Resistance oscillations and nonstationary effects in thin metallic films

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Current instability, in the form of periodic or random (parameter-dependent) self-oscillations of the voltage on a sample carrying a stabilized current was observed in thin tungsten plates. The instability is not due to any singularities whatever in the heat transfer to the helium, or to other sample-heating results. The self-oscillations were observed in the same current region as the previously observed strong differential-resistance oscillations. The transition from monochromatic to random oscillations usually proceeds in accordance with the model proposed by Ruelle and Takens. The instability, as well as the sample resistance, exhibits hysteresis as a function of current. We investigate the influence of the temperature, of an external longitudinal and transverse field, and of the sample dimensions on the self-oscillations. We discuss the physical causes of the observed effect, particularly the connection between the instability and the inhomogeneity of the current distribution over the sample cross section. Since the conductivity is essentially nonlocal in the situation considered, no satisfactory explanation can be obtained for the observed self-oscillations by using the known mechanisms that bring about instability in a conducting medium.

1. INTRODUCTION

The electric properties of thin metallic plates and wires (conduction-electron mean free path much larger than the transverse dimensions) has been the subject of many experimental and theoretical studies. Relatively little attention has been paid, however, to nonlinear dc effects not connected with heating of the sample or of its electron system. A decrease in the resistance R of thin samples as a function of the current I was first observed in zinc[1] and gallium[2] wires. In Ref. 2, besides the smooth changes of the resistance, oscillations were observed and were attributed to the Sondheimer effect.

A theory describing the nonlinear current-voltage characteristic of a thin metallic sample and its dependence on the characteristic parameters was developed in Refs. 3 and 4. To compare the conclusions of the theory with experiment, detailed investigations were undertaken[5] of the nonlinear resistance of thin metallic films. It was found that strong oscillations of the resistance $\mathscr{R}(I)$ can be observed also in tungsten, and the threshold value of the current I_1 above which the oscillations appear, depends substantially on the temperature and on the external magnetic field H. It becomes clear thus that the oscillations do not stem from the Sondheimer effect.

The purpose of the present study was to determine the physical nature of the resistance oscillations. We have observed the onset of the $\mathscr{R}(I)$ oscillations are simultaneously accompanied by an ac component U of the voltage drop across the sample, i.e., instability is observed. In other words, at $I > I_1$ the dc energy is transformed into oscillation energy. The most abrupt singularities of $\mathscr{R}(I)$ are observed usually at those current values at which a restructuring of the oscillation spectra takes place.

Instability of the stationary distribution of a dc current is a well known phnomenon in gas-discharge (see, e.g., Ref. 7) and semiconductor[7] plasmas. In many cases plasma instability is due to "filamentation" of the current by its own magnetic fields. Electromagnetic radiation from bulky semimetal (bismuth) cylindrical samples was observed when they carried a sufficiently strong direct current. The authors of Refs. 8 and 9 attributed the phenomenon they observed to the galvanomagnetic instability theoretically considered in Ref. 10. This instability is due to the Hall effect in the magnetic self-field of the current. Although bismuth is a compensated semimetal, it has a sufficient Hall conductivity owing to the large difference between the electron and hole mobilities. The tungsten investigated by us, however, has no local Hall conductivity in first-order approximation.[1)] Another instability mechanism in conductors with long mean free paths was proposed by Azbel'.[12] According to him, loss of the stationary distribution of the currents and fields can occur also in a medium having no Hall effect in the presence of a strong dependence of conductivity on the magnetic field, and hence, of a nonuniform distribution of the current density over the sample cross section.

To ascertain the nature of the instability, we have investigated the influence of various external parameters (temperature, magnetic field perpendicular or parallel to the current) and also of the plate dimensions on the threshold current I_1 and on the characteristic self-oscillation frequency. It turned out that the instability can set in both in the current region where the curvature radius of the electron trajectory is much less than all remaining parameters, and in the region where the curvature radius is of the order of the sample transverse dimensions. It follows from the analysis that in both cases there are in the conductivity strong nonlocal effects hitherto not considered in the theory.[11,12]

2. EXPERIMENT

The experiments were performed on thin plates cut by the electric spark method from a highly purified tungsten ingot. We investigated 14 samples, in two of which the sur-

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TABLE I.

Sample No.	Dimensions, mm	Resistivity ratio α^d
1	5,2×0,11×0,1	3 500
2	8×0,2×0,07	8 000
3	8×0,19×0,11	8 000
4	16×0,27×0,1	10 000
5	8×0,25×0,1	7 000
6	8×0,25×0,1	5 500
7	8,2×0,46×0,1	8 000
8	8,2×0,9×0,12	8 000

faces coincided with the (100) crystallographic plane; the remaining samples all had the same orientation, but not along any of the cyrstallographic axes. After cutting, some samples were chemically polished in a solution of nitric, hydrofluoric, and orthophosphoric acids. Other samples were first mechanically ground with a corundum abrasive having grains of about 5 μm diameter. Since the measurement results were qualitatively independent of the surface-finishing method, we shall not mention it hereafter. The characteristics of several samples are listed in the table.

To prepare current contacts, the end sections of the samples were coated with a copper layer; the samples were then annealed in vacuum at 900 °C for better adhesion of the copper in the contact region. Copper conductors were then soldered to the ends with pure tin. The contact resistance in liquid helium did not exceed $(1–2)\cdot 10^{-6}\ \Omega$. The potential contacts to the plates were spark-welded using a capacitor.

The samples were immersed directly in liquid helium. The measurements where carried using a stabilized current (source instability not higher than 10^{-4}). To measure the differential resistance of a sample the current was harmonically modulated at a frequency 9–12 Hz. A signal having the modulation frequency, proportional to $\mathscr{R}$, was picked off with a Unipan-237 selective nanovoltmeter outfitted with input transformers and a preamplifier, and was then measured with a lock-in detector (details of the procedure of measuring the differential resistance is described in Ref. 5). To check on the quality of the sample and to determine the electron mean free path in the volume, preliminary measurements were mad at $I = 0$ of the resistivity ratio $\alpha^V = \rho_{300\,\mathrm{K}}/\rho^V_{4.2\mathrm{K}}$ in a longitudinal magnetic field. It was found that for our samples the volumes α^V, estimated from the minimum of the $\mathscr{R}(H)$ plot had close values 30 000–35 000. These values exceed considerably the dimensional resistance ratios listed in Table I. The resistance reaches a minimum in fields not exceeding 3 kOe, so that the correction necessitated by the longitudinal magnetic field is small. The indicated resistance ratios correspond to an average volume electron mean free path $l^V_{4.2\mathrm{K}} \approx 1$ mm greatly exceeding the transverse dimensions of the samples.

The heat flux density from the samples did not exceed 0.1 W/cm² in all cases. That much power is easily carried off by the liquid helium without substantially heating the sample ($\Delta T < 0.2$ K). We add that no radical changes of the

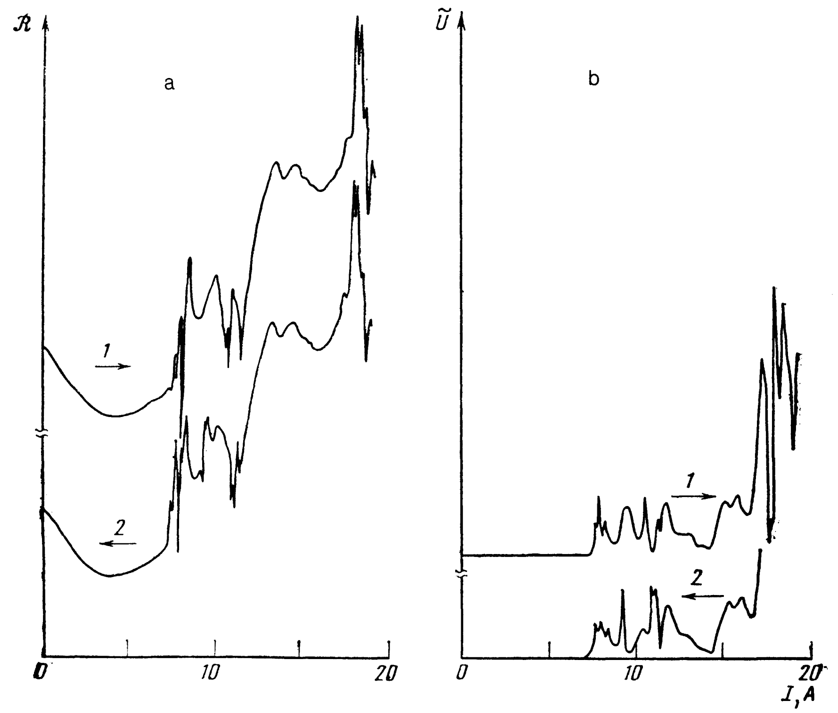

FIG. 1. Differential resistance (a) and ac component of the voltage (b) vs the dc current. Curves 1 and 2 were obtained for increasing and decreasing current, respectively, Sample 2, $T = 4{,}2$ K, $H = 0$.

system behavior were observed when the temperature was lowered to below the λ point.

The dependence of the differential resistance $\mathscr{R}(I)$ of sample 2 (hereafter we use the sample numbers of Table I), obtained with increase of the modulation current, is shown in Fig. 1a (curve 1). The use of a lower modulation current than in Ref. 5 ($\tilde{I} \approx 20$ mA) made it possible to deduce that the oscillations of the differential resistance are not quasi-harmonic, but have the form of sharp peaks. Three regions can be distinguished on the $\mathscr{R}(I)$ curve: a region of smooth variation $I < I_1 = 7.5$ A), a region of reproducible oscillations ($I \leqslant I < I_2 = 19$ A), and a region $I > I_2$ in which the differential resistance varies in arbitrary manner with time at a characteristic period of several seconds. Naturally, the $\mathscr{R}(I)$ is not reproducible in this region. It is precisely these random oscillations which suggested to us that the sharp $\mathscr{R}(I)$ peaks observed at the smaller currents are also due to nonstationary processes.

To check on this assumption, we measured the ac component $\tilde{U}$ of the voltage drop on the sample in the absence of current modulation. The signals from the potential contact were fed, after broadband amplification, to a peak-voltage detector and recorded with an automatic potentiometer. The dependence of this signal on the dc current is shown in Fig. 1b (curve 1). It can be seen from the figure that a noticeable ac voltage $\tilde{U}$, amounting to approximately 1% of the dc voltage, occurs at the same threshold value of the current I_1 as the differential-resistance oscillations. The nonreproducible regions in which the signal is random in time, occur for the same current as the $\mathscr{R}(I)$ and $\tilde{U}(I)$ curves. Comparison of Figs. 1a and 1b shows that the most abrupt singularities on the $\mathscr{R}(I)$ and $\tilde{U}(I)$ curves correlate with one another, although no detailed correspondence was observed.

The $\mathscr{R}(I)$ and $\tilde{U}(I)$ dependences are generally speaking not reversible, as can be seen by comparing curves 1 of Fig. 1 with curves 2 obtained when the current is decreased. It can be seen from the figure that the hysteresis of the differential resistance and of the ac component of the voltage on the sample are observed in one and the same region of the current.

To track the instability development we have investigated the self-oscillation spectra of the voltage on the sample. To this end, the signal from the potential contacts was fed, after broadband ($1-10^4$ Hz) amplification to a spectrum analyzer with 3 Hz resolution. Some results of such an investigation are shown in Fig. 2. It was found that the voltage oscillations near the instability thresholds are almost monochromatic (Fig. 2a). An increase of the current leads as a rule to a lowering of the oscillation frequency (Fig. 2b). The amplitude of the frequency harmonic ν_1, however, varies nonmontonically. At a large current, a second independent frequency ν_2 appears in the spectrum and is in general not commensurable with the first (Fig. 2c). Combination frequencies of the form $m\nu_1 + n\nu_2$, where m and n are integers, can also appear. Further increase of the current changes the ratio of the frequencies ν_1 and ν_2. When the current reaches a definite value I_2 the spectrum becomes abruptly continuous (Fig. 2d). With increase of the current, the noise amplitude increases noticeably (Fig. 2e) and its dependence on the frequency is described with fair accuracy by the function $A(\nu) \propto \nu^{-1}$. In the region $I > I_2$ where, as seen from the figure, the oscillation spectrum contains frequencies down to the "zero," nonreproducible changes of $\tilde{U}$ and $\mathscr{R}$ are observed. Following the "chaos" region, the oscillation spectrum again becomes discrete in a number of cases. We remark that it was usually possible to note a correspondence between the abrupt restructuring of the spectrum and the peaks of the differential resistance.

The oscillation spectra depend on the external magnetic field. Figure 3 illustrates the transition from almost-monochromatic oscillations to oscillations with a continuous

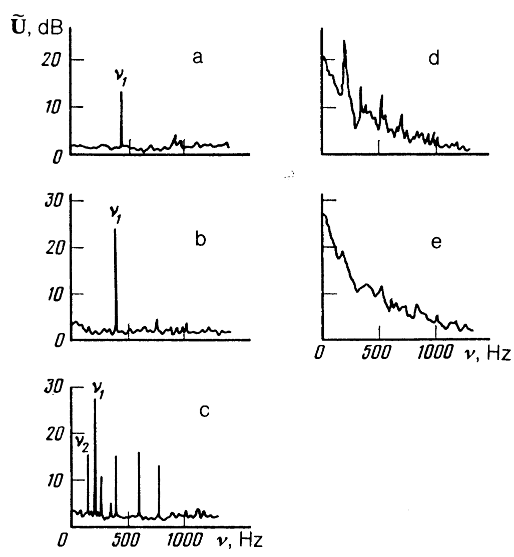

FIG. 2. Oscillation spectra of voltage on sample 5 for various currents. a) $I = 9.1$ A; b) 12.6 A; c) 10 A; d) 20.1 A; e) 20.7 A; $T = 4.2$ K, $H = 0$.

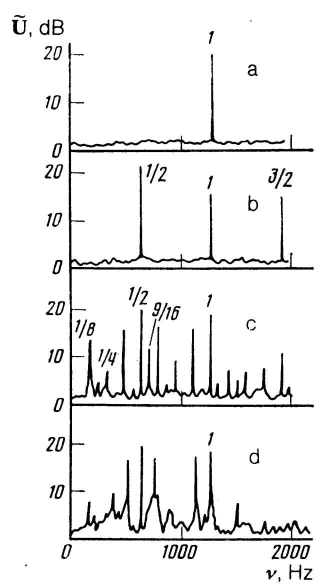

FIG 3. Transition for monchromatic oscillations to oscillations with a continuous spectrum when the external constant magnetic field is decreased a) $H_y = 340$ Oe; b) 263 Oe; c) 259 Oe; d) 257 Oe. Sample 6, $T = 4.2$ K, $I = 20$ A.

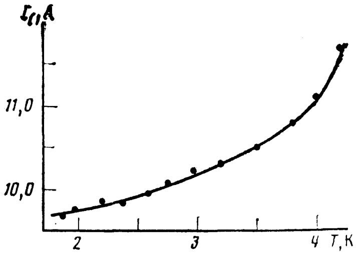

FIG. 4. Change of instability threshold in sample 6 with temperature in the absence of an external magnetic field.

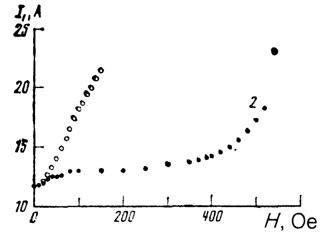

FIG. 5. Influence of external magnetic fields H_x (curve 1) and H_y (curve 2) on the threshold current, Sample 6, $T = 4.2$ K.

spectrum upon variation of the external longitudinal magnetic field H_y (the coordinate frame is chosen such that the current is directed along the y axis and the large face of the plate coincides with the xy plane), In contrast to the situation shown in Fig. 2, the frequencies that appear as H_y is lowered are subharmonics of ν_1. Thus, Fig. 3c reveals harmonics with frequencies $n\nu_1/2$, $n\nu_1/4$, $n\nu_1/8$,$n\nu_1/16$, $n = 1,2,3...$. Under other initial conditions it was possible to observe transitions to a "chaos," reminiscent of the transition in Fig. 2. Similar instability development were typical of most investigated samples.

The values of I_1 and ν_1, the shapes of the $\mathscr{R}(I)$ and $\tilde{U}(I)$ curves, and also the entire development of the instability were found to be sensitive to the direction of the current through the sample. Such a behavior was typical to some degree or another of all samples. This fact has no connection with the influence of the earth's magnetic field, since the results did not change when the sample was rotated.

Variation of the temperature and of the magnetic field influenced strongly the parameters I_1 and ν_1. The values of I_1 for all samples decreased with decreasing temperature, as illustrated in Fig. 4 with sample 6 as the example. Application of an external constant magnetic field H_x, on the contrary, causes I_1 to increase (curve 1 of Fig. 5). The influence of the field H_z on the instability threshold is qualitatively similar to the influence of H_x. A longitudinal magnetic field H_y affects the threshold current I_1 less (curve 2 of Fig. 5). The $I_1(H_y)$ plot of a number of samples have nonmonotonic sections, but the threshold current at all $H_y \neq 0$ is larger than at $H = 0$.

We consider, finally, the influence of the sample dimensions on the values of I_1 and ν_1. Figure 6a shows a plot of I_1 vs the width $2D$ of the samples, which were close in thickness, $2d \approx 0.1$ mm, and had the same orientation. In low-resistance sample 8 the self-oscillations were indistinguishable against the noise background, and the value of I_1 was therefore determined approximately from the appearance of $\mathscr{R}(I)$ oscillations. It can be seen that the threshold current increases linearly with increasing D. The deviation of the points from a straight line can be attributed to the error ($\pm 10\%$) in the measurement of D, and to the possibility that the samples are not identical (for example, unequal electron mean free paths and specularity coefficients). The plate width influences strongly the oscillation frequencies (Fig. 6b). It follows from experiment that, with good accuracy, the frequency is proportional to D^{-2}. With increasing sample thickness the value of I_1 increases and ν_1 decreases, but less than when the width is increased. No significant dependence of the threshold current on the sample length was observed.

3. DISCUSSION OF RESULTS

1. To compare the results obtained for different samples, we discuss first the extent to which the sample kinetic characteristics are identical. As mentioned in the preceding section, the bulk electron mean free paths in different samples were close. From the equations for the conductivity of thin plates and wires, and also using the known data on the product ρl^V in tungsten, we estimated the specularity coefficient of electron reflection from the surface, and obtained

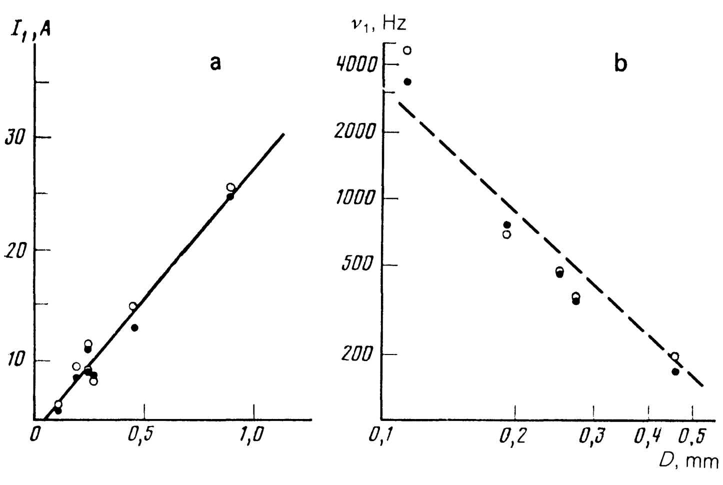

FIG. 6. Values of I_1 (a) and ν_1 (b) vs plate width. The light and dark circles correspond to different directions current flow through the sample; the dashed line is a plot of $\nu_2 \propto D^{-2}$. $T = 4.2$ K; $H = 0$.

$p < 0.2$ for all samples. This is in full agreement with specularity measurement by others (only the reflection of electrons from (110) plane of tungsten has a larger coefficient, $p \approx 0.6$; see, e.g., Ref. 11).

The absence of a large fraction of specularly reflected electrons is confirmed also by the the decrease of the sample resistance with increasing current,[3,4] a decrease nonexistent at $p \sim 1$. Note that this effect is much more pronounced in square than in rectangular plates. Thus, in sample 1 it amounts to more than 50%, whereas in sample 8, which has almost the same thickness, it is about 10%. It appears that this behavior of $\mathscr{R}$ is due to the fact that the nonlinearity region increases with decrease of D. Indeed, if $l > D$, the current I_m at which the differential resistance has a minimum is close for samples that differ in geometry[5]; on the other hand, the current I_0 at which the resistance begins to decrease is proportional to D according to Ref. 3. Consequently, in sufficiently wide plates an increase of the resistance sets in before a decrease has time to develop.

2. Since sample heating is negiligble and the electron drift velocity does not exceed 10^3 cm/s, the most likely cause of the instability (and of nonlinearity in general) in experiment is the influence of the magnetic self-field $\mathscr{H}$ of the current on the dynamics of the electron motion.

Let us consider the physical picture of current flow in thin metallic samples in the nonlinear regime. We note first that the connection between the field and the current, at any value of the latter, is nonlocal. In fact, if the current is weak the characteristic curvature radius of the electron trajectory exceeds the sample transverse dimensions, so that the conductivity depends strongly on the surface scattering. With increasing current, an ever increasing role is assumed by a group of effective electrons that are rotated by the Lorentz force around the line of reversal of the magnetic field sign and do not collide with the surface.[3,4] The effective electrons can negotiate the entire mean free path and make a noticeable contribution to the conductivity. Note that all the carriers move in a highly nonuniform magnetic field that changes within the length of the trajectory by an amount of the order of its own strength.

The situation changes qualitatively when the current reaches a value I_D at which the curvature radius r becomes equal to the plate half-width D. The effective electrons are now concentrated in the region $|x| < x_0$, where

$$x_0 \sim cp_F/e\mathscr{H}_z(x_0)$$

(here p_F and e are the Fermi momentum and the electron charge, and c is the speed of light). Owing to the twisting of the electron trajectories by the magnetic field, and also to surface scattering, the conductivity of the metal at $|x| > x_0$ is much less than the conductivity σ_e in the region occupied by the effective electrons. The current distribution over the sample cross sections become therefore highly inhomogeneous—current "filamentation" sets in. Naturally, under these conditions the metal conductivity remains nonlocal. the value of I_D, according to Ref. 5, is approximately

$$I_D \approx c^2 p_F/\pi e.$$

I_D can be easily determined in experiment, since $\mathscr{R}(I)$ has a minimum at this current. For our samples I_D is about 5 A.

The value of σ_e in a plate of square cross section is equal to σ_0, since the "filament" breaks away from its surface at $I > I_D$, whereas in a wide plate it continues to be tangent to the larger faces until the curvature radius become smaller than the plate thickness. The conductivity σ of a square sample in the region outside the "filament" is determined principally by electrons drifting in a nonuniform magnetic field parallel to the sample axis. The value of this drift is approximately

$$l^{\cdot} \approx l r \mathscr{H}'/\mathscr{H}.$$

Here $\mathscr{H}'$ is the derivative of the magnetic field with respect to the transverse coordinate. In this case the conductivity is

$$\sigma \approx \sigma_0 [1 + l^2/(r^2 + l^{\cdot 2})]^{-1}, \qquad (1)$$

and reduces in the zeroth approximation, by replacing $\mathscr{H}'$ and $\mathscr{H}/d$, to the relation

$$\sigma \approx \sigma_0 (d/r)^2. \qquad (2)$$

It is easy to show that the current I_p flowing along the filament in metallic plates with $d = D$ is a constant for a given metal and is independent of the total current through the sample, of the sample dimensions, and of the temperature. In fact, the following chain of equalities holds:

$$I_p \approx c r_0 \mathscr{H}(r_0)/2 \approx c^2 p_F/2e.$$

Here r_0 is the radius of the "filament" and is determined in the stationary situation by the ratio of the conductivities inside and outside the "filament":

$$r_0 \approx D \left[\frac{\sigma_0 (I/I_p - 1)}{\bar{\sigma}} + 1 \right]^{-1/2}, \qquad (3)$$

where $\bar{\sigma}$ is the average electron conductivity outside the "filament."

If the current is symmetrically distributed over the cross section, the magnetic field on the metal surface is set by the total current I, and a flucuating decrease of r_0 leads to an increase of the magnetic field at all points of the sample outside the "filament." According to (1) and (2), this decreases the value of $\bar{\sigma}$ and, if the $\bar{\sigma}(\mathscr{H}(r_0))$, plot is steep enough, causes further increase of the fluctuation. The system is therefore absolutely unstable. The instability leads either to self-oscillations or to a new stationary state.

Estimates show that the frequency of the produced oscillations is of the order of the reciprocal propagation time of the magnetic-field fluctuations in the sample, in a direction perpendicular to the current:

$$\nu \sim \frac{c^2}{4\pi \langle \sigma \rangle a^2}, \qquad (4)$$

where $\langle \sigma \rangle$ is the average conductivity of the sample and a is a characteristic transverse dimension. Substituting in this equation $\sigma \sim 10^{21}$ s^{-1} and $a \sim 10^{-2}$ cm we get $\sigma \sim 10^3$ Hz, close to the values of ν_1 for samples 2 and 3 (Fig. 6b). The decrease of frequency with increasing current cannot be satisfactorily explained (note that, as follows from Fig. 1a, the average sample conductivity decreases when the current exceeds I_D).

"Filamentation" of the current under the influence of the magnetic self-field in the plasma (the "pinch effect,"[6,7]) has been studied in sufficient detail. It is known that external magnetic fields of varying configurations suppress the instability in the plasma. The external magnetic field exerted its stabilizing action in our experiments (Fig. 5). One of the main causes of instability in a plasma is the decrease of the magnetic field outside the "filament" with increasing distance from its boundaries.[6] This decrease of the field can obviously be observed in a metal when $\mathscr{H}(r_0)$ turns out to be higher than on the surface. To this end, according to (3), the inequality

$$\sigma_0/\bar{\sigma}>1+I/I_p.$$

must be satisfied. What is not clear, however, is the extent to which the "filamentation" of the current is the cause of the instability. Thus, in sample 1 the self-oscillations set in already at current values $I\approx I_D$, when the conductivity is still not highly nonuniform over the cross section.

3. Kopylov *et al.*[8,9] related the low-frequency electromagnetic radiation from bulky bismuth samples, which they found to set in when current was passed, to a manifestation of the galvanomagnetic instability considered theoretically in Ref. 10. In the latter reference the magnetic self-field of the current was assumed weak, and the relation between the field and the current was assumed nonlocal. This assumptions are not valid in our case. If it is assumed that the conclusions of Ref. 10 are valid also in the strongly nonlinear situation, the frequency of the oscillations produced should be proportional to the Hall conductivity. The static Hall conductivity in tungsten is zero, therefore the oscillations cannot be caused by the mechanism considered in Ref. 10. Our experimental results are also at variance with the strong sensitivity, which follows from Ref. 10, of the threshold current and frequency to the length of the sample. It is possible that an important role may be played in thin metal samples by nonlocal effects in the Hall conductivity, and also by the influence of the static skin effect, but these cases were not considered in Ref. 10.

Magnetodynamic instability can be produced in a medium that has no Hall effect by a sufficiently rapid change of the diagonal component of the conductivity as a function of the magnetic field.[12] It is shown in Ref. 12 that a sufficient condition for the onset of absolute instability of the current flow through the metal is the presence of a sizeable second derivative of the conductivity with respect to z, enough to satisfy the inequality

$$d^2\sigma(\mathscr{H})/dz^2>(d\sigma(\mathscr{H})/dz)^2/\sigma(\mathscr{H}).$$

The theory, however, does not deal with nonlocal effects in the conductivity, effects that are important in our situation. Comparison with the theory of Ref. 12 is made difficult also be the fact that no interrelation was established in that reference between the various parameters that influence the instability.

4. The main features of instability development in thin metallic samples are analogous in many respects to stochastization processes in other nonlinear dissipative system. Thus, for example, the sequence of spectra shown in Fig. 2 recalls the transition to turbulent liquid flow between two rotating cylinders (Couette flow), observed experimentally in Ref. 13. A similar picture is explained within the framework of the model proposed by Landau and Lifshitz[14] for the transition to turbulence. According to this model, a sequence of Hopf bifurcations takes in many nonlinear dissipative systems upon variation of any parameter that influences the system; these bifurcations are accompanied by creation of new independent oscillation frequencies. It follows from the later paper of Ruelle and Takens,[15] that the second Hopf bifurcations should be followed by a strange attractor, and the oscillation spectrum should turn into a continuum. This is precisely the system behavior observed in most of our experiments. The observed relation $A(\nu)\propto\nu^{-1}$ in the "chaos" region is also typical of noise in various systems.

In a number of cases (Fig. 3) the stochastization occurred in our experiments via a sequence of period-doubling bifurcations. This development mechanism is in accord with the Feigenbaum model.[16] It was observed in experiments on many nonlinear systems, viz., in hydrodynamics,[17] for dc flow through bismuth,[9] in the development of instability of current states in metals,[18] etc. According to Ref. 16 the subharmonic amplitudes, after a sufficiently large period-doubling bifurcations, should comprise a geometric progression with an approximate denominator 6.6^{-1}. In the situation illustrated in Fig. 3 this property is not observed even qualitatively. The magnetic-field regions between the values $(H_y)_x$ at which bifurcations that lead to the onset of frequencies $\nu_1/2^x$ were observed, are 127, 24, 2 and 1 Oe and form a convergent sequence. This fact is in qualitative agreement with Ref. 16, according to whose methods the values $\beta_{x+1}-\beta_x$ (β is a parameter whose variation leads to stochastization) should make up a geeometric series with denominator $4.669\ldots^{-1}$ (the stochastization in our system differs from that of Ref. 18 in that the subharmonics $\nu_1/4$ and $\nu_1/8$ appeared at one and the same value of H_y). Some disparities between the predictions of Ref. 16 and our results may be due to an insufficient number of experimentally recorded bifurcations.

The instability hysteresis observed in our experiment is typical of many linear systems and was observed many times in experiment (see, e.g., Ref. 17). The dependence of the threshold value of I_1 on the direction of the current through the sample also recalls the hydrodynamic situation, in that the critical Reynolds number, above which turbulence sets in, depends usually on the liquid-flow direction in the pipe. The reason is that any real tube is asymmetric. It can be assumed that in our case there is also some inhomogeneity in the sample, and causes a difference between I_{1+} and I_{1-}. Finally, the lowering of ν_1 with increase of current has likewise an analogy in hydrodynamics: the characteristic frequency of the of the velocity oscillations of a liquid flowing in a pipe decreases with increase of the Reynolds number.[14]

It is possible in principle to have in nonlinear systems a stability loss that leads not to self-oscillations but to a change of symmetry (such a phenomenon is observed in studies of Couette flow.[14] A similar effect is predicted in Ref. 12 for current flow in a metal. One cannot exclude the possibility that $\mathscr{R}(I)$ oscillations due to change of the symmetry of the stationary distribution of the current can occur in thin samples prior to the onset of self oscillations, although no such behavior of the system was observed in our experiments.

We note in conclusion that according to the results of our measurements and the data of Refs. 8 and 9 current instability is observed in objects as different as thin tungsten samples and massive bismuth crystals. It can be assumed that the resistance oscillations in gallium[2] are also due to instability. This suggests that nonstationary flow of dc current is a universal property, at least of compensated metals. It is possible that instability also has a common physical nature.

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[1)]It is shown in a recent paper[11] that a noticeable Hall effect can exist in tungsten in strong magnetic fields (up to 15 kOe) on account of the static skin effect. Under our conditions, however, the magnetic self-field of the current is not large enough for this purpose.

[1]B. N. Aleksandrov, Zh. Eksp. Teor. Fiz. **43**, 1231 (1962) [Sov. Phys. JETP **16**, 971 (1963)].
[2]M. Yaqub and I. F. Cochran, Phys. Rev. Lett. **10**, 390 (1963).
[3]É. A. Kaner, N. M. Makarov, I. B. Snapiro, and V. A. Yampol'skii, Pis'ma Zh. Eksp. Teor. Fiz. **39**, 384 (1984) [JETP Lett. **39**, 463 (1984)]; Zh. Eksp. Teor. Fiz. **87**, 2166 (1984) [Sov. Phys. JETP **60**, 1252 (1984)].
[4]É. A. Kaner, I. B. Snapiro, and V. A. Yampol'skii, Fiz. Nizk. Temp. **11**, 477 (1985) [Sov. J. Low Temp. Phys. **11**, 259 (1985)].
[5]N. F. Voloshin, S. V. Kravchenko, N. A. Podlevskikh, and L. M. Fisher, Zh. Eksp. Teor. Fiz. **89**, 233 (1985) [Sov. Phys. JETP **62**, 132 (1985)].
[6]S. I. Braginskiĭ and B. B. Kadomtsev, in: Plasma Physics and the Problem of Controlled Thermonuclear Reactions [in Russian], Vol. **3**, Izd-vo AN SSSR, 1958, p. 300.
[7]V. V. Vladimirov, A. F. Volkov, and E. Z. Mikhailov, Semiconductor Plasma [in Russian], Atomizdat, 1979.
[8]V. N. Kopylov, Fiz. Tverd. Tela (Leningrad) **23**, 1948 (1981) [Sov. Phys. Solid State **23**, 1138 (1981)].
[9]V. N. Kopylov, S. S. Yanchenko, Pis'ma Zh. Eksp. Teor. Fiz. **41**, 309 (1985) [JETP Letts. **41**, 379 (1985)].
[10]L. E. Gurevich and I. B. Ioffe, Zh. Eksp. Teor. Fiz. **58**, 2047 (1970) [Sov. Phys. JETP **31**, 1102 (1979)].
[11]N. V. Volkenshteĭn, V. V. Marchenkov, V. E. Startsev, A. N. Cherepanov, and M. Glin'skiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **41**, 376 (1985) [JETP Lett. **41**, 458 (1985)].
[12]M. Ya. Azbel', *ibid.* **10**, 550 (1969) [**10**, 351 (1959)].
[13]H. L. Swinney and J. Gollub, Phys. Today **31**, 41 (1978).
[14]L. D. Landaŭ and E. M. Lifshitz, Fluid Mechanics, Pergamon, 1959.
[15]D. Ruelle and F. Takens, Commun. Math. Phys. **20**, 167 (1971).
[16]M. J. Feigenbaum, J. Stat. Phys. **19**, 25 (1978); **21**, 453 (1979).
[17]J. P. Golub, S. V. Benson, I. Steinman, in: Nonlinear dynamics, Ann. N. Y. Acad. Sci. **22**, 357 (1980).

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