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Low Temperature Microwave Impedance of Aluminum in Orthogonal Magnetic Field

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Abstract

The real part of surface low temperature impedance of aluminum and copper is analyzed on the base of the data on measurement of Q-factor for coaxial resonator. Microwave impedance (decimeter wave length range) have been tested under an action of strong magnetic field. Temperature range expands from liquid helium point to liquid nitrogen and up to room these. Non-monotonic behaviour of Q-factor in the function of magnetic field for resonator made of pure Al is observed and discussed as quasiresonance absorption of field energy by special noncentral electron group of isoenergetic sufrace. The approximation of the free electron dispertion law is attracted to speculate the negativity of surface magnetoresistance of aluminum.

Introduction

Magnetic field as a factor of an action on to moving charge particle always stimulates the transverse drift due to the direction of Lorentce force. So the probability of particle scattering during its displacement along primary direction increases under the conditions of magnetic field action. This mechanism stimulates the positive magnetoresistance under the charge transfer at steady electric field. Quantum phenomena in condensed matter (for example in metals having magnetic impurities) deliver negative magnetoresistance properties due to spin reverse of magnetic impurities. Here the negativity of surface magnetoresistance of pure aluminum is discussed as a result of quasiclassic manifestation for electron movement in aluminum. The analysis is based on the free electron dispersion law approximation that is rather suitable for closed Fermi surface. The frequency range of electromagnetic field corresponds to the approximation of weak space dispersion of electron probability density distribution function.

Experiment

Coaxial resonators have been made totally from polycrystalline in structure materials. It should be mentioned that for decimeter wave range (about 70 cm) the volume cavity approach is not suitable and the coaxial system is one of possible that to model microwave properties of materials [1,2]. The length of resonator was about 10 cm, diameter 3,8 cm, so it was able to be placed into inner cylindrical cavity of superconducting solenoid of helium cryostat. Here the magnetic field vector coincides with resonator axis. The special heating devices and temperature monitoring apparatus gave possibility to maintain temperature of system under different levels on the principle of calorimeter functioning. The inhomogeneity of magnetic field via the resonator volume was less of 0.1 % and did not disturb measurement. The transverse electro magnetic standing wave have been excited and controled by magnetic loops being placed in the maximum of magnetic field amplitude. The properties have been studied by the method of frequency-response characteristic.

Experimental results and discussions

For comparison the experiment have been made by means attraction of two different materials mainly aluminum and copper. The aluminum sample have a much higher initial purity before copper. So the temperature dependences of Q factor for Al resonator lies higher of these for copper resonator under the same conditions on magnetic field (Fig. 1).

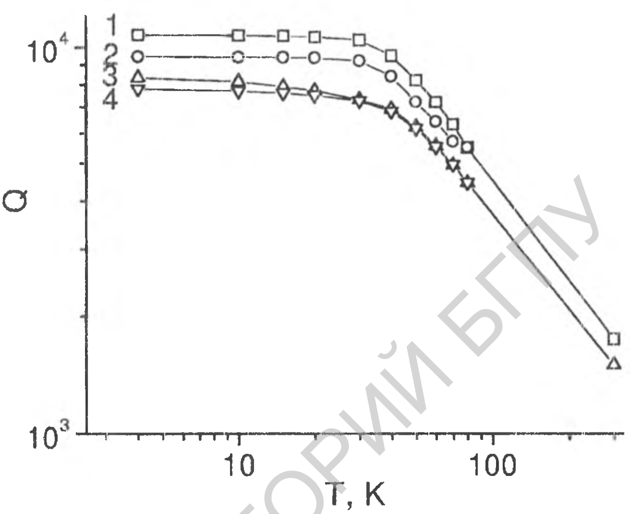

Figure 1. The temperature characteristic of Q-factor for aluminum (1,2) and copper (3,4) resonator under magnetic field B, T: 0 (1, 3); 7 (2, 4).

For the aluminum the behaviuor corresponds to Pippard conception of nonlocal connection between field and current [3-5]. Following Pippard only small part of particles,belonged to central section of Fermi surface takes part in efficient absorption of field energy. It should be state that electron free length achieves of skin depth magnitude under the temperature level of 60-70 K. In opposite to aluminum the copper resonator behaviour saturates at temperature of 10 K. This is a result of a less free electron lehgth. Magnetic field increases losses for Al higher in comparison with copper on the reason that the Cu free electron length is about 10^{-5} cm. In this task the electromagnetic field frequency $\omega = 10^8 - 10^9\ s^{-1}$, electron scattering frequency for aluminum $\tau^{-1} \simeq 10^9 - 10^{10} s^{-1}$, and Larmor frequency at magnetic field of 7 - 8 T achieves of $10^{11} - 10^{12} s^{-1}$. So all three characteristic parameters of frequency are close on value. Under weak magnetic field the impedance is determined by electron-impurities scattering, and under strong magnetic field the particle dynamics plays significant role. The particle dynamics is represented in Q-factor of Al resonator being the function of magnetic field (Fig.2.). Under the temperature range when the reversal relaxation time is higher of Larmor frequency the losses are not susceptible to magnetic field. It is interesting that at liquid helium temperature the weak magnetic field improves the frequency conductivity. In the frame of this task the magnetic field affect only the transverse radial movement of particles on shorting face of resonator. For non-stationary process there are no reasons to neglect the azimuthal component of particle displacement and respective field component [6]. Following mentioned above classical approximations the negativity of surface impedance in magnetic field is possible under resonance phenomena.

Here the resonance energy absorption is stimulated by electron groups having small Larmor radii. These electrons belong to non-central sections of Fermi surface and leave the skin-layer without any scattering. The electrons of central section can drift on its free length to trasnsverse azimuthal direction without effective absorption energy of field. Analyse the magnetic field influence on to frequency conductivity and surface impedance of aluminum in the free electron approximation under conditions when the spatial dispersion of electron probability density distribution function is neglected: $kr \ll 1$; (k — wave vector, r — Larmor radius). For the free electron approximation the static conductivity tensor is:

$$\sigma = \sigma_0 \begin{pmatrix} \dfrac{1}{1+\beta^2} & \dfrac{\beta}{1+\beta^2} & 0 \\ -\dfrac{\beta}{1+\beta^2} & \dfrac{1}{1+\beta^2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{1}$$

here σ_0 — static conductivity in zero magnetic field, $\beta = \Omega\tau$, Ω — Larmor frequency.

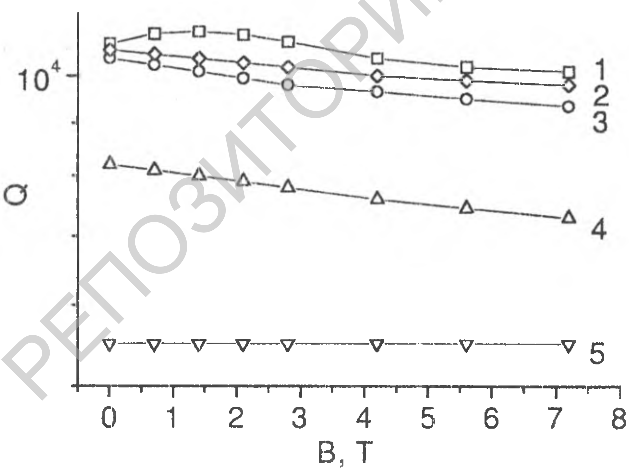

Figure 2. The characteristics of Q-factor for Al resonator in the function of magnetic field at the temperature T, K: 4.2 (1); 15 (2);30 (3); 50 (4); 80 (5)

To define the magnetic field influence on surface resistance it is necessary to analyse the next determinant

$$\begin{vmatrix} k - \dfrac{4\pi i\omega\sigma_0}{c^2(1+\beta^2)} & -\dfrac{4\pi i\omega\sigma_0\beta}{c^2(1+\beta^2)} & 0 \\ \dfrac{4\pi i\omega\sigma_0\beta}{c^2(1+\beta^2)} & k - \dfrac{4\pi i\omega\sigma_0}{c^2(1+\beta^2)} & 0 \\ 0 & 0 & -\sigma_0 \end{vmatrix} = 0 \tag{2}$$

here k — z-component of wave vector (along an external magnetic field). As a result the dispersion law for field may be represented as

$$k^2 = \frac{4\pi i\omega\sigma_0}{c^2}\frac{1 \pm i\beta}{1+\beta^2} \tag{3}$$

The reversal surface impedance Z has to be obtained on the base of wave vector

$$Z^{-1} = \frac{c}{4\pi}\left[\frac{\omega_p^2\tau}{\omega}\frac{\mp\beta + i}{1+\beta^2}\right]^{\frac{1}{2}} \tag{4}$$

here ω_p — plasmas frequency. So following to (4) it is seen that the reversal surface impedance is a non-monotonic function of magnetic field. At the conditions of $\beta \leq 1$ the Q-factor is an increasing function of magnetic field.

$$Z^{-1} \simeq \frac{c}{4\sqrt{2\pi}}\omega_p\sqrt{\frac{\tau}{\omega}}\left[\left(1 \mp \frac{\beta}{2}\right) + i\left(1 \pm \frac{\beta}{2}\right)\right] \tag{5}$$

When the condition $\beta \gg 1$ takes place, the reversal impedance is a drop function.

$$Z^{-1} \simeq \frac{c\omega_p}{4\pi}\sqrt{\frac{\tau}{\omega\beta}}\left[\pm\left(1 + \frac{i}{\beta}\right)\right]^{\frac{1}{2}} \tag{6}$$

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