RESEARCH SURFACE RESISTANCE OF COPPER NORMAL AND ABNORMAL SKIN-EFFECTS DEPENDING ON THE FREQUENCY OF ELECTROMAGNETIC FIELD

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The results of the frequency dependence of surface resistance of copper in diffuse and specular reflection of electrons from the conductive surface of the high-frequency resonance of the system depending on the frequency of the electromagnetic field in the normal and anomalous skin effect. Found, the surface resistance of copper is reduced by more than 10 times at the temperature of liquid helium, as compared with a surface resistivity at room temperature, at frequencies $f \le 173$ MHz, for diffuse reflection of conduction electrons from the surface of the conductive layer, and the specular reflection – at frequencies $f \le 346$ MHz.

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INTRODUCTION

At present to improve the parameters of high-frequency resonant systems working at room temperature, almost reached its limit. First of all it refers to such essential characteristics as efficiency, the absolute values of energy loss that always occur in resonance systems. In connection with this the development of high-Q resonant carried HF – systems that need to reduce the losses of RF power in the walls of the resonant system 10 times or more, thereby increasing system efficiency and reducing losses of high frequency energy. In the development of high-performance cryogenic resonant high frequency systems used superconductors. However, the use of superconductors in the manufacture of high-cryogenic systems is difficult due to their high cost, complexity of treatment. Superconductors are effective only within a narrow range of cryogenic temperatures. Therefore, the possibility of producing highly effective cryogenic systems considered from high-frequency resonant nonsuperconducting metal such as copper [1, 2]. This requires investigate the surface resistance of copper, depending on the cooling temperature, the frequency of the electromagnetic field. Improvement in the performance of high-frequency resonant systems with their cooling due to the decrease of the surface resistance of the metal. As the temperature decreases length of the free path of electrons increases and the skin depth decreases, there comes the anomalous skin effect [3]. If the length free path of electrons greater than the depth of penetration of the RF field in the metal, the electrons between the next collision longer interact with the electromagnetic field, and actively participate in the processes of effective conductivity, with a surface resistance of non-superconducting metal is reduced. The minimum value of surface resistance in the non-superconducting metals in the region of the anomalous skin effect can be achieved only in a very pure samples after annealing, and the conductive surface of the high-frequency resonant system must be as smooth as possible. A detailed study of the surface resistance of non-superconducting metals at cryogenic temperatures will provide a deeper understanding the possible use of non-superconducting materials as structural material for the creation high-Q cryogenic resonant systems.

PROBLEM STATEMENT

In the development of high-frequency resonant systems special place is occupied issues related to the losses of high-frequency power in the walls of the resonant system. It is known that the dissipative characteristics are crucial for such quantities as the shunt resistance and quality factor of the resonant system. If the total metal surface S, for which is valid Leontovich boundary conditions, the high-frequency power that is dissipated in its walls, determined by the equation:

$$P = \frac{1}{2}\int_S R\left|\bar{H}\right|^2 dS, \qquad (1)$$

where P – power loss, W; R – surface resistance, Ohm; $\bar{H}$ – the magnetic field vector, A/m; S – surface area m^2.

From equation (1) that the responsibility for the loss of high-frequency power is the surface resistance R.

In the normal skin-effect resistance of the non-superconducting metal surface R_k is:

$$R_k = \left(\frac{\omega\mu_0}{2\sigma}\right)^{\frac{1}{2}}, \qquad (2)$$

where σ – the specific conductance of the normal metal DC, S/m; ω – angular frequency, rad/s; μ_0 – permeability of free space henry/m.

In the region of the anomalous skin effect, the surface resistance of non-superconducting metal R_a is determined by the expression [4].

$$R_a = \left(\frac{1}{b}\right)^{\frac{1}{3}}\left(\frac{l}{\sigma}\right)^{\frac{1}{3}}\left(\frac{\omega\mu}{2}\right)^{\frac{2}{3}}, \qquad (3)$$

where b – coefficient which characterizes the conduction electrons reflected from the surface of the conductor; l – length of the free path of an electron, m.

From (2) and (3) follows that the loss of high-frequency power in the walls of the resonant system, in normal and anomalous skin effect is largely dependent on the frequency of the electromagnetic field. Thus, the classical skin effect losses are proportional, and the anomalous skin effect – $\omega^{2/3}$. In connection with this there is interest in studying the surface resistance of non-superconducting metals at cryogenic temperatures, depending on the frequency of the electromagnetic field. To do this, an analysis of the coefficient of winning «η», which is equal to the ratio the surface resistance of non-superconducting metal at room temperature R_{293} to surface resistance of the same material at cryogenic temperatures, R_T

$$\eta = \frac{R_{293}}{R_T}.$$

Coefficient «η» depends not only on the frequency of the electromagnetic field but also the length free path of electrons and the nature of reflection of the conduction electrons from the surface of the conductor. State of the electron conductivity in turn is determined by the processing technology conductive surface, composition, temperature of cooling. It is therefore necessary to carry out a series of studies nonsuperconducting metal surface resistance over a wide temperature range and frequency range, depending on the processing technology conductive layer purity and structure of the material. This will determine what type of metal is minimal loss of RF power at cryogenic temperatures, and the number of times to increase resonant high Q cooled system in comparison with the resonant high-frequency system operating at room temperature.

RESULTS

Define the advantage coefficient «η» non-superconducting metals as a function of the frequency of the electromagnetic field.

Using equations (2) and (3) the equation for the coefficient of advantage.

$$\eta = \frac{R_k}{R_a} = \frac{\left(\frac{\omega\mu_0}{2\sigma}\right)^{\frac{1}{2}}}{\left(\frac{1}{b}\right)^{\frac{1}{3}}\left(\frac{l}{\sigma}\right)^{\frac{1}{3}}\left(\frac{\omega\mu_0}{2}\right)^{\frac{2}{3}}}. \quad (4)$$

After the conversion equation (4) takes the form

$$\eta = \sqrt[6]{\frac{2}{\mu_0\omega\sigma^3\left(\frac{1}{b}\cdot\frac{l}{\sigma}\right)^2}}. \quad (5)$$

We solve this equation for ω

$$\omega = \frac{2}{\eta^6\sigma^3\mu_0\left(\frac{1}{b}\cdot\frac{l}{\sigma}\right)^2}. \quad (6)$$

As $\omega = 2\pi f$, an equation for the resonant frequency, f.

$$f = \frac{1}{\eta^6\pi\mu_0\sigma^3\left(\frac{1}{b}\cdot\frac{l}{\sigma}\right)^2}. \quad (7)$$

Analyzing the equation (7), we conclude that for ideal non-superconducting metal when η = 1, frequency of electromagnetic field f tends to the value f_1, wherein $R_к = R_a$. In the case where the frequency of the electromagnetic field $f > f_1$ then the surface resistance $R_a > R_к$, and the advantage coefficient η <1. At $\eta \to \infty$, frequency $f \to 0$.

Let us consider the dependence of the advantage «η» on the frequency f. For this we define a surface resistance of non-superconducting metal in the normal and anomalous skin effect, for example, at a frequency f_2. In the normal skin-effect resistance of the surface R_{k2} at a frequency f_2 will have the form:

$$R_{k2} = \left(\frac{\pi\cdot f_2\cdot\mu_0}{\sigma}\right)^{\frac{1}{2}}. \quad (8)$$

In the region of the anomalous skin effect surface resistance R_{a2} on frequency will be:

$$R_{a2} = \left(\frac{1}{b}\right)^{\frac{1}{3}}\left(\frac{l}{\sigma}\right)^{\frac{1}{3}}(\pi f_2\cdot\mu_0)^{\frac{2}{3}}. \quad (9)$$

From equations (8) and (9) we define σ, and l/σ.

$$\sigma = \frac{\pi\cdot f_2\cdot\mu_0}{R_{k2}^2},. \quad (10)$$

$$\frac{l}{\sigma} = \frac{R_{a2}^3}{\frac{1}{b}(\pi f_2\cdot\mu_0)^2}. \quad (11)$$

We substitute these values into equation (7), we obtain;

$$f = \frac{R_{k2}^6\left(\frac{1}{b}\right)^2\pi^4 f_2^4\mu_0^4}{\eta^6\pi^4 f_2^3\,\mu_0^4\left(\frac{1}{b}\right)^2 R_{a2}^6}. \quad (12)$$

After the transformation equation (12) takes the form:

$$f = \frac{f_2 R_{k2}^6}{\eta^6 R_{a2}^6}. \quad (13)$$

as $\frac{R_{k2}^6}{R_{a2}^6} = \eta_2^6$ expression (13) becomes:

$$\frac{f}{f_2} = \frac{\eta_2^6}{\eta^6}. \quad (14)$$

From equation (14) that the advantage «η» is back power-law dependence on the frequency. Thus, by measuring the advantage «η» of the metal at the frequency f, can be determine the advantage η_2 on the frequency f_2 of expression (15).

$$\eta_2 = \eta\cdot\sqrt[6]{\frac{f}{f_2}}. \quad (15)$$

From (7) we define the advantage «η» for pure copper in diffuse and specular reflection of electrons from the surface, depending on the frequency, Table 1.

Table 1

Changing the ratio of advantage «η» for copper from the frequency

$R\cdot10^3$, Ohm	T, K	η	F, MHz	The coefficient of reflection, b
3,5	293	10	173	diffuse
0.35	4.2		173	
4.9	293	10	346	specular
0.49	4.2		346	
$3.5\cdot10^3$	293	1	$173\cdot10^6$	diffuse
$3.5\cdot10^3$	4.2		$173\cdot10^6$	
$4.9\cdot10^3$	293	1	$346\cdot10^6$	specular
$4.9\cdot10^3$	4.2		$346\cdot10^6$	

From the results of calculation, in order to decrease the surface resistance of copper in more than 10 times, at cryogenic temperature, it is necessary work at frequencies $f \leq 173$ MHz for diffuse reflection of conduction electrons from the surface, and specular reflection – at frequencies $f \leq 346$ MHz. Advantage «η» will be unity at frequencies $f = (173\ldots346)\cdot10^6$ МГц.

Table 2 shows the results of the calculation of the surface resistance of copper at room and liquid-helium temperatures at frequencies of 150 MHz and $5\cdot10^3$ MHz. Defined advantage η on surface resistance in specular reflection of electrons from the metal surface, as well as, the values of the penetration depth of high-frequency field in the copper from the expressions.

$$\delta_k = \left(\frac{2}{\omega\mu_0\sigma}\right), \qquad (16)$$

where δ_k – depth of penetration of the electromagnetic field in the metal in normal classical skin effect, m.

$$\delta_a = \left[\left(\frac{1}{b}\right)\left(\frac{l}{\sigma}\right)\left(\frac{2}{\omega\mu_0}\right)\right]^{\frac{1}{3}}, \qquad (17)$$

where δ_a – the depth of penetration of the electromagnetic field in the normal metal in the region of the anomalous skin effect, m.

Table 2

Changing the surface resistance R, the coefficient advantage «η», the skin layer of copper from the frequency

$R\cdot10^3$, Ohm	T, K	η	F, MHz	δ, microns
3.2	293	11.42	150	5.39
0.28	4.2		150	0.47
19.0	293	6.33	$5\cdot10^3$	0.91
3.0	4.2		$5\cdot10^3$	0.15

From the results the experimental study found the advantage for copper +0.02 Y at a frequency of $5\cdot10^3$ MHz after electrochemical polishing, annealing and deformation equal to 6.23, which coincides closely with the calculated value. From these results it follows that the frequency increases the advantage «η» and the depth of penetration of the electromagnetic field in the metal is reduced and becomes the dominant scattering of conduction electrons by impurities, vacancies, surface defects, sinks, inclusions. Thus, the interaction of electromagnetic fields with metallic surfaces in the normal and anomalous skin effect depends not only on the physical and chemical properties of the parent metal, but the technology of its processing.

CONCLUSIONS

The study of the surface resistance of copper from the frequency of the electromagnetic field in the normal and anomalous skin effects will provide a deeper understanding of possibilities of their use as structural material for the creation of high-performance resonant cryogenic systems.

To continue the development of this work it is advisable to carry out further experimental studies of high-frequency resonant system at cryogenic temperatures, made of various grades of copper.

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ИССЛЕДОВАНИЕ ПОВЕРХНОСТНОГО СОПРОТИВЛЕНИЯ МЕДИ В ОБЛАСТИ НОРМАЛЬНОГО И АНОМАЛЬНОГО СКИН-ЭФФЕКТОВ В ЗАВИСИМОСТИ ОТ ЧАСТОТЫ ЭЛЕКТРОМАГНИТНОГО ПОЛЯ

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Приведены результаты частотной зависимости поверхностного сопротивления для меди при диффузном и зеркальном отражениях электронов от токопроводящей поверхности резонансной высокочастотной системы в зависимости от частоты электромагнитного поля в области нормального и аномального скин-эффектов. Установлено, что поверхностное сопротивление меди уменьшится в 10 и более раз при температуре жидкого гелия по сравнению с поверхностным сопротивлением при комнатной температуре, на частотах $f \leq 173$ МГц при диффузном отражении электронов проводимости от поверхности токопроводящего слоя, а при зеркальном отражении – на частотах $f \leq 346$ МГц.

ДОСЛІДЖЕННЯ ПОВЕРХНЕВОГО ОПОРУ МІДІ В ОБЛАСТІ НОРМАЛЬНОГО І АНОМАЛЬНОГО СКІН-ЕФЕКТІВ У ЗАЛЕЖНОСТІ ВІД ЧАСТОТИ ЕЛЕКТРОМАГНІТНОГО ПОЛЯ

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Приведено результати частотної залежності поверхневого опору міді при дифузному і дзеркальному відображеннях електронів від струмопровідної поверхні резонансної високочастотної системи в залежності від частоти електромагнітного поля в області нормального і аномального скін-ефектів. Встановлено, що поверхневий опір міді зменшиться в 10 і більше разів при температурі рідкого гелію в порівнянні із поверхневим опором при кімнатній температурі, на частотах $f \leq 173$ МГц при дифузному відображенні електронів провідності від поверхні струмопровідного шару, а при дзеркальному відображенні – на частотах $f \leq 346$ МГц.