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ENERGY STORAGE IN METAL DEVICES AND THE ADVANTAGES OF LIQUID HYDROGEN TEMPERATURES

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Peculiarities of low temperature charge transport and energy accumulation in aluminum devices are investigated by means of study of cylindrical conductors having a radial current flow between inner and outer concentric contracts. Azimuthal current and, connected with it, self magnetic field are investigated in a wide range of radial current density up to 6000 A/cm^2 under an external magnetic field up to 8 T. Electron scattering processes are investigated and it is shown that relaxation electron mechanisms are determined by strong temperature dependence on account of high susceptibility of scattering to anisotropy of electron dispersion law. The role of thermal phonons is investigated through an effective averaged conductivity tensor of polycrystalline medium. Using data of self magnetic self distribution on sample surface an energy density of self magnetic field is estimated. It is shown that at T=4.2 K average energy of self field may achieve at least 1 J/cm^3. Using data of relaxation processes at temperature of liquid hydrogen it is established that self magnetic field must be a third of helium magnitude with respective self magnetic energy density, spiral motion of carriers in this geometry being regarded as a current coils in usual inductive element.
KEY WORDS *energy storage, charge transport, magnetic field, anisotropy*

1. Introduction

Pure aluminum is applied as a conducting material for creation of different powerful magnetic systems operating at low temperatures. Small magnetoresistance of aluminum gives possibility to use this material as one component of composite cryoconductors being used for stabilization of superconductive cables and also for machines and devices. In composite cryoconductors on the base of aluminum a small magnetoresistance is a main advantage. Insufficient mechanical strength of aluminum is compensated by harder materials for example by copper. However in the interface of composite cryoconductors being inhomogeneous medium due to different type of conductivity a redistribution of electrical field connected with generation of Hall current takes place. Hall current generation through such bound is a result of rotation free type of steady electric field when the absence of curls of electric field in interface requires the appearance of transverse Hall current. This Hall current generation leads to enhancement of magnetoresistance and an excessive heat generation. Here Hall current is a negative factor of problem. It is known that Hall current appears in transverse magnetic field not only through composite interface but in single conductors having some types of inhomogeneity: charge concentration, dielectric inclusions, geometry, surface defects and inhomogeneity of external magnetic field. In any case Hall current redistributes a current density so that the effective cross section of conductor decrease and as a result the resistance enlarges.

Some aspects of the positive role of Hall current and its application in cryogenic electromagnetic systems are discussed here on the basis of investigation of current phenomena in cylindrical metallic conductors having radial charge flow. A cylindrical conductor has inner and outer concentric contacts, a current being made to flow between these contacts. An external magnetic field is coaxial with conductor. This geometry of charge flow is called Corbino and gives a possibility to realize unlimited transverse charge flow so that Hall electric field is absent in conductor and resistive property is determined only by diagonal component of conductivity tensor[1,2]. For uncompensated metal a peculiarities of electron scattering may be investigated more precisely in this geometry because strong field dependence of resistance and high magnitude of resistance give a possibility to see any small changes of relaxation process. So some data of charge flow in Corbino geometry are represented for aluminum cylindrical conductors in wide temperature range.

2. Experiment and Method of Analysis

Disk shaped aluminum conductors were used for investigation. Samples were fabricated from pure polycrystalline material so that residual resistance ratio was 12000–15000. Polycrystalline structure of material was chosen to exclude any influence of crystal anisotropy. Disk shaped conductors had inner and outer diameters 4 and 36 mm respectively, and the thickness was 0.5–4 mm. Current concentric leads were mounted on inner and outer diameters so that a current density of the order of 6000 A/cm^2 could pass through a conductor between inner and outer contacts. Potential probes and Hall sensors were mounted on sample surface along its radius. Conductors were placed in low temperature insert which was situated in liquid helium cavity of cryostat having superconducting solenoid. Heat elimination regime was a helium boiling in large volume. For temperature measurements a thermostatic chamber having an automatic monitoring unit was applied. A measurement included a registration of voltage drop on potential probes and on Hall sensors in coaxial magnetic field up to 8 T. During measurement an inversion of directions of current flow and external magnetic field was applied. Using data of measurement a self magnetic field due to Hall drift and its distribution along radius was obtained. Self magnetic field was calculated as the difference between total magnetic field on sample surface and an external magnetic field of superconducting solenoid. Resistive properties were investigated in the temperature range 4.2–50 K and characteristic relaxation time was calculated. A correlation of real relaxation time with relaxation time in free electron approximation gave possibility to estimate magnitudes of self magnetic field at the temperature of liquid hydrogen. Analytical calculation of self magnetic field distribution was done and correlation between experimental data and theory was established. Using a continuity of normal component of magnetic field induction an average energy density of self magnetic field in sample was estimated in the temperature range 4.2–22 K. A limit case of long cylindrical conductor in such geometry is discussed from the view point of increase of degree of energy localization. It is shown that the levels of energy accumulation due to Hall drift may be much higher at both helium and hydrogen temperatures when magnetic strength lines localize presumably in its volume.

3. Results and Discussion

In cylindrical conductor having radial current under a coaxial external magnetic field the following relation holds:

$$j_\theta = j\omega\tau \tag{1}$$

where j is a radial current density, j_θ is an azimuthal current density due to Hall drift, ω is Larmor frequency stimulated by an external magnetic field, and τ is an effective relaxation time. In accordance with Eq.(1) a self magnetic field is a function of parameter of efficicency of magnetic filed $\omega\tau$. So it is necessary to investigate the relaxation process before. A dependence of sample resistance on magnetic field at different temperatures is represented in Fig.1.

It is important that a dependence is not fully quadratic for all temperature range. We connect this phenomenon with anisotropy of dispersion law and respective electron scattering. In high magnetic field the open electron orbits appear due to umklapp scattering and magnetic breakdown. The effective relaxation time reduces in comparison with free electron approximation. For free electron approach a diagonal component of conductivity tensor σ is:

$$\sigma = \frac{\sigma_0}{1 + (\omega\tau_0)^2}. \tag{2}$$

Here σ_0 is a conductivity in zero magnetic field, and τ_0 is a free electron relaxation time. In polycrystalline aluminum conductor the presence of open orbits having different orientations in different crystals leads to increase of effective conductivity tensor component. A quantity of electrons in layers of open orbits is small in comparison with base quantity belonging to closed orbits. An average of conductivity tensor on orientation gives possibility to represent a diagonal component of conductivity tensor σ as follows:

$$\sigma = \sigma_0\left(\frac{1}{(\omega\tau_0)^2} + \frac{\alpha}{\omega\tau_0}\right). \tag{3}$$

Here $\alpha/\omega\tau_0$ is a term which describes conductivity properties due to elongated orbits. This term is smaller than the basic term.

For the case of radial current flow in cylindrical conductor a resistivity is equal to reverse diagonal component. In accordance with Eq.(3) a dependence of resistance is close to quadratic but is not entirely coincided. Following Eq.(3) a diagonal component of resistivity in magnetic field is expressed as a function having a weak linear dependence on magnetic field. Such behavior may be interpreted as a decrease of relaxation time τ in comparison with τ_0 if σ is represented as:

$$\sigma = \sigma_0\frac{1}{(\omega\tau)^n}; \qquad n \leq 2. \tag{4}$$

Experimental and analytical data on relaxation time and its dependence on magnetic field are represented in Fig.2 where experimental behavior of relative magnetoresistance that is $(\omega\tau)^n$ and magnetoresistance for free electron approximation are shown. Following these data one can claim that the effective parameter $\omega\tau$ is a third of the free electron one. A correlation between experimental magnitudes of self magnetic field and analytical data may be established with help of Fig.2.

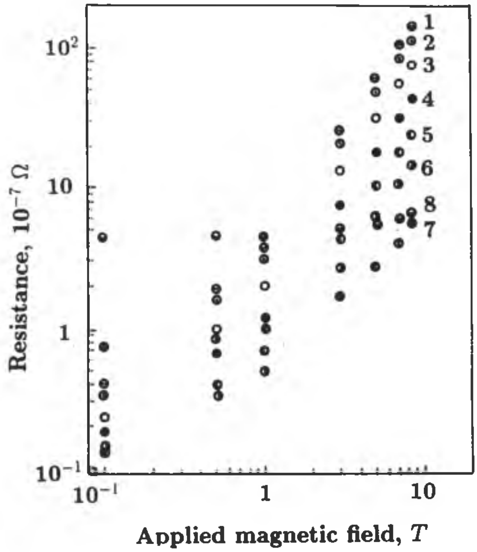

Fig.1 Dependence of sample resistance on external magnetic field at temperatures in K: 4.2 (1), 7 (2), 10 (3), 13 (4), 16 (5), 19 (6), 30 (7), 50 (8).

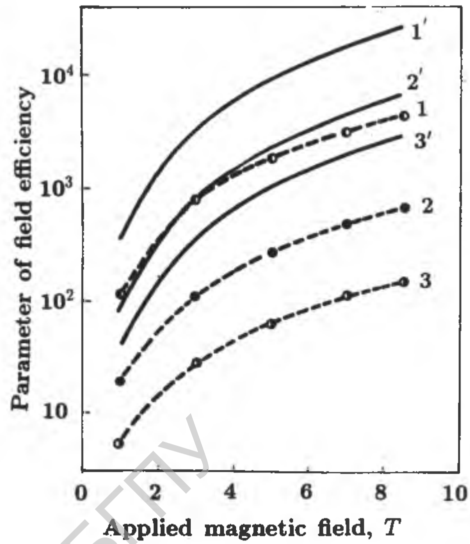

Fig.2 Parameter of field efficiency $(\omega\tau)^2$ as a function of applied field at temperatures in K: 4.2 (1,1'), 13 (2,2'), 22 (3,3'); 1,2,3-experiment, 1',2',3'-theory.

Self magnetic field was investigated at different directions of both current and an external magnetic field. It has been found that a direction of self magnetic field is parallel to an external field when current is made to flow to sample center beyond the external field direction. At alternative current direction the self magnetic field and the external one are antiparallel. In Fig.3 a self magnetic field distribution along sample radius is shown at different magnitudes of current through sample. Analytical data have been obtained which reveal the influence of magnetic field on relaxation processes. For calculation of magnetic field distribution a general connection between current density element and respective magnetic field in any point was used:

$$B(R) = \frac{1}{c}\int\int\int \frac{j_\theta(R')(R-R')}{|R-R'|^3}\mathrm{d}V. \tag{5}$$

So the dependence of self magnetic field on sample surface along radius has been calculated in accordance with expression received after integration on sample volume:

$$B(r) = \frac{I\omega\tau}{c}\Bigg\{-\frac{1}{r}\ln\left|\frac{r}{r_2}\frac{\sqrt{r_2^2+r^2}+r}{\sqrt{2r^2}+r}\right| + \frac{1}{2r}\ln\left|\frac{\sqrt{r_2^2+r^2}-r\sqrt{2r^2}+r}{\sqrt{r_2^2+r^2+r\sqrt{2r^2}-r}}\right|$$

$$+\frac{1}{\sqrt{r^2+r_2^2}} - \frac{1}{\sqrt{2r^2}} + \frac{r^4}{5}\left(\frac{1}{2^{2.5}r^5} - \frac{1}{(r_2^2+r^2)^{2.5}}\right)\Bigg\}. \tag{6}$$

An energy density of self magnetic field estimated using a continuity of normal component of induction of magnetic field is represented in Fig.4.

Here an energy density is shown as a function of current flowing through an investigated conductor. Using data of relaxation processes at higher temperature it is easy to estimate energy density of self field in the temperature range 4.2–30 K. For the temperature of liquid hydrogen the parameter of efficiency of magnetic field is a third of the liquid helium one and the energy density of self magnetic field may achieve a magnitude of the order of 0.1 J/cm^3. It should be mentioned that a real energy accumulated in conductor volume is greater than that in Fig.4 because a representative energy density is estimated only for coaxial component of self magnetic field. It is known that in short cylindrical conductor being investigated here other components of field take place. Other components are not small for short cylinder so a real energy accumulated in conductor volume is larger than magnitudes indicated in Fig.4. For energy accumulation a long cylindrical conductor is more suitable because for such a conductor presumably axial component of self magnetic field occurs. Besides in long conductor an effect of self interaction can take place when an external magnetic field interferences with self magnetic field so that self field distribution is expressed by order law instead of modified logarithmic dependence of short cylinder.

$$B = B_0(r_2/r)^b; \quad b = \frac{2e\tau \, I}{mc^2 \, h}. \tag{7}$$

Here r_2 is an outer radius, h is a cylinder length, and m is an electron mass.

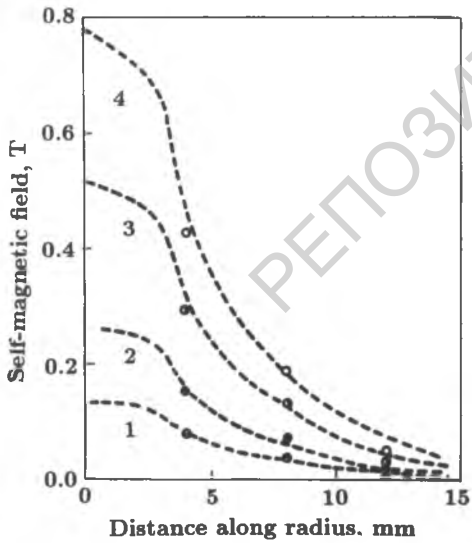

Fig.3 The distribution of self magnetic field along radius under external field 7 T for current I in A: 40 (1), 80 (2), 160 (3), 240 (4). Dashed lines-calculated data.

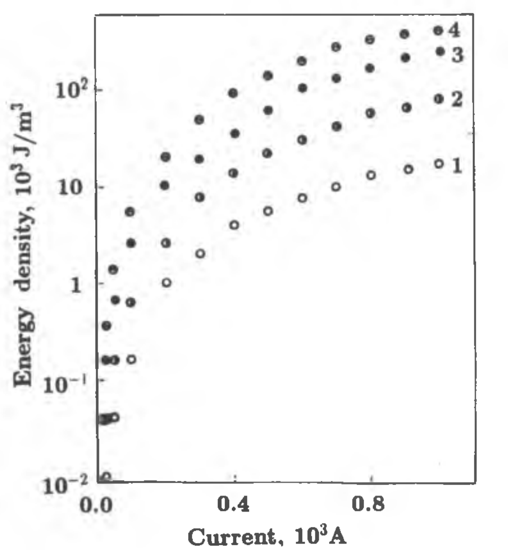

Fig.4 Averaged density of self magnetic field W as a function of current for different applied fields B_0 in T: (1), 2 (2), 4 (3), 8 (4).

Material used for sample fabrication has a resistivity at liquid helium temperature $2{\cdot}10^{-10}$ Ohm-cm. High susceptibility of relaxation processes to temperature is observed in such geometry. An effective relaxation time at T=22 K is one a third as much as resistivity at 4.2 K. It is clear that for successive operation of devices functioning on this principle there is no necessity to use for hydrogen temperatures an aluminum material having RRR of the order of 12000. It will be sufficient to have more impurity material with helium resistivity $6 \cdot 10^{-10}$ Ohm-cm which corresponds to RRR=4000.

In conclusion energy storage in metal devices such as cylindrical conductors fabricated from pure aluminum can be realized at cryogenic temperatures on the basis of using of Hall current generation in transverse external magnetic fields. Poor aluminum mechanical strength is not important in such devices because this inductive element is a coilless variant. It consists of massive conductor, and a number of effective current coils are determined by parameter of efficiency of magnetic field.

Relatively small parameter of efficiency of magnetic field $\omega\tau$ at hydrogen temperature in comparison with that at helium temperature may be easily compensated by higher magnitude of radial current density because a boiling crisis of hydrogen takes place at levels of energy generation which are much higher than the helium ones.

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