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Mechanisms of periodic pinning in superconducting thin films

M.I. Montero[a], O.M. Stoll, and Ivan K. Schuller

Department of Physics, University of California San Diego, La Jolla, CA 92093, USA

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Abstract. We studied the changes in the superconducting properties of Nb films due to an array of Ni dots used as collective pinning sites. To determine the pinning mechanism, thin Ag layers of varying thicknesses were deposited on the Ni dots prior to the Nb film deposition. The Ag deposited on the pinning dots has little effect on the collective pinning phenomena, which implies that the main pinning mechanism is of magnetic origin.

PACS. 74.25.Qt Vortex lattices, flux pinning, flux creep – 74.78.-w Superconducting films and low-dimensional structures

1 Introduction

Vortex pinning in type-II superconductors displays a rich phenomenology that is interesting from a fundamental standpoint as well as essential for potential applications. Many mechanisms, including some of magnetic and/or non-magnetic origin, may contribute to vortex pinning with varying degrees of relative strength. The use of nanostructured periodic arrays has opened up the possibility for investigations on the microscopic origin of pinning and for studies of commensuration effects. In particular, nanostructured magnetic arrays produce periodic pinning structures in the resistivity, critical currents and magnetization of thin superconducting films. Although extensive research has been performed in this area, the origin of the pinning phenomena is not completely clear. One of the crucial issues is to distinguish between mechanisms which are magnetic or non-magnetic in origin. To solve this problem we studied a series of samples in which the regular magnetic pinning sites were gradually separated from the superconducting film, using a normal metal Ag separator.

Regular arrays of magnetic dots were fabricated using electron beam nanolithography. An Nb film is deposited on top of the dot arrays, creating a superconducting thin film with the magnetic dot array serving as artificial pinning centers. Previous studies have demonstrated that many factors including magnetic dot size [1], geometry [1–5], temperature [6], material [1,2], and non-magnetic dots [1–3,7–9], and holes [10–12] affect the pinning phenomenology. These experiments suggest that non-magnetic mechanisms play an important but not dominant role in vortex pinning, with the corrugation of the Nb film (leading to a locally depressed critical temperature) believed to be the strongest of these non-magnetic mechanisms.

This paper addresses the relative strength of the magnetic mechanisms responsible for vortex pinning by varying the interface between the magnetic dot and the superconducting thin film. The results presented here show that the collective pinning phenomena, as evidenced by clear periodic structure in the resistance vs. magnetic field, is very weakly affected by the Ag layer separator. This implies that there is a very strong contribution of magnetic origin to the collective pinning.

2 Experiment

Nanostructured array of magnetic dots were prepared using e-beam lithography as described earlier [13]. Briefly, a PMMA layer was spun onto a silicon substrate. After e-beam writing, DC magnetron sputtering is used to deposit Ni films, which are then coated with Ag layers of various thicknesses. Finally, the PMMA is lifted-off, leaving behind an array of Ag covered Ni dots. This procedure allows preparation of sub-micrometer dots, on the scale of the superconducting coherence length ξ (40 nm) and the magnetic penetration depth λ(500 nm). For this experiment, a rectangular array of $a \times b = 400$ nm $\times$ 900 nm was used (see Fig. 1).

Three of the four samples studied had Ag layers deposited on top of the Ni, with thicknesses of approximately 1.0 nm, 4.5 nm, and 9.0 nm (see Tab. 1). The remaining sample had no silver layer deposited. Finally, an 100 nm Nb film was sputtered on top of the dots.

Magnetoresistance measurements were performed in a magnetic field oriented perpendicular to the film plane. By convention, measurements began at a positive field (700 G) and incrementally decreased (in steps of 2 G) to

[a] e-mail: mmontero@ucsd.edu

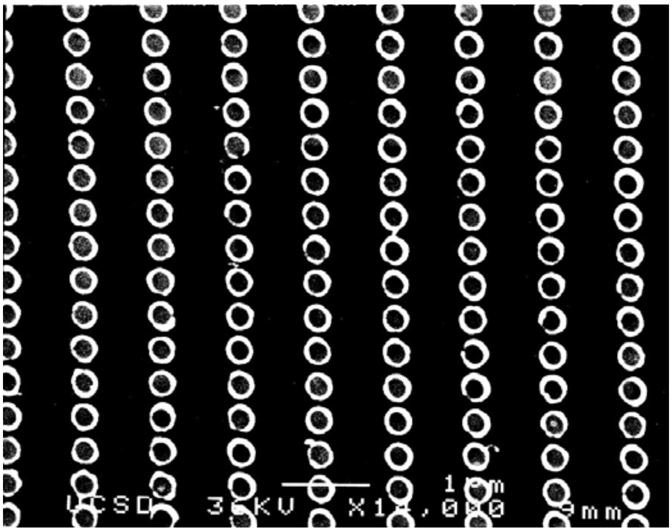

Fig. 1. Scanning electron micrograph of a 400 nm × 900 nm array of Ni dots fabricated using e-beam lithography.

Table 1. Sample characteristics. t_{Ni} is the Ni dot thickness, t_{Ag} is the Ag layer thickness, t_{Nb} is the Nb film thickness.

Sample	t_{Ni}[nm]	t_{Ag}[nm]	t_{Nb}[nm]	T_c[K]	ΔT_c[K]
A	∼27.0	-	∼100	8.3	0.05
B	∼32.0	9.5	∼100	8.3	0.08
C	∼30.0	∼4.5	∼100	6.4	0.15
D	∼30.0	∼1.0	∼100	6.4	0.09

a negative field (−700 G). The strongest matching effects, are generally observed in the range $T/T_c = 0.95-0.98$ and a wide range of currents (0.01 mA−1.0 mA).

3 Results

Figure 2 shows the magnetoresistance at various constant currents for the four samples, at $T/T_c \sim 0.98$. The samples of lower transition temperature (C and D) exhibit much weaker periodic pinning, a narrower superconducting region and an enhanced zero temperature resistance. Moreover, the samples with lower critical temperatures are symmetric about zero magnetic field as opposed to the samples of higher T_c (A and B) which are clearly asymmetric. No hysteresis was observed in either set of samples.

A striking difference is observed when the high T_c samples (A and B) are compared with the low T_c (C and D) ones. While samples A and B show marked periodic minima, C and D show very weak oscillations. The effect of the Ag layer is minimal in both sets of samples; i.e. addition of Ag at the interface affects in a minor way the flux flow resistance curves.

4 Discussion

In general there are two types of pinning mechanisms, which maybe operating in these experiments: magnetic and non-magnetic in origin. Normal pinning mechanisms maybe caused by: ordinary proximity effect which may depress the superconductivity in the region above the dot, and corrugation of the Nb films may depress the superconducting properties of the Nb at the edges of the dots. Three magnetic mechanisms have been suggested as being partially responsible for vortex pinning [6–9,14]: the high permeability of the dots relative to the film, the interaction of the stray fields of the dots with the vortices, and the ferromagnetic proximity effect, caused by diffusion of spin-polarized electrons from the dots into the superconductor. Earlier experiments with Ni dots and antidots, where structural and magnetic mechanisms were compared, suggest that it is the latter two that may be responsible [6,15]. The thin Ag layer would strongly affect the nonmagnetic mechanisms and would have only very slight effects on two first magnetic mechanisms. It was found that the injection of spin polarized electrons from a ferromagnetic material into a normal metal is strongly depressed if there is a resistivity mismatch between the two layers [16–18]. Therefore the magnetic proximity effect may be affected the most by a non-magnetic barrier between the Ni dots and the Nb film. The relative insensitivity to the Ag thickness, especially for the samples with the highest T_c, suggests that the magnetic proximity effect is not the main mechanism operating here. This is consistent with the relatively weak sensitivity to the type of ferromagnetic material used for pinning [19].

The pinning strength in this experiment is very different in samples that have different critical temperatures (see Fig. 2). A very thin Ag layer is not expected to substantially alter the transition temperature of Nb films, because in all these experiments the Nb thickness is much larger than the coherence length ξ bulk ($\xi \sim 40$ nm) [20] or thin film ($\xi \sim 20-40$ nm) [21] Nb. On the other hand the superconducting properties of Nb thin films depend very strongly on the preparation conditions (pressure, rate, substrate temperature, etc.) [22,23]. In particular, in Nb strong changes in the superconducting transition temperature and pinning were found earlier with disorder in bulk and thin film. The depression of the superconducting transition temperature thus is an indication of the amount of background pinning present. This background pinning masks the periodic pinning due to the magnetic arrays and for this reason the periodic pinning in the samples with depressed T_c is strongly reduced.

To avoid any possible influence of T_c on our conclusions we compare the two samples with lower critical temperatures to each other, and likewise the ones with higher critical temperatures. In the case of the two samples with low critical temperatures, we find that the pinning is only slightly weaker for the sample with the thicker silver layer. In the samples with higher T_c the periodic pinning and the background are very similar in the sample with zero and 9.5 nm of Ag.

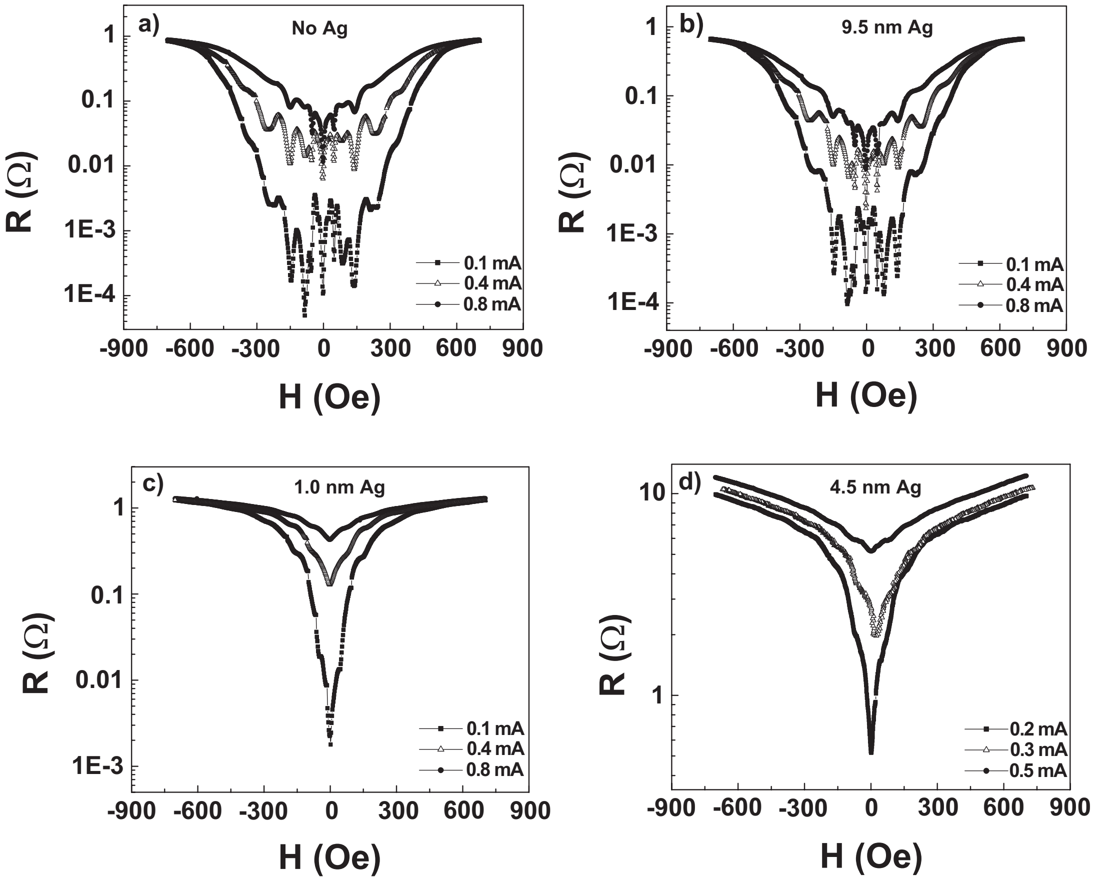

Fig. 2. Resistance vs. applied field measured at $T/T_c = 0.98$ with different current for samples: a) with no Ag (sample A), b) with 9.5 nm Ag (sample B), c) with 1.0 nm Ag (sample D) and d) with 4.5 nm Ag (sample C) measured at $T/T_c = 0.963$.

The possibility that the spin diffusion length [24] could be greater than 10 nm (the thickest Ag layer) and that the Nb-Ag interface has a negligible depolarization effect must be considered. This would imply that the Ag layer should have a small effect on the periodic pinning as observed here. More theoretical work and/or samples with even thicker Ag layers would be necessary to test this hypothesis specifically. However, our experiment has already shown that the Nb-Ag interface does not seem to be of crucial importance. In any case, all this points to the fact that the pinning mechanism is magnetic in origin.

The reconfiguration of the vortex lattice gives further support to the above-mentioned ideas. This reconfiguration manifests itself as a change in the periodicity and shape of the matching peaks as shown earlier [4]. A way to quantify this is by plotting the field positions of the various collective matching peaks as a function of order n. The reconfiguration is signaled by a change of the slope of this curve as shown earlier [4]. For the high T_c samples, where the collective matching peaks are clearly observed, their positions in Figure 3 are virtually identical. Since the Ag layer separator affects neither the shape, depth, nor positions of the periodic matching peaks, we must conclude that the pinning effect is dominated by a magnetic mechanism.

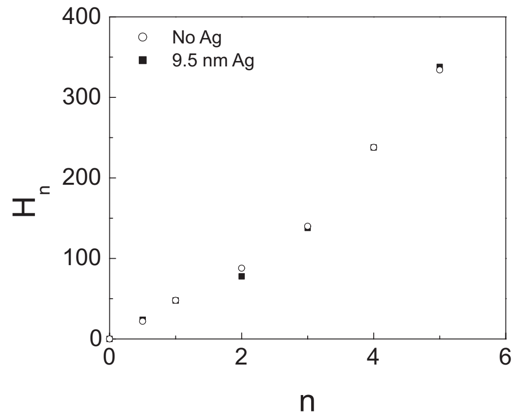

Fig. 3. Matching fields vs. index number for sample with none Ag and sample with 9.5 nm Ag as extracted from Figure 2 for $I = 0.1$ mA and $T/T_c = 0.98$.

5 Conclusions

In summary, the periodic pinning in the resistance vs. magnetic field curves are strongly dominated by the background pinning, which is connected to the T_c of the Nb films. We have shown evidence that neither the simple proximity effect nor the corrugation play a dominant role for periodic pinning. Thus periodic pinning with magnetic nanostructures is possibly controlled by magnetic effects in which the vortices prefer to sit on top of magnetic dots. For this reason the effects on the transport properties of samples with magnetic dots are much stronger than the ones with holes.

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