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Effect of a Transversal Channel on the Vortex-Antivortex State in a Superconducting Film

Efecto de un canal transversal sobre el estado vórtice-antivórtice en una película superconductora

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Abstract

In this work, the resistive state of a mesoscopic superconducting sample in presence of an external transport electric current, J_a, and at zero magnetic field was studied. A non-centered channel of depleted superconductivity (of width m and at lower critical temperature T_c) is positioned at a distance d of the center of the sample. We vary the width a of the metallic contact in which the external current is applied. We study the superconducting electronic density, the vortex-antivortex velocity, and the annihilation rates of the supercurrent for several widths of the metallics contacts and position of the channel. Our investigation show that critical currents and the velocity of the $v-Av$ of the studied system depend strongly on the size of the contact and of the position of the channel in the sample.

Keywords**:** Ginzburg-Landau, Kinematic vortex, Mesoscopics, Superconductor

Resumen

En este trabajo se estudió el estado resistivo de una muestra superconductora mesoscópica en presencia de una corriente de transporte J_a, y a campo magnético nulo. Un canal no centrado de superconductividad depreciada (de ancho m y temperatura crítica más baja T_c) se ubicó a una distancia d del centro de la muestra. Variamos el ancho a del contacto metálico por el cual es aplicada la corriente externa. Estudiamos la densidad de electrones superconductores, la velocidad vórtice-antivórtice y las tasas de aniquilación de la supercorriente para varios anchos de los contactos metálicos y para la posición del canal. Nuestra investigacin mostró que las corrientes crı'ticas y la velocidad de los pares $v-Av$ dependen fuertemente del tamaño del contacto y de la posición del canal en la muestra.

Palabras clave**:** Ginzburg-Landau, Vórtice cinemático, Mesoscópicos, Superconductor

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1 Introduction

The resistive superconducting state of a mesoscopic sample in presence of a transport current can be explained by the well know kinematic vortex-anti-vortex (*v-Av*) pair. This *v-Av* pair is considered as propagating waves of the order parameter ψ, in which, the electronic superconducting density nearly vanishes along the line where kinematic vortices move [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. Sivakov *et al* experimentally found that the *V-Av* pairs move with velocity $\upsilon_{kv} \simeq 10^5$ m/s, while that the Abrikosov vortices velocity is $\upsilon_{av} \simeq 10^3$ m/s. Due to their high velocity, kinematic vortices resemble a line where the order parameter is deprecated [1, 2, 4]. Several theoretical research in superconducting films in presence of external currents has been carried out in the last years, i.e., Sardella *et al* showed that an external current can active magnetically the kinematic vortices in a superconducting square with a central hole. Also, they found that the superconducting electronic density alongside the slip phase line has crucial importance to describe the maximum of the current-resistance curve [12, 13, 14, 15]. Berdiyorov *et al* studied the kinematic vortex state on the time response of a bridge with pinning in presence of an applied current. They show that the resistive state is characterized by the possible vortex states and depends strongly on the external current, also studied the kinematic state in samples with magnetic dots, finding that dots increase the interval of currents for which a resistive state occurs, where a change in the phase θ of π, is the responsible of this kinematic vortex [5, 6, 7, 8, 16]. An analysis of the superconducting electronic density at the border of the sample was studied by Benfenati *et al*, they found that due to the inter-band coupling effect in a two-band system exist a difference between the critical temperature in the bulk and the surface, also, the presence of the border (boundary) induce strong variations of the gaps with the presence of several length scales [17]. Also, several experimental works in superconductrs and semi-conductor materials have been carried out, for example, structural analysis, surface morphology, magnetic ordering, dielectric response and optical characteristic in a complex perovskite Dy_2BiFeO_6, clay mineral Illite, Chlorite, Hematite was studied, they found that the reflectance curve as a function of wavelength reveals the typical behavior of a double perovskite-type semiconductor. Also the electrical properties of the clay showed a strong non-linear insulating behavior [18, 19]. Also, the influence of the rugosity of the sample on the critical currents and the kinematic vortex velocity was studied in the references [20, 21, 22]. In this work, we study the resistive response of the superconducting film with a non-centered transversal channel under an applied current at zero magnetic field (see Figure 1). A study was carried out by considering different widths of the channel, distance of the center of the film, and sizes of the metallic contact in which the external current is applied. We found that the value of the critical current density, at which the first kinematic vortex enters the sample J_1, and the superconducting-normal state transition current J_2, strongly depends on these parameters. This paper is outlined as follows. In Section 2 we describe the theoretical formalism used to study a mesoscopic film n the presence of an applied current at zero magnetic field. In Section 3 we present the results that come out from the numerical solution of the Ginzburg-Landau equations, finally, in Section 4 we present our conclusions.

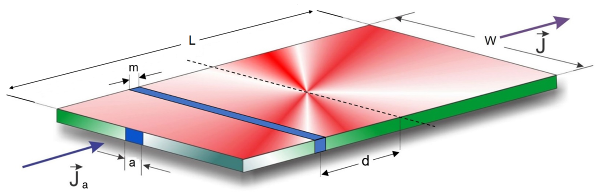

Figure 1. (Color online) Layout of the studied sample: a thin film of length $L = 12\xi$, width $w = 8\xi$; the size of the metallic contact is a. A non-centered defect of depleted superconductivity or metallic channel of width m at a distance d of the center of the film.

2 Theoretical Formalism

The studied sample is a thin superconducting film of length L and width w; the width of the contacts through which a constant current density J_a is applied is a. We treated this system as a 2D system [23, 24, 25]. The general form of the time-dependent General Ginzburg Landau equations (G-TDGL) in dimensionless units is given by [26, 27, 28]:

$$\frac{u}{\sqrt{1+\Gamma^2|\psi|^2}}\left[\frac{\partial}{\partial t}+i\varphi+\frac{\Gamma^2}{2}\frac{\partial|\psi|^2}{\partial t}\right]\psi = (\bigtriangledown - i\mathbf{A})^2\psi+(f(\mathbf{r})-|\psi|^2)\psi\,, \quad (1)$$

and

$$\Delta\varphi = \nabla\cdot\bar{\psi}(\nabla-\mathrm{i}\mathbf{A})\psi \quad (2)$$

The function $f(\mathbf{r}) = 1$ for all regions except in the channel were we choose $f(\mathbf{r}) = 0$ simulating a thermal defect at lower critical temperature T_c or a metallic channel. The heating effects are not taken into accout [29, 30]. The electrostatic potential is $\Delta\varphi$ and is given in units of $\varphi_0 = \hbar/2et_{GL}$, the distances are given in the coherence length ξ units, the time is in units of the Ginzburg-Landau time $t_{GL} = \pi\hbar/8k_BT_cu$, and the vector potential $\mathbf{A}$ is given in $H_{c2}\xi$, where H_{c2} is the upper critical field. $u = 5.79$ and $\Gamma = t_E\psi_0/\hbar = 10$, t_E is the inelastic scattering time [26]. $\psi \neq 0$ is used in all the boundary of the sample, except at the metallic contact, where we used $\psi = 0$ and $\nabla\varphi\mid_n = -J_a$, where J_a is the external current in units of $J_0 = c\sigma\hbar/2et_{GL}$, σ is normal electrical conductivity, and the mesh-grid size is $\delta = 0.1$ [2, 7, 13]). To solve the equation (1) and Equation (2), we used the popular link-variable method [31, 32, 33].

3 Results

In Figure 1, we illustrate the studied sample, a thin film with $L = 12\xi$, and $w = 8\xi$. The external *dc* current density J_a is uniformly applied through the electrodes width a ($a/\xi = 2,4,6,8$).

In Figure 1, we show the analyzed sample, a thin film with $L = 12\xi$, and $w = 8\xi$. The external *dc* current density J_a is uniformly applied through the electrodes of width a ($a/\xi = 2,4,6,8$). A non-centered channel of depleted superconductivity of width m is present at a distance d of the center of the film. In the Figures 2 and 3, we plotted the time-averaged voltage V and the resistivity $\partial V/\partial J_a$ (right) as a function of the applied current J_a respectively, we use metallic contact of size $a/\xi = 2,4,6,8$. This figure shows a decreasing of the critical currents in which the vortex anti-vortex pair occurs in the sample, J_1 and J_2 by increasing a for a homogeneous sample and a slight dependence of a and d on these critical currents.

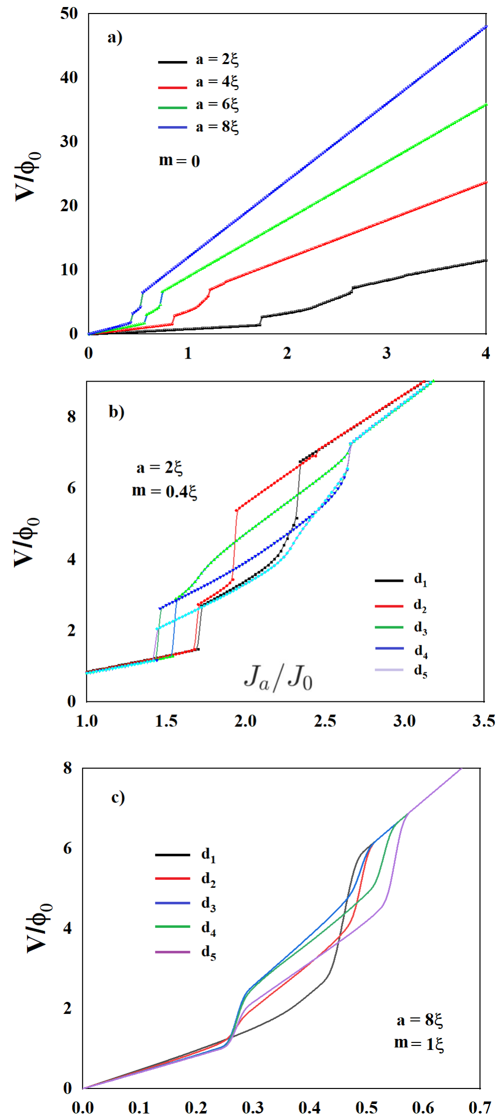

Figure 2. (Color online) Time-averaged voltage V as function of the applied current-density J_a for a) Homogeneous sample with $a/\xi = 2,4,6,8$, (b) $m = 0.4\xi$, $a = 2\xi$ and the channel positioned in $d_1 = 5.6\xi$, $d_2 = 4.2\xi$, $d_3 = 2.8\xi$, $d_4 = 1.4\xi$, $d_5 = 0$ (as is evident this value simulates a centered channel), measured from the center of the sample, and c) $m = 1\xi$, $a = 8\xi$ and a channel positioned in $d_1 = 5.6\xi$, $d_2 = 4.2\xi$, $d_3 = 2.8\xi$, $d_4 = 1.4\xi$, $d_5 = 0$.

In the Figure 2(b) and Figure 3(b), the same curve is plotted for $m = 0.4\xi$, $a = 2\xi$ and the channel positioned in $d_1 = 5.6\xi$, $d_2 = 4.2\xi$, $d_3 = 2.8\xi$, $d_4 = 1.4\xi$, $d_5 = 0$. Being $d_5 = 0$ a centred channel. It would be expected that given the width of the metallic contact and the position of the channel, which generate different electronic densities that would favor the movement of Cooper

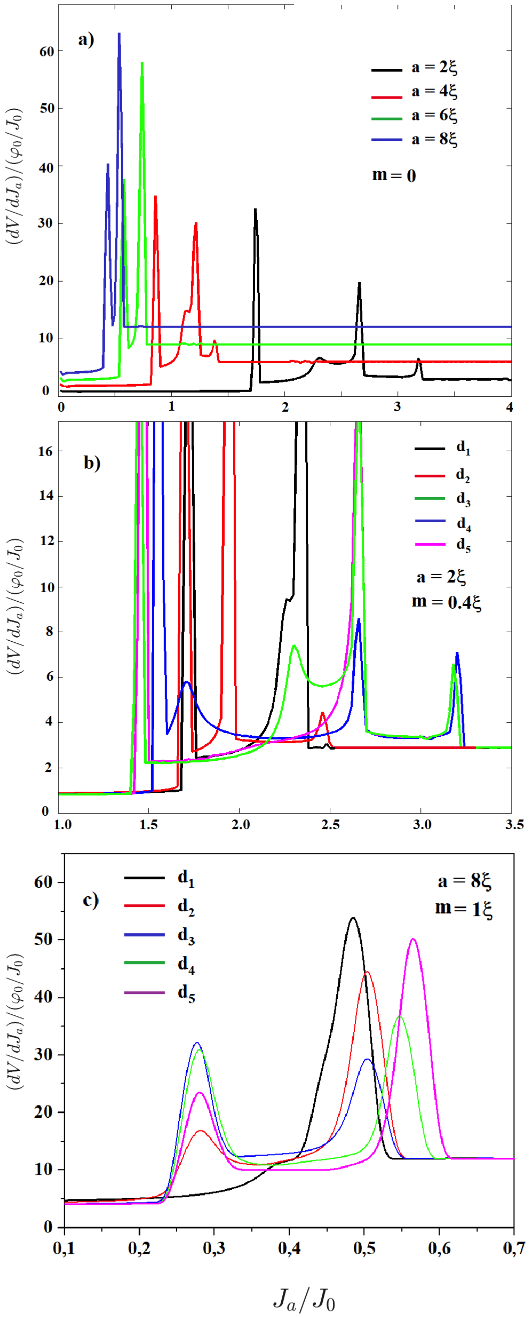

Figure 3. (Color online) Resistivity $\partial V/\partial J_a$, as function of the applied current-density J_a for a) Homogeneous sample with $a/\xi = 2,4,6,8$, (b) $m = 0.4\xi$, $a = 2\xi$ and the chanel positioned in $d_1 = 5.6\xi$, $d_2 = 4.2\xi$, $d_3 = 2.8\xi$, $d_4 = 1.4\xi$, $d_5 = 0$ (as is evident this value simulates a centered channel), measured from the center of the sample, and c) $m = 1\xi$, $a = 8\xi$ and a channel positioned in $d_1 = 5.6\xi$, $d_2 = 4.2\xi$, $d_3 = 2.8\xi$, $d_4 = 1.4\xi$, $d_5 = 0$.

pairs, increasing a and d has a strong influence on the creation of $v-Av$ pairs. In addition, it is shown that the maximum of the peaks in the resistivity

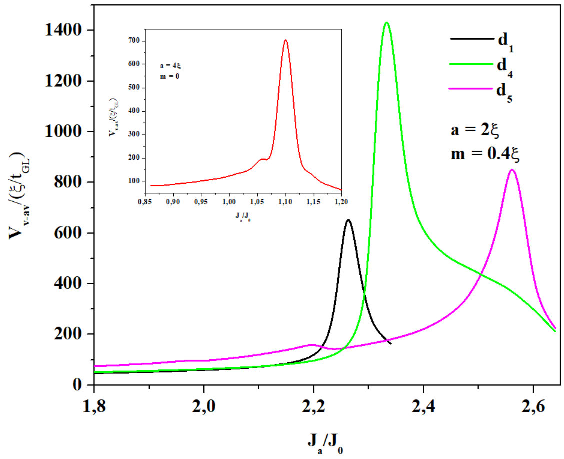

Figure 4. (Color online) Average velocity of the *V-Av* pairs for $a = 2\xi$, $m = 0.4\xi$ and $d_1 = 5.6\xi$, $d_4 = 1.4\xi$, and $d_5 = 0$. (Inset) $a = 4\xi$, $m = 0$.

curve increase as a increases for a sample without a channel, but this maximum does not show any variation when taking a constant a and varying the channel distance d.

In Figure 4, the velocity of a $v-Av$ pair during the annihilation process ($v-Av$ interaction) is plotted for $a = 2\xi$, $m = 0.4$ and $d_1 = 5.6\xi$, $d_4 = 1.4\xi$, and $d_5 = 0$. And for a homogeneous sample with $a = 4\xi$,(Inset).

We note that the value of the current where the maximum of the velocity of the kinematic vortices diminishes as d decreases. So, due to the presence of the defect in the sample, the kinematic vortices movement is directly affected by the presence of the channel, and due to that, the interaction is due to the oscillations of the phonos of the crystalline network, which could be in out of phase, due to the difference of the electronic density of the $v-Av$ pair. As we showed in the reference [22], the $V-Av$ pairs are nucleated at the edge of the sample and annihilate each other at the center, in our system not is possible to appreciate this dynamic (Figure 5), maybe due to the size of the computational mesh. It is very interesting to note (Figures 5 (b,c)), that when the channel is at a distance $d_4 = 1.4\xi$, and only for this case, and considering $J = J_1$, the kinematic vortices are created in a line perpendicular to the current applied in that position. Quite the contrary of the other cases, when $J \neq J_1$ is considered, this line is created in the center of the sample. In a

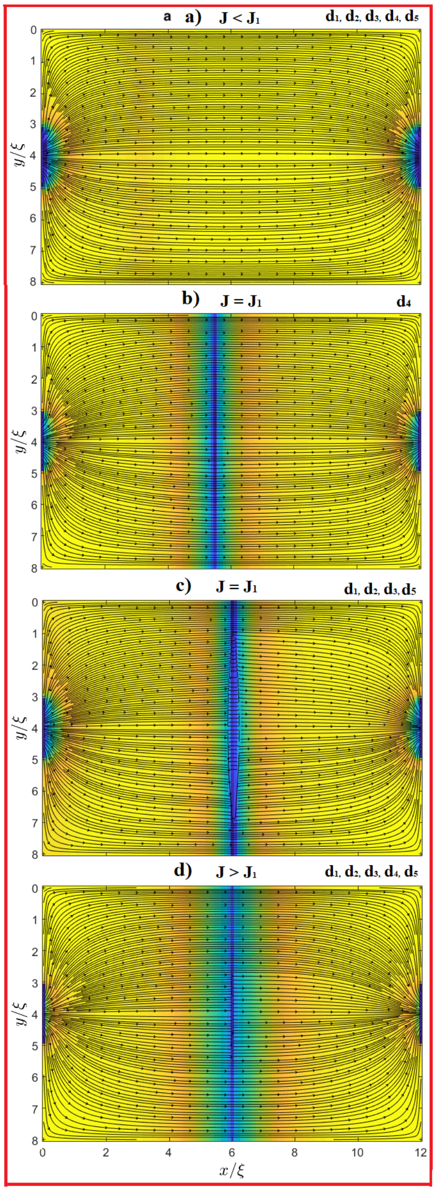

Figure 5. (Color online) Snapshots of the logarithm of the order parameter, $ln|\psi|$ (yellow/blue corresponds to largest/zero $|\psi|$) for a) $J < J_1$ for all d; $J = J_1$ for b) d_4, c) d_1, d_2, d_3, d_5 and d) $J > J_1$ for all d.

previous work [22], we studied the resistive state of a superconducting strip with an engineered centered defect at different T_c. We found that the asymmetry induced by the defect affects the current distribution in the sample and the *V-Av* pair enters at the sample, not through the central line. We think that due to the small width of the channel m, only when the channel is located at d_4 does it have an asymmetric current distribution that affects the central entry point. In Figure 6, we plot the relationship between J_1 (J_2 and

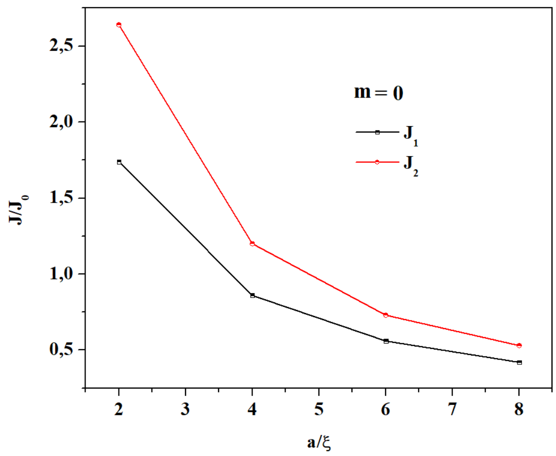

Figure 6. (Color online) Critical currents J_1 and J_2 as a function of the width of the contacts a, for a homogeneous sample $m = 0$.

the width of the metallic contact a. As can be seen, J_1 and J_2 decrease with a. $J_1 = 1.75$ for $a = 2\xi$, $J_1 = 0.82$ for $a = 4\xi$, $J_1 = 0.59$ for $a = 6\xi$ and $J_1 = 0.46$ for $a = 8\xi$, also, $J_2 = 2.69$ for $a = 2\xi$, $J_2 = 1.24$ for $a = 4\xi$, $J_2 = 0.74$ for $a = 6\xi$ and $J_1 = 0.52$ for $a = 8\xi$. The decrease of J_1 and J_2 means that for higher a, will be necessary to apply a small current to reach the normal state, it its due to the less diamagnetic the material will be. So the appearance of a resistive state occurs for smaller J_1 as a increases.

4 Conclusions

By solving the time-dependent Ginzburg-Landau equations, we studied the superconducting state of a mesoscopic thin film under a transport electric current at a zero magnetic field. A non-centered channel of depleted superconductivity is present in the sample. We vary the width of the metallic contact in which the external current is applied. The numerical solutions of the time-dependent Ginzburg-Landau equations show that critical currents diminished as the size of the metallic contact increases, also, the value of current where the maximum of the velocity of annihilation of the kinematic vortices occurs grows as the distance of the channel at the center to the sample increases. Finally the resistive state in stripes can be controlled by a pulsed current, in case of stroboscopic resonances with the induced v-av motion.

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