Dissipation in Mesoscopic Superconductors with Ac Magnetic Fields

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The response of mesoscopic superconductors to an ac magnetic field is investigated both experimentally and with numerical simulations. We study small square samples with dimensions of the order of the penetration depth. We obtain the ac susceptibility $\chi = \chi' + i\chi''$ at microwave frequencies as a function of the dc magnetic field $H_{dc}$. We find that the dissipation, given by $\chi''$, has a non monotonous behavior in mesoscopic samples. In the numerical simulations we obtain that the dissipation increases before the penetration of vortices and then it decreases abruptly after vortices have entered the sample. This is verified experimentally, where we find that $\chi''$ has strong oscillations as a function of $H_{dc}$ in small squares of Pb.


The response of superconductors to an ac magnetic field has been of interest in the last years. The microwave surface impedance and the ac magnetic susceptibility $\tilde{\chi} = \chi' + i\chi''$ have been extensively studied. The imaginary part of the susceptibility, $\chi''$, is proportional to the dissipation in the sample. In macroscopic type II superconductors, the ac dissipation increases with magnetic field, proportional to the vortex density. Very recently, there has been an interest in the study of mesoscopic superconductors where the sample dimensions are of the order of the London penetration depth. In this work we will show that in mesoscopic superconductors the ac dissipation has a non monotonous and oscillating dependence with magnetic field.

We first show the results of numerical simulations of mesoscopic squares
Fig. 1. ac dissipation, $\chi''$, and number of vortices, $N_v$, vs. magnetic field $H$. (a) Large sample, $40\lambda \times 40\lambda$. (b) Mesoscopic sample, $10\lambda \times 10\lambda$

using the time-dependent Ginzburg-Landau (TDGL) equations:\textsuperscript{3,4}

$$\frac{\partial \Psi}{\partial t} = \frac{1}{\eta}[(\nabla - i\mathbf{A})^2 \Psi + (1 - T)(1 - |\Psi|^2)\Psi]$$ (1)

$$\frac{\partial \mathbf{A}}{\partial t} = (1 - T)\text{Im}[\Psi^*(\nabla - i\mathbf{A})\Psi] - \kappa^2 \nabla \times \nabla \times \mathbf{A}$$ (2)

where $\Psi$ and $\mathbf{A}$ are the order parameter and vector potential respectively and $T$ is the temperature. Lengths are normalized by the coherence length $\xi(0)$, times by $t_0 = 4\pi\sigma_n\lambda_L^2/c^2$, $\mathbf{A}$ by $H_{c2}(0)\xi(0)$, $T$ by $T_c$, and we have $\eta = c^2/(4\pi\sigma_n\kappa^2 D)$. The boundary conditions are $$(\nabla - i\mathbf{A})\Psi = 0 \text{ and } B_z|_S = (\nabla \times \mathbf{A})_z|_S = H_{z\text{ext}}.$$ We consider an ac-dc magnetic field: $H_{z\text{ext}} = H_{dc} + h_{ac}\cos(\omega t)$ with $h_{ac} \ll H_{dc}$. The magnetization is given by $4\pi M(t) = \langle B(t) \rangle - H(t)$, with $\langle B(t) \rangle$ averaged over the sample. The ac magnetic susceptibilities are obtained as $\chi' = \frac{1}{\pi h_{ac}} \int_0^{2\pi} M(t)\cos(\omega t) d(\omega t)$ and $\chi'' = \int_0^{2\pi} M(t)\sin(\omega t) d(\omega t)$.