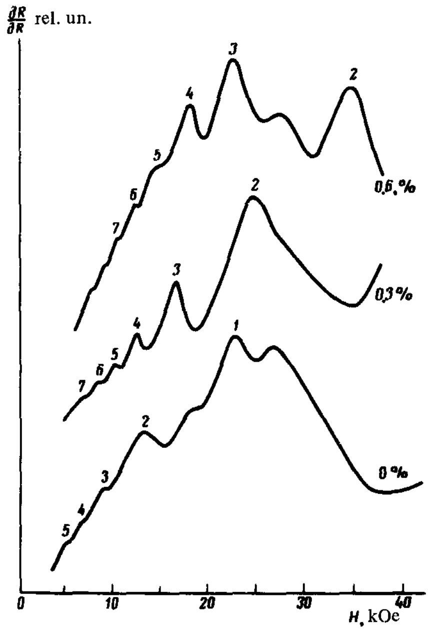

FIG. 3.

with the magnetic field inclined 30° to the $\bar{C}_3$ axis. A large increase in the oscillation frequency and points to a considerable deformation of the electron ellipsoid of the FS of Bi.

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