Frequency dependence of the surface impedance of mixed-state type-II superconductors

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The frequency dependence of the real part of the surface impedance $R(\omega)$ of type-II superconductors with a small bulk pinning has been studied experimentally in an external magnetic field $H_{c1} < H < H_{c2}$ in a perpendicular geometry. The change in the functional dependence $R(\omega)$ as a result of increasing the number of defects at the surface of a mixed-state superconductor has been observed for the first time. Experimental results have shown that this change is linked with the dynamics of the vortex lattice. The results obtained experimentally are qualitatively compared with the existing theoretical models.

The real part of the surface impedance of type-II superconductors was calculated in a review article by Gor'kov and Kopnin.[1] When a type-II superconductor is in the resistive state, i.e., when the bulk pinning is negligible, the surface resistance of the superconductor is equal, in the small-frequency limit, to the surface resistance of the normal metal, whose conductivity is equal to the flux-flow conductivity σ_f. Since the skin penetration depth of the electromagnetic field at low frequencies is much greater than the London penetration depth (λ_L), it is quite justifiable to ignore terms on the order of $(\lambda_L)^2$ in the calculations.[1]

Sonin *et al.*[2] have calculated the surface impedance of a superconductor in the mixed state, ignoring the small term λ_L. The most surprising result,[2] from our viewpoint, is that the frequency dependence of the surface impedance can change in the low-frequency limit. It was found that if the external magnetic field is perpendicular to the surface of the sample, pinning at the surface plays an important role. Sonin *et al.*[2] obtained, in the low-frequency limit, the following expression for the case in which the pinning at the surface is strong:

$$R = [2\pi\mu\omega^3/\sigma_f(c\omega_c)^2]^{1/2}, \tag{1}$$

where ω_c is a constant. An increase in the surface pinning (in the case of small bulk pinning) thus causes the frequency dependence $R \propto \omega^{1/2}$ to change to $R \propto \omega^{3/2}$.

In the present letter we report the first experimental verification of the results obtained by Sonin *et al.*[2]

The test sample, made from a $Pb_{0.8}In_{0.2}$ alloy, is a rectangular slab 15×30 mm in size and 1.5 mm thick. The choice of the alloy was based on satisfying the conditions that the material would have a small bulk pinning[3] and that it would be relatively simple to fabricate the samples. We used a polished mold to obtain a slab with a flat, mirror-smooth surface.

As the absorbing cell we used a spiral resonator 15 mm long and 4 mm in diameter, made from a copper wire 0.3 mm in diameter. The resonance frequency of this resonator was ~ 170 MHz. The resonator was coupled capacitively by means of coaxial lines connected to its ends. One coaxial line supplied rf power to the resonator and the voltage supplied by the second line was measured with a narrow-band detector, whose signal was stored in a personal computer. The external magnetic field was set by an electromagnet and monitored by a Hall sensor. The resonator was placed above the sample in such a way that its Q-factor would change by no more that 10% in the field range $0 \leqslant H \leqslant H_{c2}$.

We have thus obtained a plot of the change in the real part of the surface impedance as a function of the external magnetic field. These measurements were generally carried out at five frequencies corresponding to the resonant modes of the spiral resonator.

In the analysis of the experimental data we made the following assumptions. First, the sample's impedance in the normal state is proportional to $\omega^{1/2}$. Secondly, since the frequencies used in the experiment are much lower than the decoupling frequency, we set the zero-field impedance equal to zero. The field dependences of the real part of the impedance, which were normalized as discussed above, are shown in Fig. 1. Also shown in this figure is the field dependence of the impedance in a parallel field (the lower curve). We clearly see that the losses in the region of interest to us are smaller, by more than an order of magnitude, than those in the case in which the field is perpendicular to the surface of the sample. Such a ratio holds for all of the samples

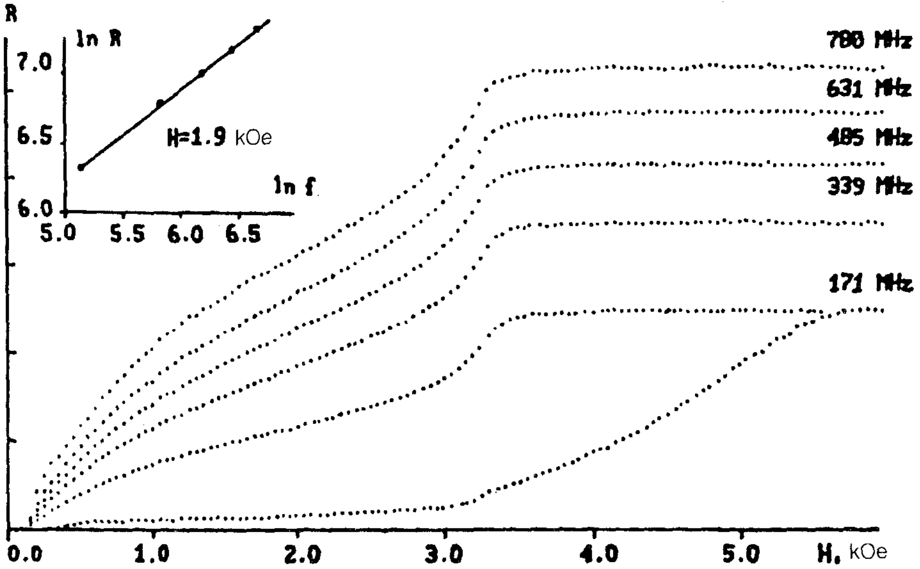

FIG. 1. Field dependence of the real part of the impedance at various rf bombardment frequencies. Lower curve—External magnetic field is parallel to the surface of the sample; the remaining curves were measured in a perpendicular field. Inset—Logarithmic plot of the impedance versus the frequency.

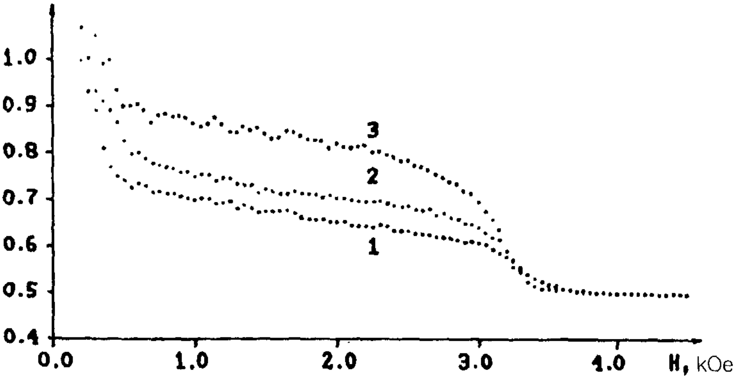

FIG. 2. The exponent n of the frequency dependence of the impedance plotted as a function of the magnetic field (curve 1—no bombardment; 2—ion flux of 10^{16} ions/cm^2; flux of 10^{17} ions/cm^2).

at all frequencies used in the experiment. It can thus be concluded that the loss mechanisms which are not linked with the dynamics of the vortex lattice in a perpendicular geometry need not be considered in the evaluation of the results.

The frequency dependence of the impedance in fields $H_{c1} \leqslant H \leqslant H_{c2}$ was reconstructed from the curves shown in Fig. 1. The $R(\omega)$ points on the log plot fit the straight line nearly in the entire interval (except in the fields near H_{c1}). Such an example is shown in the inset in Fig. 1.

To change the number of defects at the surface, we bombarded the samples with 1-keV oxygen ions, which corresponds in the material to an average ion range profile of a few tens of angstroms. Measurements similar to those described above were then carried out for samples bombarded by a flux of 10^{16} ions/cm^2 and 10^{17} ions/cm^2.

A logarithmic plot of $R(\omega)$, constructed for the bombarded samples, showed a good fit of the points, as in the case of the plot in the inset in Fig. 1. The slope of this straight line determines the power n of the frequency dependence of the real part of the surface impedance. The field dependence of n for the samples that were bombarded and for those that were not bombarded is shown in Fig. 2. The results show that the power of the frequency dependence $R(\omega)$ increases appreciably with increasing number of defects at the surface. This result is in qualitative agreement with the model-based predictions.[2]

It is interesting to note that $n > 1/2$ even for a sample which has not been bombarded. We attribute this behavior to the presence of a residual pinning in the bulk of the sample or at its surface. The presence of this pinning would qualitatively explain the field dependence of n. In low fields, the incipient vortices are, in fact, pinned at the pinning centers. The relative number of free vortices increases with increasing field. This behavior accounts for the decrease in n as the field is increased (Fig. 2).

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