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AC conductivity of a niobium single crystal in a swept magnetic field

M.I. Tsindlekht [a,*], V.M. Genkin [a], G.I. Leviev [a], Y. Schlussel [a], V.A. Tulin [b], V.A. Berezin [b]

[a] The Racah Institute of Physics, The Hebrew University of Jerusalem, 91904 Jerusalem, Israel
[b] Institute of Microelectronics Technology and High Purity Materials RAS, Institutskaja St. 6, 142432 Chernogolovka, Moscow Reg., Russia

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ABSTRACT

We report results of experimental studies of the ac susceptibility of a Nb single crystal at low frequencies in swept magnetic fields applied parallel to the surface. Analysis of the experimental data shows that the swept magnetic field significantly changes the bulk conductivity for $H_{c1} < H_0 < H_{c2}$. It becomes dissipative with substantial frequency dispersion. At the surface, a layer with enhanced conductivity in comparison to the bulk was detected for $H_{c1} < H_0 < H_{c2}$. This layer provides a considerable contribution to the shielding and absorption of the ac field even in the mixed state. There is anomaly of an ac susceptibility in the field near the transition between Abrikosov's phase and surface superconducting states. Conductivity of the surface layer in large dc fields $H_{c2} < H_0 < H_{c3}$, measured in point-by-point mode, and in a swept field is unexpectedly small in spite of the large value of the order parameter near the surface. We demonstrate that the swept magnetic field affects the ac response of the surface superconducting states.

1. Introduction

The first measurements of an ac response of superconductors in a swept magnetic field were performed by Strongin et al. in 1964 [1]. This experiment demonstrated a qualitative difference between the results of measurements in fixed and swept dc fields. In a fixed dc field, when the dc field is kept constant during the actual measurement, the complete shielding of the ac field was observed for $H_0 < H_{c2}$ while in a swept dc field an incomplete shielding was detected already at $H_0 > H_{c1}$. Two years later Maxwell and Robbins [2] noted that within a factor of two, the ac susceptibilities χ' and χ'' in the mixed state are a function of the parameter $q = \dot{H}_0/\omega h_0$, where ω is the frequency, h_0 is the ac amplitude, and $\dot{H}_0$ is the dc magnetic field sweep rate. Later Schwartz and Maxwell [3] proposed the explanation of this experimental result. They assumed that if an instant value of the applied field $H(t) = H_0 + \dot{H}_0 t + h_0 \sin(\omega t)$ begins to decrease, $q < 1$, the magnetization of the sample follows a diamagnetic line $dM/dH_0 = -1/4\pi$. In increasing fields $H(t)$ dM/dH_0 remains equal $-1/4\pi$ until $H(t)$ reaches its previous value [4]. During the remaining part of the ac cycle the magnetization follows an ascending branch of the magnetization curve until $H(t)$ begins to decrease again. This static model provided fair agreement with the experimental results of Ref. [2]. Essentially the same ideas were used by Fink [5] when he proposed a model for calculation of the ac susceptibility in the surface superconducting states [6], for $H_0 > H_{c2}$. In addition to parameter q Fink's model has a new dimensionless parameter h_c/h_0 where $h_c = 4\pi J_c/c$ and $J_c(H_0)$ is the surface critical current. The nonlinear response in the swept magnetic field was studied by authors of Ref. [7] considerably later. It was found that the signal at the second harmonic appeared in a swept field while it was not observed in a constant field.

In this paper we report the first measurements of the bulk ac conductivity in a swept magnetic field in the mixed state of a type-II superconductor. All previous studies concerned only the measurement of an ac magnetic susceptibility and did not report the conductivity data. We demonstrate in this work that the connection between the observed susceptibility and the bulk conductivity is not simple. We observed that in the mixed state at the surface there is a layer with enhanced conductivity. The conductivity of this layer has both dissipative and nondissipative components, while the bulk conductivity has actually dissipative component only. Substantial frequency dispersion was observed. In high magnetic fields, when the sample is in the surface superconducting state, i.e. for $H_{c2} < H_0 < H_{c3}$, the swept magnetic field affects the ac response significantly.

2. Experimental details

The ac response was measured with the pick-up coil method [8]. The sample, with sizes 1 by 2.4 by 10 mm, was electrochemically polished and then annealed at 1500 C in oil less vacuum. The sample was inserted into one of a balanced pair of coils, and an unbalanced signal was measured by a lock-in amplifier. The residual resistance ratio of our sample was ≈200. Measurements

* Corresponding author. Tel.: +972 26585834; fax: +972 26586347.
E-mail address: mtsindl@vms.huji.ac.il (M.I. Tsindlekht).

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were performed over a considerably wide range of frequencies (73–1465 Hz), sweep rates (5–30 Oe/s), and ac amplitudes, h_0, (0.02–0.2 Oe) as a function of the dc magnetic field. A "home-made" measurement cell of the experimental setup was adapted to a commercial SQUID magnetometer. Both ac and dc fields were parallel to the longest axis of the sample. Magnetic field dependence of the ac response was measured in point-by-point mode when during the actual measurement the dc field was kept constant, and in a swept dc field. For the measurements in a swept field, the standard power supply of the SQUID magnetometer solenoid was replaced by the external Oxford Instruments superconducting magnet power supply. A block-diagram of the experimental setup was published elsewhere [9]. All measurements presented in this paper were done at $T = 4.5$ K.

3. Experimental results

DC magnetization curve data (inset to Fig. 1) show that at T = 4.5 K $H_{c1} \approx 1$ kOe and $H_{c2} \approx 2.6$ kOe. The magnetization curve in the vicinity of H_{c2} is a linear function of H_0 which permitted us to estimate the value of the Ginzburg–Landau parameter at this temperature as $\kappa \approx 1.6$. The apparent normal conductivity is $\sigma_n \approx 1.1 \times 10^{19}$ s^{-1} as was determined from the ac response in magnetic fields $H_0 > H_{c3}$.

Fig. 1 shows the difference between measured in point-by-point mode and in a swept field with $\dot{H}_0 = 5$ Oe/s susceptibilities χ' and χ''. The sweeping of the dc field affects the ac response both in the mixed and surface superconducting states. The effect of a swept field is more noticeable at low frequencies. We found that in point-by-point and swept modes there are some peculiarities of χ near H_{c2}. In a swept dc field, χ'' exhibits the minimum at H_{c2}. This minimum gives evidence of the change in the underlying mechanism that is responsible for forming the ac response in the mixed and surface superconducting states. Fig. 2a and b present the frequency dispersion of the ac response in a swept magnetic field. Here we showed ($\Delta\chi = \chi_{sw} - \chi_{st}$) at frequency 146.5 Hz (panel a) and 879 Hz (panel b) for sweeping rates of 5 and 30 Oe/s as a function of H_0. χ_{st} is the susceptibility in point-by-point mode, χ_{sw} -in a swept field mode.

Fig. 3 demonstrates the nonlinear character of the ac response. Increasing of the ac amplitude effects the response in a different way for mixed and surface superconducting states. In the mixed state, increasing the ac amplitude does not change the character of the response, the swept field leads to a decrease of the shielding and an increase of the dissipation. In the area of surface superconductivity, $H_0 > H_{c2}$, it takes place only for weak ac amplitudes. At larger amplitudes, the swept field increases the shielding while the losses are decreased.

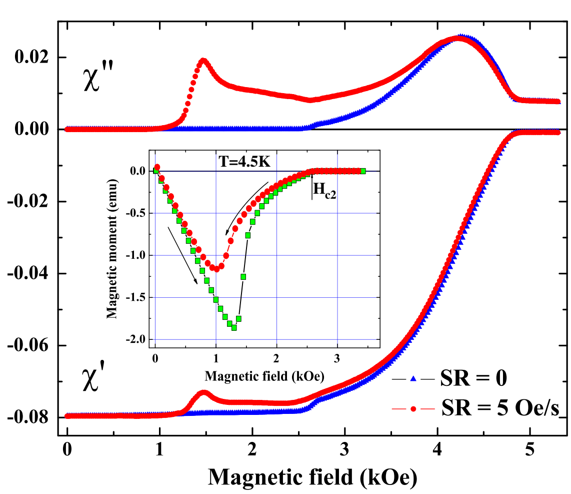

Fig. 1. Field dependencies of χ' and χ'' for $\dot{H}_0 = 0$ and 5 Oe/s at T = 4.5 K, frequency 146.5 Hz, and at $h_0 = 0.1$ Oe. Inset: ZFC magnetization curve.

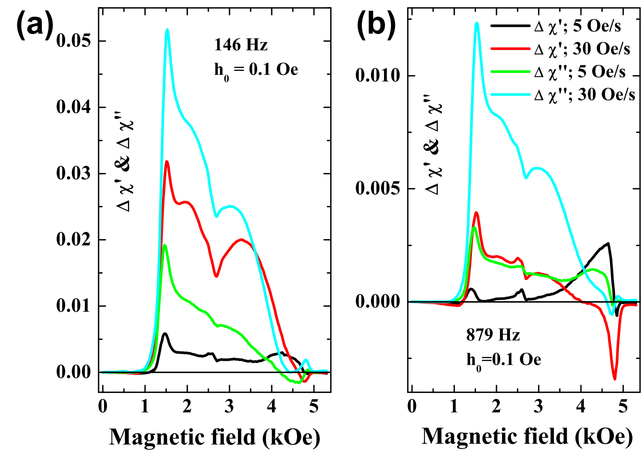

Fig. 2. Field dependence of $\Delta\chi = \chi_{sw} - \chi_{st}$ at 146.5 Hz (a) and 879 Hz (b), ac amplitude $h_0 = 0.1$ Oe. Symbols are the same in both panels.

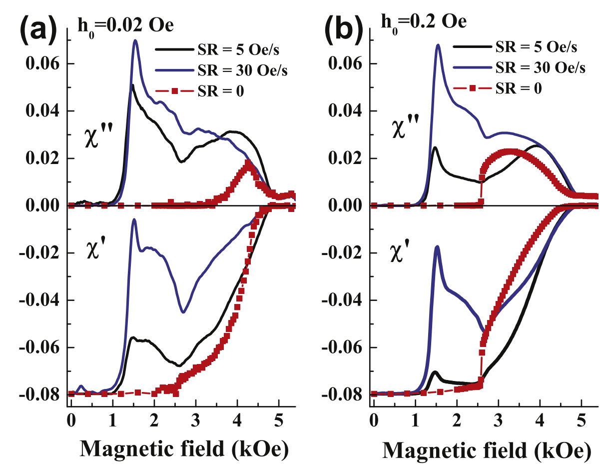

Fig. 3. Field dependence of χ at different sweep rates and ac amplitudes for 73 Hz. (a) $h_0 = 0.02$ Oe and (b) $h_0 = 0.2$ Oe.

4. Discussions

The observed ac response is formed by both surface and bulk currents. For $H_0 > H_{c2}$ the interior of the sample is in a normal state with known conductivity and we could obtain the surface current J_s directly from the measured susceptibility. Assuming that the thickness of the surface layer is small in comparison to the sample sizes, we can write $(1 + 4\pi\chi)h_0 = (1 + 4\pi\chi_\infty)(h_0 - 4\pi J_s/c)$, where χ_∞ is the susceptibility for $H_0 > H_{c3}$. We obtain

$$J_s/h_0 = (\chi_\infty - \chi)/(\chi_\infty + 1/4\pi). \tag{1}$$

From Maxwell's equation $curl\ \vec{E} = i\omega\vec{B}/c$ we can find the average electric field on the surface as

$$\overline{E} = iS\omega[1 + 4\pi\chi]h_0/Lc, \tag{2}$$

where L and S are the perimeter and area of the cross section that is perpendicular to the applied ac field. The average conductivity of the surface layer $\sigma = J_s/\overline{E} = \sigma' + \sigma''$ is