Ferromagnetic/superconducting interface in a hybrid nanoscopic disc

J D González[1],[2], J L Aguilar[1], J Barba-Ortega[2]

[1] Departamento de Física, Universidad del Magdalena, Santa Marta, Colombia
[2] Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia

E-mail: jedgonzalezac@unal.edu.co

Abstract. The oscillations exhibited by the magnetization of superconducting nano and mesoscopics structures as a function of the applied magnetic field has attracted attention in the last few years. Nano/Mesoscopic hybrid systems in contact with ferromagnets exhibit interesting transport properties related to the influence of the exchange field on the density of states of clean ferromagnetic structures in contact with superconductor. In this work we study the vortex configurations in a superconducting disk with one central defect inside. The sample is surrounded by a ferromagnetic medium. We calculate the spatial distribution of the Cooper pairs and the phase of the superconducting order parameter and curves of magnetization and vorticity as a function of the magnetic applied field. We found that the first vortex penetration field decrease when a ferromagnetic/superconducting interface is used.

1. Introduction

We studied physical phenomena which appear when two mutually exclusive states of matter, superconductivity and ferromagnetism, are combined in a unified ferromagnet-superconductor hybrid (FSH) system. In the hybrid systems fabricated from materials with different and even mutually exclusive properties, a strong mutual interaction between subsystems can dramatically change properties of the constituent materials, in consequence, the spatial distribution of the Cooper pairs, the phase of the superconducting order parameter, vorticity and magnetization. The interplay of superconductivity and ferromagnetism has been thoroughly studied experimentally and theoretically [1, 2] for homogeneous system. In this paper, we solved the time dependent Ginzburg Landau (TDGL) equations for a superconducting thin disc with central pentagonal barrier (red), surrounded with a ferromagnetic material (blue) Fig.1.

2. Theoretical Formalism

The general form of the time dependent Ginzburg-Landau equations in the zero electric potential gauge are given by [3]−[5]:

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

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

In Eqs. (1) and (2) dimensionless units were introduced as follows: $|\psi|$ is the order parameter
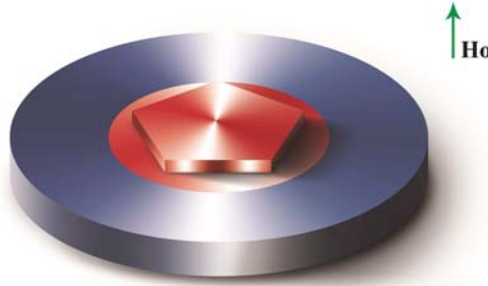
Figure 1. Layout of the studied sample: Superconducting thin disc with central pentagonal barrier (red), surrounded with a ferromagnetic material (blue).

in units of $\psi_\infty(0) = \sqrt{-\alpha(0)/\beta}$, where $\alpha(0)$ and β are two phenomenological constants; lengths in units of the coherence length $\xi(0)$; time in units of $t_0 \equiv \pi\hbar/8K_BT_c$; A in units of $H_{c2}(0)\xi(0)$, where $H_{c2}(0)$ is the second critical field, temperature in units of the critical temperature T_c [4]. For a very thin disk of variable thickness, Eq. (1) can be rewritten as [6]−[9]:

$$\frac{\partial\psi}{\partial t} + \frac{1}{F}\left(i\nabla + \mathbf{A}_0\right)\cdot F\left(i\nabla + \mathbf{A}_0\right)\psi - \psi + \psi^3 = 0 \tag{3}$$

where $F(r,\theta)$ is just a function which describes the thickness of the sample [10, 11]. In this case, the magnetic field can be taken nearly uniform inside the superconductor $\mathbf{H}_0 = \nabla \times \mathbf{A_0}$, so that Eq. (2) do not need to be solved.

3. Results and Discussion
We consider $F(r,\theta) = 1$ everywhere, except at defects position in the disk which are simulated by using $F = 1.2$ for the pentagonal barrier, see Fig.1. The parameters used in our numerical simulations were: $\kappa = 0.885438$, $T = 0.0$, $b = 0$ simulating the ferromagnetic boundary. The applied magnetic field was ramped in steps of $\Delta H = 10^{-4}$. Fig.2 (left) shown the magnetization as a function of increasing applied magnetic field, this curve exhibit the first clear jump at the field $H_0 = 0.8041H_{c2}(0)$ corresponding to the first entrance of vortices into the sample. The magnetization drops to zero for a value of the applied magnetic field $H_0 = 1.2464H_{c2}(0)$, therefore, our sample reaches the normal state. The Fig. Fig.2(right) shows the number of vortices entering whereas the applied magnetic field is increased. Following the jumps from the left to the right, in this order, we can see how many vortices there is in the sample for different values of $H_0/H_{c2}(0)$. When higher values of magnetization is reached, the contour plot of the phase of the superconducting order parameter is useful to determine the number of vortices into the sample. It is possible, by counting the phase variation in a closed path around this region. Values of the phase close to zero are given by blue regions and close to 2Φ by red regions. In Fig. 2 (right)(inset) shows the contour plot of phase of order parameter, additionally of the number of vortices in the superconductor, also is possible see their positions in the sample. For a value of $H_0 \approx 0.8149H_{c2}(0)$ we can see that the vortices are in outermost part of the disk, due to the repulsion caused by the defect, for this reason the vortices are not found inside. But by increasing the applied magnetic field, the pressure generated by the number of vortices in the superconductor exceeds the repulsion due to pentagonal barrier and the vortices can penetrate into the defect as shown in the graph of phase for a value of $H_0 = 1.0546H_{c2}(0)$. The panels of Fig. 3 (line up) show several spatial pattern of the order parameter for a disk with a pentagonal
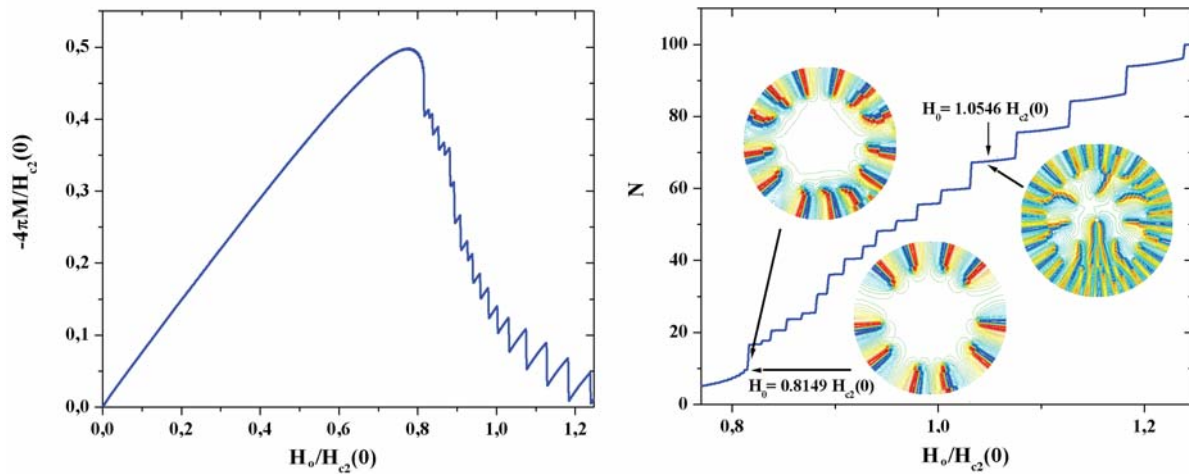
Figure 2. a). Magnetization curve (left) and vorticity N (right) as a function of the external applied magnetic field (the phase of the superconducting order parameter inset)
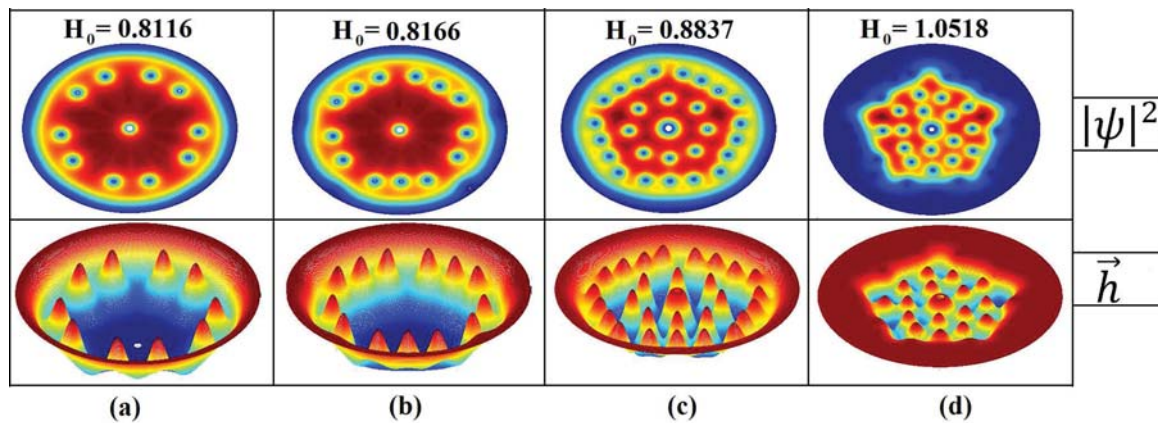

Figure 3. (Color online) The vortex structure in the indicated magnetic field for proposed sample. (line up) Square modulus of the order parameter $|\psi|^2$, (line down) Magnetic induction $\vec{h}$.

barrier by using $b = 0$. Following the panels from the left to the right, from (a, d) we can see that initially at $H_0 = 0.8116 H_{c2}(0)$ pairs of vortices are located in every side of pentagono, whereas the blue region at the perimeter is the part of the disk which is reaching to normal state. When $H_0 = 0.8166 H_{c2}(0)$ is applied the number of vortices grows a 33 percent aprox., despite the small increment en H_0, however, at $H_0 = 0.8837 H_{c2}(0)$ its number reach almost 100 percent outside of defect and the vorticity $N_d = 8$ is obtained inside it. Fig. 3 (line down) shown the snapshot of the magnetic induction in which the red and/or blue regions indicate high and/or low values. We can see in the panel (a) and (b) that the blue color is centred on the disk and this confirm the Meissner effect on the pentagonal defect, so its behaviour is like type I superconductor. However, when the applied field reaches great values, the vortices penetrate the defects and the peaks of magnetic induction can even be counted (panel (c) and (d)).

4. Conclusions

We studied the effect of the geometry of a pentagonal barrier on the thermodynamical properties of a mesoscopic superconducting disk solving the time dependent Ginzburg-Landau equations. We take the value for the deGennes parameter $b = 0$, simulating a sample with its lateral surface sorrounded by a ferromagneto. Our results have shown that the vortex configuratin depend strongly of the chosen boundary condition and the nature of the defects, it is seen in the order parameter figure, for small changes in the applied magnetic field, the ferromagnet boundary encourages the entry of vortices.

5. Acknowledgments

6. References

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