Magnetic pinning of the vortex lattice by arrays of submicrometric dots

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We have prepared regular square arrays of Ni and Ag dots with typical diameter and thickness approaching characteristic low-T_c superconducting length scales. The transport properties of Nb films, grown on top of these dots, were studied in a wide temperature and magnetic-field range. The Ni dots act as pinning centers, thereby producing oscillations in the field dependence of the resistance and critical current of the Nb film. The periodicity of the oscillations corresponds to the matching field of the dots lattice spacing. Such an oscillatory behavior is absent for arrays of nonmagnetic Ag dots. The comparison between the two types of arrays implies a magnetic origin of the enhanced pinning effect. [S0163-1829(98)03737-0]

New technologies provide the means for the preparation of controlled structures of size comparable to the important length scales which control the physical properties of materials.[1] Artificial structures can be made with sizes of the order of the relevant length scales such as the coherence length ξ and the penetration depth λ of low-T_c superconductors. This has produced a renewed experimental[2–5] and theoretical[5–7] interest in pinning effects by ordered arrays of defects in type-II superconductors.

In 1957, Abrikosov[8] predicted the existence of the ''mixed state'' where the magnetic field B penetrates inside the superconductor in the form of vortices carrying one quantum of flux ϕ_0. In a clean superconductor (no defects), these vortices form a hexagonal lattice (the ''Abrikosov'' lattice) as confirmed experimentally by magnetic decoration experiments.[9] However, as soon as a driving force is applied, this vortex lattice moves producing dissipation. On the other hand, defects act as pinning centers which lock the vortex lattice and as a consequence increase the critical current. Many studies on artificially introduced ordered pinning centers have been focused on the effects of arrays of holes in superconductors such as Al films[10] and Pb/Ge multilayers.[3] The pinning of a vortex lattice by stray fields of μm size GdCo magnetic particles has been studied in Nb films.[11] Recently, synchronized pinning by hexagonal arrays of submicrometric magnetic dots was found in Nb films.[12]

In this work, we have studied the influence of regular, square arrays of magnetic and nonmagnetic dots in Nb films to analyze the relevant pinning mechanisms. The resistivity versus magnetic field of Nb films shows, in the mixed state, evenly spaced minima which appear only for the magnetic dots. The periodicity of the minima is given by the field corresponding to the magnetic dot array spacing, the so-called ''matching'' field. So, even a square array of pinning centers is able to pin the vortex lattice. A comparison with the monotonic dependence of the resistivity in the case of nonmagnetic Ag dots implies that this oscillatory behavior is related to the magnetic properties of the dots.

Briefly, 40-nm-thick Ag or Ni dot arrays were patterned using e-beam lithography and dc magnetron sputtering. On top of these dots, a 100-nm-thick Nb film was sputtered. Optical lithography and reactive ion etching (RIE) were then used to define a 40 μm wide bridge for the transport measurements. The fabrication details are found elsewhere.[13]

Figure 1(a) shows a scanning electron microscopy (SEM) image of a square lattice of Ni dots on a Si (100) substrate, after the e-beam lithography and the lift-off process. Typical dot diameters are of the order of 100 nm. Figure 1(b) shows an optical micrograph of the Nb film on top of the dot array after patterning. There are eight (vertical) voltage contacts which allow measurements of the sample or a reference Nb film without underlying dots.

Transport measurements were performed in a helium cryostat with a superconducting magnet and a rotating (precision of 0.5°) sample holder with the current and magnetic field perpendicular.

The measurements presented below have been made on a 100 ± 5 nm thick Nb film covering a square array of Ni or Ag dots. For both type of dots (Ni or Ag), their diameter and thickness are $c=200\pm20$ nm and $t=40\pm4$ nm, respectively, while the lattice spacing is $d=400\pm10$ nm. In both types of samples, the Nb bridge on top of the dots shows metallic behavior below room temperature and similar values of the superconducting critical temperatures.

Figure 2 shows the field dependence of the resistivity of the patterned Nb film on top of Ni or Ag dot arrays in a logarithmic scale. The pinning interaction between the magnetic Ni dot array and the vortices in the Nb film produces periodically spaced minima in the resistivity (see also the inset of Fig. 3 for a fixed angle) up to the eighth order. This behavior is reversible as the magnetic field is swept up and down and is independent of the magnetic-field sweep rate. The periodicity of these minima, $\Delta B=122\pm5$ G, corresponds to the matching field of the dot array[14] $B_m=\phi_0/d^2=129\pm7$ G with $d=400\pm10$ nm. This indicates that pinning is enhanced each time an integer number of vortices exists per unit cell of the array. On the other hand, the mixed-state magnetoresistance of the Nb film on top of the Ag dots is below the detection limit (0.1 $\mu\Omega$ cm) at low fields and increases monotonically until it saturates in the normal state above the critical field H_{c2}.

The two curves for the Ni sample (Fig. 2) show that the number of observed minima increases as the temperature is reduced. This implies that, at lower temperature, more vortices can be packed per unit area. This may be explained by

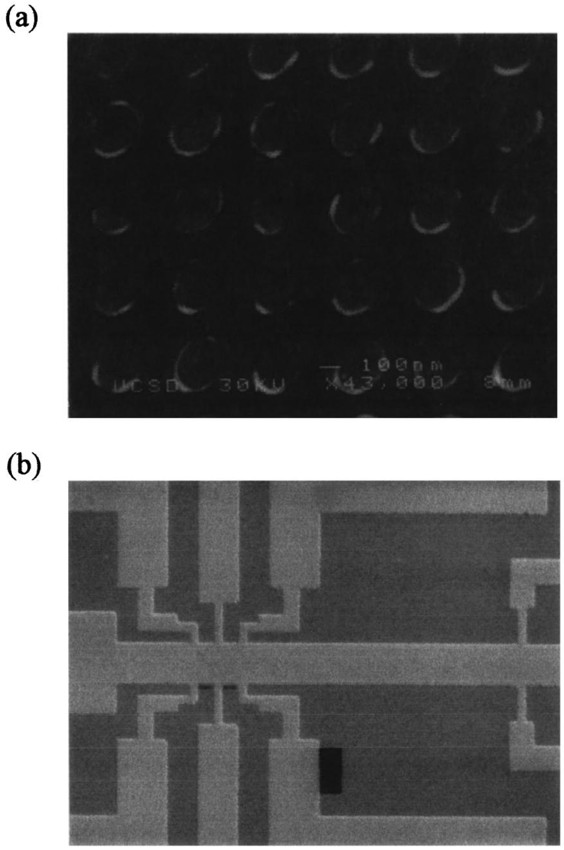

FIG. 1. (a) SEM image of a square array of Ni magnetic dots fabricated by *e*-beam lithography on a Si substrate. The lattice constant is $d=400\pm10$ nm and the Ni dots have a diameter $c=200\pm20$ nm. (b) Micrograph of the 40 μm width Nb bridge defined by optical lithography and RIE in the array region.

the decrease in coherence length or penetration depth with decreasing temperature, which allows a higher packing density. However, the number of observed minima saturates at about 8–9 at lower temperature. This underlines that the vortex-vortex interactions become important for a high vortex density.

The inset of Fig. 3 shows the dependence of the minima as a function of their order for various angles θ between the magnetic field and the sample normal. At a fixed angle, the various order minima lay on a straight line indicating that they are associated with integer number of vortices per unit area. The slope $\Delta B(\theta)$ of each line plotted as a function of angle (Fig. 3) reveals a dependence $\Delta B(\theta)=\Delta B(0)/\cos(\theta)$ with $\Delta B(0)=124\pm2$ G. This implies that only the perpendicular field component contributes to the pinning of the vortex lattice. Therefore the effect from the in-plane magnetization of the Ni dots should be negligible.[11]

The pinning effect by the array of magnetic dots can also be observed in the *I*-*V* characteristics of the Nb bridge patterned on top of the Ni dots. Figure 4 shows a set of *I*-*V* curves measured at different fields up to the first matching field. Between 0 and 64 G, the dissipation increases with magnetic field and, as a consequence, the critical current decreases. Above 64 G, the curves return to higher currents in such a way that the *I*-*V* characteristic closest to the matching field almost coincides with the zero-field one. This implies that the pinning by the periodic array is relevant in the whole

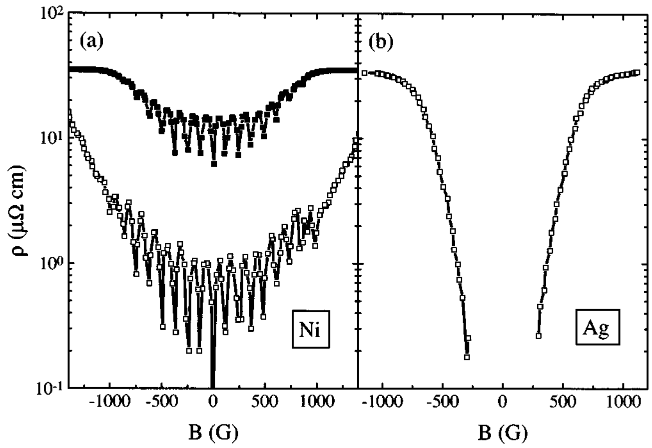

FIG. 2. Field dependence of the resistivity of a 100 ± 5 nm thick Nb bridge on top of a square array of Ni or Ag dots with a lattice spacing of $d=400\pm10$ nm. The applied current density is $J=2.5\times10^2$ A/cm^2. (a) Two curves with temperatures of $T=8.1$ K (■) and $T=7.9$ K (□) are presented for the Ni. (b) For comparison, the curve presented for Ag was measured at $T=7.9$ K.

current range.[12] The critical current (defined by a 5×10^{-3} V/m criteria) presents several peaks at the same magnetic-field values as the dips in the resistivity curves (see inset of Fig. 4). Therefore, for this sample, in this temperature and field range, the synchronized pinning by the periodic array is always stronger than the pinning effect by random defects, different from earlier finding.[12] The variation from sample to sample is probably related to the relative pinning strength due to random defects in Nb and collective pinning by the array of magnetic dots. Nb is very sensitive to growth conditions which is reflected in large variations in T_c and normal-state resistivity. This, therefore, may mask the synchronized pinning in different ways. Further systematic studies are needed to address this point quantitatively.

Pinning could be produced by two nonmagnetic effects. The first one may arise from the geometry of the fabrication

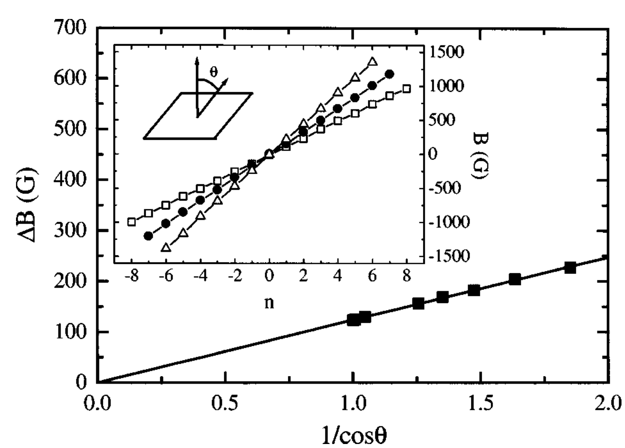

FIG. 3. Magnetic-field angular dependence of the distance between consecutive minima as observed in Fig. 2 for the Nb film on top of the square array of Ni dots. The measurement has been done at a temperature of $T=8.0$ K with a current density of 2.5×10^2 A/cm^2. The solid line is a fit to the expression $\Delta B(\theta)=\Delta B(0)/\cos(\theta)$ with $\Delta B(0)=124\pm2$ G. Inset shows the order dependence of the minima for the following angles: $\theta=0°$ (□), $\theta=45°$ (●), $\theta=60°$ (△).

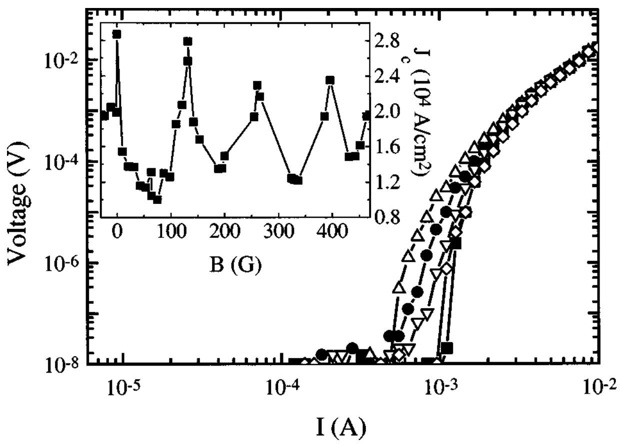

FIG. 4. *I-V* curves as a function of field at $T=7.7$ K for the 100 ± 10 nm thick Nb film on top of the square array of Ni dots. The curves are shown for the following fields: 0 G (■), 10 G (●), 64 G (△), 110 G (▽), 132 G (◇). Inset shows the critical current extracted from the *I-V* curves with a 5×10^{-3} V/m criteria.

process, such as thickness modulations[15,16] or strains in the Nb film grown on top of the dots. The lack of any distinct feature in the resistivity of the Nb film grown on top of the Ag array indicates that these geometrical effects are not relevant in our case.[17] The second effect may arise from a reduction in the superconductor order parameter due to proximity effect with the Ag dots. However, this proximity effect may be reduced due to the poor quality of the interface between the Ag dots and the Nb film resulting from the fabrication process. Therefore random defects present in the Nb probably mask the possible influence of the ordered array of nonmagnetic dots.

It is therefore an experimental conclusion that, the resistivity and critical current oscillations originate in the magnetic character of the dots. Possible mechanisms such as the magnetic proximity effect, the flux concentration by the higher permeability of the ferro-magnetic material, and/or a reduction of the order parameter due to the stray field of the dots are discussed below.

Since in bulk superconductors, magnetic pinning centers are found to be much stronger than nonmagnetic ones,[18] the synchronized pinning effect in Nb films may be related to a ferromagnetic proximity effect caused by the Ni dots. In a similar way, Gd atoms are found to depress the superconducting order parameter close to a Nb surface.[19] For a clean interface, the magnetic dots may depress the superconducting order parameter within a coherence length and this may give rise to an effective thickness modulation. Comparisons in thin Nb films with artificially produced thickness modulation imply that the magnitude of this kind of an effect is small.[17]

Another possible mechanism for the pinning of the vortex lattice by the ferromagnetic dots is related to the concentration of magnetic field on the dot due to the high permeability μ of the ferromagnetic material. The angular dependence of the $R(B)$ curves shows that only the perpendicular component of the field is relevant for this synchronized pinning effect. Thus, the flux concentration must be related to the permeability of the dots in the perpendicular direction ($\mu_\perp$). To estimate this, it should be kept in mind that the magnetic dots have an aspect ratio $c/t\approx5$ (where $c\approx200$ nm is the diameter and $t\approx40$ nm is the thickness) which implies a magnetic shape anisotropy so that the magnetization is mainly in the sample plane. Experiments with different magnetic materials may shed light on this issue.

Other magnetic effects such as those due to the stray field of the dots seem to be less important for the three following reasons. First, the magnetoresistance oscillations amplitude due to the stray field found by Otani *et al.*[11] is small compared to what we observe. Second, to observe the oscillatory behavior produced by the stray field, application of an in-plane field was first needed.[11] In our case, the magnetic-field angular dependence study has shown that this is not required. Third, from the calculations used to explain this oscillatory behavior by the stray field of dots,[20] the smaller size of our dots and the magnetic material used (Ni) will still reduce this effect in our array. Moreover, since the magnetic moment of the dots is mainly confined to the substrate plane, the stray field influence on the Nb should be small due to the high value of the critical field of a superconducting thin film in the parallel direction.[21]

In summary, we have studied the vortex pinning in a superconducting Nb film by a square array of magnetic and nonmagnetic dots fabricated by *e*-beam lithography. Sharp, regularly spaced, minima (maxima) are found in the resistivity (critical current) versus perpendicular field curves, only for the samples containing magnetic dots. This implies that the hexagonal vortex lattice distorts to match the square pinning array and that the pinning is caused by the magnetic properties of the dots. With decreasing temperature, the number of pinning minima increases before saturating which implies that long-range interactions between vortices play an important role. Possible pinning mechanisms for the synchronized pinning effect are related either to a magnetic proximity effect or to flux concentration due to the high permeability of the ferromagnetic material.

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