ELECTRONIC PROPERTIES OF METALS AND ALLOYS

Nonlinear conductivity of a compensated polycrystalline metal in high magnetic field

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The current–voltage (I–V) characteristics in a magnetic field are studied at helium temperatures for thin polycrystalline samples of a metal (pure tin) embedded in a solid-state medium in order to create reproducible experimental conditions. In these samples a nonlinear S-shaped I–V characteristic is obtained for the first time with this type of heat sinking at the surface of the metal. The conditions for the onset of a temperature–electric instability in a metal with an S-shaped I–V characteristic are investigated in relation to the reactive parameters of the circuit. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1542474]

The nonlinear phenomena that can arise in metallic conduction in the case of Joule heating of samples[1] remain little studied because of the specific conditions for their observation, viz., in order for the nonlinear regime to be realized in a given experiment it is necessary to have quasiadiabatic conditions for the electron–phonon system of the metal, for which reason it is necessary to use samples that are not too thick, deliver current densities of the order of 10^5 A/cm^2 to the sample, and at the same time maintain a constant temperature in the thermostat without allowing a boiling crisis for the liquid helium.

In experiments with direct contact of metal samples with a low-temperature liquid coolant, N- and S-shaped I–V characteristics in the case of Joule heating of the sample are due, in the majority of cases, to nonlinearity of the heat removal in these media.

In the case of liquid helium such a regime arises at heat flux densities q through the metal surface in the range from $q \sim 0.1$ W/cm^2 ("bubble" boiling) to $q \geqslant 0.5$ W/cm^2 ("film" boiling characterized by the formation of a gas film around the sample), which correspond to considerable amounts of power delivered to the cryostat (1–10 W) and to a large expenditure of cryogenic liquid.

However, the use of the boiling crisis is not the only way of realizing a nonlinear conduction regime. In our previous studies it became clear that such a possibility also arises in the absence of direct contact of the samples with the liquid.[2,3] Here one eliminates the instability of the heat removal via the liquid coolant, which is due to convective flow and the boiling crisis, making it possible to study the characteristics of a metal in a reproducible nonlinear regime, which includes effects due to the temperature-electric instability. At low temperatures the heat flux through the dielectric heat-removal medium is a monotonically increasing function of temperature, and there exists a region of temperatures in which the rate of growth of the resistivity $\rho(T)$ is higher than the rate of growth of the heat flux $q(T)$ as the temperature is increased.

Indeed, the heat conduction equations at thermal balance between the specific Joule power released in the sample and the specific heat flux from the surface of the sample imply the following expression for the differential conductivity of the metal:[1,4]

$$\frac{dj}{dE}=\frac{\rho(T)[q(T)/\rho(T)]'_T}{[q(T)\rho(T)]'_T}. \tag{1}$$

Thus it follows from Eq. (1) that in order to obtain an N- or S-shaped form of the nonlinear I–V characteristics the behavior of the functions $q(T)$ and $\rho(T)$ should be such as to bring about a change of sign of this expression. It is known[5] that for many heat-removal media the heat flux $q(T)$ from the sample to the thermostat can be approximated by the a function of the form $q(T)\approx \alpha T^{m(T)}$, where α and m are positive numbers. As a result, one can write for a metal the approximate expression $\rho_{H=0}(T)=\rho_0+\beta T^{n(T)}=\rho_0+\rho_T$, where β and n are also positive, $(q\rho)'_T$ is an everywhere positive function, and the sign of expression (1) for different parts of the I–V characteristics can be determined from the relationship of the following parameters:

$$\frac{dj}{dE}=\{m\rho_0+[m-n]\rho_T\}F_1(T), \tag{2}$$

where $F_1(T)$ is a positive function.

It follows from expression (1) that in the case of an inverted temperature dependence of the resistivity, e.g., for $\rho(T)\propto[\rho_T(H=0)]^{-1}$, we obtain for the differential resistivity an expression analogous to Eq. (2):

$$\frac{dE}{dj}=\{m\rho_0+[m-n]\rho_T\}F_2(T), \tag{3}$$

where the function $F_2(T)$ is positive definite.

Thus the I–V characteristic of the sample can assume a nonlinear form characterized by the presence of segments of negative differential conductivity (N- or S-shaped I–V characteristics) only when several conditions hold simultaneously. First, $\rho_T \gg \rho_0$ if $[n-m]\rho_T > m\rho_0$, and, second,

$m-n<0$, which requires that the temperature dependence of $q(T)$ be weaker than that of $\rho(T)$, and that is possible when the electron temperature coincides with the temperature of the crystal lattice. This corresponds to the regime of quasiadiabatic heating of the sample, i.e., when the relaxation time of the electrons is much shorter than the thermal times. As a result, the temperature region in which negative differential conductivity (resistivity) can exist in a metallic sample is bounded both below and above, and that makes for an N- or S-shaped form of the I–V characteristic of such samples.

As follows from Eq. (1), for $\rho(T)\propto\rho_T$, i.e., for temperature dependence of the resistivity like that of the metal in the absence of magnetic field, the differential conductivity decreases with increasing temperature, passes through zero to negative values, and then rises again: such an I–V characteristic has an N-shaped form. The presence of an inverted temperature dependence of the resistivity in comparison with the $\rho(T)$ curve for $H=0$ leads to a lowering of the differential resistivity with increasing temperature, and upon reaching negative values it leads to an S-shaped I–V characteristic. This sort of dependence of $\rho(T)$ can be obtained by applying a strong magnetic field, in which for some (compensated) metals the behavior is close to $\rho_H(T)\propto H^2/\rho_{T(H=0)}$ even at those temperatures where satisfaction of the necessary inequalities $\rho_T\gg\rho_0$ and $[m-n]<0$ takes place under conditions for which $\omega\tau_{(H=0)}$ is not too different from 1. Here ω and $\tau_{(H=0)}$ are the cyclotron frequency and relaxation time.

It is known that for suitable geometric parameters of the metallic samples under the conditions of the nonlinear regimes considered, it is possible for spatially inhomogeneous distributions of the temperature, electric field, and current to arise.[1,4] For N-shaped I–V characteristics the nonuniformity is along the length of the sample, in the form a temperature–electric domain, while for S-shaped I–V characteristics the nonuniformity is over the width of the sample, in the form of a current pinch.

In view of the many restrictions listed above for realization of a nonlinear regime for metallic samples, the phenomena associated with negative differential resistivity in metals remain insufficiently well studied at the present time. In particular, it has not been possible to observe S-type I–V characteristics in thin metallic slabs.

In the present study we have for the first time investigated a nonlinear regime with an S-shaped I–V characteristic, obtained in a polycrystalline metal (tin) in the absence of a boiling crisis on its surface and in the cryogenic system on the whole, and we have observed an instability of the voltage across the sample due to its temperature-electric instability (without the formation of a current pinch). We have investigated the possibility of realizing a stable regime with negative differential resistance through the use of different kinds of heat-removal media—glass-reinforced plastic, a dielectric with high thermal conductivity (Araldite), and a crystalline medium.

The indicated regime was studied in samples of pure polycrystalline tin in the form stripes with dimensions $L\times W\times d\approx 100\times 0.8\times 0.09$ mm. The principle of the measurements and the technique used are analogous to those described in Ref. 3, and they are supplemented by equipment that permits making measurements in an external transverse magnetic field with an induction of up to 5 T. All of the results presented were measured at a dc current through the sample in the range from 0 to 80 A.

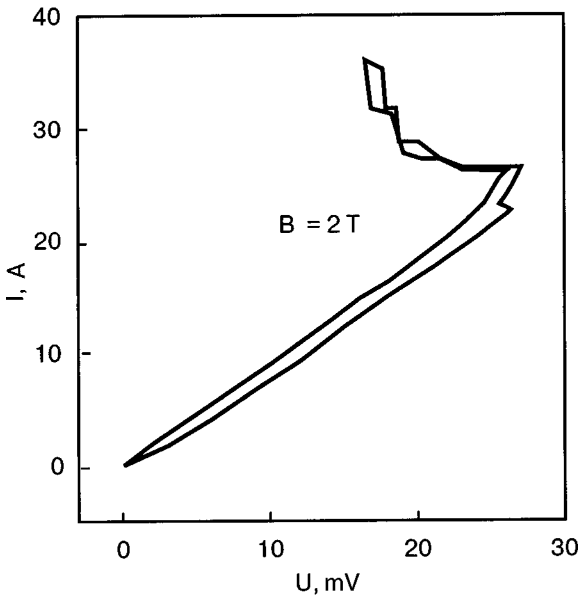

FIG. 1. Current–voltage (I–V) characteristic of a polycrystalline tin slab in a liquid helium medium.

Figure 1 shows the I–V characteristic of a sample directly immersed in liquid helium in a magnetic field of 2 T. It is seen that in thin polycrystalline samples under conditions of comparatively low values of $[\rho(T,H)]'_T\approx 0.3\Omega\cdot\text{m/K}$ ($\omega\tau_{(H=0)}$ just barely greater than 1) at temperatures maintaining a boiling crisis of the helium at their surface, one can observe a regime of negative differential resistance, which previously had not been successfully realized in such samples in the same magnetic fields.[6] However, it can be seen in the figure that the effect is accompanied by hysteresis, as is confirmed by the temperature instability of the nonlinear regime under these conditions. Previously we had encountered instability in a study of the N-shaped regime of the I–V characteristic (in particular, see Ref. 7, where the boiling crisis on the surface of a metallic sample significantly reduced the current necessary for obtaining a temperature–electric domain and also led to hysteresis).

Figures 2–4 show the results of studies of S-shaped I–V characteristics under conditions such that there is no boiling crisis of the liquid at the surface of the samples and in the cryogenic system as a whole. It is seen that under such experimental conditions the S-shaped regime of nonlinearity obtained on heating of a sample with an inverted temperature dependence of $\rho(T,H)$ in comparison with the temperature dependence of $\rho(T,H=0)$ is manifested most distinctly with the use of a crystalline heat-removal medium (Fig. 4). This case corresponds to temperature behavior of the functions $q(T)$ and $R(T,H=5\text{ T})$ (curves *2* and *3* in Fig. 5) calculated from the data of measurements of the I–V characteristic with the use of the heat balance equation

$$R(T)I^2=q(T)A$$

(where A is the surface area of the sample). The temperature

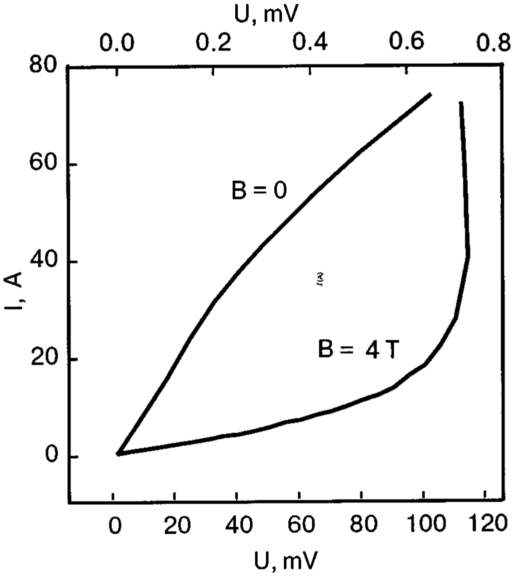

FIG. 2. I–V characteristic of a polycrystalline tin slab with a glass-reinforced plastic heat-removal medium; $T_0=4.2$ K.

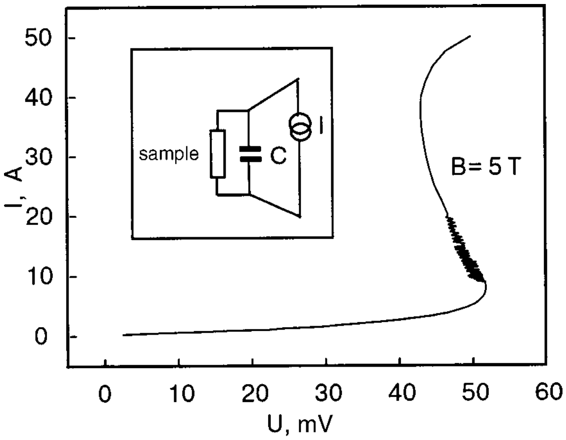

FIG. 4. The I–V characteristic of a polycrystalline tin slab in a crystalline sulfur medium. $T_0=4.2$ K, $B=5$ T. The inset shows a diagram of the connection of the capacitance in the circuit.

dependence of the function $[qR](T)$ (curve *1*) gives an idea of the temperature region of negative differential resistivity of the sample under study.

As is known from the theory of nonlinear circuits, a circuit containing a dc current source, an energy store, and an element with negative differential resistance (NDR) can undergo relaxation self-oscillations. It is known that for samples with an S-shaped I–V characteristic the connection of a sufficiently large capacitance C in parallel with the sample leads to a self-oscillatory instability, which was realized in an experiment on the part of the I–V characteristic having the greatest value of the NDR. When the I–V characteristics were registered using a recording potentiometer the instability was manifested in the appearance of nonmonotonicity at that place, as is seen in Fig. 4. The inset shows a measurement circuit employing a capacitance. Unlike the case of an N-shaped I–V characteristic, when an self-oscillatory process can be excited in a fixed-voltage regime with a suitable inductance in the circuit,[8] in the case of an S-shaped I–V characteristic the self-oscillations can arise in a fixed-current regime and can be described by a system of equations including, in addition to the heat balance equation, the following differential equation of the circuit:

$$C\frac{dU}{dt}+\frac{U}{R(T,H)}=I_0,\quad R(T,H)=\rho(T,H)L/Wd. \tag{4}$$

The period Δt of the oscillations observed for a sample with resistance $R(293\text{ K})\approx 0.16\ \Omega$ equals ≈ 0.1 s, in agreement with the following dependence on the parameters of the system:

$$\Delta t - R(T,H)C + c_V(T)/q(T),$$

where $c_V(T)$ is the specific heat of the sample. The condition for the appearance of oscillations reduces to the requirement

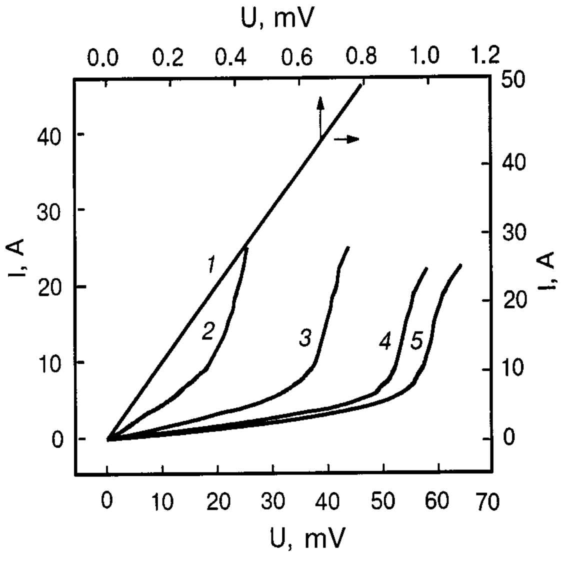

FIG. 3. I–V characteristics of a polycrystalline tin slab in a solid dielectric (Araldite) medium in various magnetic fields B [T]: 0 (*1*), 1 (*2*), 2 (*3*), 3 (*4*), and 4 (*5*); $T_0=4.2$ K.

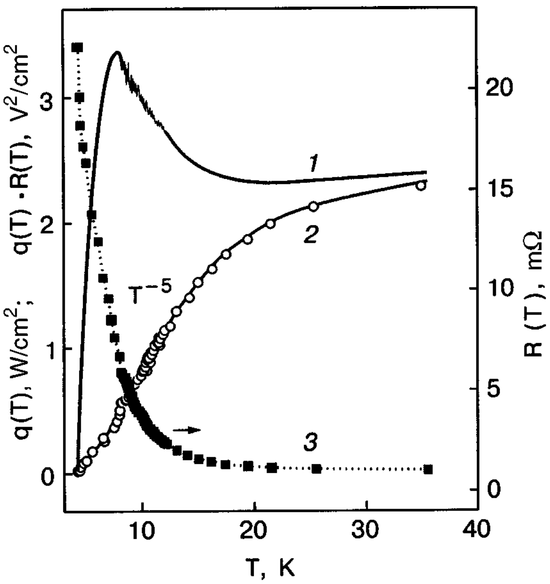

FIG. 5. Temperature dependence of the functions $[qR](T)$ (*1*), $q(T)$ (*2*), and $R(T)$ (*3*) for the I–V characteristic of a polycrystalline tin slab in a medium of crystalline sulfur in a magnetic field of 5 T.

that the relations $R < -dU/dI$ and $RC > [c_V(T)/q(T)]$ be satisfied. The value of $c_V(T)/q(T)$ does not exceed 10^{-3} s.

Let us conclude with a summary of the results of this study. We have for the first time obtained nonlinear current–voltage characteristics of thin polycrystalline samples of a metal (pure tin) in a magnetic field at helium temperatures in the absence of a liquid boiling crisis at the boundary of the sample for different types of heat removal. It was found that the use of a crystalline dielectric as the heat-removal medium makes it possible to realize a nonlinear conduction regime corresponding to an S-shaped I–V characteristic in a pure compensated metal in a magnetic field of up to 5 T. In that regime we studied the dynamics of the observed temperature–electric instability in relation to the reactive parameters of the circuit.

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[1] A. A. Slutskin and A. M. Kadigrobov, JETP Lett. **28**, 201 (1978).

[2] Yu. N. Chiang and A. G. Ordynets, Fiz. Nizk. Temp. **6**, 1279 (1980) [Sov. J. Low Temp. Phys. **6**, 622 (1980)].

[3] I. I. Logvinov and Yu. N. Chiang, Fiz. Nizk. Temp. **21**, 867 (1995) [Low Temp. Phys. **21**, 668 (1995)].

[4] A. M. Kadigrobov, A. A. Slutskin, and I. V. Krivosheĭ, Zh. Ėksp. Teor. Fiz. **87**, 1314 (1984) [Sov. Phys. JETP **60**, 754 (1984)].

[5] W. Frost (Ed.), *Heat Transfer at Low Temperatures*, Plenum Press, New York (1975), Mir, Moscow (1977).

[6] V. A. Bondar', A. M. Kadigrobov, V. N. Morgun, and N. N. Chebotaev, Metallofizika **13**, 49 (1991).

[7] Yu. N. Tszyan (Chiang) and I. I. Logvinov, Fiz. Nizk. Temp. **8**, 774 (1982) [Sov. J. Low Temp. Phys. **8**, 388 (1982)].

[8] Yu. N. Tszyan (Chiang), I. I. Logvinov, and A. M. Kadigrobov, Fiz. Nizk. Temp. **12**, 1248 (1986) [Sov. J. Low Temp. Phys. **12**, 702 (1986)].

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