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GALVANOMAGNETIC PROPERTIES OF METALS AT BOILING OF LIQUID HELIUM

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Galvanomagnetic properties of metals at boiling point of liquid helium and some problems relating to Joule heating in cylinder conductors are investigated by the method of voltage current characteristics. Radial current under an external coaxial magnetic field is used to get high magnetoresistance of conductor. High level of magnetoresistance in this geometry offers the possibility to investigate a wide range of heat generation. The stabilization of voltage observed in definite current range is discussed in terms of analysis of heat aspects of problem when a heat generation function and heat elimination they are regarded at helium temperature. An electric temperature ordering of system is proposed as a factor responsible for voltage stabilization when the presence of more heated and less heated sections along conductor radius is connected with negativity of derivative of heat elimination function with respect to temperature between first and second boiling crisis.
KEY WORDS *galvanomagnetic property, current density, critical temperature, cryogenic system*

1. Introduction

The problem of heat generation due to Joule energy dissipation exists at low temperature galvanomagnetic measurements. Especially this problem is actual at high current density and large resistivity. The phenomena of temperature charge and heat transfer in metals are known to be determined mainly by an electron system in accordance with its dispersion law and scattering mechanisms. Usually a heat elimination regime of a sample is not simple and isotropic because specimens are placed in liquid helium cavity with help of low temperature inset where a sample is mounted between rigid dielectric plates for the sample to be fixed in an external magnetic field and for ponderomotive forces to be canceled. Such mounting of sample leads to anisotropy of heat elimination and temperature field in such conditions is not symmetric. This may be a reason of the appearance of additional voltage drop on potential probe because spurious galvano-thermomagnetic effects are stimulated in such anisotropy conditions. To estimate this influence it is necessary to solve generalized equations on heat and charge transfer in accordance with respective boundary conditions[1–3]. Galvanomagnetic measurements require usually not too large current density for a voltage signal to be measured. So Joule energy dissipation is not high and heat removal in steady regime takes place at bubble type of helium boiling. On the other hand in powerful magnetic cryogenic systems a current density is very high and heat generation may achieve such magnitudes that heat elimination takes place through boiling crisis. Here the results of investigation of current density influence on heat removal process and galvanomagnetic properties of metal are presented. A role of an external magnetic field oriented coaxially with cylindrical conductor is analyzed at heat exchange crisis at boiling of liquid helium. An investigation is being done by a method of voltage current characteristics taking into account peculiarities of dispersion law of electrons.

2. Experimental Procedure

For the phenomena of influence of boiling crisis on charge transport in metals to be studied it is necessary to achieve a high level of conductor heating. Heat generation due to Joule energy dissipation has been chosen to realize such a regime. A cylindrical geometry of conductors having radial current was applied to use high susceptibility of metal conductivity to magnetic field. The presence of coaxial external magnetic field gave possibility to realize high magnetoresistance in cylindrical samples in regime of current supply. Polycrystalline aluminum was used to exclude crystal anisotropy action as a disturbing factor here. Aluminum has a quasiisotropic dispersion law and its magnetoresistivity in such geometry is high in comparison with other metals. Samples for investigation were disk shaped conductors having inner and outer diameters of 3 and 36 mm respectively. Sample thickness was 0.5–4 mm. Concentric current leads were mounted on inner and outer diameters so a current of magnitude of 1500 A might be passed through a sample. Potential probes and magnetic field Hall sensors were arranged on sample surface along its radius for measurement of voltage current characteristics, resistivity and self magnetic field distribution. Self magnetic field was measured as a difference between total measured signal and an external magnetic field generated by superconducting solenoid of helium cryostat. During measurements an inversion of both current and external magnetic field was made to estimate a role of self magnetic field for such charge transport. Samples were mounted in low temperature insert situated in helium cavity of cryostat. A heat removal regime was a helium boiling in large volume. High level of heat generation and its susceptibility to temperature and magnetic field were ensured by high purity of material which corresponded to residual resistance ratio of an order of 15000. Some temperature measurements of sample magnetoresistance were made too. For this purpose the investigated conductors were placed in thermostatic chamber with temperature monitoring. A current magnitude during such measurements was small to exclude sample heating.

3. Experimental Data and Analysis

To investigate peculiarities of low temperature charge transport in metals at boiling crisis of liquid helium it is necessary to divide a problem for two aspects. At first it is desirable to study a dependence of resistance on temperature in this temperature range and then to analyze heat regime of system when energy dissipation is so large that sample temperature may act on heat and resistance state. As a source of resistivity here is a spiral electron movement a problem is to establish a degree of influence of magnetic field on electron-phonon scattering and relaxation processes. For this purpose measurements of magnetoresistance have been made and data of temperature action on magnetoresistance of system are presented in Fig.1. In Fig.1 a typical magnetoresistance as a function of the temperature is shown. It is seen that a strong quasi-quadratic dependence takes place in the temperature range 4.2–30 K. In other words a condition of strong magnetic field is realized when cyclotron frequency is much higher than reversal relaxation time. At T=50

K a cyclotron frequency even at B=8 T is of the same order as reversal relaxation time and a magnetoresistive effect is almost absent. For helium temperature a magnetoresistance increase in field of 8 T consists of about 10^3. High susceptibility of relaxation processes in such geometry to electron scattering leads to effective electron-phonon interaction due to an absence of Hall field. The dependence of magnetoresistance on temperature shows that small changes of temperature simulate and abrupt decrease of magnetoresistance. Here electron-phonon contribution to relaxation process is of the order of impurity term and a resistance may be represented as

$$\rho = \rho_0 \left[1 + (\omega\tau)^2\right] \tag{1}$$

where ρ_0 is a resistance in zero magnetic field, ω is a cyclotron frequency, τ is an effective relaxation time as a result of two scattering processes on an impurity atoms and on thermal phonons. A minimum in Fig.1 corresponds to transition from strong magnetic field to a weak one. In this region a relation $\omega\tau \approx 1$ takes place. Actually a dependence of resistance on magnetic field at this point is linear.

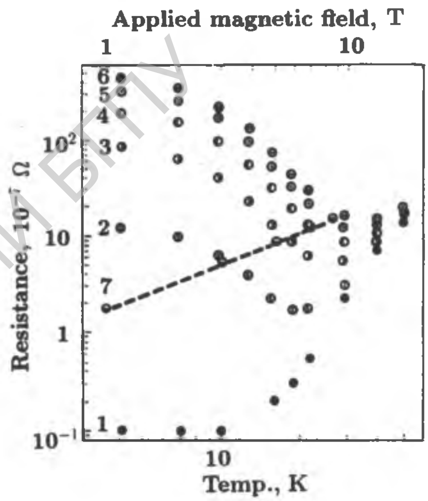

Fig.1 Temperature dependence of resistance in magnetic fields B_0 in T: 0(1), 1(2), 3(3), 5(4), 7(5), 8.5(6). Dashed line (7)-resistive minimum as a function of magnetic field (upper axis).

So strong magnetic field ensures a negative derivative of magnetoresistance with respect to temperature for 4.2–30 K. Respectively a heat generation function at regime of current supply will correspond to such law if a homogeneous temperature distribution takes place in sample volume.

High density charge transport in magnetic field was used to achieve a boiling crisis due to magnetoresistive effect. This regime was investigated by a method of voltage current characteristics in magnetic field. Three types of voltage current characteristics have been observed. First type is a monotone dependence of voltage on current. This type of dependence is realized in magnetic field up to 2 T. A second type of dependence is a nonmonotone behavior of voltage drop. There is a maximum of voltage at definite value of current. This extreme magnitude depends on current value and magnetic field. In other words extreme magnitude of U increases and displaces to small current region when magnetic field grows. Second type of characteristics is realized in magnetic field of the order of 2/8 T. At last a third type of dependence is a voltage current behavior resembling a second non-monotone type but here an extreme is extended in plateau so a section with voltage stabilization is observed in some current range. It should be mentioned that first type of characteristics does not alter at inversion of current and external magnetic field. Second and third types depend on direction of current through a sample. So a third type is realized presumably when current flow from outer to inner contact beyond a direction of external magnetic field. All typical dependencies of voltage drop on current value and its direction are represented in Fig.2 where a section with voltage stabilization is seen.

Now consider qualitatively the heat part of problem for possible regimes and determine the reasons of appearance of different voltage current curves. In this case we have no discrete system with limited number of variables but a continuous one, its parameters depending on spatial coordinates. The temperature as a field function corresponds to the equation in partial derivative with respect to time and coordinates because the temperature spatial inhomogeneities can lead to heat transfer. The stationary state consideration is based on linear analysis of system stability when the decision is presented as a multiplication of time function and coordinate one. At this consideration there may appear new elements as a result of action of an operator on the coordinate function. These new elements are the proper values of spatial operator describing the system during its linearization and depending on transport coefficients. The equation describes the temperature field evolution with time when the radial heat flux takes place:

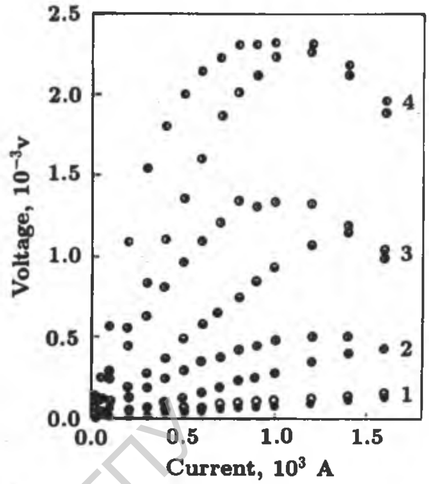

Fig.2 Voltage current characteristics at applied fields B_0 in T: 1(1), 2(2), 3(3), 8(4); filled symbols-current flows out of the center, open symbols-current flows toward the center.

$$c\frac{\partial T}{\partial t} = \rho_0(\omega\tau)^2 j^2 - q_- + \lambda\left(\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2}\right). \tag{2}$$

Here c is the heat capacitor, q_- is the function of heat removal, λ is the heat conductivity. The disk sample is thin, heat flux is symmetrical, the temperature distribution along the axis is absent because of the heat conductivity is high along field direction comparing to radial one. Heat elimination function as a second parameter determining a heat and electric state of conductor in these conditions is connected with regimes of boiling of liquid helium. Parameters of transition from bubble boiling to film that have been estimated here using the characteristics of heat removal by liquid helium from different surfaces. Parameters of first and second crisis are represented in the next manner: saturation temperature T_5=4.21 K; critical temperature T_c=5.2 K; first boiling crisis: heat flux density q_1=0.15–0.35 W/cm^2; temperature T_1=4.4–4.6 K; second boiling crisis: heat flux density q_2=0.1–0.14 W/cm^2; temperature T_2=4.9–5.1 K. The characteristics are schematically represented in Fig.3. The analysis of characteristic equation

$$\alpha = q'_+ - q'_- - \nabla^2 \tag{3}$$

enables to establish a correlation with experimental data. Here α is a parameter of stability, q_+ is the function of heat generation, q'_+ and q'_- are the derivatives with respect to temperature, ∇^2 is the parameter of proper value of the proper task of Laplacian at accepted boundary conditions when there is no temperature gradient in the vicinity of inner and outer current contacts. So the temperature distributions for proper task is described by the proper functions and proper values:

$$\begin{aligned} &\psi_k(r) = c_1 I_0(\gamma_k r) + c_2 Y_0(\gamma_k r); \\ &\gamma_k^2 = \frac{\mu_k^2}{r_1^2}; \quad k = 0, 1, 2, \ldots; \;\; \mu_o = 0; \;\; \mu_k \geq 0; \;\; \psi_0 = 1. \end{aligned} \tag{4}$$

Here I_0 and Y_0 are the Bessel and Veber functions. As the proper values $\gamma_k^2 \geq 0$ it is clear that the heat transfer processes can not lead to additional unstability.

The system state is characterized by the relation between the components of Eq.(2), the steady stae being determined by the value and sign of parameters of Eq.(3). From Fig.3 and Eq.(3) it is seen that for $q_- < q_1$ and $q_- > q_2$ when respectively $q'_- > 0$ and $q'_+ < 0$ a stationary state is realized at γ_k^2=0, the temperature field being homogeneous along the sample radius. First and second types of voltage current characteristics may be explained by this mechanism. The analysis shows that characteristics having an extreme correspond to a heat flux density of the order of 0.3–0.5 W/cm^2. In other words the voltage current characteristic extremes take place at heat generation corresponding to the first boiling crisis. Under these conditions the heat removal function leads to such temperature increasing when the heat balance of system is realized on increasing with temperature bubble and film sections of boiling curve. Under the film boiling and when $T > 5$ K the decrease of resistance dominates in the process and stimulates the falling-down section of voltage current characteristics. At small external fields (up to 2 T) there takes place a monotone dependence of U in all range of I because the heat removal function realizes the most favorable bubble boiling and samples resistance almost does not decrease in this narrow temperature region.

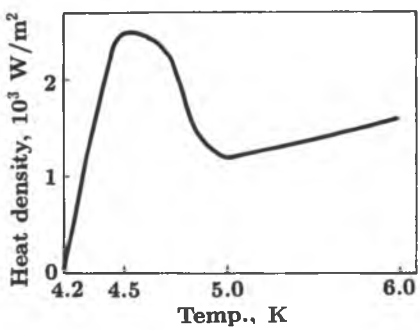

Fig.3 Schematic illustration of liquid helium boiling.

For the range $q_1 < q_- < q_2$ the value $(q'_+ - q'_-)$ is positive because $|q'_-| > |q'_+|$; $q'_- < 0$ and stationary state may take place when $\gamma_k^2 \neq 0$. This leads to the voltage stabilization observed experimentally because the regions with changing temperature lead to the spatial oscillations of resistance. So the measurement of voltage means the registration of resistivity value oscillating near some average magnitude. However the existence of voltage stabilization is only sufficient condition of temperature structure appearance. There is no evidence that any temperature ordering is impossible without voltage stabilization. Here a system is not too far from equilibrium state so the symmetry of kinetic coefficients and the linearity of phenomenological relations takes place. The speed of entropy production is positively defined form of state variables that is of temperature. So the stationary entropy production being Lyapunov function describing the minimal heat generation is responsible for the voltage stabilization.

In conclusion the critical regimes of heat generation and heat removal show a possibility of electric-temperature of ordering in cylindrical aluminum conductors having radial charge transport in regime of current supply. An external magnetic field and Hall drift of carriers define a type of voltage current characteristics. Stabilization of voltage drop as a particular case of nonmonotone dependence of voltage on current is connected with appearance of more heated and less heated sections along sample radius. Increase of heat generation leads to non-equal contribution to heat state from bubble and film sections and more heated sections expand depressing bubble sections. After that a temperature structure disappears and a characteristic transforms into characteristic of second type.

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