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Effect of meter-range electromagnetic irradiation on the current-voltage characteristics of wide superconducting films

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ABSTRACT

We experimentally studied the effect of meter-range electromagnetic field (tens of MHz) on the current-voltage characteristic (I-V curve) of a wide superconducting film. The vortex resistivity region is shown to significantly extend under the effect of meter-range (MR) electromagnetic irradiation owing to rapid suppression of critical current with a slower change in the upper boundary of stability of the vortex state. We found that as the MR irradiation power increases, the I-V curve structure related to phase slip lines is smoothed out to eventually vanish. A model of the film I-V curve in the adiabatic regime is proposed that explains the effect of blurring of voltage steps and suppression of critical current.

INTRODUCTION

The mechanisms by which electromagnetic irradiation affects a superconducting film may be divided into two groups: bolometric and nonbolometric mechanisms. The bolometric mechanisms that are due to overheating of electronic systems are well studied.[1,2] However, studies of nonbolometric (non-equilibrium) effects of electromagnetic field are still of interest because they reveal microscopic mechanisms of the electromagnetic response and order parameters that are of importance for efficient operation of superconducting sensors of electromagnetic radiation. Historically, standard objects of research into these effects were narrow films (superconducting channels) in a frequency range of $\gtrsim 1$–10 GHz, primarily owing to the interest in stimulation of superconductivity by SHF fields. We experimentally study the effect of high-frequency fields on the resistive state of broad superconducting tin films in the relatively unexplored meter range (tens of MHz) or, using international classification, VHF (very high frequencies).

Original technology[3] was used to produce films, which ensured high quality of their edges and uniform thickness. This was confirmed by good agreement between experimentally measured values and temperature dependences of their critical currents[3,4] and calculations based on the Aslamazov-Lempitskii theory[5,6] for defect-free films. Films were deposited on a substrate made of optically polished single-crystal quartz, a technique that ensured efficient heat dissipation[7] and prevented overheating. Resistive current state is realized in such films owing to viscous motion of Pearl-vortex lattice[8,9,10] and the emergence of phase slip lines (PSLs), this mechanism being activated sequentially as transport current increases. Initially, when current attains some critical value I_c, as the current density at film edges comes close to the decoupling current density j_c^{GL} of the Ginzburg-Landau theory, the edge energy barrier for penetration of vortices vanishes, and vortices of opposite signs start penetrating into the film from various directions;[5,11] as a result, a vortex-resistive segment emerges on the current-voltage characteristics (I-V curve). Annihilation of vortices in the center of the films creates a peak in current density,[5,12] as has been shown in experiments.[13] If transport current I_m is sufficiently large, the height of this peak may be as large as j_c^{GL}, and the vortex lattice becomes unstable,[5] which results in the emergence of PSLs and voltage surges on the I-V curve.

Production of uniform wide films with even edges is a rather challenging problem; therefore, first, films with a large number of defects have been studied. For example, study[14] found, in exploring absorption of HF field by vortices in $Pb_{0.83}In_{0.17}$ and $Nb_{0.95}Ta_{0.05}$, films containing a large number of pinning centers that the effect of an alternating field at frequencies higher than some frequency $f_0 \sim 3.9–15$ MHz results in depinning of vortices as a result of which vortex resistivity develops, and absorbed power increases. However, in studying the effect of a microwave SHF field (1–15 GHz range) on the vortex resistive state in our films with a small number of defects,[15] an effect inverse to that found in Ref. 14 has been discovered: vortex resistivity is suppressed by electromagnetic fields. It was shown that as SHF irradiation power P increases, the resistive vertex segment of the I-V curve shrinks, and at $P \geq 0.4P_c$ (P_c is the power at which critical current vanishes), the vortex mechanism of resistivity is no longer operational. The issue of the effect of electromagnetic field of a lower frequency remained open, and this was prompted our interest in studying the resistive state of the films under irradiation with a VHF-range electromagnetic field.

We studied tin films 18–42 μm wide, about 90 μm long, and 120–330 nm thick; the results featured good reproducibility. Figure 1 shows I-V curve families of a Sn4w specimen (width 42 μm, length 92 μm, thickness 120 nm, superconducting transition temperature $T_c = 3.795$ K, normal resistance 0.14 Ohm at $T = 4.2$ K) measured at different power levels at frequencies 35.5 MHz (a) and 5.56 GHz (b). The irradiation power for the first I-V curve is zero; for other I-V curves, it increases with the sequential number of the I-V curve. In measuring the I-V curve using a four-probe method, specimens were placed into a double screen made of annealed permalloy that reduced the magnetic field in the vicinity of the specimen to $H_\perp = 7 \cdot 10^{-4}$ Oe and $H_{||} = 6.5 \cdot 10^{-3}$ Oe. The electric component of the electromagnetic irradiation field was directed parallel to the transport current. Because the length of the film under study is less than 1% of the minimal wavelength, the high-frequency current $I_f \sim \sqrt{p}$ that flows through the specimen was, at each moment of time, virtually the same along the entire film length.

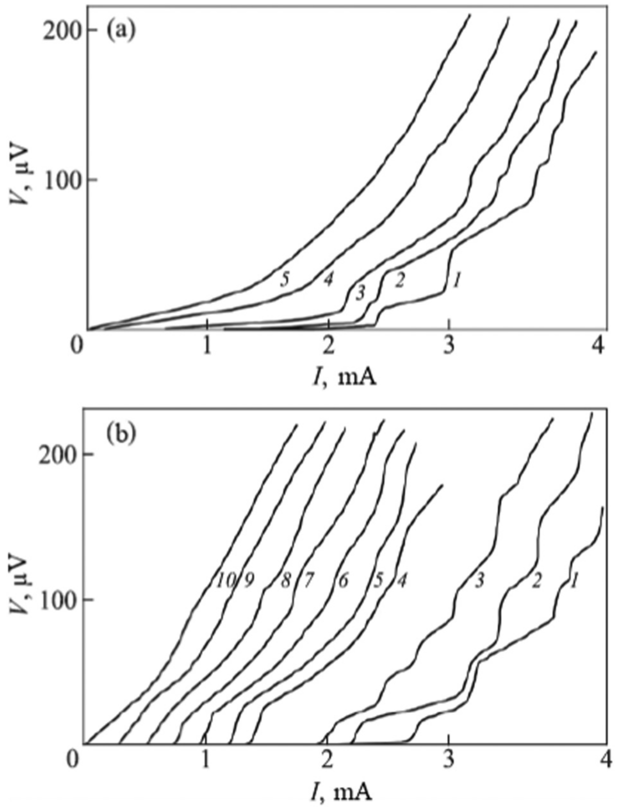

FIG. 1. Families of experimental I-V curves of a wide (42 μm) Sn4w film for various levels of VHF-range electromagnetic radiation $f = 35.5$ MHz, $T = 3.747$ K (a) and SHF range $f = 5.56$ GHz, $T = 3.744$ K (b). The irradiation power for I-V curve No. 1 is $P = 0$, and for other I-V curves, it increases with the sequential number of the I-V curve.

Figure 1(b) shows that under the effect of SHF irradiation ($f = 5.56$ GHz), the resistivity of the film due to motion of vortices (initial segment of I-V curve No. 1) rapidly vanishes if power is applied (in accordance with earlier results,[15] and further increase in power only results in a decrease in the current I_m at which the first PSL emerges. The effect of a VHF-range alternating electromagnetic field [$f = 35.5$ MHz, Fig. 1(a)] on a superconducting film is dramatically different: as power increases, the critical current $I_c(P)$ decreases much faster than I_m; as a result, the initial I-V curve segment significantly extends and its slope increases, while the larger part of this segment, beginning from $I_c(P)$, remains linear. Apart from this, the voltage surges that are due to sequential emergence of PSLs are smoothed out as the VHF power increases to eventually vanish, while in case of SHF irradiation this effect is much weaker. A similar effect of voltage surges being smoothed out in the VHF range (75 MHz) has been discovered earlier in narrow channels where I-V curves are formed by phase slip centers, and there is no vortex resistivity.[16]

Proceeding to discussion of the results obtained, we note that the the relaxation time of the order parameter τ_Δ plays a fundamental role in the formation of the superconductor's response to an alternating field[17,18] that is related, in the vicinity of T_c, to the time of energy relaxation of electrons τ_ϵ by the formula $\tau_\Delta \approx 1.2\tau_\varepsilon(1 - T/T_c)^{-1/2}$. Given our specimens and temperatures, $\tau_\varepsilon = 4.3 \cdot 10^{-10}$ s,[19] while the order parameter relaxation time is of the order of $\tau_\Delta \approx 4.2 \cdot 10^{-9}$ s. Thus, the relaxation time τ_Δ in the SHF range proves to be large compared with the electromagnetic wave period ($\approx 2 \cdot 10^{-10}$ s); as a result, the order parameter $\Delta(t)$ fails to significantly change during the SHF field oscillation period and only experiences minor oscillations around an average value $\bar{\Delta}$ that is determined by the average strength of the alternating field.[18] Therefore, the effect of the alternating field on voltage surges, which are due to the emergence of PSL, is primarily reduced in the high frequency limit $\omega\tau_\Delta \gg 1$ to a decrease in the I_m current due to suppression of Δ. A plausible reason for the disappearance of the vortex resistivity may be rapid oscillatory motion of vortices induced by SHF current with a small period. This hinders production of new vortices on film edges that, according to,[5] requires much longer time of the order of τ_Δ (see a detailed discussion in Ref. 15).

In the VHF range where the times of order parameter relaxation and generation of vortices are small compared with the electromagnetic wave period ($\approx 3 \cdot 10^{-8}$ c), the order parameter and vortex structure follow the field variations almost adiabatically. One may hypothesize in this case that at each moment of time t the film is in a locally steady quasistatic regime where the full current is $I_{tot}(t) = I + I_f \sin \omega t$. Thus, as soon as the total of transport current I and alternating-current amplitude I_f exceeds the critical current of vortex generation $I_c(0)$ in the absence of the field, vortex resistivity emerges in the film, and the corresponding critical current

$$I_c(P) = I_c(0) - I_f \tag{1}$$

decreases rather rapidly as power increases, as has been experimentally observed. It should be stressed that Eq. (1) enables estimation for each experimental I-V curve of the alternating current I_f induced in the film, a value that cannot be directly measured [Fig. 1(a)]. In particular, the critical current of the film should vanish at a value $I_f^{(c)}$ equal to the critical current $I_c(0)$ in the absence of pumping, which is in our experiment approximately 2.1 mA. Similar arguments may be applied to describe the shape of the film I-V curve based on the observation that the instantaneous value of voltage $V_t(I, P)$ in the adiabatic limit is close to its value $V(I_{\mathrm{tot}}(t), 0)$ on the I-V curve in the absence of irradiation that corresponds to the instantaneous value of current I_{tot}. Because the experimentally measured constant component of voltage is the result of averaging $V_t(I, P)$ over the field oscillation period $T = 2\pi/\omega$,

$$V(I, P) = \int_0^T \frac{dt}{T} V(I + I_f \sin \omega t, 0), \tag{2}$$

each point $V(I, P)$ along the I-V characteristics of the film is essentially the result of a certain averaging of the I-V curve $V(I, 0)$ in the absence of pumping near the transport current I with a width of $2I_f$. This explains, in particular, the experimentally observed smoothing out of voltage surges that enhances as power increases.

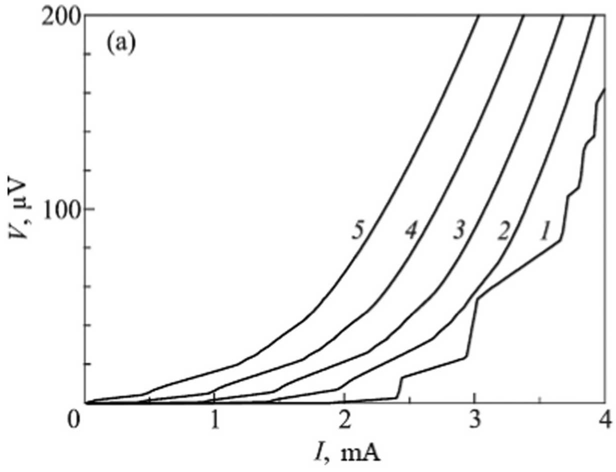

FIG. 2. I-V curves (curves 2–5) calculated using Eq. (2) and the experimental I-V curve measured at $P = 0$ (curve *1*). Numbering of the calculated I-V curves corresponds to different values of alternating current; mA: 1 (*2*), 1.5 (*3*), 2 (*4*), and 2.5 (*5*).

Numerical calculation of $V(I, P)$ according to Eq. (2) and using an experimental I-V curve at $P = 0$ (curve *1*) and various I_f displayed in Fig. 2 yields the results that are in qualitative agreement with experimental data, with the only difference being that smoothing out of surges with an increase in power occurs much faster than in the experiment. A plausible reason for this disagreement may primarily be an insufficiently low irradiation frequency (the relaxation parameter in the experiment $\omega\tau_\Delta \approx 0.9$ most likely corresponds to a regime of transition to the adiabatic limit $\omega\tau_\Delta \ll 1$), and the existence of other characteristic times, for example, the time τ of the vortex flyby through the film, which, according to estimates,[15] may be an order of magnitude larger than τ_Δ. Because the adiabaticity condition $\omega\tau_\Delta \ll 1$ may be not fulfilled for this value of time in our experiment, the assumption regarding the locally established regime may fail, and, to check quantitative applicability of the model, radiation with a lower frequency should be used.

To conclude, we summarize the main results obtained in this study. While irradiation of a wide film with an SHF-range electromagnetic wave results in suppression of vortex resistivity on the film I-V curve, the opposite effect was observed in the VHF range: significant extension of the linear segment of I-V curve that may be interpreted as more rapid suppression of the critical current of vortex penetration into the film $I_c(P)$ in comparison with the upper boundary of instability of the vortex state I_m, above which phase slip lines emerge. We have shown that as the power of VHF-range irradiation increases, the stepwise I-V curve structure that is related to the emergence of PSLs is smoothed out to eventually vanish. We have proposed a model of the film I-V curve in the low-frequency (adiabatic) regime based on averaging static I-V curve over oscillation of the alternating current component. This model explains, in qualitative terms, smoothing out of voltage levels and rapid decrease in critical current, and enables estimation of the amplitude of the alternating current induced in the film.

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