Nonlinear dynamics of carriers in aluminum cryoconductors under the action of crossed electric and magnetic field

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Magnetic field as a reason of nonlinear electric phenomena is studied experimentally for normal metal conductors. For material under investigation being pure aluminum Corbino geometry of current flow and sample arrangement is applied. This approach gives a possibility to exclude an electric Hall field and to enlarge a sensitivity of conductor resistance to self magnetic field stimulated by transverse Hall drift under the action of Lorentz force. In accordance with a direction of radial current through the disk sample the own magnetic field coincides on direction with an external magnetic field or not. As a result the electric kinetic properties are modified by this additional action of own carrier movement. The self magnetic field distribution on sample surface is measured at different conditions for the current flow value and external magnetic field intensity. Nonlinear additions to the electric field potential distribution due to the own magnetic field are determined on the base of data for potential curves for collinear and anticollinear geometry. The physical reasons of nonlinearity and their connection with carrier dispersion law are discussed by the means of analytical investigation of high density charge transport under Corbino geometry. Phenomenological theory of electric field potential distribution under similar charge transport is constructed with indication of metal specific difficulties for experimental realization of this phenomenon.

Key words: electric nonlinearity, electric field, magnetic field, aluminum

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1 Introduction

Recently the nonlinearity of electric properties of metals was hardly possible due to high concentration of charge carriers and high conductivity in comparison with the semimetals where the electric nonlinearity takes place [1, 2]. For metals having high level of conductivity it is very hard to create a large electric field to achieve an electric anomaly. Besides the velocity of energy exchange of carriers with phonons is much higher than the velocity of energy exchange of carriers with each other. So the energy of an electric field directs on the heating of metal material. In metals of high purity the electrons have the macroscopic free length achieving the order of few tenthes of mm. As a result the role of magnetic component of field action on the electron movement enlarges. So the nonlinearity of kinetic electric phenomena in pure metals are stimulated with an additional action of the magnetic field on the carrier movement. This additional action may be stimulated with both the external magnetic field and the magnetic field of own carrier movement. Nonlinearity takes place under interaction of the magnetic field component of highly intensive radio frequency wave with the high purity metal [3, 4, 5]. Under steady field the nonlinear kinetic properties of compensated metals have been regarded [6]. Kinetic electron properties of metals are sensible to the magnetic field spatial inhomogeneity which stimulates the strong current flow redistribution through the sample volume [7, 8]. Here some results of low temperature study of kinetic properties of normal metal are represented. The base principle of the study was to stimulate the nonlinearity via the additional magnetic field of own carrier movement. The circular carrier movement was chosen to most effectively produce the additional magnetic field. Crossed electric and magnetic fields are the main sources of electron movement. The circular electron movement creates the own magnetic field that algebraically sums with external magnetic field.

2 Methodology of research, material, experimental procedure

Magnetic nonlinearity of dynamical nature may be determined via electric field. The electric field is highly sensible characteristic when the coefficient between the electric field and the current density is a strong function of magnetic field. The condition of strong magnetic dependency takes place in the sample of cylinder geometry placed in an external coaxial transverse magnetic field. When the steady current flows between the inner and outer leads the transverse electric field is absent. At this geometry the electric field value along radius is proportional to the reversal diagonal component of the conductivity tensor. This takes place because the azimuthal electric field component is absent. As a result the crossed radial electric and axial magnetic fields stimulate a transverse carrier drift.
Circular component of the transverse current flow is

$$j_\theta = -\left(\rho_{\theta r} j_r + \rho_{\theta z} j_z\right) \frac{1}{\rho_{\theta\theta}} \tag{1}$$

Here ρ_{ij} are the resistivity tensor components in the cylindrical coordinate system, j_k are the current density components.
Parameter $\rho_{\theta r}/\rho_{\theta\theta}$ determines the intensity of radial current transformation into the additional circular motion. From the condition for j_θ it is followed that the most preferable material for investigation is the material having the electron dispersion law close to that of free electron gas. Free electron gas has maximal value of this parameter being equal l/L, where l is a free electron length, L is Larmor radius. Real conducting materials among metals have more complicated dispersion law. Only aluminum, indium and gallium have the electron structure partly similar to the dispersion law of free electron gas. Among these three metals the aluminum as the most used material in cables for cryogenic energetic devices has been chosen for research.
The samples having the form of short hollow cylinder with thickness 4 mm were made from polycrystal aluminum. Polycrystal structure of sample averages its kinetic coefficients. But as the dispersion law of electrons in aluminum is similar to free electron law the averaging procedure doesn't influence on asymptotic behavior of kinetic coefficients. As a result the value of Hall drift current is a strong linear function of the parameter of magnetic field effectiveness being expressed with l/L. The resistivity of material at liquid helium temperature is $4{,}6{\cdot}10^{-10}$ Ohm·cm. The radii of inner r_1 and outer r_2 concentric current leads are 2.5 and 15 mm respectively. Potential probes are mounted on the surface along radial direction. The distance from sample axis to probes is 5, 7, and 12 mm. The external coaxial magnetic field B of magnitude up to 8 T was generated with superconducting solenoid of helium cryostat. Small Hall sensors are mounted on the sample surface to measure own magnetic field of transverse circular drift. Mounted sample was placed in liquid helium bath of cryostat. During measurement the electric field potential distribution was determined at the different values and directions of a radial current. In accordance with the direction of a radial current the second magnetic field of own circular movement is collinear or anticollinear to external magnetic field. Besides the potential difference between two probes along the radius r was measured as a function of current value under different magnitude of the external magnetic field. Nonlinear electric properties of material were calculated by the subtraction of the potential difference for anticollinear geometry from that for collinear one. Self magnetic field was measured with help of Hall sensors by the method of the subtraction of total magnetic field value registered on sample surface from the known value of magnetic field generated

by solenoid.

3 Results and discussion

The electric field potential distribution along the radius is represented in Fig.1.

T. However for the case when the current density is 250 A/cm^2 and higher the curves for collinear and anticollinear geometry diverge. So the nonlinear dynamics of carriers in this regime of operation is observable.

Nonlinear addition to the potential difference on the pair of radial probes is shown in Fig.2.

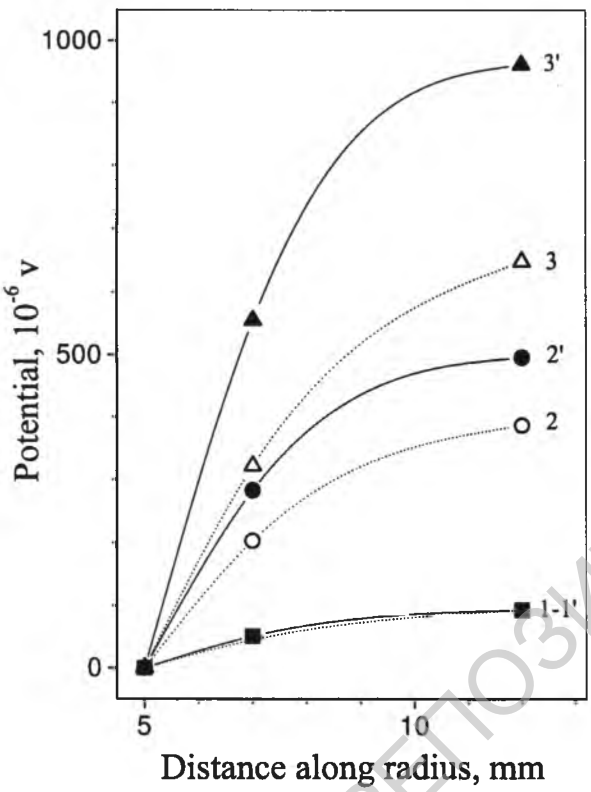

FIG. 1. Electric potential dependence along sample radius when the self magnetic field is collinear (1', 2', 3') and anticollinear (1, 2, 3) to an external magnetic field. Curves correspond to current density 50 (1, 1'); 250 (2, 2') and 500 A/cm^2 (3, 3').

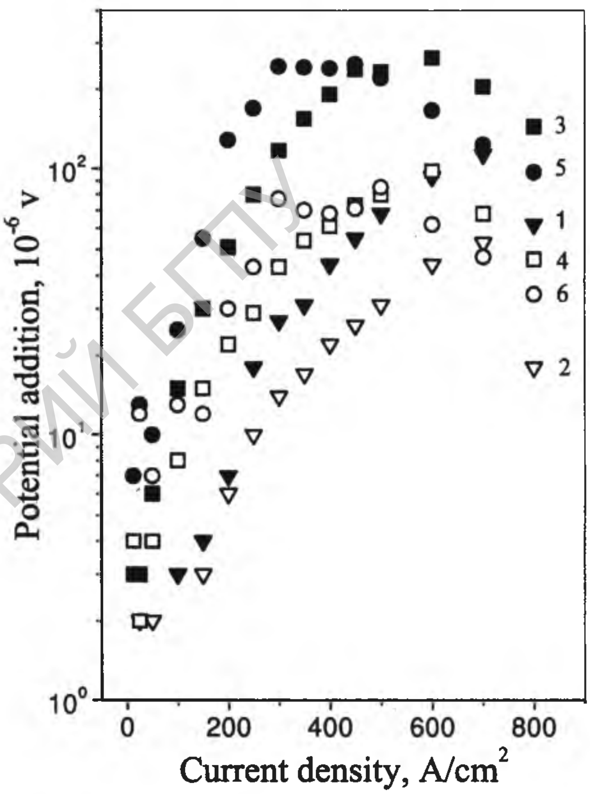

FIG. 2. Nonlinear addition to electric potential as a function of current density at different magnitude of an external magnetic field: 2 (1, 2); 4 (3,4) and 8 T (5, 6) for inner (1, 3, 5) and outer (2, 4, 6) pairs of potential probes.

Here the data are shown at different magnitude of the radial current density. The current direction is also taken into account. It is shown that for current density 50 A/cm^2 the nonlinearity as an indication of characteristic divergence for collinear and anticollinear geometry is negligible. This behavior takes place at the external magnetic field up to 8.5

Here the nonlinear addition is presented as the function of current density at different magnitude of external magnetic field. Here we use the approach that the nonlinear addition increases a signal at collinear geometry and decreases it at anticollinear geometry symmetrically. Nonlinear addition was calculated as the difference between two signals on the same pair of potential probes.

$$\Delta U = \frac{1}{2}\left(U_c - U_a\right) \tag{2}$$

Here U_c and U_a are the potential differences at collinear and anticollinear geometry respectively. One can see the process of appearance of magnetic nonlinearity. The voltage signal was measured on two pairs of potential probes. The nonlinear addition on inner pair of potential probes is larger than that on outer pair. Inner pair is undergone to the most action of own magnetic field generated with a transverse carrier drift. Actually the energy of self magnetic field is localized in the region being close to the sample axis. The role of external magnetic field is clear from this presentation. It is shown that the level of self magnetic action on the material properties is very strong at moderate magnetic fields and current densities. The potential difference at external magnetic field is non-monotonic function of radial current.

The nonlinear factor as a function of current density is shown in Fig.3. Here a nonlinear factor is the ratio of the additional potential difference due to self magnetic field to the potential difference in the linear approximation. To get the ratio it is necessary to take nonlinear addition (Fig.2) and to divide it by potential difference for linear approach

$$\frac{\Delta U}{U} = \frac{U_c - U_a}{U_c + U_a}. \tag{3}$$

The combination of these signals allows to determine the relative nonlinear potential addition as the mentioned nonlinear factor. It is seen that the most value of the relative nonlinear factor is achieved at the magnetic fields which are much lower of the maximal those under experiment. So the nonlinearity achieves of 0.3 - 0.4 at current density magnitude of 500 A/cm^2. It is interesting that in the range of relatively low current density through the sample the nonlinearity factor is rather close for different external magnetic field magnitude. This indicates that the discussed nonlinearity depends mainly on current value.

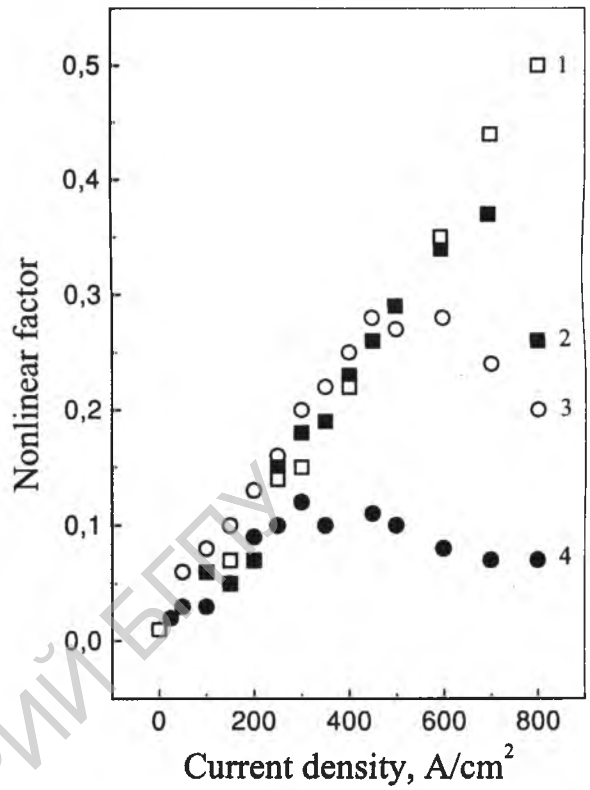

FIG. 3. Relative nonlinear factor as a function of current density at different values of an external magnetic field: 1 (1); 2 (2); 4 (3); and 8 T (4).

Self magnetic field as a function of the external field is shown in Fig.4. Here a current value is an independent parameter of the task. Self magnetic field is measured with a sensor placing near inner current lead. As seen from Fig.4 the self magnetic field is a saturating function of the external magnetic field at large magnitude of radial current. This indicates that the intensity of growth of circular current flow becomes smaller at high levels of the radial current density and external magnetic field. So it follows that the parameter of magnetic field efficiency l/L decreases in this range of operation. As Larmor radius depends only on magnetic field so the main reason of decrease is a free length. Free length depends on the electron scattering process on crystal defects and phonons. The temperature dependent part of l decreases with temperature growth due to increase of electron phonon scattering intensity at thermal heat generation.

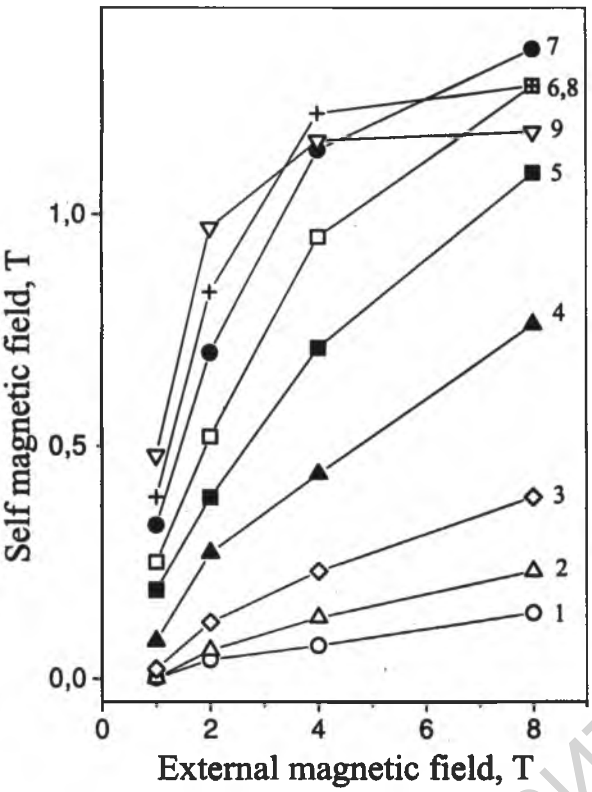

FIG. 4. Self magnetic field as a function of an external magnetic field at different values of averaged current density: 25 (1); 50 (2); 100 (3); 200 (4); 300 (5); 400 (6); 500 (7); 600 (8) and 700 A/cm^2 (9).

The results for the electric field potential obtained in experiment are analyzed on the base of existence of circular current movement and connected with it the own magnetic field. Here for simplicity only azimuthal current is taken into account. Base relations for analysis are

$$\begin{aligned} E_\theta &= \rho_{\theta\theta} j_\theta + \rho_{\theta r} j_r \\ E_r &= \rho_{rr} j_r + \rho_{r\theta} j_\theta \end{aligned} \tag{4}$$

ρ_{ij} and j_k as mentioned above are the components of resistivity tensor and current density in the plane being orthogonal to magnetic field vector. In this approximation we neglect the include of electron motion along magnetic field. Using the approximation of curl-less character for steady electric field one can obtain the next integral dependence for electric potential

$$\varphi(r) = \int \left(\rho_{rr} - \rho_{r\theta} \frac{\rho_{\theta r}}{\rho_{\theta\theta}} \right) j_r dr \tag{5}$$

and self magnetic field of transverse drift is

$$B_s(r) = \mu_0 \mu \frac{I}{4\pi} \frac{RB}{\rho} \frac{1}{r} \ln \frac{(1+\sqrt{2}) r_2}{r + \sqrt{r^2 + r_2^2}} \tag{6}$$

$$j_r = \frac{I}{2\pi r h}.$$

Here μ_0 is the magnetic constant, μ is the magnetic permeability of aluminum, R is Hall coefficient, ρ is the diagonal component of resistivity tensor, h is the thickness of sample.

Self magnetic field distribution is obtained in approximation of a small value of sample thickness in comparison with its averaged radius. For strong magnetic field it is possible to neglect the diagonal component of resistivity tensor inclusion into potential distribution and to write the potential expression as

$$\varphi(r) = \frac{I}{2\pi h} \int \frac{(RB_\Sigma)^2}{\rho} \frac{1}{r} dr \tag{7}$$

here B_Σ is a total magnetic field being the algebraic sum of the external and own magnetic field. As a result the electric potential distribution along sample radius has a form

$$\begin{aligned} \varphi(r) = \frac{I}{2\pi h} \frac{(RB)^2}{\rho} \ln\left(\frac{r}{r_1}\right) \Bigg\{ 1 + \frac{2RI}{\rho c \ln(\frac{r}{r_1})} \Bigg[\frac{1}{r} \\ \times \ln \left(\frac{r + \sqrt{r^2 + r_2^2}}{r_2} \right) - \frac{1}{r_1} \ln \left(\frac{r_1 + \sqrt{r_1^2 + r_2^2}}{r_2} \right) \\ + \frac{1}{r_2} \ln \left(\frac{r_1}{r} \frac{r_2 + \sqrt{r^2 + r_2^2}}{r_2 + \sqrt{r_1^2 + r_2^2}} \right) + \left(\frac{1}{r_1} - \frac{1}{r} \right) \\ \times \ln \left(1 + \sqrt{2} \right) \Bigg] \Bigg\} + \varphi_0 \end{aligned} \tag{8}$$

This expression represents the process of additional increase or decrease of electric potential taking place at collinear and anticollinear geometry respectively. The mentioned nonlinear factor is here an additional term that sums with unit in braces. This additional term depends on current linearly. Besides this additional term does not depend on magnetic field. Similar behavior actually takes place for nonlinear factor being shown in Fig.3. where at not very large current densities all curves for nonlinear factor are almost coincide. Behavior of curve for own magnetic field observed in Fig.4 has tend for saturation. Two reasons of this phenomenon are present. The first one is an increase of diagonal component of resistivity tensor with increase of magnetic field. The second one is the heating of sample due to electric energy dissipation. Heating of the sample is the main reason of own field saturation at large current densities. As to less than linear growth of own magnetic field at small current densities the next information should be taken into account. There is a weak linear dependence of diagonal component of resistivity tensor on magnetic field. Such a behavior is a result of action the elongated electron orbits on transport phenomena. In this approximation an aluminum is similar to copper. But the number of electrons situated on elongated orbits in aluminum is much smaller of the number of the same electrons in copper. As a result the diagonal component of resistivity tensor in polycrystal copper has strong linear dependence on magnetic field but diagonal component of resistivity tensor for aluminum has not large coefficient of linearity. The expression for own magnetic field shows that electric nonlinearity of magnetic nature in copper conductors is much smaller than these phenomena in aluminum. The own magnetic field of transverse drift in copper is much smaller of that in aluminum having the same zero magnetic field resistivity. So in aluminum the most efficient transformation of external magnetic field energy into the energy of own magnetic field takes place. In other word the magnetic energy concentration takes place.

4 Conclusion

Next basic results of study may be formulated in conclusion.

Experimental study has confirmed the prospect of application of the aluminum based conductor for modeling of electric nonlinearity of magnetic nature. Corbino geometry is the only geometry being most suitable to obtain such a nonlinearity because this geometry excludes the difficulties of uncompensation of the electron and hole volumes.

Electric nonlinearity manifests in increase or decrease of effective resistance of conductors due to increase or decrease of the parameters of total magnetic field effectiveness. Total magnetic field is an algebraic sum of an external magnetic field and self magnetic field of transverse carrier drift under the action of Lorenze force.

The own magnetic field of transverse carrier drift as a base reason of electric anomaly has strong dependence on averaged current density and an external magnetic field.

Small quantity of electron belonging to open orbits partly restricts the linear growth of the self magnetic field at small current densities.

The intensity of an energy dissipation process being proportional to the parameter of effectiveness of magnetic field restricts the magnitude of self magnetic field via the sample material heating and the decrease of free electron length.

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