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Impedance of superconducting tin in a magnetic field at frequencies of 300–1200 MHz

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An investigation was made of the active component of the impedance of superconducting tin at frequencies 300–1200 MHz in magnetic fields below the critical value. The field dependence of this component had an absorption maximum at $H=0$ throughout the investigated frequency range. The amplitude of the absorption maximum decreased rapidly when temperature was reduced below the critical value. The temperature dependence was anisotropic and the width of the absorption peak changed considerably when the frequency was increased. The results were analyzed on the basis of surface levels formed by normal excitations in a superconductor subjected to a magnetic field.

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INTRODUCTION

Electrons in metals may be reflected specularly from a sufficiently smooth metal–vacuum boundary and in the presence of a magnetic field they may form bound surface states known as magnetic surface levels. At microwave frequencies these bound electrons make a considerable contribution to the surface current and are responsible for the easily observed resonance spectra of magnetic surface levels.[1,2] In the rf range some of the levels are not resolved and their spectrum is quasi-continuous; in this case the contribution of surface electrons to the impedance is a peak in zero magnetic field.[3] In the superconducting state of metals there are normal electrons, which exist for $T \neq 0$, that can also form surface states in the presence of a magnetic field, as observed by Maldonado and Koch at frequencies of 10–70 GHz.[4] In the rf frequency range it is not possible to observe the contribution of normal electrons to the impedance because of the screening action of the superconducting condensate. When the frequency is increased, the contribution of normal electrons to the surface impedance increases and at frequencies exceeding 10^8 Hz it becomes possible to observe normal carriers.

Investigations of the impedance of superconductors at frequencies used in the present study were carried out by Pippard[5] and Spiewak.[6] Pippard investigated the temperature dependence of the real part of the surface impedance of tin in zero magnetic field associated with the screening action of the superconducting condensate. Spiewak studied the dependence of the surface impedance on the magnetic field but the shape of the samples and the configuration used in his work were such that it was not easy to isolate the absorption due to surface levels. We used samples prepared from pure tin and the orientation of the surface of a sample relative to static and hf magnetic fields was optimal for the observation of surface levels.

METHOD AND SAMPLES

We determined the dependence of the derivative dR/dH of tin on the magnetic field applied at 300–1200 MHz (R is the real part of the surface impedance and H is the magnetic field). A block diagram of the apparatus is shown in Fig. 1. The microwave power was generated by an oscillator and passed through a resonator to a measuring receiver. After amplification and phase-sensitive detection the signal was plotted by an X–Y recorder. The resonator was a helix made of electrical-

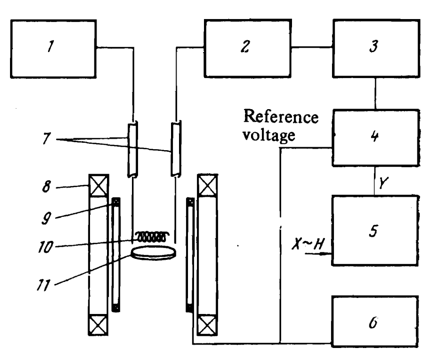

FIG. 1. Block diagram of the apparatus for investigating the dependence of dR/dH on the magnetic field in the frequency range 300–1200 MHz: 1) oscillator (300–1200 MHz); 2) receiver (200–1200 MHz); 3) amplifier (30 Hz); 4) phase-sensitive detector; 5) X–Y plotter; 6) oscillator (30 Hz); 7) coaxial lines; 8) Helmholtz coils; 9) modulation coils; 10) resonator helix; 11) sample.

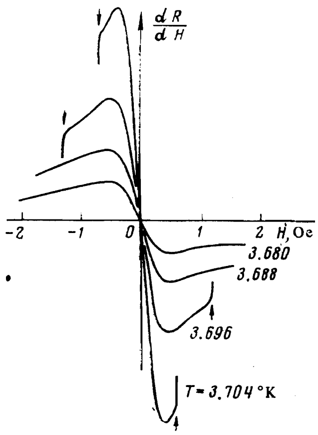

FIG. 2. Dependences of dR/dH of a cylindrical sample of tin on the magnetic field at 658 MHz. Here, H ∥ h and it is parallel to the cylinder axis.

engineering-grade aluminum wire 0.5–1 mm in diameter and 15–50 cm long, depending on the working frequency. The internal diameter of the helix was 5 mm and its length was 10–20 mm. At liquid helium temperature the Q factor of this resonator was of the order of 500.

The resonator was coupled to a coaxial line by a wire which was located inside the inner tube of the line. The coupling was varied by altering the distance from the end of the wire to the end of the helix. Single-crystal samples of tin were cylinders or disks with the resistivity ratio $\rho_{300}/\rho_{4.2} \sim 40\,000$.

The angle between the fourfold axis and the axis of the cylindrical sample was 36°, and the angle between the twofold axis and the projection of the cylinder axis onto the (001) plane was 40°. The diameter of the cylinder was 3.4 mm and its length was 30 mm. Three disks, 18 mm in diameter and 0.5 mm thick, had the [001], [100], and [110] axes oriented along the normal to the disk. The cylindrical sample was located inside a helix ~20 mm long, whereas the disks were placed alongside a helix ~10 mm long leaving a gap of ~0.3 mm between the disk and the helix. In this way only the central parts of the samples were coupled to the helix and the edge effects could be ignored.

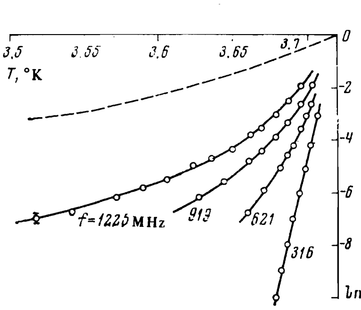

FIG. 3. Temperature dependences of the amplitude of the dR/dH peak of a cylindrical sample at four frequencies. The ordinate is the natural logarithm of $A = dR(H_0)/dH - dR(0)/dH$, where H_0 is the position of the dR/dH maximum. The dashed curve is the dependence $R_S(T)/R_N(T_c)$ obtained by Pippard[5] at 1200 MHz.

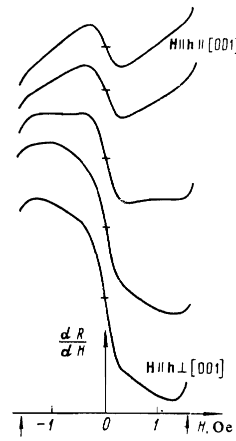

FIG. 4. Profile of the dependence of dR/dH on H obtained for various angles between H and the [001] direction. A sample in the form of a disk with n ∥ [110] was rotated through 22.5°; $T = 3.696$ °K, $f = 485$ MHz. The curves are shifted along the vertical axis.

EXPERIMENTAL RESULTS

Figure 2 shows the magnetic field dependences of dR/dH determined experimentally for a cylindrical sample. In this case the fields were parallel (H ∥ h) and detected along the axis of the sample (h was the microwave magnetic field in the resonator).

It is clear from Fig. 2 that the amplitude of the peak in the dependence of dR/dH on H varied strongly with temperature but the line profile was practically unaffected. The constancy of the profile enabled us to associate the amplitude of the dR/dH peak with the amplitude of the change in R. The arrows were used in Fig. 2 to indicate the onset of the transition of the sample to the normal state.

The temperature dependences of the amplitude of the dR/dH peak are plotted in Fig. 3. A sample was placed in a helix whose resonance frequency was 316 MHz. The experimental results were obtained at the fundamental and higher harmonics of the resonator. Since the fill factor of the resonator for a cylindrical sample inside the helix was greater than for a disk, the temperature dependence could be determined in a wider range for the cylinder. This was why the samples used in this determination were cylindrical. The anisotropy of the effect was studied using disks which could be rotated about their axes.

In the case of the sample with the [001] ∥ n axis (n is the normal to the plane of the disk) the profile of the dR/dH peak and the temperature dependence of its amplitude were practically independent of the orientation of a sample relative to the field H. In the case of the samples with the normals along the [100] and [110] axes there was a strong dependence of the dR/dH profile on the angle between the magnetic field and the [001] axis.

Figure 4 shows a family of curves obtained for a sample with [110] ∥ n for various angles between the magnetic field and the [001] axis. It is clear from Fig. 4 that rotation of the sample from [001] ∥ H to [001] ⊥ H broadened the curve considerably. For the last two curves the profile was distorted by the transition to the normal state. Figure 5 gives the temperature dependences of the amplitude of the dR/dH peak of a sample with [110] ∥ n for three angles between the magnetic field

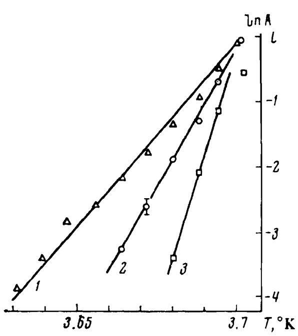

FIG. 5. Anisotropy of the temperature dependence of the amplitude of the dR/dH peak of a disk with n ∥ [110]: 1) H ∥ [001]; 2) angle between H and [001] equal to 45°; 3) H ⊥ [001].

and the [001] axis.

An investigation of the impedance at various frequencies demonstrated that the width of the absorption curve (half the distance between the maxima of the dR/dH derivative) was a function of the frequency. This function was determined for a cylindrical sample in a multimode helical resonator. The results were obtained in one experiment without any movement of the sample. The results of such an experiment are plotted in Fig. 6.

One should compare also the results obtained for superconducting and normal states of the samples. In the normal state the position of the dR/dH maximum varied from sample to sample, which could possibly be due to the quality of the samples, and it was not greatly affected by variations of the frequency (Fig. 6), whereas in the superconducting state the position of the dR/dH peak was practically the same for the various samples which we investigated (allowing for the anisotropy) but it depended strongly on the working frequency. On the other hand, the absorption curves obtained in the normal state were somewhat more complex: the absorption maximum in zero field was usually split in the range of frequencies under investigation. This splitting increased with rising frequency for planar samples and decreased for cylindrical ones. Therefore, it would be premature to draw conclusions from this comparison.

DISCUSSION OF RESULTS

The temperature dependence of the amplitude of the dR/dH peak is affected strongly by two factors. The first is that cooling from T_c reduces the density of normal electrons and increases the density of superconducting carriers. This reduces the normal component of the total microwave current because of the reduction in the microwave electric field acting on the normal electrons, which is inversely proportional to the density of the superconducting electrons, and due to reduction in the density of the normal electrons. Consequently, the real part of the surface impedance decreases. The mechanism of this reduction in the impedance was discussed by Pippard. The contribution to the active component of the impedance due to the surface levels should behave in the same way if the number of such levels does not vary with temperature.

The second factor influencing the temperature dependence of the peak amplitude is the change in the number of surface levels when the depth of penetration λ of the magnetic field into the superconductor decreases as a result of cooling from T_c. In fact, we have $\lambda = \lambda_0(1 - t)^{-1/2}$, where λ_0 is the depth of penetration at $T = 0$ and $t = T/T_c$ is the relative temperature. In the normal state the surface electrons are in an effective potential field $V \propto Hz$, where z is the distance from the surface of the metal and the depth of the first level is then $z_1 \approx 3\times10^{-5}$ cm in a field $H \sim 1$ Oe.

In the superconducting state the potential is $V \propto \lambda H e^{-z/\lambda}$.[7] This potential is equivalent to that of the normal metal in the limit $T \to T_c$, when λ exceeds the skin depth of a normal metal subjected to an electromagnetic field in impedance studies. In this case the observed spectrum should consist of a large number of levels, which corresponds to the normal state (see Prange and Nee[2]). When temperature is reduced from superconducting transition, the depth of penetration of the magnetic field λ becomes much smaller than z_1. In this situation there is only one surface level in the superconductor. In the presence of just one level, which is true at low temperatures, the temperature dependence is governed by the first factor, i.e., by the density of the normal electrons and by the shunting action of the superconducting electrons.

It is clear from Fig. 3 that the slope of the curve corresponding to 1225 MHz approaches at low temperatures the slope $R(T)$ (dashed curve) obtained by Pippard. On approach to T_c, the value of dR/dH is dominated by the second factor, i.e., by the increase in the number of the surface levels on transition from the superconducting case ($\lambda < z_1$) to the normal state ($\lambda > \delta$), where δ is the depth of the skin layer, which indeed corresponds to a steeper temperature dependence of dR/dH compared with the dashed curve in Fig. 3 in the limit $T \to T_c$.

We shall assume that if λ becomes less than z_n, where z_n is the depth of the n-th level, then this level disappears. The value of z_n is a function of the effective mass of the electrons which form the level. The temperatures at which the depth of penetration becomes comparable with z_n and below which the n-th level disappears vary with the effective masses. This gives rise to different temperature dependences for different crystallographic orientations of the surface of the sample and direction of the magnetic field. It can be used to

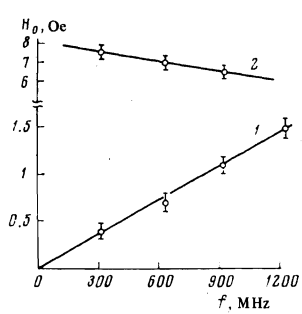

FIG. 6. Frequency dependences of the position of the dR/dH maximum on the magnetic field axis plotted for a cylindrical sample: 1) $T = 3.68$ °K, superconducting state; 2) $T = 3.73$ °K, normal state.

explain the anisotropy of the temperature dependences. Since the inequality $\omega\tau \gg 1$ is not satisfied in the investigated range of frequencies, some of the surface levels are not resolved in the impedance measurements and, therefore, the anisotropy data are only qualitative. At higher frequencies this range of temperatures cannot be investigated because the critical magnetic field is too low.[4]

The investigated singularity of the impedance appears in zero magnetic field due to magnetic surface levels and the width of the integrated absorption curve may be governed by two effects. If there are many unresolved levels and the width of a single level governed by the collision frequency is greater than the magnetic field interval in which the levels are located, the total width of the absorption peak is governed by the collision frequency and is independent of the observation frequency, as found by Sibbald *et al.*[3] In the second case the magnetic field interval within which the levels are located is greater than the width of an individual level. Then, the width of an absorption peak is governed by the resonance field of the lowest-energy level and depends on the frequency at which impedance is observed. It is clear from Fig. 6 that the second case applies to our investigation.

The width of the absorption peak was measured in the range of temperatures corresponding to rapid variation of dR/dH. It follows from our discussion that in this range there are several magnetic surface levels. We can then apply the treatment of the surface levels in normal metals. An analysis of the results on the basis of the dependences $\omega \propto H^{2/3}$[2] is found to be in good agreement with the experimental data and extrapolation to zero frequency gives the average collision frequency of ~200 MHz for the investigated cylindrical sample. A similar absorption maximum in zero magnetic field is also observed in superconducting indium.

Thus, the singularity of the impedance of superconducting tin observed in the present study is due to normal excitations forming surface levels, whose number decreases with decreasing depth of penetration of the magnetic field.

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The thermoelectric field in superconductors

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The possibility of the appearance and measurement of a thermoelectric field E in a superconductor S is discussed theoretically. An equation is derived which describes the coordinate dependence of the field E in a superconductor with a nonzero energy gap. It is shown that the characteristic scale of the spatial variation of E is the distance l_b over which equilibrium is established between the branches of the energy spectrum and which, in pure superconductors, greatly exceeds the correlation length $\xi(T)$. It is shown that the field E arises in the presence of a temperature gradient near the boundary between S and a dielectric, a normal metal, or another superconductor, and falls off in S exponentially over the distance l_b.

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INTRODUCTION

The thermoelectric effect in homogeneous isotropic superconductors consists in the fact that in the presence in a superconductor of a temperature gradient T_x' there arises a thermocurrent $\beta T_x'$, which in an open sample is balanced by the superconducting current $e^* n_s v_s$.[1] Thus, the total current

$$j=\beta T_x'+e^* n_s v_s$$

is equal to zero, and so is the electric field.[1)]

Another picture arises if the superconductor is inhomogeneous in the direction of the temperature gradient, as when it borders on a dielectric D, a normal metal N, or another superconductor $\tilde{S}$ in which $\tilde{\beta} \neq \beta$. Then there arises near the boundary a quasiparticle-current divergence ($\operatorname{div} \mathbf{j}_n \neq 0$), since $\mathbf{j}_n = 0$ in D and N, and $\mathbf{j}_n \neq \tilde{\mathbf{j}}_n$ in the $S-\tilde{S}$ system. It has previously been shown on the basis of phenomenological equation[6,7] and equations obtained from a microscopic theory and valid for gapless superconductors with paramagnetic impurities[8] that in the presence of a nonzero divergence of $\mathbf{j}_n$ (or,

