Effect of tension on the Fermi surface in bismuth

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A new method is proposed for producing strong elastic tension strains (0.6–0.7%) in single-crystal samples. This method was used to investigate for the first time the change of the Fermi surface of Bi when stretched along the binary axis.

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The effect of tension on the energy spectrum of the carriers in bismuth has not been investigated to this date, since attempts to obtain sufficiently strong strains were unsuccessful as a result of the very small rupture strength of bulky Bi samples.

We report here the results of an investigation of the shape of the Fermi surface in single-crystal Bi samples under elastic tension strains reaching 0.6–0.7%, approximately 1.5 times larger than the strains corresponding to the listed value of the yield point, and comparable in magnitude with the strains attained in whisker crystals.

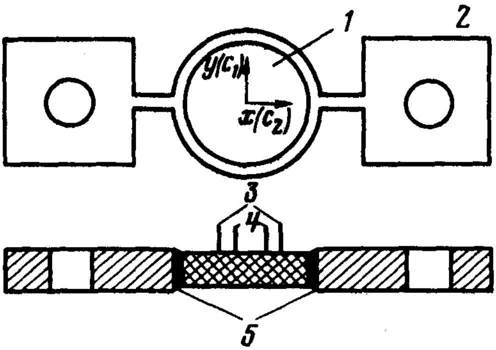

FIG. 1. Band with sample: 1—sample; 2—lug for fastening in the dilatation device; 3—current electrodes; 4—potential electrodes; 5—"Araldite" layer.

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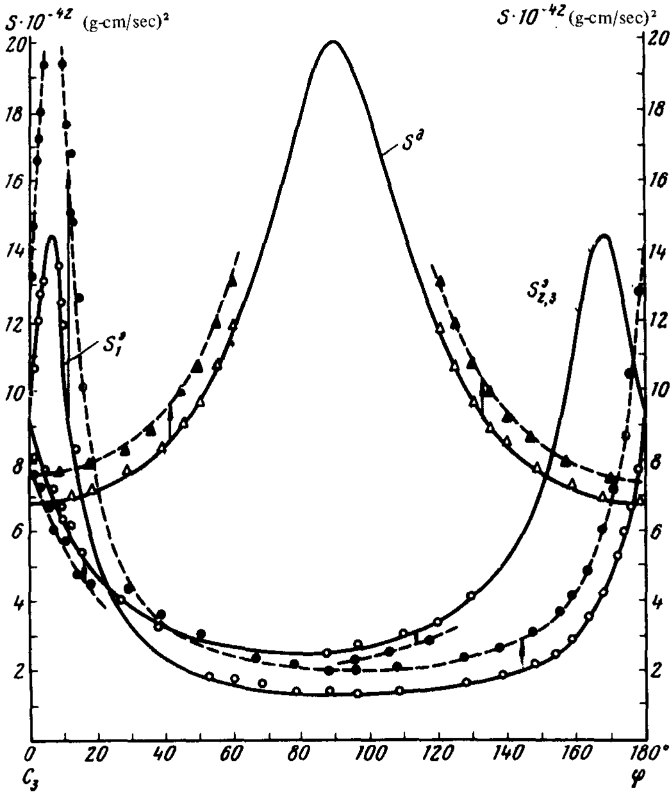

FIG. 2. Angular dependences of the extremal sections of the Fermi surface of Bi in the trigonal-bisector plane: 0, Δ – $\varepsilon_{xx}=0$; ●, ▲ – $\varepsilon_{xx}=0.16\%$ ($\sigma=8$ kgf).

The dilatation was carried out in special bands in the form of rings with outside diameter 4 mm and inside diameter 3 mm (Fig. 1). The band was machined from refined beryllium bronze BRB-2 or heat-treated non-magnetic alloy 40 KhNYu, using a program-controlled electric-spark lathe. The same lathe was used to cut the Bi sample in the form of a disk of 3 mm diameter and 0.75 mm thickness. The gap between the sample and the band (not exceeding 20 μm) was filled with the polymerized resin "Araldite." The entire system was fastened with lugs to a special device which made it possible to stretch the sample at liquid-helium temperature.

A computer calculation for such a system shows that its strain has a complicated character, but is sufficiently uniform in the central part of the sample measuring 1×1 mm. In this region, the shear strains are negligibly small. The central part of the sample was stretched along the direction of the applied force (the x axis) and compressed in the perpendicular direction (the y axis) by approximately the same amount. The strain along the z axis was much less than the strain along the x axis. For the bands made of BRB-2 (Fig. 1), the calculated values of the longitudinal (ε_{xx}) and transverse (ε_{yy}) strains are $\varepsilon_{xx} = -\varepsilon_{yy} = 0.02\%\text{-kg}^{-1}$. The strain was measured at room temperature with the aid of FKPA-1 small-base foil resistance strain gauges and yielded values (ε_{xx})

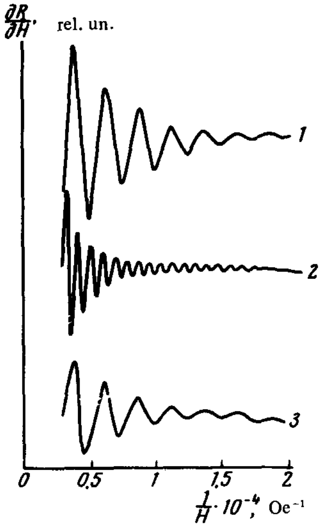

FIG. 3. Oscillations of the magnetoresistance derivative ($\partial R/\partial H$) for the section S_1^e at $\phi = 168°$: 1—$\varepsilon_{xx} = 0$; 2—$\varepsilon_{xx} = 0.6\%$; 3—load removed.

$= 0.025 \pm 0.007\%$-kg^{-1}. The experimental values of (ε_{yy}) are 30% smaller. The strains in the 40 KhNYu band had approximately the same values. We cite henceforth the calculated values of the strains.

The Shubnikov—de Haas oscillations were measured by the usual low-frequency modulation procedure in fields up to 45 kOe and at temperatures 4.2 and 2.1 K, with the Bi stretched along the binary axis C_2. The magnetic field was rotated in the trigonal-bisector plane. The directions of the crystallographic axes in the plane, and also the location of the current and potential contacts, are shown in Fig. 1. At the indicated arrangement of the contacts, the main contribution to the oscillations is made by the central homogeneously deformed part of the sample.

In the chosen crystallographic orientation, the oscillations of the magnetoresistance are superpositions of three frequencies connected with the extremal sections S^h of the hole "ellipsoid," S_1^e of the electron "ellipsoid," the maximum axis of which is perpendicular to the tension axis, and the coinciding sections $S_{2,3}^e$ of the other two electron "ellipsoids."

To separate the frequencies, we used not only longitudinal but also transverse modulation of the magnetic field. The most complicated curves were reduced with a computer.

The character of the variation of the Fermi surface under tension at $\varepsilon_{xx} = 0.16$ is shown in Fig. 2. Whereas under hydrostatic compression[1] and compression along the trigonal axis C_3[2,3] all three equal-energy surfaces of Bi change in similar fashion, in the case of tension along the C_2 axis the electron "ellipsoid" has a qualitatively different behavior, whereby the sections S_1^e increase linearly with the load σ at a rate $\partial \ln S_1^e / \partial\sigma = 6.4 \pm 0.3\%$-kg^{-1}, while the sections $S_{2,3}^e$ decrease linearly and $\partial \ln S_{2,3}^e / \partial\sigma = -(1.8 \pm 0.2)\%$-kg^{-1}. The sections continue to vary linearly up to the maximum strains obtained in the present study, $\varepsilon_{xx} = 0.6\%$ at $\sigma = 30$ kg ($\varepsilon_{xx} \sim \sigma$), at which the sections of the "ellipsoid" S_1^e increase by a factor of 3 (Fig. 3). It should be noted that the quantity $\varepsilon_{xx} = 0.6\%$ is therefore apparently not the limit for this method, since the oscillations curves turn out to be practically fully reversible when the load is removed.

The observed character of the variation of the electron part of the Fermi surface of Bi is the consequence of the violation of the equivalence of the electronic extrema at the point L of phase space as a result of the vanishing of the threefold symmetry axis at deformations perpendicular to C_3. An estimate based on the Abrikosov model[4] for small strains[1)] indicates that the electronic extrema L_1 and $L_{2,3}$ are shifted relative to one another at a rate ~ 1 meV/kgf, with L_1 dropping and $L_{2,3}$ rising relative to their values at $\sigma = 0$.

The linear decrease of the sections $S^e_{2,3}$ in tension, which amounts to 36% at $\varepsilon_{xx} = 0.4\%$, suggests that at $\varepsilon_{xx} \approx 1.1\%$ ($\sigma \approx 55$ kg) the "ellipsoid" 2 and 3 should vanish and the electronic part of the Fermi surface of Bi should consist of a single ellipsoid.

It follows also from Fig. 2 that the anisotropy of the increasing "ellipsoid" remains essentially unchanged, at least up to the value $\varepsilon_{xx} \approx 0.2\%$. The anisotropy of the decreasing "ellipsoid," oscillations from which are observed in a narrower angle interval, require, in light of the latest data[5] a special study. The cross sections of the hole "ellipsoid" increase linearly with increasing tension at a rate $\partial \ln^h/\partial\sigma = (1.4 \pm 0.2)\%\text{-kg}^{-1}$. The anisotropy of this part of the Fermi surface remains apparently unchanged.

The cyclotron effective mass for the minimal section S^e_1, determined from the temperature dependence of the oscillation amplitude, increases in tension by $\sim 60\%$ at $\sigma = 10$ kg.

In conclusion it should be noted that the proposed method of producing strains can be used equally well for unilateral compression of the samples.

[1)] If it is assumed that the Abrikosov model remains in force at small deformations that violate the symmetry of the lattice.

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