Enhancement of synchronized vortex lattice motion in hybrid magnetic/amorphous superconducting nanostructures

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Superconducting a-Mo_3Si and Nb films have been grown on arrays of Ni nanodots. We have studied the vortex lattice dynamics close to critical temperatures. Different vortex lattice configurations are obtained with the same array unit cell. These different vortex lattices occur at matching conditions between the vortex lattice and the array unit cell. The interplay between the random intrinsic pinning of the superconducting films and the periodic pinning of the array govern the vortex lattice configurations. Different vortex lattice configurations and enhancement of synchronized vortex lattice motion are obtained by increasing the periodic pinning strength and decreasing the random pinning strength. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3103560]

Superconducting vortex lattice pinning and vortex lattice dynamics could be strongly modified by arrays of nanodefects embedded in superconducting samples. A state of the art can be found in the review by Velez *et al.*[1] This engineering of the superconducting samples could improve the performance of superconducting electronic devices, as for instance, making easier the reduction of noise due to unwanted vortices in the device,[2] or guiding vortices in devices based on vortex flow,[3] as for example, superconducting rectifiers.[4]

This topic has been studied using arrays of antidots[5] or array of dots.[6] In this work we study superconducting films with magnetic dots. Many effects have been reported on these hybrid samples, as effects induced by arrays made with different materials,[7] different diameters of the pinning centers,[8] and arrays with different symmetries.[9] In this work, we explore the effect of softening the strength of the intrinsic random pinning potentials. This goal can be achieved by using amorphous superconductors.

Amorphous superconducting films are powerful tools to study superconducting mixed state properties. Among them WGe, MoGe, and MoSi systems have called the attention of many researchers in the field. These works span from device related topics[10] to peak effect regime[11] or from interstitial vortex phases[12] to vortex dynamics.[13] In this work, we are going to benefit from the very appropriate structural characteristic of amorphous superconductors, i.e., the homogenous and isotropic intrinsic defects on the scale of the superconducting coherence length that these samples show. These hybrids develop vortex lattice configurations and increase the number of vortices, which move synchronized due to the enhancement of the periodic pinning potential strength in comparison with the random intrinsic pinning potential. We study this effect by the comparison of two kinds of superconducting/magnetic hybrids: (i) amorphous Mo_3Si (a-Mo_3Si) film on top of array of submicrometric Ni dots and (ii) Nb film on top of the same array of Ni dots as in the a-Mo_3Si film. We have chosen a rectangular array of 600×400 nm^2 Ni dots (array size is 100×100 μm^2) as the artificially fabricated pinning array, since this array in Nb film, induces a very rich scenario with vortex channeling effects[14] and a remarkable reconfiguration of the moving vortex lattice[15] from rectangular (600×400 nm^2) to square (400×400 nm^2) when the applied magnetic field is increased.

Electron beam lithography technique has been used to obtain a 600×400 nm^2 patterned array on Si substrates. Different Ni film thicknesses were deposited by sputtering technique. Arrays of Ni dots are obtained with two different thicknesses 40 nm and 80 nm. More details are in Ref. 16. Nb films and a-Mo_3Si films of 100 nm thicknesses are deposited on top of the arrays by magnetron sputtering technique, in the case of a-Mo_3Si films using two cathodes and coevaporation at room temperature. X-ray diffraction scan was used to test the amorphous character of these films. The hybrids have been patterned to a 40 μm wide square bridge. Magnetoresistance has been measured with magnetic field applied perpendicular to the film and using a commercial liquid He cryostat with superconducting solenoid and control temperature.

Magnetoresistance of superconducting thin films with periodic arrays of pinning centers show minima when the vortex lattice matches the unit cell of the array.[6] These minima are well defined since geometric matching occurs when the vortex density is an integer multiple of the pinning center density. Two types of vortices appear when the applied magnetic field is increased: vortices placed in the pinning centers and highly ordered interstitial vortices.[17]

Figure 1 shows the magnetotransport data in the mixed state in Nb film at $0.99T/T_c$ (Ni dot thickness is 40 nm). Rectangular array minima appear at applied magnetic fields $H_n=n\Phi_0/(a\times b)$, where a and b are the lattice parameters of the rectangular array and $\Phi_0=2.07\times10^{-15}$ Wb is the flux-

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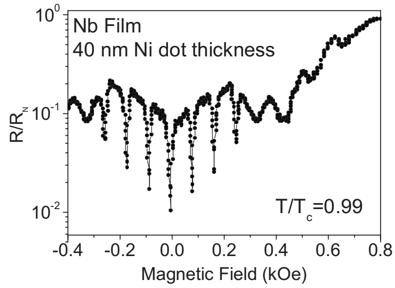

FIG. 1. Normalized resistance vs applied magnetic field for a 100 nm Nb film on top of a rectangular (400×600 nm^2) array of Ni circular dots (40 nm thickness, 200 nm in diameter) at $0.99T_c$ (T_c=8.5 K) and current density $J=2.5\times10^7$ A m^{-2}. Two sets of equally spaced minima are observed: low field spacing ΔH_1=83.2 Oe (corresponding to a rectangular unit cell vortex lattice of 400×600 nm^2) and high field spacing ΔH_2=108.7 Oe (corresponding to a square unit cell vortex lattice of 400×400 nm^2).

oid. The number of vortices n per array unit cell can be known by simple inspection of the magnetoresistance curves, in which the first minimum corresponds to one vortex per unit cell, the second minimum to two vortices per unit cell, and so on. In this sample, a vortex lattice reconfiguration occurs;[15] i.e., at low applied magnetic fields the vortex lattice shows a rectangular symmetry and, increasing the applied magnetic field, a crossover to a square lattice happens.

Magnetoresistance data of a-Mo_3Si film, at $0.99T/T_c$, (Ni dot thickness is 40 nm) are shown in Fig. 2. In this case, the matching effects are smeared out in comparison with the Nb film data. In a-Mo_3Si film two minima are only observed which correspond to a rectangular (600×400 nm^2) lattice. We can conclude that the strength of the Ni dot periodic pinning potential, in a-Mo_3Si superconducting system, is only able to synchronize the vortex lattice up to two vortices per array unit cell. In a-Mo_3Si film the periodic potentials (40 nm thick Ni dots) are not effective enough to slow down the moving vortex lattice and induce synchronized motion for a number of vortices higher than two. In the following, the effect of an enhanced periodic pinning potential induced by the Ni dots will be studied in both hybrid systems. One possible way to increase the pinning strength could be increasing the lateral dimension,[8] this approach has not been explored in this work. We want to keep the same array and the same dot diameter, therefore the only way to obtain deeper pinning potential is increasing the thickness of the Ni dots. The same kinds of samples (Nb and a-Mo_3Si films)

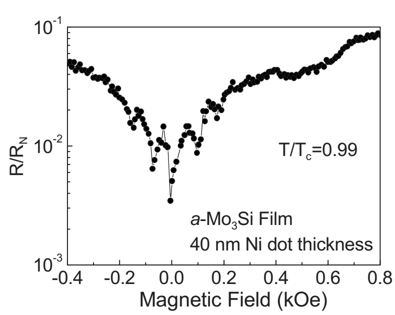

FIG. 2. Normalized resistance vs applied magnetic field for a 100 nm a-Mo_3Si film on top of a rectangular (400×600 nm^2) array of Ni circular dots (40 nm thickness, 200 nm in diameter) at $0.99T_c$ (T_c=7.5 K) and current density $J=0.9\times10^7$ Am^{-2}. Minima are observed with a field spacing ΔH=81 Oe (corresponding to a rectangular unit cell vortex lattice of 400×600 nm^2).

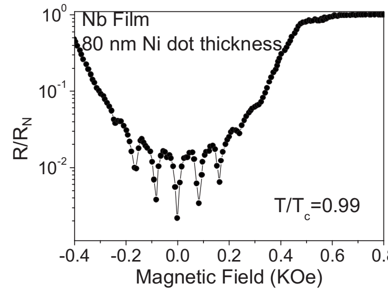

FIG. 3. Normalized resistance vs applied magnetic field for a 100 nm Nb film on top of a rectangular (400×600 nm^2) array of Ni circular dots (80 nm thickness, 200 nm diameter) at $0.99T_c$ (T_c=8.3 K) and current density $J=6\times10^7$ Am^{-2}. Minima are observed with a field spacing ΔH=81 Oe (corresponding to a rectangular unit cell vortex lattice of 400×600 nm^2).

were fabricated with 80 nm dot thickness, instead of dots with 40 nm thickness. Figure 3 shows the results in the case of Nb/Ni hybrid. The reconfiguration vanishes and only the rectangular vortex lattice appears. The hybrid sample Nb film (100 nm thickness) on array of Ni dots (80 nm thickness) shows lower upper critical field (see Fig. 3) than the former hybrid (100 nm Nb film/40 nm Ni dots, see Fig. 1). Therefore, the hybrid 100 nm Nb film/80 nm Ni dots is in the normal state when the crossover to the second lattice (square) would occur.

In the case of a-Mo_3Si film (100 nm thickness) on array of Ni dots (80 nm thickness), two new effects appear: (i) the number of minima is enhanced in comparison with the previous experimental data and (ii) the vortex lattice matches a 600×600 nm^2 square lattice (see Fig. 4). The subtle balance between the intrinsic potential and the periodic potential is the key to understanding this behavior with different vortex lattice configurations and different numbers of synchronized vortices in comparison with the until now known, most favorable matching condition for this rectangular array, i.e., rectangular vortex lattice 600×400 nm^2. In Nb/Ni hybrids with periodic pinning potentials 600×400 nm^2 Ni dots, these periodic potentials overcome the intrinsic defects and the driven vortex lattice could be matched exactly to the 600×400 nm^2 array (see Figs. 1 and 3). However, the intrinsic pinning landscape in amorphous film is homogenous and weak with a length scale similar to the vortex core. Therefore, the effects due to periodic potentials are enhanced and the ordered vortex lattices could be synchronized to matching conditions with larger lattice spacing, and hence

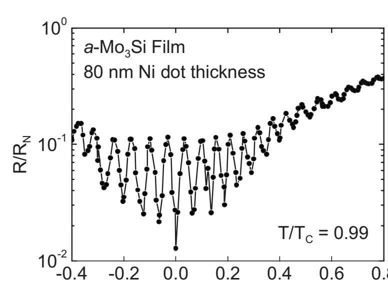

FIG. 4. Normalized resistance vs applied magnetic field for a 100 nm a-Mo_3Si film on top of a rectangular (400×600 nm^2) array of Ni circular dots (80 nm thickness, 200 nm in diameter) at $0.99T_c$ (T_c=7.5 K) and current density $J=2.5\times10^7$ Am^{-2}. Minima are observed with a field spacing ΔH=57 Oe (corresponding to a square unit cell vortex lattice of 600×600 nm^2).

lower matching field values. A $600 \times 600\ \text{nm}^2$ lattice is the lowest possible matching condition which the vortex lattice could fit, which corresponds to a magnetic field of 57 Oe. This is exactly the experimental value that is obtained (Fig. 4). This matching effect is achieved with an enhancement of the number of synchronized vortices; up to 14 minima are observed (Fig. 4). This underlines the overwhelming effect of the artificially induced periodic pinning landscape on the vortex lattice dynamics in the case of amorphous superconducting/magnetic array hybrids.

In summary, by decreasing the random intrinsic vortex pinning landscape (amorphous superconductors) and increasing the periodic pinning landscape (thicker magnetic dots) allows obtaining different vortex lattice configurations, and the number of synchronized vortices is enhanced. These superconducting/magnetic hybrids could be a promising tool to drive vortices out of superconducting devices or to get a net flow of a large number of ordered vortices with different vortex lattice symmetries.

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[1]M. Velez, J. I. Martín, J. E. Villegas, A. Hoffmann, E. M. González, J. L. Vicent, and I. K. Schuller, J. Magn. Magn. Mater. **320**, 2547 (2008).
[2]C. S. Lee, B. Janko, I. Derényi, and A. L. Barabasi, Nature (London) **400**, 337 (1999).
[3]J. Mannhart, Supercond. Sci. Technol. **9**, 49 (1996).
[4]J. E. Villegas, S. Savel'ev, F. Nori, E. M. Gonzalez, J. V. Anguita, R. Garcia, and J. L. Vicent, Science **302**, 1188 (2003).
[5]M. Baert, V. V. Metluskho, R. Jonckheere, V. V. Moshchalkov, and Y. Bruynseraede, Phys. Rev. Lett. **74**, 3269 (1995).
[6]J. I. Martin, M. Velez, J. Nogues, and I. K. Schuller, Phys. Rev. Lett. **79**, 1929 (1997).
[7]Y. Jaccard, J. I. Martin, M. C. Cyrille, M. Velez, J. L. Vicent, and I. K. Schuller, Phys. Rev. B **58**, 8232 (1998).
[8]A. Hoffmann, P. Prieto, and I. K. Schuller, Phys. Rev. B **61**, 6958 (2000).
[9]M. Velez, D. Jaque, J. I. Martín, F. Guinea, and J. L. Vicent, Phys. Rev. B **65**, 094509 (2002).
[10]S. Kubo, J. Appl. Phys. **63**, 2033 (1988).
[11]N. Kokubo, T. Asada, K. Kadowaki, K. Takita, T. G. Sorop, and P. H. Kes, Phys. Rev. B **75**, 184512 (2007).
[12]V. V. Metlushko, L. E. DeLong, M. Baert, E. Rosseel, M. J. van Bael, K. Temst, V. V. Moshchalkov, and Y. Bruynseraede, Europhys. Lett. **41**, 333 (1998).
[13]N. C. Yeh, D. S. Reed, W. Jiang, U. Kirplani, C. C. Tsuei, C. C. Chi, and F. Holtzberg, Phys. Rev. Lett. **71**, 4043 (1993).
[14]J. E. Villegas, E. M. Gonzalez, M. I. Montero, I. K. Schuller, and J. L. Vicent, Phys. Rev. B **68**, 224504 (2003).
[15]J. I. Martin, M. Velez, A. Hoffmann, I. K. Schuller, and J. L. Vicent, Phys. Rev. Lett. **83**, 1022 (1999).
[16]J. I. Martin, Y. Jaccard, A. Hoffmann, J. Nogues, J. M. George, J. L. Vicent, and I. K. Schuller, J. Appl. Phys. **84**, 411 (1998).
[17]V. Metlushko, U. Welp, G. W. Crabtree, R. Osgood, S. D. Bader, L. E. DeLong, Z. Zhang, S. R. J. Brueck, B. Illic, K. Chung, and J. Hesketh, Phys. Rev. B **60**, R12585 (1999).