Impedance of a type-II superconductor with a surface superconductivity

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The surface impedance of a type-II superconductor with a surface superconductivity was studied experimentally. Small changes in the external magnetic field lead to a nonmonotonic behavior of the surface impedance. A qualitative model is proposed for the observed effect.

The impedance of type-II superconductors at $T<T_c$ and $H_{c2}<H<H_{c3}$ was studied in the late 1960s. Rothwarf *et al.*[1] worked from a numerical solution of the Ginzburg–Landau equation[2] and from the assumption of a uniform order parameter to propose a simple model for the behavior of the impedance, in particular, as a function of an external magnetic field. The experimental results found for a Pb–In alloy turned out to agree well with the model-based predictions.[1] We have returned to this question now because the sensitivity of the apparatus has been improved substantially by the use of computers and by the particular geometry which we have used. Our

results are quite different from those in the literature. In this letter we wish to call attention to these new features of the impedance.

The test sample was a cylinder of $Pb_{0.8}In_{0.2}$ with a diameter of 3.5 mm and a length of 30 mm. The real part of the surface impedance was measured at a frequency of about 400 MHz. The absorbing cell was a coil resonator wound tightly around the sample. This resonator was made of copper wire 0.2 mm in diameter. The resonator was excited in its fundamental mode; i.e., the length of the spiral was half the wavelength of the electromagnetic radiation. The capacitive coupling with the resonator was arranged by bringing the central conductors of coaxial cables close to the ends of the coil. The rf power was supplied by one of these cables; the other picked up a voltage and sent it to a receiver. Small changes in the measured signal are proportional to the change in the active part of the impedance.

A static magnetic field (the "driving field") was produced by an electromagnet and monitored by a Hall pickup. A slowly varying magnetic field (the "scanning field") was produced by a solenoid with $\simeq 100$ turns of copper wire 0.5 mm in diameter. This solenoid was fed a sawtooth current with a frequency varied over the range 0.05–80 Hz.

Preliminary measurements showed that in the case of a surface superconductivity (at a driving field $H > H_{c2} \approx 3.5$ kOe) the impedance increased significantly when a scanning field of low amplitude ($\leqslant 1$ Oe) was applied. To study the "fine structure" of the effect, we fed the measured signal to a personal computer synchronized with the power supply of the solenoid. This arrangement was necessary because in the case of small changes in the magnetic field the signals were on the order of the noise of the input circuits of the receiver; it was necessary to build the signal up over a number of passes, ranging into the tens of thousands.

Figure 1 shows some representative results. Here are the basic features of the observed curves as a function of the external parameters.

1. As the driving field is raised, the amplitude of the features at the edges of the scan decreases. At fields near H_{c3}, these curves become triangles, while above H_{c3} they degenerate into a horizontal straight line.

2. As the frequency of the scanning field is varied over the range 0.05–80 Hz, the curves remain qualitatively the same as in Fig. 1. A quantitative analysis shows that the details of the curves do depend on the frequency, but we do not have room here to discuss that question, which goes beyond the scope of the present letter.

3. Figure 1 shows the behavior of the real part of the surface impedance in a magnetic field for various amplitudes of the scanning field. Note that at amplitudes below a certain value the situation is such that the impedance increases with decreasing field (the lower curve in Fig. 1).

To explain these results, we consider a simple model based on two assumptions. First, the relative volume of the sample occupied by the superconducting region depends on the strength of the undamped current flowing through the sample. In other words, the spatial distribution of the order parameter is a function of the superconducting current. Second, small changes in the external field are accompanied by a

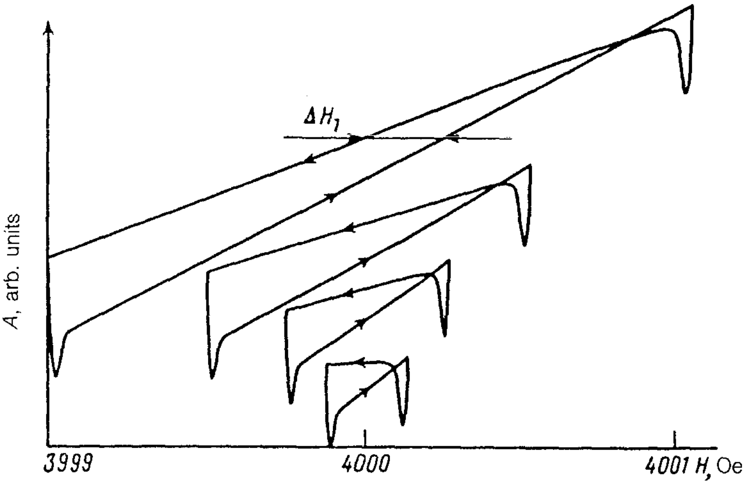

FIG. 1. Real part of the surface impedance versus the external magnetic field for various scanning amplitudes. The scanning direction is shown by the arrows. The curves have been displaced vertically for clarity.

partial screening of the field in the interior of the sample. (This assumption is discussed below.) As the external field H_0 is increased, the field inside the sample, H_{in}, is then of such a magnitude that the relation $H_0 - H_{in} = \Delta H > 0$ holds. The superconducting current density at the surface is equal to the critical value. The situation is illustrated by the schematic diagram in Fig. 2b. Upon a change in the direction in which H_0 is scanned, the abrupt field change ΔH decreases, and at $H_0 = H_{in}$ we find $\Delta H = 0$. This situation corresponds to a minimum of the impedance, since the density of the screening superconducting current is zero in this case. This process is illustrated by the model field dependence of the impedance in Fig. 2a (region *ab*). The difference $H_a - H_b$ corresponds to the abrupt field change ΔH. With a further decrease in H_0, the superconducting current density increases. This increase corresponds to an increase in the impedance. At point *c* (Fig. 2a) we have $|\Delta H| = \max$; i.e., the screening current density reaches the critical value. Coming next on the model curve in Fig. 2a is the "linear" region *cd*. The final slope here is governed by the dependence of the impedance on the external magnetic field. Region *def* is analogous to region *abc*. Finally, we have linear region *fa*, with a slope different from that of region *cd*. The reason for the difference is as follows: In the model which we are using, the impedance in the case of increasing H_0 is equal to the impedance in the case of decreasing H_0 if and only if the abrupt field change $\Delta H > 0$ becomes equal in absolute value to the abrupt change $\Delta H < 0$. This situation is shown in Fig. 2, b and c. The horizontal distance between the linear regions on the model curve thus gives the functional dependence $\Delta H(H_0)$. It follows that lines *dc* and *fa* should intersect at the field H_{c3}, where $\Delta H = 0$.

Comparing the experimental curves (Fig. 1) with the model curve (Fig. 2a), we

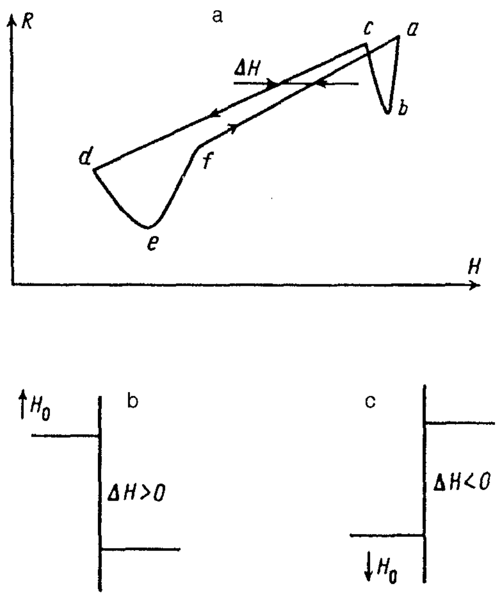

FIG. 2. a: Model plot of the impedance as a function of the magnetic field. b,c: The abrupt field change ΔH upon an increase in the external magnetic field (region *fa*) and upon a decrease in this external (*cd*), respectively.

conclude that there is only a qualitative agreement. A particularly significant result is that the angle between the linear regions of the impedance is far greater than the predicted angle. In other words, the value of ΔH_1, found from the horizontal cross section of the experimental curve, is larger than the value of ΔH found from the half-width of the structural feature at the edge of the scan (Fig. 1). The model thus needs some substantial refinement.

The model outlined above assumes that the spatial distribution of the order parameter $|\psi|^2$ is independent of the sign of ΔH. However, we know quite well that the condition imposed on the order parameter at the superconductor–vacuum interface is

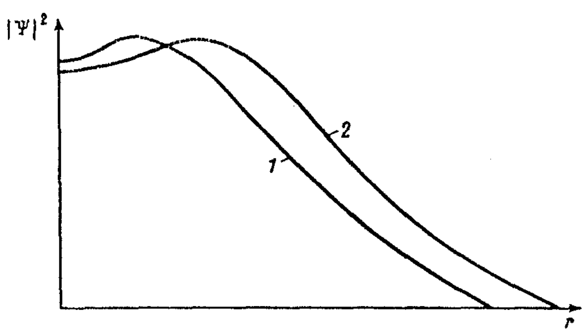

FIG. 3. Schematic diagram of the spatial profile of the order parameter along the normal to the surface. 1—$\Delta H < 0$; 2—$\Delta H > 0$.

$\partial\psi/\partial x = 0$. In the case of an interface between a superconductor and a normal metal, we would have $\psi = 0$. It can thus be assumed that in this case the asymmetry in the boundary conditions leads to an asymmetry in the spatial distribution of the order parameter with respect to the sign of ΔH. This situation is illustrated in a qualitative way in Fig. 3. As the sign of ΔH changes from positive (curve 2 in Fig. 3) to negative (curve 1), the width of the superconducting region in the sample decreases, because of a suppression of superconductivity at the superconductor–(normal metal) interface. The result is a further increase in the impedance.

We conclude with a few words about the assumptions which we have used in explaining the experimental results. We regard the first of our assumptions as quite natural. With regard to the second assumption, the question is more complicated. In the case of a surface superconductivity in the equilibrium state, undamped currents cannot screen the field in the interior of the sample.[3] In other words, the resultant current in the surface layer is zero. This is the situation most favorable from the energy standpoint. We believe that the equilibrium condition does not hold for the times involved in these experiments, that the screening current does not decay, and that this current has a significant effect on the spatial distribution of the order parameter and therefore on the magnitude of the surface impedance.

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[2]H. J. Fink and R. D. Kessenger, Phys. Rev. A **140**, 1937 (1965).
[3]A. A. Abrikosov, *Fundamentals of the Theory of Metals*, Elsevier, New York, 1988.

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