AC conductivity of a niobium thin film in a swept magnetic field

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We report the results of the measurement the ac conductivity of a Nb superconducting thin film in a swept dc magnetic field applied parallel to the surface. Analysis of the experimental data in a mixed state shows that changes of the ac conductivity are due to generation by the swept magnetic field unpinned vortices on the film surface. The number of these vortices is much smaller than the pinned ones and their density decreases with increasing of both the amplitude and frequency of an ac field.

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It is known that the ac response of type II bulk superconductors in slow ramped dc fields differs qualitatively from the ac response in constant dc field [1]. Increased ac losses in the mixed state [2] and the second harmonic generation [3] were observed in a swept dc field. The swept dc field induces currents in the sample that can change the ac response. DC currents, which exist in superconductors with pinning in a constant dc field, change the ac response in constant dc field [1]. Increased H\(_c2\) is due to the unpinned vortices that were generated at the surface. These vortices move into the film and provide flux-flow resistance. The presence of a small ac field (\(h_0 \approx 0.1\) Oe) decreases the number of unpinned vortices in the film, and the real component of resistivity decreases with \(h_0\).

The imaginary part of the conductivity \(\sigma_2\) is decreased by the swept dc field and it cannot be ascribed to the change the Campbell penetration depth [9] by dc the current in the film.

Nb thin films, 200 nm thick, were deposited by DC magnetron sputtering on rotated sapphire substrates at room temperature. The size of substrate with rounded corners (radius 0.2 mm) is 1.5 by 3 by 15 mm. Actually the sample was a thin walled cylinder and external applied fields were parallel to the cylinder axis. Monitoring the ac field inside this cylinder permits measurements of the conductivity of the film. RRR of the film was \(\approx 4, T_c \approx 8.5\) K. The ac response was measured by the pick-up coil method. The sample was inserted into one of balanced pair of coils, and the unbalanced signal was measured by a lock-in amplifier. A ”home-made” measurement cell of the experimental setup was adapted to a commercial SQUID magnetometer. A block-diagram of the experimental setup was published elsewhere [10]. Both the ac and dc fields were parallel to each other. The magnetic susceptibility of the sample at frequencies 293 and 1465 Hz and \(h_0\) from 0.04 to 1.2 Oe was measured in a point-by-point mode while during the measurement the dc field was kept constant and in a swept mode when the dc field was ramped at a given rate.

In zero dc field and of low enough temperatures the superconducting film completely shields the small external ac field [11], and the susceptibility of the sample should be \(-1/4\pi\). In order to test this, we compared the phases of the signals from the sample and from a bulk superconductor where complete shielding is observed. It turns out that the phases of these two signals coincide with high accuracy. This allowed us to obtain the ac susceptibility for any field and temperature in absolute units. Measurements were performed at two temperatures, 7 and 8 K. Results for both temperatures are similar, and here we will discuss only the data for 7 K.

The ac conductivity of the film was calculated from experimental data following this simple consideration. The thickness of the film was 200 nm and its volume was
2.7 \times 10^{-5} \text{ cm}^3$, while the volume of the substrate was $6.7 \times 10^{-2} \text{ cm}^3$. The ac magnetic moment of the sample is defined actually by the magnetic field inside the sample, i.e. by the total ac current in the film that shields the interior. We can thus write $\chi(\omega)h_0 S = j_s(\omega)dS/c$, where $L$ and $S$ are the perimeter and area of the perpendicular to the field direction cross section of the sample, $j_s(\omega)$ is the average current density in the film, and $d$ is the film thickness. We neglected the influence of demagnetizing fields because the demagnetizing factor for our geometrical arrangement is 0.036. From Maxwell’s equation, curl$\mathbf{E} = i\omega \mathbf{B}/c$ we can obtain the average electric field in the film as $E = i\omega S(1 + 4\pi\chi)h_0/eL$. And then for average conductivity, $\sigma(\omega) = j_s(\omega)/E$, we have

$$\sigma(\omega) = \sigma_1(\omega) + i\sigma_2(\omega) = -\sigma_0 \frac{i\chi(\omega)h_0}{1 + 4\pi\chi(\omega)},$$  \hspace{1cm} (1)

where $\sigma_0 = c^2 L/\omega_0 S d \approx 1.4 \times 10^{26} \text{ CGS}$, for our sample, and $\omega_0/2\pi = 1 \text{ Hz}$.

The field dependencies of the ac susceptibility were measured in point-by-point and in swept modes. For the employed frequencies, ac amplitudes, and sweep rates, we neglect the variation of the dc field during an ac period. Fig. 1 shows the magnetic susceptibility at frequencies 293 and 1465 Hz, sweep rates 0 and 18 Oe/s, and ac amplitude 0.04 Oe.

In point-by-point data we do not see any observable difference of $\chi$ for 293 and 1465 Hz. Application of Eq.(1) shows that the frequency dispersion conductivity is $\propto 1/\omega$. This is correct only for large dc fields where incomplete shielding is observed. For small dc fields, more precise measurements are required because in these fields we observe complete shielding, and in the denominator of Eq.(1) we get the small value $1 + 4\pi\chi \approx 0$. In the swept dc fields $\chi''$ differs from zero if $H_0 > H_{c1}$ and, as for bulk superconductors [2], there is a large plateau-like region of magnetic fields where $\chi''$ is approximately constant in value. Here, the measured $\chi''$ depends on the frequency and in accordance with Eq.(1) the frequency dispersion $\propto 1/\omega$ of the conductivity practically disappears, Fig. 2. In the surface superconducting state, before the transition into the normal state, the observed $\chi$ does not depend on frequency, Fig. 1, and the dispersion $\rho_1 \propto 1/\omega$ is restored.

In [2] it was noted that $\chi''$ is a function of the single parameter $q = H_0/\omega h_0$. The inset to Fig. 2 shows the measured resistivity of the film for two sets of frequencies and sweep rates but with the same value $q$. There is a difference approximately six times between these two curves in the plateau region.

DC magnetization data provide us with the value of the critical current of the film. The measured dc magnetic moment of the sample is proportional the difference between the magnetic field inside the substrate $H_i$ and the applied dc field $H_0$. $\Delta H \equiv H_i - H_0 = 4\pi M/V$. Fig. 3 presents $\Delta H$ as a function of $H_0$ after zero field cooling. Here $M$ is the magnetic moment of the sample in emu and $V$ is the sample volume. It is seen that near 4.6 kOe $\Delta H$ and the observed magnetization disappear.

We can consider this magnetic field as the second critical field $H_{c2}$ or as the irreversibility field where only pinning disappears. In the latter case we should expect the increasing of $\chi''$ due to increasing the number of unpinned vortices when the dc field exceeds 4.6 kOe. However, $\chi(\omega)$ does not have any peculiarities for point-by-point data near this field, and $H_0 = 4.6$ kOe is probably the...
second critical field. Absence of anomaly of \( \chi(\omega) \) near \( H_{c2} \) at low amplitudes of excitation in the bulk samples with strong pinning was observed in [1, 6–8].

The conductivity of the film at frequency 293 Hz, \( h_0 = 0.04 \text{ Oe} \) as a function of dc field for some values of the sweep rate is shown in Fig. 4. While the loss component \( \sigma_1 \) exhibits plateau-like behavior, the reactive component \( \sigma_2 \) is strongly affected by the dc field. Both components of the conductivity decrease with increasing the sweep rate. The accuracy of experimental data does not permit us to calculate \( \sigma_2 \) for a sweep rate of 2 Oe/s in all dc fields because in this case the measured \( \chi(\omega) \) is weakly different from \( \chi(\omega) \) measured in point-by-point mode.

The conductivity of the film depends on the ac amplitude, Fig. 5. Here we present \( \sigma \) at a frequency of 293 Hz in the ac field with amplitudes 0.04 and 0.12 Oe. Both components of \( \sigma \) are increasing with \( h_0 \). These results show that for the swept field mode data we actually have to deal with nonlinear conductivity, while the point-by-point mode data (not shown here) did not reveal any nonlinear behavior in the mixed state. For the point-by-point mode there is a complete shielding in the mixed state and the nonlinear response in the surface superconducting state, as for bulk superconductors [6, 8]. The ac response in the parallel to the surface magnetic fields larger than \( H_{c2} \) is usually ascribed to the surface superconducting states. In Fig. 1 it is seen that over 5.7 kOe \( \chi = 0 \) and we could consider this field as \( H_{c3} \). The ratio \( H_{c3}/H_{c2} \approx 1.24 \) which is considerably smaller than the theoretical value of 1.69 [12]. For \( H_0 > H_{c3} \) both components \( \sigma_1 \) and \( \sigma_2 \) are approximately the same. The effect of sweeping does not so distinctive as in the mixed state and in \( H_0 > 5.3 \text{ kOe} \) \( \sigma_1 \) actually does not depend on the sweep rate. In these fields \( \sigma_1 \) is approximately larger by two orders than in the normal state. The resistivity as a function of the sweep rate exhibits approximately a power dependence with exponent 1.3 for \( H_0 = 4.5 \text{ kOe} \). Fig. 6 shows \( \rho_1 = \text{Re}(1/\sigma) \) and \( \sigma_2 \) at frequency 293 Hz and \( h_0 = 0.04 \text{ Oe} \) for several dc fields as a parameter. It is seen that there are approximately two regions of ac fields with different characters of the swept field effect. These experimental results can be understood using the following model. Dissipation in the mixed state is due to unpinned vortices that were generated at the surface by a swept dc field. Vortex generation rate is proportional to the sweep rate and doesn’t depend on the equilibrium vortex density. The ac field decreases the number of unpinned vortices in the film and it is more efficient at higher frequencies and ac amplitudes. Unpinned vortices provide losses through the flux-flow mechanism and we
observe approximately constant $\chi''$ as a function of the dc field. The flux-flow dissipation should be frequency independent. In Fig. 2 we showed $\rho_1$ as a function of the dc field for frequencies 293 and 1465 Hz and sweep rate 18 Oe/s. It is seen that with an accuracy $\pm 20\%$ $\rho_1$ does not depend on frequency while $\chi'' \propto 1/\omega$. For example, in the field 3.5 kOe $\chi''(293)/\chi''(1465) \approx 4.8$ while $\rho_1(293)/\rho_1(1465) \approx 1.2$. Such weak frequency dispersion could be ascribed to the decreasing of the number of unpinned vortices by the ac field.

The resistivity of the film $\rho_1 \approx 10^{-23} \div 10^{-24}$ CGS for 5 Oe/s, $h_0 = 0.04$ Oe, and 293 Hz is smaller by several orders magnitude than the normal state resistivity $\rho_n$ of bulk Nb ($\approx 10^{-18} \div 10^{-19}$ CGS). In accordance with the Bardeen-Stephen formula for flux-flow resistivity $\rho_f = \rho_n n_\phi H_{c2}/H_{c2}$, where $n$ is the vortex density and $\phi_0$ is the flux quantum, we could conclude that the density of unpinned vortices is very small in comparison with equilibrium density $n_{eq} \approx H_0/\phi_0$. From the present experimental data it is not clear that this is due to the decreasing generation rate of unpinned vortices at the surface or the increasing of the relaxation rate into the pinned state.

Experiment shows that the reactive component of conductivity $\sigma_2$ decreases with increasing sweep rate, Fig. 5. The number of unpinned vortices in the film is considered small in comparison to the number of pinned vortices and we can write [13]

$$\sigma_2 = c^2/(4\pi\omega(\lambda_L^2 + \lambda_C^2)), \quad (2)$$

here $\lambda_L$ and $\lambda_C$ are the London and the Campbell penetration depth, respectively. Our estimation gives $\lambda_L \approx 61$ nm at 7 K (for $\lambda_L(0) \approx 46$ nm [14]). It is evident that $\lambda_C \gg \lambda_L$ otherwise Eq.(2) gives $\sigma_2 \approx 10^{27}$ CGS at 293 Hz which is very large in comparison with the experimental value $\approx 10^{23}$ CGS. The decreasing of $\sigma_2$ with increasing sweep rate possibly can be ascribed to the change of $\lambda_C$ due to the dependence of the Labusch parameter on the dc current in the film [4] for nonparabolic pinning well. But $\sigma_2$ depends also on $H_0$ (Fig. 5). It shows that the mechanism of the influence the swept field on the conductivity cannot be reduced to the simple change of the Labusch parameter by the dc current and has to include some interaction between pinned and unpinned vortices.

In a large dc field, $H_0 > 5$ kOe, both real and imaginary components of the conductivity are decreasing with increasing dc field for all sweep rates. The character of the ac response differs from the response in the mixed state. The conductivity weakly depends on sweep rate and exhibits approximately the reciprocal frequency dispersion. We did not find any peculiarities in $\rho_1$ near $H_{c2}$ ($=4.6$ kOe). This presents some difficulties. The thickness of the film is larger than the London penetration depth. Above $H_{c2}$ the superconductivity could exist only in the thin surface layer while the interior of the film is in the normal state. The skin depth of Nb in the normal state is very large in comparison with the film thickness and the interior of the film is opaque to the ac field. We should expect some peculiarities near $H_{c2}$ because below $H_{c2}$ the ac response is formed by the whole film while over $H_{c2}$ only by the thin superconducting layers. In the point-by-point mode we observe actually complete shielding at $H_0 \approx H_{c2}$ that could be provided by surface layers below or over $H_{c2}$ [11] and the observed picture ($\chi = -1/4\pi$) will not depend on the opaqueness of the interior. In the swept dc field the shielding is not complete and observed ac response should depend also on the interior properties. Below $H_{c2}$ the whole film is in superconducting state, above $H_{c2}$ there is only a thin surface superconducting sheath.

In conclusion, we have presented the results of measuring the conductivity of a superconducting Nb film in swept dc fields. A model of the influence of the swept dc field on the conductivity of a superconducting film in the mixed state was proposed. We found that the swept dc field generated unpinned vortices at the surface, while the weak ac field decreases the number of these vortices. Unpinned vortices move into the film and decrease both the real and imaginary components of the conductivity.

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