Observation of a non-ohmic emf with a nonlinear dependence on the current

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The existence of an hitherto unnoticed emf that depends nonlinearly on the current is observed in a sample. The effect is universal for metals and is particularly strong in the case of magnetic-breakdown open trajectories. The nature of the effect is discussed.

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1. In a single-crystal beryllium sample at 4.2 °K in a magnetic field H directed along the hexagonal C axis of the crystal and perpendicular to the current in the sample, there was observed, besides the usual magnetic-breakdown resistance oscillations,[1] also a hitherto unnoticed giant emf that oscillates in the magnetic field with the same periodicity as the resistance, but with a phase shift of a quarter period relative to the field. The emf is strongly nonlinear in the current, its contribution at weak currents is negligible, but with increasing current its amplitude can greatly exceed the signal due to the resistance. The signals becomes intermixed, but switching and variation of the current permits them to be separated, owing to the phase shift, and it is possible to establish that the effect is even in the magnetic field as well as in the current; it follows therefore that it has no connection with the Hall emf and with other transverse galvanomagnetic effects. It must be noted immediately that this is not a thermal emf—its magnitude amounts to dozens of microvolts at a current of only 100 mA through the sample,[1)] and it oscillates when the magnetic field is rotated.

2. It is most convenient to observe this emf in the following manner: Four contacts (1,2,3, and 4) are placed in sequence along the sample. A current $J_{1,2}$ is made to flow through 1 and 2, and the potential difference $U_{3,4}$ is measured between 3 and 4. The current does not flow, nor does it extend to contacts 3 and 4, as can be easily verified ($U_{3,4} < 10^{-8}$ V at $J_{1,2} = \pm 100$ mA, $H = 0$, and $T = 300$ °K) so that the Ohmic part of the voltage is completely excluded. Figure 1 shows a plot of $U_{3,4}(H)$ at $J_{1,2} = 100$ mA. Attention must be called to the amplitude—the swing of the oscillations is larger than that resulting from that given by resistance oscillations if the same current were to flow between potential contacts. A small section of the plot at various currents $J_{1,2}$ is shown to the right, and the nonlinearity in the current is obvious. The zero of $U_{3,4}$ at $\partial U/\partial H > 0$ cor-

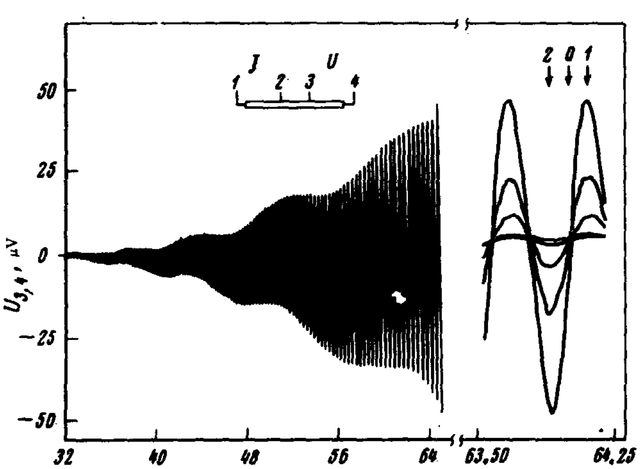

FIG. 1. Dependence of $U_{3,4}$ on the magnetic field. The left-hand plot is at $J_{1,2} = 100$ mA (the low-frequency envelope oscillations are due to the domain structure).[2] On the right is shown the superposition of the plots of $U_{3,4}$ at currents $J_{1,2} = 60$, 70, 80, 90, and 100 mA. The arrows 0, 1, and 2 correspond to the fields H_0, H_1, and H_2. The wiring of the sample is shown schematically on top; the distances between contacts are ~1 mm.

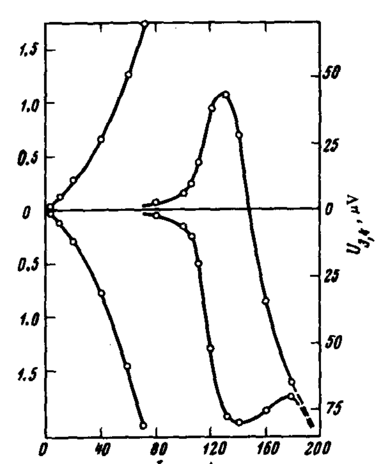

FIG. 2. Dependence of $U_{3,4}$ at the maxima H_1 (upper curve) and at the minima H_2 (corresponding to Fig. 1) on the current $J_{1,2}$. The small-current section is shown magnified and its scale is on the left side.

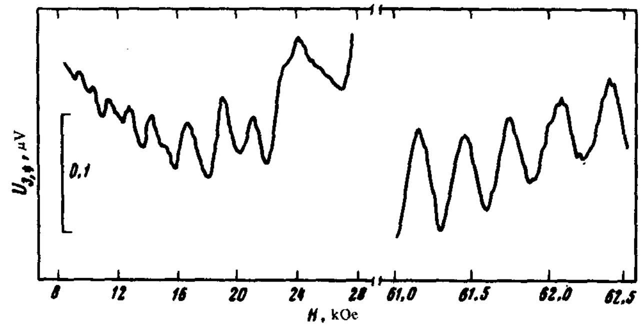

FIG. 3. Plots of $U_{3,4}$ at $\theta = 90°$ and $J_{1,2} = 100$ mA against the magnetic field. The selected sections are shifted vertically for convenience.

responds to the minimum of the resistance. Plots of $U_{3,4}(J_{1,2})$ for the points $H = H_1$ and $H = H_2$ are shown in Fig. 2, and the section for small J is shown in an enlarged scale. It is curious that at large J the oscillations collapse while the emf remains and is negative. The emf depends strongly and aniosotropically on the angle θ between the magnetic field and the C axis—it oscillates in accord with the variation of the phase $\cos 2\pi F/H$ (F is the magnetic frequency of the central section of the cigar), and decreases in amplitude to zero with increasing θ (more accurately, almost to zero, see Sec. 5 below).

3. In a metal, generally speaking, it is difficult for an electric field to impart to the electrons any noticeable energy—this calls for appreciable current densities. In a magnetic field, if there are open trajectories, the situation is different. If the layer of open trajectories is narrow and $\omega\tau \gg 1$ for the closed orbits, then at definite directions of the magnetic field all or almost all the current is carried by electrons on the open trajectories, and this should lead to an appreciable increase of their drift velocity in comparison with the remaining ones. On the other hand if the open trajectories are the result of magnetic breakdown, then the number of electrons is effectively even lower than in the layer, since the breakdown probability is as a rule small (~0.1 in these experiments). In addition, the coherence on the small orbit through which the breakdown takes place (in our case this is the central section of the cigar) gives rise to sufficiently narrow Landau levels, and this is equivalent to oscillations of the "transparency" of the cigar orbit to the magnetic-breakdown tunnel current. If the Fermi level coincides with the Landau level ($H = H_0$ in Fig. 1), then a maximum of the transparency takes place, and accordingly a minimum of the resistance and a zero emf. If the magnetic field is barely larger ($H = H_1$), then the transparency is larger above the Fermi level, the accelerated electrons rise higher in energy and their tunneling is more and more facilitated, while the decelerated electrons moving in the opposite direction drop below the Fermi levels into conditions with worse transparency, and encounter more and more difficulty in tunneling. As a result of this kind of separation, the electrons in the current-flow band occupy effectively ever increasing energy states. This nonequilibrium increment is distributed over the sample with a corresponding shift of the chemical potential and the nearest potential contact 3 becomes positive. If the magnetic field is barely lower than H_0 ($H = H_2$), then the transparency band lies below the Fermi level, and the sign of the effect is reversed. It can be said that the emf behaves like the derivative of the density of states on the central orbit with respect to the energy (at the Fermi level), the observation is, as it were, by a modulation method, and the current strength is equal to the modulation amplitude.

4. The area of the current contact is smaller than the cross section of the sample, and the current density near this contact is maximal. The described phenomenon should therefore start earlier near the contact, i.e., at smaller currents. This makes it possible, on the one hand, to observe the effect at relatively large current, but complicates the situation, on the other hand, from the point of view of the geometry.

5. If the sample is turned so that $\mathbf{H} \perp \mathbf{C}$ (there is no magnetic breakdown, all the orbits are closed, the situation is universal as for any metal), and $U_{3,4}$ is measured with the current $J_{1,2}$ flowing as before, then it is found that a definite relation $U_{3,4}(H)$ results just the same, with superposition of typical Landau oscillations, with the periods of the oscillations in the reciprocal field corresponding to the closed sections of the corona and the cigar. This effect is weak, and the sensitivity in Fig. 3 is 1000 times larger than in Fig. 1, so that it would be utterly impossible to observe it by letting $J_{1,4}$ flow in the usual manner and measuring $U_{2,3}$. In spite of the difference in the situation, this effect exhibits in principle a similarity with that described above, namely, it is even and there is an analogous nonlinear dependence on the current; thus, the signal is at the noise level $\sim 2\times10^{-9}$ V at $J_{1,2} = 50$ mA.

6. If the scattering is isotropic then, generally speaking, it is difficult to understand, from the point of view of the discussion in Sec. 3, the onset of an emf on the closed orbits, inasmuch as some anisotropy is required. It is possible that the cause of the phenomenon lies in tunneling between closed orbits with the aid of Umklapp; on the other, a no less probable cause is the existence of near-surface trajectories of reflected electrons (the Azbel' static skin effect).

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[1)]Sample dimensions $3\times0.25\times0.28$ mm, $R_{300K}/R_{4.2K} = 105$.

[1]N. E. Alekseevskiĭ and V. S. Egorov, Zh. Eksp. Teor. Fiz. 55, 1153 (1968) [Sov. Phys.-JETP 28, 601 (1969)].
[2]W. A. Reed and J. C. Condon, Phys. Rev. Ser. B1, 3504 (1970).