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Nuria Del-Valle, Carles Navau, Alvaro Sanchez, and Rafael B. Dinner

Transport critical-current density of superconducting films with hysteretic ferromagnetic dots

Nuria Del-Valle,[1,a] Carles Navau,[1] Alvaro Sanchez,[1] and Rafael B. Dinner[2,b]

[1]Grup d'Electromagnetisme, Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), Spain
[2]Department of Materials Science and Metallurgy, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ, UK

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Superconductor-ferromagnet hybrids present a rich and complex phenomenology. Particularly, a hysteretic behavior on the transport critical-current density, as a function of a uniform perpendicular applied field, has been experimentally found in superconducting films with some embedded ferromagnets. Here we analyze the interaction superconductor-ferromagnets by means of an iterative model based on the critical-state model with field-dependent internal critical-current density and compare the results with actual transport measurements. By using arguments of field compensation, we show how the change in the magnetization of the ferromagnetic inclusions is responsible for the observed hysteresis on the transport critical current. [http://dx.doi.org/10.1063/1.4732314]

The capability of carrying current without losses is a fundamental property that makes superconductors (SCs) attractive for power applications. However, lossless conductivity is limited to current densities lower than a critical value, J_c, so increasing J_c has been one of the most important challenges in superconductivity during the last decades.[1] In all transport applications, the superconductors are immersed in magnetic fields (at least the self field created by the supercurrents) and it is known that, in general J_c decreases with the applied field.[2] For this reason, it is interesting not only to increase J_c in general, but to do so when there are applied magnetic fields.

How can J_c be increased at a given applied field? There are different approaches to achieve this. One of them is to increase the internal pinning landscape by introducing different types of defects that can act as pinning centers in order to prevent the movement of vortices.[3–5] Another way is to introduce an adequate additional magnetic field that can reduce the local one in superconducting regions. This additional field can be due to the presence of ferromagnetic materials (FMs) that can be located close to the superconductor[6–8] or even inside it.[9–16] The introduction of the FMs inside the SCs can also modify the intrinsic pinning and this is known as magnetic pinning.

When increasing J_c by the interaction with some FMs, two types of effects can appear, in general, when measuring J_c in both transport (current is fed into the SC via an external source) and magnetic (current in the SC is induced by an external field) cases. One effect appears in SC-FMs hybrid systems with ferromagnetic parts in the form of ordered structures such as periodic arrays of magnetic dots,[17,18] antidots[19] or even inclusions,[15] for which peaks or plateaus appear in the applied-field dependence of the critical current and magnetization curve. These effects are commonly known as matching effects and they are produced when an integer number of vortices commensurates at the artificially induced pinning lattice at certain external magnetic fields. These effects are usually studied within Ginzburg-Landau formalism.[20]

[a]Electronic mail: nuria.delvalle@uab.es
[b]Present address: Areté Associates, 9301 Corbin Ave, Northridge, CA 91324, USA

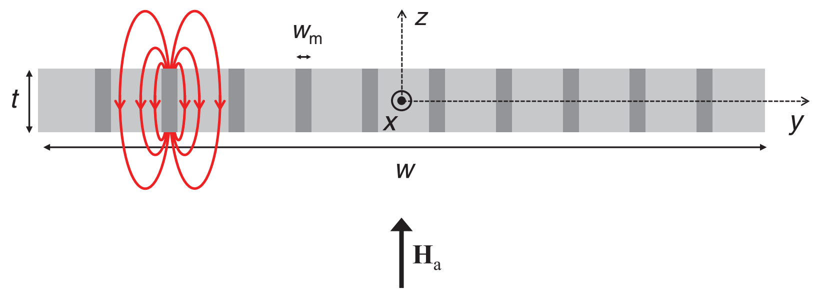

FIG. 1. Sketch of the cross-section of the simulated system where the light and dark regions correspond to superconducting and ferromagnetic regions, respectively. As an example, the field lines created by one of the FMs with magnetization parallel to the applied field on the neighboring superconducting regions are also sketched.

Another important effect observed in transport and magnetic measurements is the different response of the SC, in absolute value, when subjected to processes of descending or ascending applied field (applied field starts from large positive value and then decreases to reach a large negative value or from large negative value to large positive one, respectively). We refer to this effect as hysteretic behavior and it is related to the magnetic interaction between SC and FMs and the existence of hysteresis in the ferromagnetic materials. The results of Refs. 13–15 present the hysteretic behavior in the transport critical-current density versus applied field curve, and in Refs. 14 and 16 a similar hysteretic behavior is also visible in the superconducting magnetization loop which is dependent on the relative direction of ferromagnetic magnetization and measuring field. Although in these experimental works some explanations of the hysteretic response are attempted, there is not a single general idea that can explain the hysteresis of all the results. This is our aim in this work. Here we present a combination of theoretical calculations and experimental measurements that reproduces the hysteretic behavior observed in previous experiments based on the idea of field compensation.

In our numerical model we consider an infinitely long (in the x direction) type-II superconducting strip of rectangular cross-section located at $-w/2 \leq y \leq w/2$ and $-t/2 \leq z \leq t/2$. Inside this strip there are N identical FMs, uniformly distributed, also infinitely long in the x direction with a width w_m in the y direction and with the same thickness as the strip t in the z direction. Both SC and FMs are immersed in a uniform applied field $\mathbf{H}_a = H_a\hat{\mathbf{z}}$. A sketch of the simulated system is shown in Fig. 1. The SC is assumed to obey the critical-state model (reversible magnetization is disregarded) with a field-dependent critical-current density $J_c(H_i)$, where H_i is the modulus of the total magnetic field (the sum of the applied field, the field of the FMs, and the self field created by the SC currents). Thus, we take into account the demagnetizing effects arising from the thin-film geometry but we disregard the effect produced by the finite length of the tape.

In order to obtain the J_c distribution of the superconducting regions we follow an iterative procedure similar to that described in.[21,22] First, the superconducting zone is discretized in infinitely long (in x direction) cells of rectangular cross-section in the yz plane, and it is assumed that the critical-current density in each cell k, $J_{c,k}$, is uniform over the cell and with a value given by the Kim's critical-state model equation[23]

$$J_{c,k}(H_i) = \frac{J_{c0}}{(1 + H_{i,k}/H_0)}, \qquad (1)$$

where J_{c0} and H_0 are constants and $H_{i,k}$ is the total magnetic field at the center of the cell k. Then, the iterative procedure starts by setting $J_{c,k} = J_{c0}$ for all k's. With this current-density distribution, the total magnetic field is calculated and a new set of $J_{c,k}$ is found using Eq. (1). In each iteration step, the transport J_c is calculated as the sum of all the $J_{c,k}$ values divided by the number of cells. The iterative process is repeated until the difference between two consecutive evaluations of J_c is less than $10^{-6}J_{c0}$.

The choice of this Kim dependence is based on the experimental results of Ref. 15, where the response of superconducting niobium thin films is analyzed when through-thickness nanoscale pores

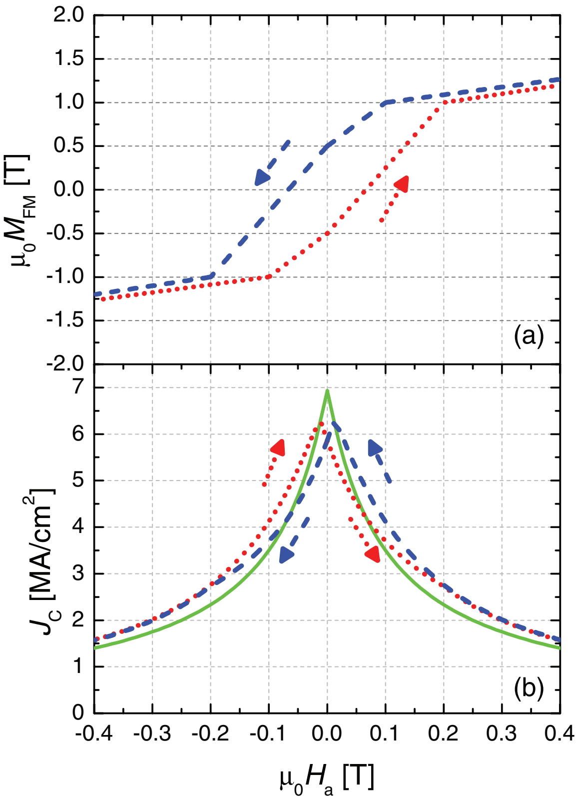

FIG. 2. (a) Magnetization loop of the each FM where the dashed and dotted lines indicate increasing and decreasing applied field, respectively. (b) Critical-current density J_c of the SC as a function of the applied field $\mu_0 H_a$ where the dashed and dotted lines correspond to the case of FMs following the descending dashed and the ascending dotted curves of (a), respectively, and the solid line corresponds to the case of demagnetized FMs. The solid line is practically identical to the $J_c(H_a)$ function.

are drilled via an anodized aluminum oxide template and then these pores are backfilled with the magnetic material cobalt. In these experiments, the measured transport J_c of the niobium plain film as function of the applied field obeys a Kim-like dependence. When the film is milled, the transport J_c curve shifts to larger values but mantaining the shape. Except for the fields around the matching field, there remains a decreasing behavior with the applied field of Kim's type. Also, a similar behavior is obtained when the cobalt is added, with a reduced J_c. For this reason, in our model we assume, as a first approximation, that the commensuration and hysteresis effects are uncoupled. We consider that the pinning effects caused by the FM inclusions become part of the pinning of the SC matrix by changing the parameters of Eq. (1), and assume that the only role of the FM inclusions is to modify the local magnetic field.

Choosing typical parameters of the experimental works,[15] our simulated system has dimensions $w = 33.77\mu$m, $w_m = 67$ nm, and $t = 33.5$ nm, and the parameters of the Kim dependence are $J_{c0} = 7$MA/cm^2 and $\mu_0 H_0 = 0.1$T. Inside the SC we consider $N = 100$ FMs with a magnetization in the z direction that obeys the magnetization loop in Fig. 2(a), which tries to reproduce in a simple (linear) way the experimental magnetization loop of the ferromagnetic material in the Ref. 15. We also assume that the FMs only respond to the applied field, which can be justified because, in our case, both the self field created by the SC and the magnetic field created by the ferromagnetic neighbors are small compared to the applied field (the maximum self field is 4 mT and occurs without FMs and the maximum magnetic field that a FM feels because of the ferromagnetic neighbors is 12 mT and occurs at the saturation).

Figure 2(b) shows the calculated transport J_c of the SC with FMs inside as a function of the applied field H_a when $\mu_0 H_a$ starts from large positive value (1T) and decreases to reach a large negative value (-1T) (descending case, dashed line) and from -1T to 1T (ascending case, dotted line).

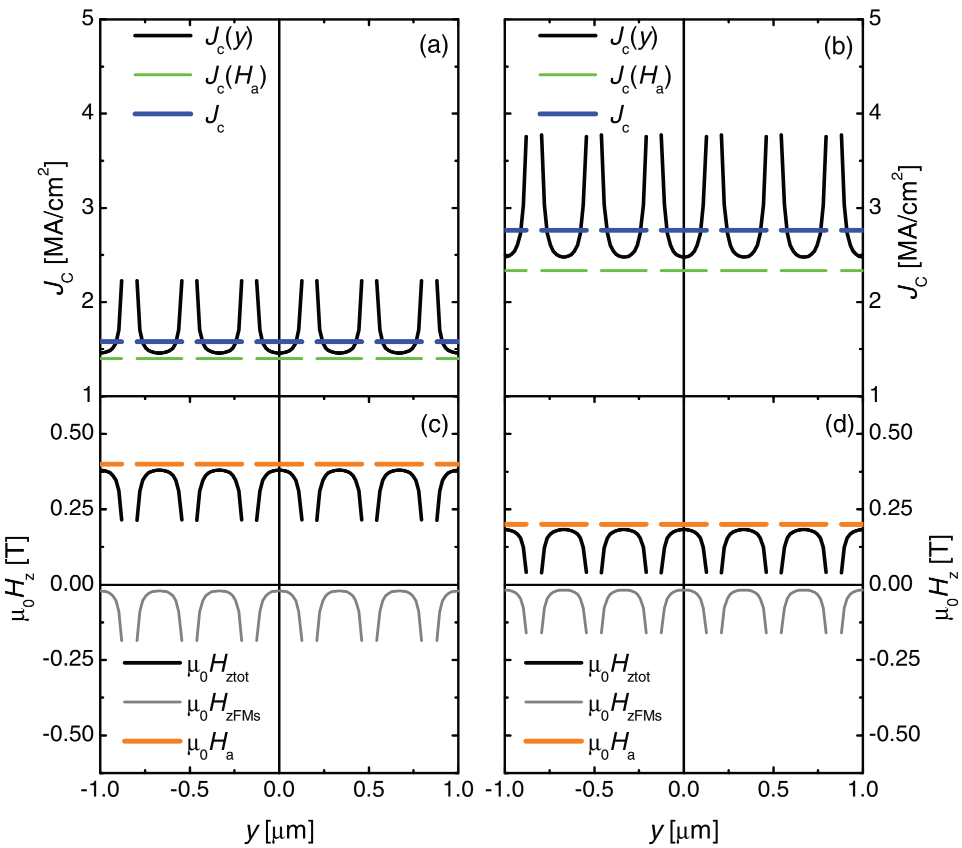

FIG. 3. Calculated local critical-current density $J_c(y)$ (top) and vertical component of total magnetic field $\mu_0 H_z$ (bottom) as functions of the horizontal position of the SC in the midplane when $\mu_0 H_a$ is 0.4T (left) and 0.2T (right) in the decreasing way. For comparison, on top the transport J_c, and the $J_c(H_a)$ function are also plotted, and, in the bottom part the applied field $\mu_0 H_a$ and the vertical component of the FM field $\mu_0 H_{zFMs}$. For the sake of simplicity, only the superconducting zones of the central region of the strip are shown.

For comparison, we also plot, in solid, the J_c of the SC when there are not FMs but only the holes. Since the self field of the supercurrents is very small, this curve is practically identical to the $J_c(H_a)$ function.

When the applied field is large and positive ($1\text{T} \geq \mu_0 H_a \geq 0.2\text{T}$), all the FMs have large positive magnetization, which creates a negative magnetic field in the superconducting zones, especially in the superconducting zones close the FMs, which opposes to the H_a and can reduce it. Nevertheless, this magnetic field is small compared with the applied one, so the total magnetic field felt by the SC is the applied field slightly reduced (see Figs. 3(c) and 3(d)). The FM magnetic field is not uniform and, consequently, neither is the local J_c profile (at midplane), $J_c(y)$. This J_c profile has a maximum of current density close the FMs, where the total magnetic field is small, and a minimum in the regions between the FMs, where the total field is large (see Figs. 3(a) and 3(b)). Since in all superconducting points the total magnetic field is smaller than H_a, the transport J_c, is larger than $J_c(H_a)$ (dashed curve is slightly higher than the solid one in Fig. 2(b)). If the applied field goes on decreasing, its partial reduction still holds, but when it is very small (0.01T), J_c has a maximum. At this point, the small applied field is compensated by the magnetic field of the FMs -also small-, the modulus of the total field is minimum, and J_c is maximum (see Figs. 4(a) and 4(c)). Naturally, the field is not perfectly compensated at all points in the SC, but on average is minimized. For zero applied field, the FMs remain magnetized creating a magnetic field that reduces J_c to a lower value than the case with only holes (solid curve is higher than the dashed one in Fig. 2(b)).

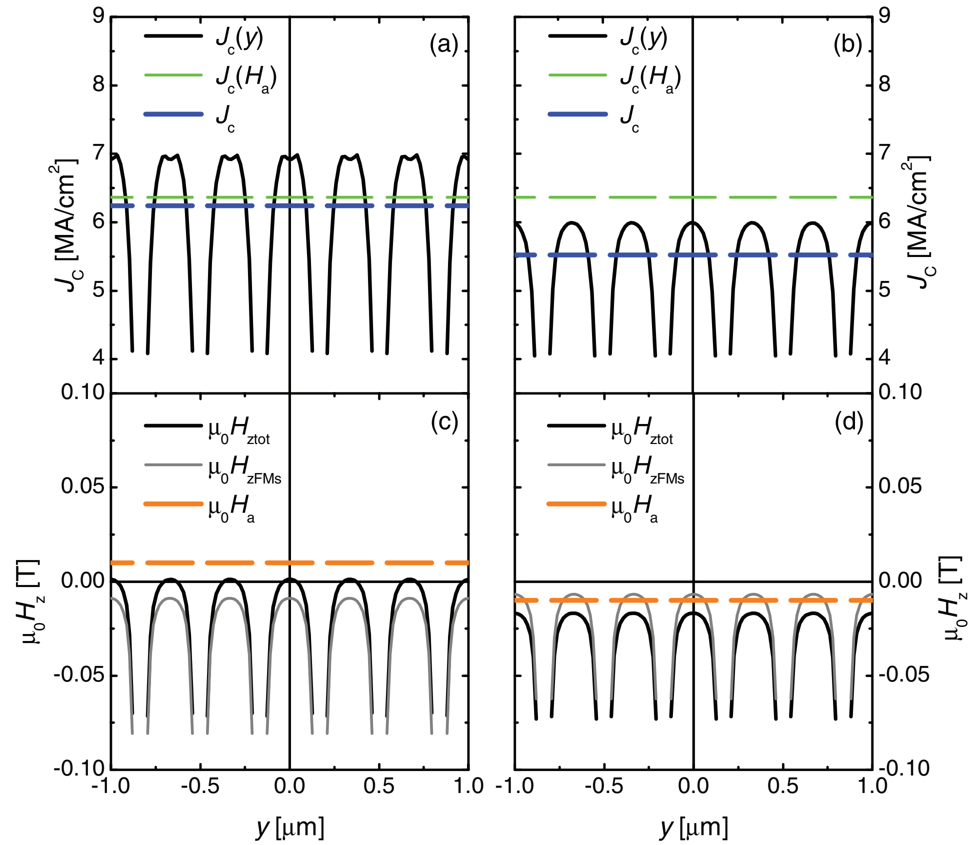

FIG. 4. The same as Fig. 3 but when $\mu_0 H_a$ is 0.01T (left) and -0.01T (right).

If the applied field is further decreased toward more negative values, there is no compensation by the field of the FMs but, on the contrary, an increase of the total magnetic field and consequently a reduction of J_c (solid curve higher than the dashed one in Fig. 2(b)). At small negative applied fields, the FMs are still positively magnetized and create a negative magnetic field in the superconducting zones that is added to the H_a (see Figs. 4(b) and 4(d)). However, when the applied field becomes more negative, the magnetization of the FMs becomes negative as well. This magnetization creates a positive magnetic field in the superconducting zones that partially reduces (in magnitude) the negative applied field, improving J_c (dashed curve higher than solid one in Fig. 2(b)). In this case there is not a maximum in the $J_c(H_a)$ curve because the applied field is always larger than the field of the FMs. Finally, for very large and negative applied field (-1T), all the FMs become saturated, this time negatively, and they create a maximum positive field in the SC but this magnetic field is small when compared with H_a and the field in the SC is basically the applied one.

In our case the magnetization loop of the FMs of Fig. 2(a) is antisymmetric, i. e., the behavior of the descending dashed curve for positive applied fields is the same as the ascending dotted curve for negative applied ones with the sign reversed, and vice versa. So the explanation of the behavior of the J_c for ascending applied field (dotted curve of Fig. 2(b)) is analogous to the case of descending applied field explained above.

We can also observe in Fig. 2(b) that around ±0.2T the dashed and dotted curves coincide. This fact is not surprising because, as seen in Fig. 2(a), around these fields the magnetization curves of the FMs start to be very similar.

The calculations shown in Fig. 2 reproduce quite well the hysteresis of J_c measured at 5K in Ref. 15 (except the matching field experimentally observed which is not the object of our model). Furthermore, our model can also simulate data at other temperatures by only changing the value J_{c0} in accordance with Ref. 24. If the J_c of same experimental system as[15] is measured at 4.5 K the Fig. 5(a)

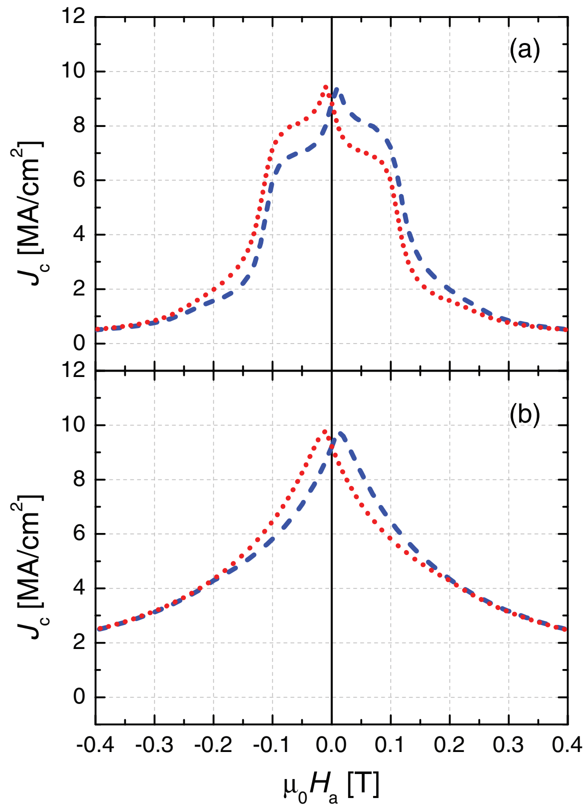

FIG. 5. (a) Measured critical-current density for the same system as Ref. 15 at 4.5 K as function of the applied field. (b) Calculated critical-current density where the parameters of the Kim dependence are $J_{c0} = 11\text{MA/cm}^2$ and $\mu_0 H_0 = 0.1\text{T}$.

is obtained. For comparison, in Fig. 5(b) is plotted the simulated system where the parameters of the Kim dependence are $J_{c0} = 11\text{MA/cm}^2$ and $\mu_0 H_0 = 0.1\text{T}$. Apart from the matching effect, a good agreement between calculated and experimental results can be observed.

In conclusion, we have theoretically explained by arguments of field compensation why a superconducting film with many embedded ferromagnets has a hysteresis in J_c and the presence of a maximum in J_c at non-zero applied field, effects widely observed in experiments. Although our model does not consider the matching effects present in some experiments, we can quantitatively reproduce the hysteresis observed in the transport critical-current density, using only experimental parameters. The conclusions are supported by experimental data at different temperatures. Our explanation of the hysteretic effect of magnetic materials on the superconductors properties may be a useful step to identify and study other effects observed in superconducting-magnetic hybrid systems.

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