Anomalous impedance of a superconductor in the resistive state caused by microwave irradiation

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The frequency dependence of the impedance of a thin superconducting film in the resistive state, which is produced by microwave irradiation, was investigated. It is shown that at frequencies $f \lesssim 300$ MHz the impedance of the resistive state exceeds that of the normal state.

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It was shown in previous papers[1,2] that a thin superconductor film, which is placed in a constant magnetic field parallel to its surface, enters the resistive state when a certain critical microwave irradiation power is reached. This transition is evident in the form of an abrupt jump in the resistive component of the film impedance. A broad resistive region of irradiation power and of magnetic field was observed after the jump, and the impedance of the resistive state was always less than that of the film in the normal state at the frequencies used in Refs. 1 and 2.

Our investigation was performed in order to investigate certain properties of the observed state of the superconductor, in particular its reaction to a weak, electromagnetic field with a frequency different from the irradiation frequency. We studied aluminum films with a thickness of about 700 Å, which were vacuum-deposited on glass or silicon substrates. The strong microwave field was produced by means of a helical coil, which was placed on the substrate parallel to the film. To prevent the influence of the microwave field at the film edges that were usually imperfect, a copper shield with a 3-mm-diam diaphragm was placed between the substrate and the helix; typical film dimensions were approximately 1×1 cm^2. The gap between the helix and the film surface was about 2 mm. More detailed information about the design of the irradiation unit is given in Ref. 2. A helical coil, which was used to measure the impedance, was placed on the opposite side of the film parallel to the latter. A variable capacitance connected in parallel with the coil made it possible to vary the frequency of this resonant loop from 150 to 750 MHz. To avoid a possible influence of the irradiation field inhomogeneities at the diaphragm edges, a second copper shield with a 2-mm-diam diaphragm was placed between the measuring coil and the film. The centers of the diaphragms in both shields were on the same axis, and their planes were parallel, so that we were actually measuring the impedance of the film at the center of the spot being irradiated. The power supplied to the measuring coil was much less than that supplied to the irradiation coil, which did not exceed 10^{-2} W. The microwave magnetic fields of both coils were parallel to each other and to the external constant magnetic field. The entire assembly described above was placed in a container of superfluid helium.

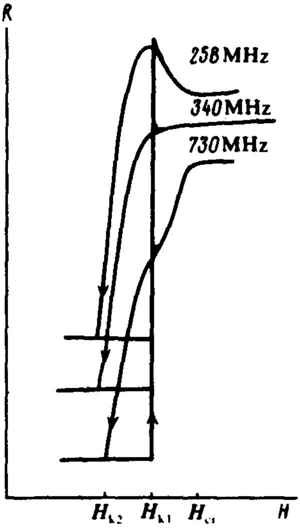

FIG. 1. Dependences of the resistive component of the surface impedance of an aluminum film with $T_c = 1.50$ K on the magnetic field at $T = 1.27$ K. The frequency of the microwave irradiation is 400 MHz. The curves are plotted along the Y axis.

The experiment was conducted in the following manner at a fixed temperature and irradiation power, and the dependence of the variation of the power transmitted through the measuring coil on the external magnetic field was recorded. In the absence of dispersion, this power variation is proportional to the variation of the resistive component of the film impedance, since the cavity parameters are independent of the magnetic field. To eliminate dispersion, the oscillator was tuned to the resonance frequency of the loop at each value of the magnetic field. Figure 1 is an example of a trace of the dependence of the resistive component of the film impedance of the magnetic field for several frequencies for irradiation at a frequency of 400 MHz. We can see that an impedance jump occurs at a certain magnetic field H_{c1}, in accordance with the results of Refs. 1 and 2. If the measurement frequency is sufficiently high, then the impedance variation will match that described in Refs. 1 and 2, i.e., the impedance after the jump is smaller than the impedance of the normal state of the film, increases smoothly with increasing magnetic field, and reaches the level of the normal state in a field equal to the parallel critical field H_c. As the measurement frequency decreases, however, the size of the jump increases, and beginning with some characteristic frequency a sudden jump occurs to a state with an impedance that is greater than that of the normal state. The magnetic-field dependence of the impedance now has the form of a curve with a maximum, whose location may not necessarily coincide with the field H_{c1}. The impedance in the field H_c again is equal to that of the normal metal. The observed anomalous impedance increases with decreasing measuring frequency. Figure 2 shows the frequency dependence of the quantity $R_{\text{jump}}/(R_N - R_S)$, where R_{jump} is the amplitude of the jump, R_N is the impedance of the normal state, and R_S is the impedance of the superconducting state in the field H_{c1}. The solid circles correspond

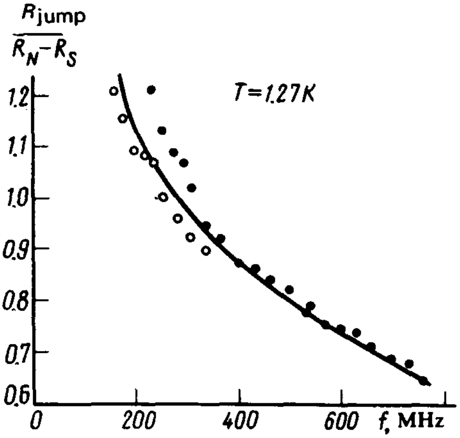

FIG. 2. Dependences of the resistive component of the surface impedance of an aluminum film at a frequency of 169 MHz on the magnetic field for two irradiation powers P at a frequency of 700 MHz.

to an irradiation frequency of 400 MHz and to the power at which $H_{c1}/H_c = 0.78$, and the open circles were obtained using another sample at 700-MHz irradiation frequency and $H_{c1}/H_c = 0.83$. The characteristic frequency at which the impedance of the resistive state begins to exceed the impedance of the normal metal changes slightly from sample to sample but always remains around 300 MHz. Unfortunately, thus far we have been unable to investigate the frequency range below 100 MHz; therefore, we cannot say whether the anomalous impedance will continue to increase or reach saturation, or whether it will have the shape of a curve with a maximum. We performed experiments using primarily three irradiation frequencies—400, 700, and 1000 MHz. The qualitative picture of the effects described above is the same. It is important that if the irradiation frequency is less than the characteristic frequency, then the impedance measured at the irradiation frequency will have an anomalous maximum. Therefore, we can state that the anomalous behavior of the impedance in the resistive state is not related to the fact that two electromagnetic waves with different frequencies are acting on the superconductor.

Figure 3 shows traces of the resistive component of the film impedance at a frequency of 169 MHz for irradiation at a frequency of 700 MHz for two irradiation powers. As the irradiation power increases, the maximum impedance in the resistive state increases and saturates. However, the dome-shaped curve is broadened because the jump field and the field H_{c2} at which superconductivity is restored decrease. Note that even in the absence of high-power irradiation, the impedance near the phase-transition point H_c has an anomalous maximum. This maximum is present only when the measurement frequency is lower than the characteristic frequency. We observed it without high-power irradiation and without a magnetic field but in a close proximity of another phase-transition point T_c.

The question of absorption of electromagnetic radiation by a superconductor, which is larger than that of a normal metal, was raised long time ago. This absorption can be observed on the experimental curves[3–5] near the field H_{c2} in the mixed state of

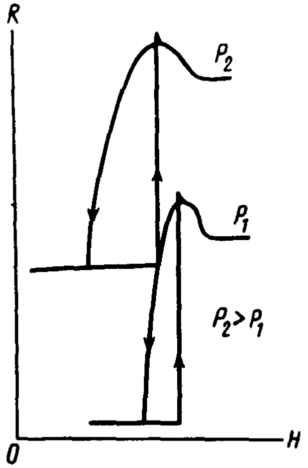

FIG. 3. Frequency dependence of $R_{\text{jump}}/(R_N-R_S)$ for two samples: •, 400-MHz irradiation frequency; °, 700-MHz. The irradiation powers are approximately the same.

the superconductors. It is unclear, however, whether these curves contain a dispersion impurity, which is very important. We observed an anomalous impedance maximum in the vortex state near the field H_{c2} when the magnetic field forms a small angle (up to $\sim 7°$) with the film surface without high-power irradiation. Since these results will be discussed in detail at a later time, we note only that the amplitude of the impedance maximum in this case is of the same order of magnitude as in the resistive state. We can, therefore, assume that the resistive state has a finely dispersed structure like the mixed state of a thin film.

An excess absorption was also observed in the region of surface superconductivity (see, for example, Ref. 6). A characteristic feature in this case was the dependence of the absorption on the relative orientation of the microwave electric vector and on the external constant magnetic field. We did not observe such a dependence in the resistive state.

It can be concluded from the foregoing discussion that the excess absorption occurring near the critical points of the superconductor may be due to the appearance of an inhomogeneous state in the superconductor, which is induced in some cases by a magnetic field and in others by microwave irradiation.

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