ON THE FREQUENCY DEPENDENCE OF THE SURFACE RESISTANCE ISOTHERMS IN SUPERCONDUCTORS

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It is well known that complex dielectric constants of superconductors can be obtained from the surface resistance measurements in the frequency range 10^{10}–10^{11} Hz [1–3]. The same measurements can reveal the dispersion of the dielectric constant and can be used to test the validity of the existing models of superconductivity.

At present, there are no reliable measurements of the frequency dependence of the surface resistance of superconductors. The frequency dependence of the surface impedance Z cannot be established from the available measurements which were performed at a few individual frequencies. Moreover, the data for the same frequency often differ by several times. For example, the R_s/R_n ratios obtained from the measurements made at a frequency of 9×10^9 Hz [4–6] at 2°K differ by a factor of 2.7.

This discrepancy can probably be attributed to some differences in the properties of sample surfaces [4, 7]. Hence, the measurements of the frequency dependence should be performed using the same sample in order to exclude the effect of the surface condition. Generally speaking, a single resonator in different oscillation modes can be used for this purpose.

The most suitable resonators are those, in which monocrystals of superconducting metals are used as samples. However, such a technique requires the use of widely tunable generators, since the resonator parameters cannot be changed without damaging the single crystal samples when switching from one frequency to another.

Lacking such a tunable generator, we could not use the above-described technique and had no choice other than to measure only the active part of the surface resistance $\mathrm{Re}(Z(\omega))$. In this context, we supposed that such data would suffice to test various models of superconductivity, even though the measurements of $\mathrm{Re}(Z(\omega))$ could not provide full information on $Z(\omega)$.

The device used to measure $\mathrm{Re}(Z(\omega))$ was described in our earlier works [7, 8]. An electropolished single-crystal 99.999%-pure tin wire was used as a sample.

Figure 1 shows the measurement results in the frequency range $(1.88 \div 4.5) \times 10^{10}$ Hz. One can see that the frequency dependence of the active resistance at low temperatures can be described by the relation $R_s/R_n \sim \omega^{4/3}$.

Such a dependence of the high-frequency surface resistance at $T < 3.5$°K disproves the earlier claims from [2, 4] which suggested that $R_s/R_n \sim \omega^{2/3}$. Indeed, the last relation cannot be relied on because it was obtained from measurements performed on different samples.

Figure 2 shows the ratio $(R_n - R_s)/R_n$ as a function of $\lambda^{2/3}$. The difference $R_n - R_s$ seems to vanish at $\omega_0 = 4.7 \times 10^{11}$ s^{-1} for all isotherms. This fact can be of crucial importance, since, for every superconductor, a certain critical frequency seems to exist, above which the difference between the normal and superconducting states of the material disappears. This conclusion is also supported by the fact that the frequency ω_0 extrapolated from the curves in Fig. 2 coincides with the frequency given by $\omega_k = kT_k/n$.

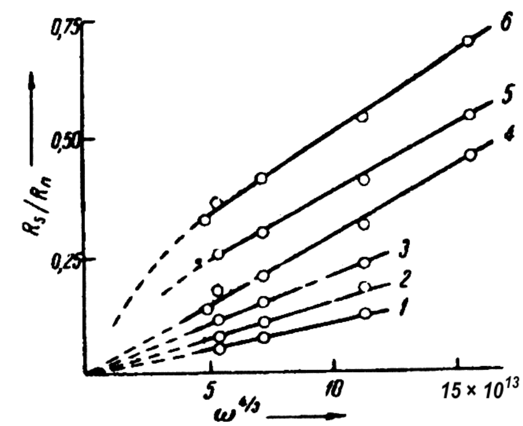

Fig. 1. *1* – T = 2.5 °K; *2* – T = 3.0 °K; *3* – T = 3.2 °K; *4* – T = 3.4 °K; *5* – T = 3.5 °K; *6* – T = 3.6 °K

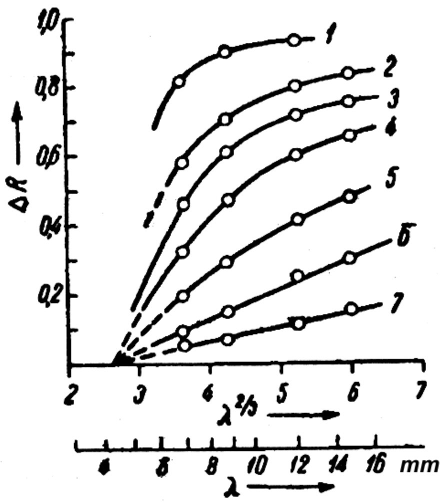

Fig. 2. *1* – $T = 3.0$ °K; *2* – $T = 3.4$ °K; *3* – $T = 3.5$ °K; *4* – $T = 3.6$ °K; *5* – $T = 3.68$ °K; *6* – $T = 3.70$ °K; *7* – $T = 3.71$ °K

The ratio R_s/R_n can be determined from the equation derived by using the results of work [1]:

$$\frac{R_s}{R_n} = \alpha\nu^{1/3}\lambda\left(\frac{\sigma_n}{l}\right)^{1/3}\frac{(3-\eta)^{1/2}}{\eta+9}\times$$

$$\times\left[\left(\frac{3}{\eta}+1\right)\sqrt{\eta}\arctan\sqrt{\eta}+\ln\frac{1+\eta}{4}\right]=$$

$$=\alpha\nu^{1/3}\lambda\left(\frac{\sigma_n}{l}\right)^{1/3}\Phi(\eta)\ . \quad (1)$$

Here, α is a numerical factor, σ_n is the metal conductivity at $T > T_k$, l is the electron mean free path, λ is the static field penetration depth in the superconductor (it is given by the formula $\lambda = \lambda_0[1-(T/T_k)^4]^{-1/2}$), and η is a parameter which can be expressed in terms of the superconductor material constants as

$$\left(\frac{\epsilon\omega^2}{c^2}\right)^3\Big/\left(\frac{\sigma_s}{l}\frac{3\pi^2\omega}{2c^2}\right)=\frac{(\eta-3)^3}{(\eta+1)^2}\ .$$

The function $\Phi(\eta)$ in Eq. (1) has a maximum at $\eta = +0.8$. Multiplying Eq. (1) by $[1-(T/T_k)^4]^{1/2}\nu^{-1/3}$, we get

$$\left\{\frac{R_s}{R_n}\left[1-\left(\frac{T}{T_k}\right)^4\right]^{1/2}\nu^{-1/3}\right\}=\alpha\lambda_0\left(\frac{\sigma_n}{l}\right)^{1/3}\Phi(\eta).\ (2)$$

This expression attains a maximum at $\eta = +0.8$ and should not depend on the frequency in the framework of the classical two-liquid model of superconductivity.

The experimentally observed frequency dependence of the quantity

$$\left\{\frac{R_s}{R_n}\left[1-\left(\frac{T}{T_k}\right)^4\right]^{1/2}\nu^{-1/3}\right\}_{\max}$$

is probably due to the growth of the effective penetration depth λ with the frequency. To achieve a satisfactory agreement between the experimental data and formula (2), one should assume that $\lambda(\omega) \sim \omega^{1/4}$ in the frequency range $(1.88 \div 4.5)\times 10^{10}$ Hz and that this dependence is even stronger at higher frequencies.

The dependence $\lambda = \lambda(\omega)$ is probably a result of the manifestation of inertial effects [7].

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1. A.A. Abrikosov, Doklady AN SSSR **86**, 43 (1952).
2. E. Maxwell, P. Marenus, and J. Slater, Phys. Rev. **76**, 1332 (1949).
3. M. Khaikin, Doklady AN SSSR **86**, 517 (1952).
4. C. Grebenkemper and J.K. Hagan, Phys. Rev. **86**, 673 (1952).
5. W. Fairbank, Phys. Rev. **76**, 1106 (1949).
6. M. Khaikin, Doklady AN SSSR **75**, 661 (1950).
7. A. Galkin and P. Bezugly, Doklady AN USSR **6**, 414 (1951).
8. A. Galkin and P. Bezugly, Doklady AN USSR, no. 2 (1954).
9. A.B. Pippard, Physica **15**, 40 (1949).

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Alexander Aleksandrovich Galkin, Corresponding (1960) and Full (1965) member of the Academy of Science of Ukraine, was born in the family of an exiled Socialist-Revolutionary Party member who lived under the police surveillance both in tsarist Russia and during the Soviet times. In 1937, his parents were executed. A.A. Galkin managed to enter Kharkiv University, where he started his scientific career as a third-year student. Then he worked at the Physico-Technical Institute of the Acad. Sci. of the UkrSSR (1937–1941, 1945–1960); later on, he became Deputy Director of the Institute of Low Temperature Physics and Engineering (1960–1965), and Director of the Donetsk Physics and Technology Institute (1965–1982). His field was the physics of solid state at extremely low temperatures, strong magnetic fields, and high pressures. In 1938, he was the first in USSR who started the microwave studies of superconductors and discovered the rectification effect in the superconducting state. In 1954, before the development of the BCS theory, A.A. Galkin made an insightful prediction of the existence of a critical frequency, above which the response of a superconducting metal does not differ from that of a normal one (the paper is presented in this issue). In fact, this was a prediction of the superconducting energy gap. Subsequently, he was working on the creation of superconductors with high critical parameters (State's Prize of Ukraine, 1982). Since 1956, A.A. Galkin intensively developed new methods of cyclotron resonance, ultrasound, radio-frequency, tunnel, NMR, AFMR, and EPR spectroscopy in the solid state. He discovered giant quantum oscillations in the electron–phonon interaction, gave the first direct proof of the existence of electronic topological transitions, and discovered, together with his collaborators, the doppleron–phonon resonance (State's Prize of Ukraine, 1980). A.A. Galkin found the intermediate state of antiferromagnets (State's Prize of Ukraine, 1971) and the process of irreversible switching to a magnetic state of matter after the application of an external magnetic field (Sinelnikov's Prize of the Acad. Sci. of Ukraine, 1975). He was a powerful figure in the scientific community, co-organized the Institute of Low Temperature Physics and Engineering, and personally organized the Donetsk Physics and Technology Institute (presently, Galkin Institute), including the experimental plant for hydraulic extrusion, where he developed the method of non-stationary extrusion.