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Behavior of the flux-flow resistivity in mesoscopic superconductors

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ABSTRACT

In this work we solved the time dependent Ginzburg–Landau equations numerically finding profiles of the flux-flow resistivity for different widths of superconducting stripes. We found vortex pinning induced by the surface superconductivity. This pinning avoids the movement of the vortex lattice preventing the generation of a voltage. We also found the existence of a mesoscopic region where the flux-flow resistivity shows size effects and we observed a transition to a macroscopic regime as the width increases.

1. Introduction

One of the most important features of a superconductor is the absence of a resistivity when a current is applied on it. However when a magnetic field is applied in the superconductor the interaction between the vortex lattice and the current could induce the appearance of a resistivity. The origin of this resistivity is a Lorentz force between the current in the superconductor and the magnetic flux of the lattice. This Lorentz force causes a continuous movement of the lattice. This movement is transverse to the current and induces an electric field: $\mathbf{E} = \mathbf{B} \times \mathbf{v}/c$, where $\mathbf{v}$ is the velocity of the vortex lattice. For a superconductor without pinning, the displacement of the lattice is retarded only by a viscous force per unit length, $\mathbf{F}_\mu$. This force is modeled proportional to the velocity of the vortices and includes a viscous coefficient, μ: $\mathbf{F}_\mu = -\mu\mathbf{v}$.

Therefore, the relation between $\mathbf{E}$ and the applied density current $\mathbf{J}$ defines the flux-flow resistivity $\rho_{ff} = \frac{\mathbf{E}}{\mathbf{J}} = \mathbf{B}\frac{\Phi_0}{\mu C^2}$, where Φ_0 is the quantum of magnetic flux [1].

Previous works with numerical solutions of the time-dependent Ginzburg–Landau (TDGL) and the generalized TDGL showed several kinds of regimes with different velocities of the vortex lattice motion [2–5]. In particular, for an infinitely long slab the transition from the low to the fast vortex motion was studied solving the generalized TDGL equations. For this geometry, a transition from a moving Abrikosov lattice with triangular structure to a set of parallel rows is found when the applied current increases [5]. The creation of phase-slip lines and the interplay with a vortex lattice in a finite-length thin stripe with finite-size normal leads was studied showing channels with fast and slow vortices. The leads at the edge of the stripe produce the curvature of the channels in the vicinity of the leads [6]. However, the effects of the surface superconductivity in the movement of the vortices have not been studied in the flux-flow regime. In this work we studied the flux-flow resistivity for different widths of an infinite superconducting strip searching the transition between a microscopic regime, where the flux-flow resistivity is proportional to B, and a mesoscopic regime where the effects of the surface superconductivity are present.

2. Model system

As a model system, we use a bulk superconductor which is infinite in the *z* and *x* directions and is finite in the *y* direction (Fig. 1). With this model we neglect the possibility of curved vortices in the *z* direction.

The time-dependent Ginzburg–Landau equations for our system are:

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

$$\frac{\partial}{\partial t}\mathbf{A} = Re[\psi^*(-i\nabla - \mathbf{A})\psi] - \kappa^2\nabla \times \nabla \times \mathbf{A}$$

Where the physical quantities are measured in dimensionless units: length in units of the coherence length ξ, magnetic field in units of the critical field H_{c2}, ψ in units of $4k_BT_c\eta^{1/2}/\pi(1-T/T_c)^{1/2}$, temperature in units of the critical temperature T_c, and time is scaled in units of the Ginzburg–Landau relaxation time $t_0 = h/16k_B(T_c-T)\eta = \xi^2/\eta D$. In the last units D is the diffusion constant, k_B and h are the Boltzmann

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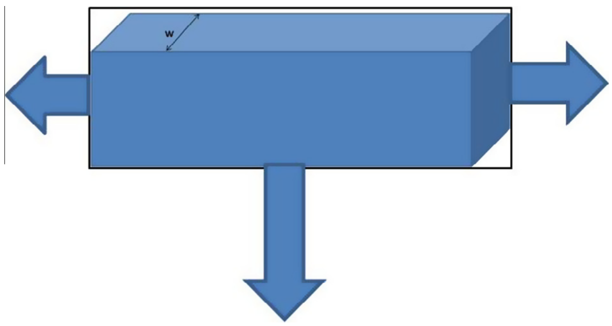

Fig. 1. The model system is a slab (infinite in the z and x directions). The applied magnetic field is parallel to the z axis and the transport current is parallel to the x axis.

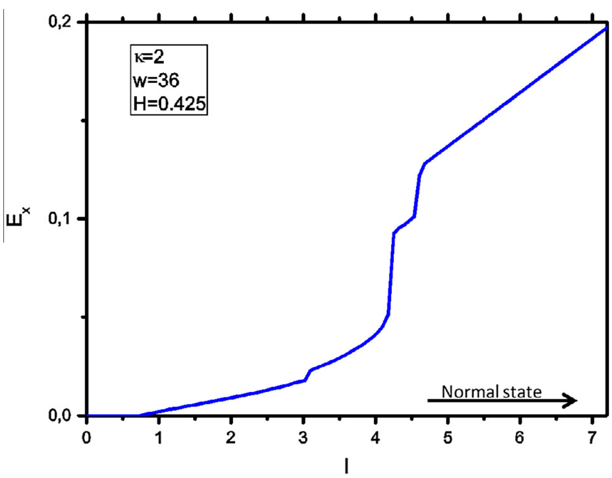

Fig. 2. E_x vs. I of a superconducting slab with $w = 36$, $H = 0.425$ and $\kappa = 2$. The current zone where the superconductivity disappears is marked with an arrow.

and Planck constants and the parameter η is taken to be equal to 5.79 [7].

Periodic boundary conditions are applied in the x direction: $\psi(x) = \psi(x + L)$ and $\mathbf{A}(x) = \mathbf{A}(x + L)$, where L is the period. The usual boundary condition superconductor-vacuum is applied in the y direction:

$$\left(\frac{\partial}{\partial y} - iA_y\right)\psi\bigg|_{y=0,y=w} = 0$$

The transport current is introduced via the boundary condition for the vector potential in the y direction, $\nabla \times \mathbf{A}|_z(y = 0, y = w) = H \pm H_{ind}$, where H is the applied magnetic field and H_{ind} is the magnetic field induced by the current [5].

To solve the TDGL equations we consider a rectangular mesh consisting of $n_x \times n_y$ cells, with mesh spacings a_x and a_y. We use finite difference method based on gauge-invariant link variables [8]. This numerical method is defined by the finite unknowns of the method, ψ, A_x, and A_y, plus the equations relating these unknowns.

3. Results and discussion

As the electric field $\mathbf{E}$ is a time-dependent variable, we averaged it over a long finite time interval. In Fig. 2 we show the current-E_x characteristic of our system, where the current I is the current per unit length in the z-direction, E_x is the electric field parallel to the current direction, $\kappa = 2$, $L = 80$ and the width $w = 36$ at $H = 0.425$. Due the presence of the surface barrier the vortices start to flow for a finite current and the vortex lattice is close to the Abrikosov structure. Above this current the vortices start to flow incoming from the superior edge and outgoing to the inferior edge. The gradient of the magnetic field in the system helps the movement of the vortices. Thus, on the edge where the applied and induced fields have the same orientation, superconductivity is depressed and this depression allows the entry of new vortices. In the flux-flow regime (small currents and linear behavior in the E_x vs. I

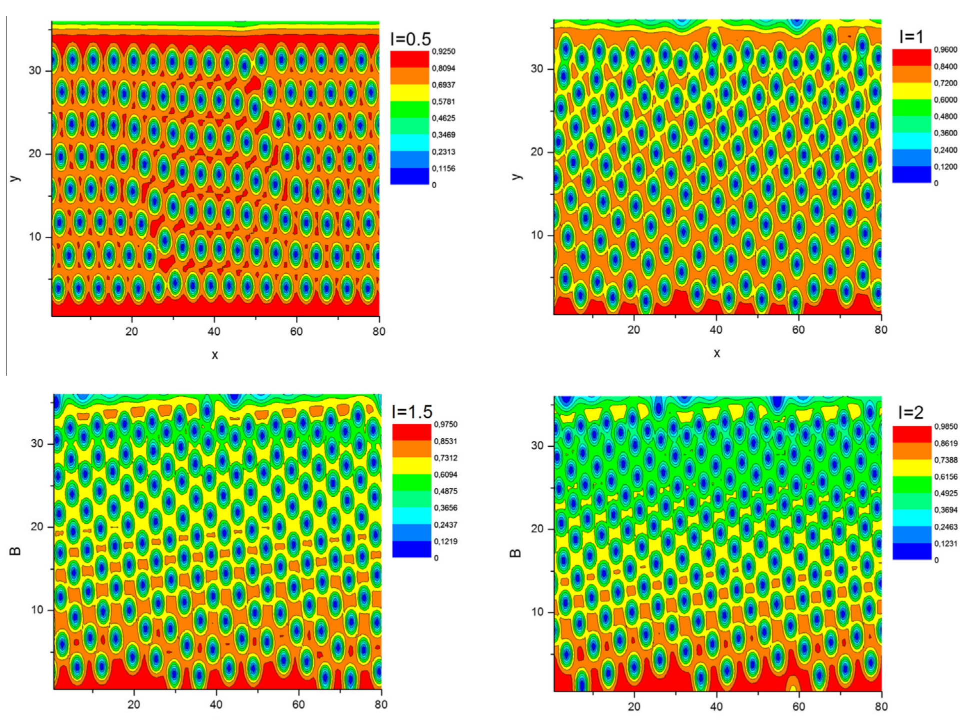

Fig. 3. Snapshots of the order parameter at different values of the current in the flux-flow regime for the system described in the Fig. 2. The currents are $I = 0.5$, 1, 1.5 and 2.

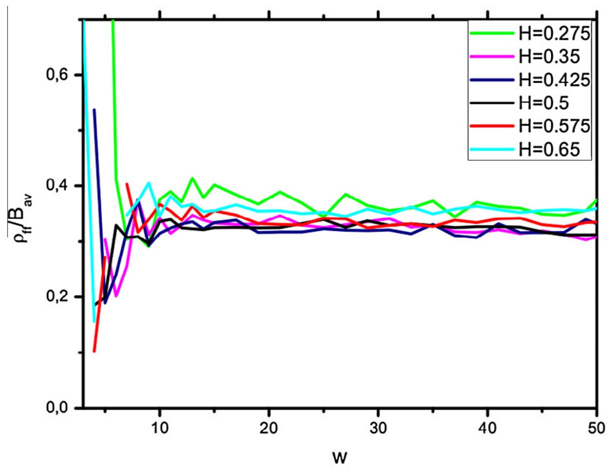

Fig. 4. ρ_{ff}/B_{av} vs. w. All the curves for different applied magnetic fields converge for wider systems. However under a critical width ($w\sim15$) the macroscopic prediction does not work.

curve) the vortex structure is a slightly deformed Abrikosov lattice (Fig. 3). With increasing current there are several jump transitions where the vortex velocity increases and we have a state with voltage jumps. A detailed study of these jumps can be obtained in [5]. Finally for $I = 4.5$ the system evolves to the normal state.

Keeping $\kappa = 2$, we calculated the flux-flow resistivity and the average magnetic induction B_{av} for different widths and applied magnetic fields. As were shown previously, in the macroscopic case the flux-flow resistivity ρ_{ff} is proportional to B and therefore ρ_{ff}/B is a constant. For widths greater than $w = 15$, the system obeys the predicted macroscopic behavior, but under this critical width we found evidence of the existence of a mesoscopic region where the flux-flow resistivity shows the effects of the existence of the surface barrier (Fig. 4).

4. Conclusions

From the characteristic curves, we have evidence that surface superconductivity acts like a surface barrier. That surface barrier avoids the outgoing of the vortex lattice below a critical current. We determined also the existence of different widths where a mesoscopic regime for the flux-flow resistivity is manifested. For wider stripes a transition from mesoscopic to macroscopic regime is found.

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