Formation of a dumbbell Fermi surface and intraband magnetic breakdown due to uniaxial compression of the alloy $Bi_{0.78}Sb_{0.22}$

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(Submitted 23 June 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **46**, No. 6, 224–226 (25 September 1987)

Two isolated Fermi-surface cavities are observed to merge into a single dumbbell-shaped cavity during uniaxial compression of the alloy $Bi_{0.78}Sb_{0.22}$. This merging is accompanied by an intraband magnetic breakdown.

Intraband magnetic breakdown is distinguished from interband magnetic breakdown in that it is a less common effect, observed only in the valence band of tellurium.[1] As in the case of interband breakdown, a transition from one classical trajectory to another is possible if the p-space trajectories lie close together. Such a situation may occur on a Fermi surface which has saddle points or conical points. If the self-intersecting orbits which arise in a magnetic field in this case are not extremal, the intraband breakdown will not be manifested macroscopically.[2] If the Fermi level E_F passes through a saddle point E_k in the energy spectrum, however, two isolated cavities will merge to form a single dumbbell-shaped Fermi surface (an electron topological transition of the "bridge formation" type, as described by I. M. Lifshits). The charge carriers which have a trajectory with a self-intersection in the $p_z \| \mathbf{H}$ ($p_z = 0$), plane in the case of semiclassical quantization belong to a band on the Fermi surface near the extremal cross section S and determine quantum oscillation effects in a magnetic field.

Recent data indicate the appearance of a saddle point in the electron and hole spectra of $Bi_{1-x}Sb_x$ alloys at L points[3] ($X \cong 0.15$), so that the $E(\mathbf{k})$ dependence becomes a double-humped curve with increasing x. When E_F passes through a saddle point ($E_F = E_k$), an electron topological transition involving the formation (or rupture) of a dumbbell-shaped Fermi surface should occur (Fig. 1). In the dumbbell formation process, there are two types of closely spaced momentum-space trajectories which allow a probability for an intraband breakdown: a breakdown between two isolated quasiellipsoids at $E_F \lesssim E_k$ (trajectories of type 2 in Fig. 1a) and a breakdown through the "neck" of the dumbbell at $E_F \gtrsim E_k$ (trajectories 3 and 4 in Fig. 1a). In the first case, the intraband breakdown should be manifested as a doubling of the frequency (F) of Shubnikov–de Haas oscillations from the maximal extremal cross sections of the Fermi-surface "ellipsoids," $S_{\max} \sim F_{\max}$, in strong magnetic fields H. In the second case, breakdown frequencies of half the magnitude will appear against the background of the high frequency associated with the maximal cross section of the dumbbell.

In the present experiments we studied the Shubnikov–de Haas effect in the alloy $Bi_{0.78}Sb_{0.22}$ during uniaxial compression along the bisector axis C_1, which runs perpendicular to the twofold axis C_2. In a deformation of this sort, one of the previously equivalent electron L extrema descends below the Fermi level, while two others rise

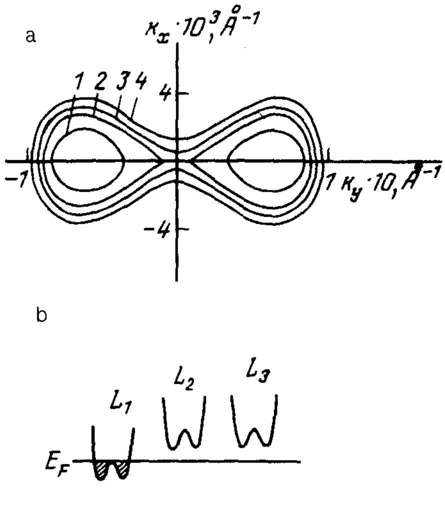

FIG. 1. a: Contour map of the extremal (maximal) cross section of the electron Fermi surface in the trigonal-bisector plane of the $Bi_{0.78}Sb_{0.22}$ alloys according to calculations from the energy-spectrum model of Ref. 5, shown in the space of wave vectors $\mathbf{k}(\mathbf{H}\|k_z,\ k_z=0)$ for E_F. 1—19 meV; 2—21.5 meV; 3—22 meV; 4—23 meV. b: Relative arrangement of the electron L extrema during compression along the C_1 axis (E_F–E_k).

above it[4] (Fig. 1b). The result is a unique possibility to send the Fermi level at the lowered extremum through the presumed saddle point in the course of a single experiment and to observe a corresponding change in the Fermi surface.

Figure 2 shows the strain (ϵ) dependence of the Shubnikov–de Haas frequencies from the maximal cross section of the Fermi surface in the trigonal-bisector plane (C_1C_3). At small values $\epsilon \leqslant 0.07\%$, the angular dependence $S(\phi)$ in the (C_1C_3) plane corresponds to an ellipsoidal Fermi surface with an anisotropy $A = (S_{\max}/S_{\min}) = 12$ ($A = 11$ for pure Bi), and the corresponding Shubnikov–de Haas oscillations are mo-

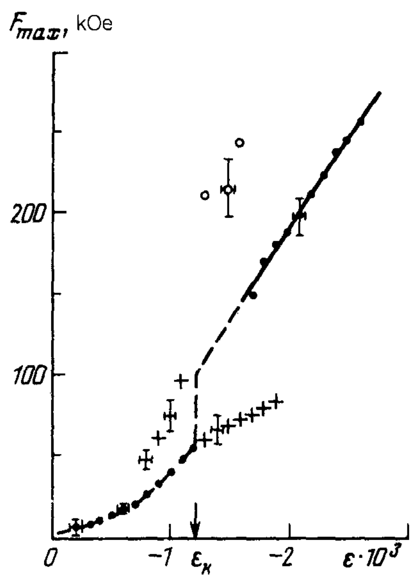

FIG. 2. Strain dependence of the Shubnikov–de Haas frequency from the extremal (maximal) cross section of the $Bi_{0.78}Sb_{0.22}$ Fermi surface corresponding to the contours in Fig. 1a ($\mathbf{H}\|k_z$). The plus signs represent magnetic-breakdown frequencies.

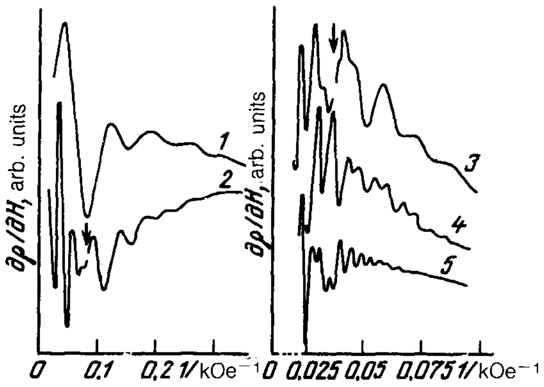

FIG. 3. Change in the form of the Shubnikov–de Haas oscillations corresponding to the data in Fig. 2b as the strain is varied. The strain (ϵ) is: 1— -0.05%; 2— -0.08%; 3— -0.15%; 4— -0.19%; 5— -0.25%. The arrows show changes in the scale along the $\partial\rho/\partial H$ axis.

nochromatic up to limiting magnetic fields $H \cong 50$ kOe (curve 1 in Fig. 3). At $\epsilon \gtrsim 0.18\%$, beats of two frequencies are observed near the minimal cross sections $S_{\min}$, while a branch with the doubled frequency appears on the $F_{\max}(\epsilon)$ dependence at $\epsilon \gtrsim 0.08\%$. The $F_{\max}(\epsilon)$ behavior in Fig. 2 can be attributed to the merging at $\epsilon = \epsilon_k$ of two isolated Fermi surfaces to form a single dumbbell-shaped surface (Fig. 1a). As a result of this merging, the $F_{\min}(\epsilon)$ dependence acquires two frequencies, associated with the "neck" and the "belly" of the dumbbell, and $S_{\max} \sim F_{\max}$ doubles.

Figure 3 shows the dynamics of the changes in the oscillation dependence from the maximal cross section, where a self-intersecting trajectory arises at the point ϵ_k, as the strain is varied. The appearance of the doubled frequency on curve 2 in Fig. 3 at fields $H \gtrsim 30$ kOe should be regarded as a tunneling through a barrier separating two parts of the potential well at L at strain values in the subcritical region (Fig. 1b). The Shubnikov–de Haas frequencies in weak fields correspond to isolated semiclassical orbits; in strong fields, doubled magnetic-breakdown orbits arise. The doubled frequencies cannot be interpreted as a second harmonic, since the pattern reverses in the region of maximum strain: In weak magnetic fields the oscillations are determined by the high-frequency component from the maximal cross section of the dumbbell, while a lower frequency, which arises as a result of breakdown through the "neck" of the dumbbell, appears in strong fields H (curve 5 in Fig. 3). As the strain is increased (as the neck of the dumbbell grows), the breakdown field H_b intensifies (cf. curves 4 and 5 in Fig. 3). The breakdown field $H_b \approx 35$ kOe found for a dumbbell at $\epsilon = -0.25\%$ from the relation $H_b = \Delta E/\mu$, where $\Delta E = E_F - E_k$ is the energy distance to the saddle point in the spectrum, and μ is the Bohr magneton (a calculation based on the model of Ref. 5), agrees with the corresponding behavior $(\partial\rho/\partial H)(H)$ (curve 5 in Fig. 3).

The transition region $(0.11 \leqslant \epsilon \leqslant 0.18)\%$ is a region of proximity to a conical point of the Fermi surface (self-intersecting orbits). Quantization conditions for such orbits were derived in Refs. 6 and 7. In this region the distances between Landau levels are very nonuniform,[7] so that higher harmonics appear at strain values in this interval (Fig. 2; curve 3 in Fig. 3). The strain $\epsilon_k \cong 0.12\%$, which corresponds to the point at which the dumbbell forms, was chosen in this interval on the basis of a best fit of the experimental results and theoretical results calculated from the model of Ref. 5 ($\epsilon_k \sim 0.1\%$).

We wish to thank M. I. Kaganov, I. I. Farbshteĭn, and Ya. G. Ponomarev for useful discussions and comments.

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Translated by Dave Parsons