Short-period oscillations of the collector voltage in the case of transverse electron focusing in bismuth

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Short-period oscillations of the collector voltage were observed when electrons were transversely focused in bismuth. The oscillations are possibly due to quantization of the motion of the electrons hopping over the surface. The period of the oscillations is 0.1–0.2 Oe, while the focusing field is ~5 Oe.

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Experiments[1] aimed at observation of the focusing of electrons by a transverse homogeneous magnetic field (*EF*) in bismuth have revealed that collector-voltage spikes are observed in magnetic fields that are multiples of H_0 (the electron-trajectory diameter is equal to the distance between the contracts at H_0), and are due to specular reflection of the electrons by the sample surface. It was also observed in[1] that the first *EF* line had a fine structure (*fs*) (an additional maximum in a field ~4.5 Oe is well resolved on Fig. 2 of[1], whereas $H_0 = 6$ Oe). This paper reports results of a study of the *fs*, carried out with an installation having a larger resolution than that used in[1].

The system used to observe the *EF* was the same as in[1]. Two needle-type electrodes, an emitter and a collector, separated by a distance L (0.15—0.3 mm), were mounted on the surface of a bismuth single-crystal plate 2 mm thick. Current was made to flow through the emitter and the dependence of the collector voltage U on the magnetic field H was measured. The measurements were performed with alternating current in the frequency range 20—1000 Hz. The voltage sensitivity of the installation was not worse that 10^{-11} V. Provision was made for measuring the derivative $\partial U/\partial H$. When U was recorded, an alternating sinusoidal voltage $\tilde{J}_e$ was made to flow through the emitter, and when $\partial U/\partial H$ was recorded, direct current $J_e^=$ flowed through the emitter, and the magnetic field H was amplitude-modulated. The measurements were performed on a number of samples, whose C_2 axis was in the plane of the sample and the C_3 axis made an angle ϕ with the normal n to the surface of the sample ($\phi = 0$ and 30°). The line joining the contacts was directed along C_2, so that transverse focusing of the central-section electrons of one of the "ellipsoids" could be observed. *EF* in multiple fields was observed in all the samples. The specular-reflection coefficient of the focused electrons, determined from the ratio of the amplitudes of the neighboring *EF* lines,[1] was not less than 0.5 for all the investigated samples. Besides focusing in multiple fields, the *fs* of the first *EF* line was observed as a rule in all the samples. Figure 1 shows typical singularities of the *fs*, which manifest themselves in the appearance of additional maxima on the $U(H)$ curves. The plots of the derivative $\partial U/\partial H$ (curves 2 and 3 of Fig. 1) show clearly that U oscillates and the distance between the $\partial U/\partial H$ maxima amounts to several dozen oersteds, whereas $H_0 = 5.0$ Oe. The wavy character of the *fs*, the number of maxima, their position on the H scale are all more sensitive than the *EF* to the quality of the sample surface and to the angles between the line joining the contacts and the crystallographic axes of the sample. Characteristic features of the observation of the *fs* are the narrow *EF* line and the small emitter currents. With increasing emitter current, the

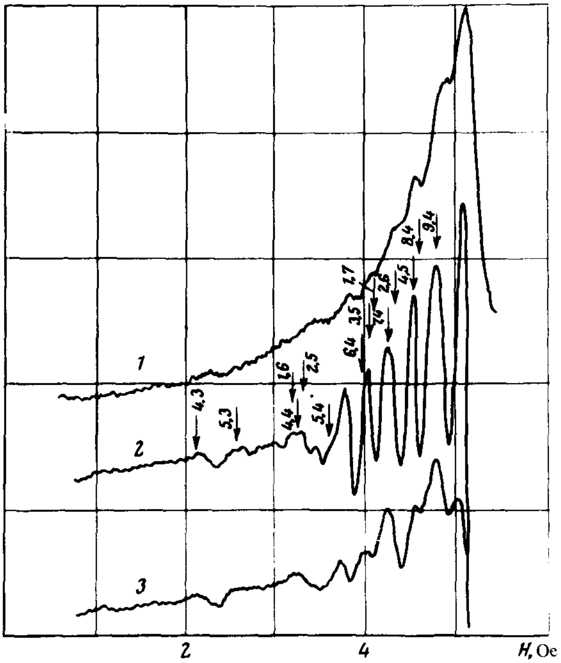

FIG. 1. $\phi = 30°$, $L = 0.23$ mm, $\mathbf{H} \parallel \mathbf{n}$, C_2. Curve 1—$J_e^= = 0.2$ mA, $T = 1.8$ K. Curves 2 and 3—$J_e^=$ $= 1$ mA, modulation-field amplitude 0.04 Oe.

maxima of the plane structure shift and become smeared out. When J_e^c flows from the emitter into the sample and is increased, the maxima of the fine structure shift towards weaker fields. When the current flows in the opposite direction, the maxima of the fine structure shift towards stronger fields. The displacements of the different maxima of the fine structure are different. When **H** makes an angle ψ with the axis of the "ellipsoid," the maxima shifted towards stronger fields in proportion to sec ψ. A fine structure is observed only in fields $\lesssim H_0$, and, in contrast to the lines, no *EF* appears in multiple fields. The temperature dependence of the amplitudes of the fine-structure maxima are different (cf. curves 2 and 3 of Fig. 1, which were plotted at 1.8 and 4.2 K respectively).

One of the causes of the fine structure of the short-period oscillations of the collector voltage may be the quantization of the trajectories of the hopping electrons (QTHE). Allowance for the quantum character of the motion of an electrons hopping over the surface in specular reflection from the surface in a weak magnetic field (a trajectory of this type is shown in Fig. 2, arc *ACB*), has made it possible[2] to explain the oscillations previously observed Khaĭkin.[3] Owing to the QTHE, trajectories *ACB* (Fig. 2) with different values of *AB* are allowed (see, e. g., [4]), such that the magnetic flux Φ that penetrates through the area of the segment *ACB* is equal to $\Phi_0(n+1/4)$, where $n=1,2,\ldots$ is the quantum number, and Φ_0 is the flux quantum.[2,4] Figure 2 shows the calculated values of *AB* for a Fermi surface comprising an elliptic cylinder with semiaxes $P_1=5.4\times10^{-22}$ and $P_2=7.9\times10^{-22}$ g cm/sec. P_1 and P_2 are the dimensions of the central section of the electronic "ellipsoid" of bismuth[4]. On Fig. 2 are marked the values $n=1-10$ for the curves as well as the integer number *m* of the values of *AB* spanned by the distance between the contacts in the case of the geometry of the experiments whose results are shown in Fig. 1 ($L=mAB$, $m=2-8$). The effective electrons leaving the emitter and reaching the collector can be classified in accordance with trajectories described by two numbers (n,m), namely the quantum number *n* and the number *m* of the hops. The possibility, in principle, of the existence of a quantum size effect in electron focusing has been noted in[5] and is due to the fact that the electrons moving along the trajectory (n,m) can strike the collector only at definite values $H=H_{n,m}$, and this should lead to oscillations of $U(H)$. It is obvious that relatively large contact dimensions should impede the resolution of the spikes of *U* due to the electrons with large *n*. On the other hand, at small values of *n* the electron strikes the collector at a small angle and is extremely sensitive to the microstructure of the collectors and to the defects of the surface near the collector, which undoubtedly are produced when the needle electrodes are mounted, thus decreasing the effectiveness of the electrons with small *n*. In view of the increased probability of diffuse reflection as a result of the increased number of collisions with the surface, the electrons with large *m* are less effective. A real surface can have various random local defects, which can influence differently the electrons with different (n,m) and even prevent the appearance of series with definite *m*.

The numbered arrows in Fig. 1 mark the fields $H_{n,m}$ determined by the intersections of the $AB(H,n)$ curves with the L/m lines located within ±0.1 Oe of the maximum of $\partial U/\partial H$ (with allowance for the inclination of **H** to the direction of the major semiaxis of the electron "ellipsoid"). It is seen from Fig. 1 that the proposed mechanism explains satisfactorily the singularities of the fine struc-

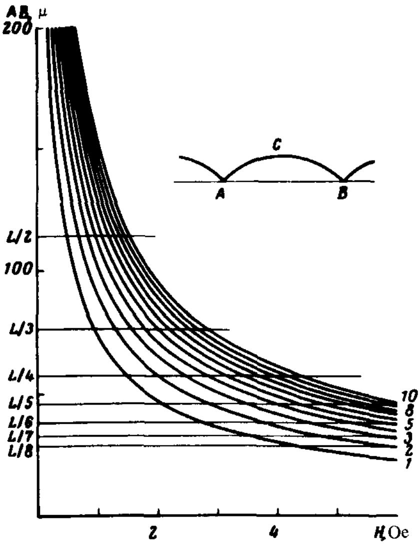

FIG. 2.

ture. The majority of $H_{n,m}$ (see Fig. 2) are located in the vicinity of the $\partial U/\partial H$ maxima in the interval 2—5 Oe (see Fig. 2) with $m=4,5,6,7, n \leq 10$ (with the exception of 2, 4;10, 4;1, 5;5, 5;6, 5;3, 6;2, 7). Allowance for the QTHE makes it also possible to explain the following: 1) The absence of a fine structure in multiple fields 2) The shift of the fine structure when $J_e^=$ is increased or changes direction. With increasing $J_e^=$, the contribution of the field of the emitter current $J_e^=$ to the magnetic flux that is linked with the electron trajectory becomes noticeable, and the trajectories apparently become so modified that the linking flux Φ remains unchanged, and this should lead to a shift of the fine structure similar to that observed in experiment. 3) The shift of the fine structure when **H** is inclined by an angle ψ to the direction of the major semiaxis of the electron "ellipsoid."

It is not excluded that a number of singularities of the fine structure are due to interference or diffraction of the electrons. At parameter values $L \sim 10^{-2}$ cm, emitter (collector) dimension $\sim 10^{-4}$ cm, and electron wavelength $\sim 10^{-5}$ cm, the wave properties of the electrons should come into play.

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