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Interplay between the vortex lattice and arrays of submicrometric pinning centers

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Abstract

Ordered arrays of submicrometric magnetic pinning centers have been fabricated in superconducting Nb films by electron beam lithography. Periodic pinning effects, observed when the vortex lattice matches the array of dots, have been studied as a function of temperature, current and array geometry in order to analyze the physics of the interaction between the vortex lattice and the periodic array of microscopic pinning centers. These results have allowed pointing to the magnetic origin of the relevant pinning mechanism in this system and to dynamic ordering effects of the vortex lattices. The effect of the relative direction of the driving force with respect to the pinning potential is dependent on the anisotropy configuration of the artificial submicrometric array. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The influence of both applied magnetic field and driving current on the behavior of type II superconductors is of great scientific and technological interest. The interplay of several interactions [1–3] leads to a complex behavior in the flux line lattice (FLL) phases. Transport measurements [4], neutron scattering [5] and Bitter decoration experiments [6] have clarified the behavior of FLL, providing strong evidence of new vortex physics effects, including creep, plastic flow and ordered (elastic) flow. The vortex lattice behavior is strongly influenced by the presence of defects that can act as pinning centers for the vortex lines. In general, defects are randomly distributed in the samples (both in the case of intrinsic defects or artificial defects created by metallurgical processes). On the other hand, the fast development of nano and micro-engineering techniques has provided the possibility of fabricating ordered arrays of pinning centers of reduced size, i.e. of a scale comparable to the coherence lengths of conventional superconductors [7]. Therefore a renewed experimental and theoretical interest has emerged on the topic of periodic pinning potentials created

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by arrays of identical defects with well defined shape and geometrical distribution, such as thickness modulations [8], holes [9] or magnetic dots [10]. Since the first observation of pinning interaction between the vortex lattice and ordered arrays of submicrometric magnetic dots [10], a great scientific effort has been done in order to get a full understanding of this kind of systems and, also, to exploit the possibility of designing specific pinning potentials [11,12] that allow to probe elastic and dynamic properties of the vortex lattice.

In this paper we summarize different experimental results obtained from Nb films with periodic arrays of microscopic magnetic pinning centers (dots or lines). In particular, we will describe the influence on the vortex lattice-pinning center array interaction of several factors such as temperature, driving current and array geometry.

2. Experimental

The fabrication of small magnetic structures using e-beam lithography has been described in detail in [7]. Briefly, e-beam lithography is used to define the desired structure on an electron sensitive resist (PMMA), which is coated on top of a Si(1 0 0) substrate. During the e-beam lithography the size of the dots/lines is controlled by varying the electron beam dosage between 0.4 and 0.6 nC/cm. Following, the e-beam lithography a 40 nm thick film of the desired magnetic material is deposited on the PMMA template using a dc magnetron sputtering. A final lift off step removes the remaining PMMA, and the array of the dots/lines is left on the substrate. As an example, Fig. 1 shows a scanning electron microscopy (SEM) image of a rectangular array of Ni dots (0.35×0.5 μm^2) and of an array of Ni lines. The shape of the dots is very circular, without any average elongation along any particular direction.

After the pinning array is fabricated, it is covered with a 100 nm thick superconducting Nb film deposited by dc magnetron sputtering. Finally optical lithography and reactive ion etching are used to define a bridge for transport measurements. Two kinds of geometries have been used: a standard four points measurement linear bridge and a special cross shaped bridge (shown in Fig. 2(a)) that allows to change the driving current direction in order to investigate the influence of the relative motion between vortex lattice and pinning center array. This pattern consists of a 40 μm width Nb cross centered on the dot/line array, so that the current can flow along the two orthogonal paths along the two principal directions of the array. The Nb films show critical temperatures as high as 8.7 K with sharp superconducting transitions as shown in Fig. 2(b).

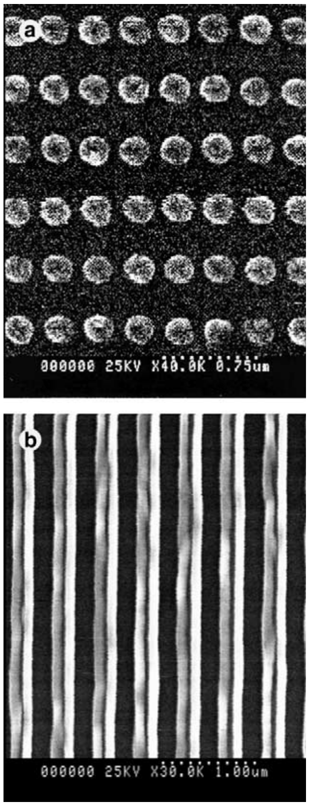

Fig. 1. (a) SEM image of a rectangular array of Ni dots (0.35×0.5 μm^2) and (b) array of Ni lines with a line–line separation of 0.5 μm.

Magnetotransport measurements have been performed on a helium cryostat with the magnetic field B applied perpendicular to the sample plane.

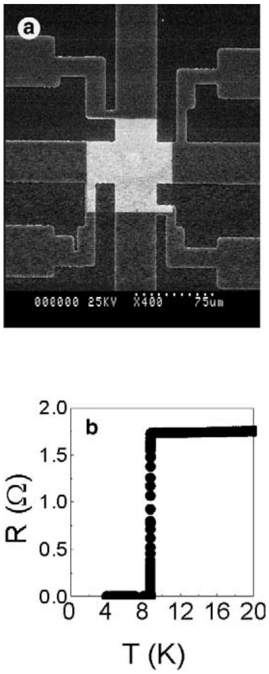

Fig. 2. (a) SEM image of the Nb bridge defined by optical lithography in the array region. The width is 40 μm and the distance between the voltage contacts is 50 μm. (b) Superconducting transition of the Nb film.

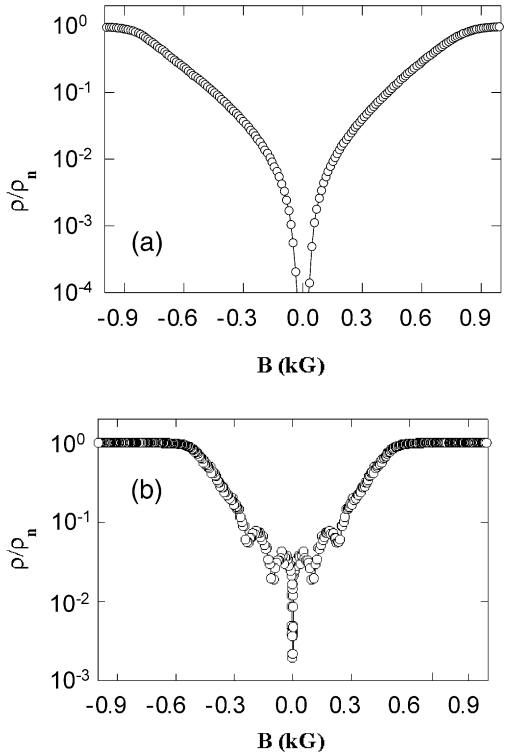

Fig. 3. Field dependence of the normalized resistivity of (a) an as grown Nb film and (b) a Nb thin film with a square array of Ni dots ($d = 400$ nm), measured at $T = 0.99T_c$.

3. Results and discussion

Fig. 3 shows the resistivity versus magnetic field of a Nb film (a) and of a Nb thin film with a square array of Ni dots with a separation $d = 400$ nm (b). In the first case, a monotonic behavior is observed: sample resistance increases with the applied magnetic field as was expected. On the other hand, for the second case, the resistivity shows a set of minima at regularly spaced values of magnetic field. These minima have been associated with matching effects between vortex lattice and the Ni dot array [10]. The field interval between minima $\Delta B = 130$ Oe, corresponds to a vortex lattice constant $a_0 = (\Phi_0/B)^{1/2} = 399$ nm, in good agreement with the lattice parameter of the array of Ni dots. That is, a minimum appears in the resistivity curve when there are an integer number of vortices per unit cell of the array of pinning centers. By studying the field position as well as the shape of these minima, many interesting properties of the vortex lattice can be analyzed.

3.1. Influence of driving current density and sample temperature

From the earliest experimental results on Nb films with Ni dot arrays, it was observed that commensurability effects (minima) take place in a limited current range. In addition, this current range was observed to be temperature dependent [13].

We have performed magnetoresistance measurements on the rectangular array of Ni dots described in Fig. 1(a) for different current densities. Experiments were carried out at $0.99T_c$ and with the applied current flowing along the short side of the rectangular cell. It is worth to note that in the low and high current ranges no minima were observed in this array, they only appear for intermediate currents. Fig. 4 shows the depth of the first matching minima (monitored by the so-called

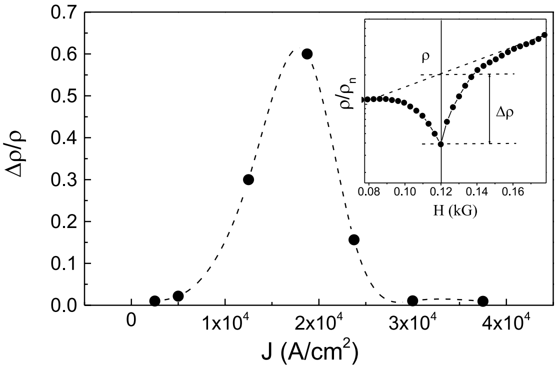

Fig. 4. Normalized resistivity change ($\Delta\rho/\rho$) for the first matching minimum as a function of the applied current. Data have been obtained from the rectangular array of Ni dots shown in Fig. 1(a). Sample temperature was set to $0.99T_c$. Inset shows the criteria used to calculate the normalized resistivity change for each driving current.

normalized resistivity change; $\Delta\rho/\rho$) as a function of the applied current. Inset shows the criteria used to calculate the normalized resistivity change for each case. It should be noted that depth minima curve shows a peak, with the largest resistivity change occurring for $J = 2 \times 10^4$ A/cm^2. Similar experiments have been performed with other array geometries (square and triangular) and, in all the cases, the qualitative behavior is very similar to that shown in Fig. 4, indicating that in these Nb films, there must be a competition between two different pinning mechanisms which is governed by the general dynamic properties of the vortex lattice.

Therefore, two facts have to be considered in order to explain this current dependence: first, the existence of intrinsic random defects in the Nb films that compete with the artificial array of dots and, second, the dynamic ordering of the vortex lattice at high velocities. The behavior, showed in Fig. 4, points out that, at low currents, pinning by the Nb intrinsic random defects is the dominant mechanism, leading to a disordered vortex lattice. Then, for the intermediate current range, the increase in the depth of the minima is correlated with an enhancement in the vortex lattice long range order, since for a perfectly ordered vortex lattice the vortex lattice-dot array interaction would be the maximum value. Finally, for high vortex velocities (high current regime) there is a reduction in the vortex lattice-dot array interaction. This reduction has been numerically predicted in simulations of the similar problem of friction between two lattices at atomic scale [14].

Magnetotransport measurements carried out at different driving currents and temperatures have also shown that the optimum current for the observation of periodic pinning decreases with temperature, in the same way as the critical current at the first matching field as $J \propto (1 - T/T_c)^{3/2}$ [13]. This temperature dependence has been used to analyze the pinning mechanisms due to the individual magnetic dots. These results are consistent with the interplay of two pinning mechanisms related with the ferromagnetic character of the dots, the proximity effect and the vortex-magnetic moment of the dot interaction. These mechanisms provide the correct temperature and order of magnitude dependence [13].

3.2. Influence of the array and pinning center geometry

The presence of minima in the magnetoresistance at regular field intervals has been found in several high symmetry configurations such as triangular [10], square [15] or Kagome arrays [16]. In these geometries the pinning force from the magnetic dot is strong enough to distort the vortex lattice into the array geometry. This distortion is observed for any magnetic field. Periodic pinning has been also found in lower symmetry arrays of pinning centers such as rectangular arrays [11]. In this case the vortex lattice shows an interesting behavior at low fields, the pinning force from the dots is strong enough to distort the vortex lattice into a rectangular configuration that matches the dot array. As the field is increased, the elastic energy associated with the lattice becomes dominant and the rectangular distortion becomes unstable, so that vortex lattice is reconfigured to a square geometry, being the crossover field between the two regimes governed by the asymmetry ratio of the Ni dot array.

A more subtle geometrical effect comes from the interplay of the different array geometrical dimensions (lattice spacing, dot size, interdot separation) with the characteristic superconducting length scales, such as the coherence length ξ. For example, a crossover from weak to strong pinning behavior was found [12] as the interdot separation became comparable to ξ, and the pinning potential wells, associated with the individual dots, started to overlap.

In the case of a rectangular array of magnetic dots the pinning potential is anisotropic and can be tuned from a rectangular array of "point-like" pinning wells to a set of parallel linear pinning potential channels as the interdot distance is reduced along the short side of the rectangular unit cell. The extreme behavior would correspond to a parallel array of submicrometric Ni lines. In any case, it is clear that the interaction between the vortex lattice and the dot array is of anisotropic nature and depends on the direction of motion of the vortex lattice with respect to the artificial array, which is ruled by the Lorentz force $F_L = J \times B$. Therefore, in order to obtain a complete picture of this problem, it is essential to characterize the vortex lattice behavior for different driving current directions.

Magnetotransport measurements have been performed on the rectangular array of magnetic dots shown in Fig. 1(a) and with the cross shaped Nb bridge. So that, using this cross shape bridge the current can be applied along the main directions of the rectangular array. In this way, depending on the chosen current path, the Lorentz force $F_L = J \times B$ can point along one of the two perpendicular directions relative to the array of Ni dots. In this sample, close to T_c, the superconducting coherence length becomes comparable to the dot separation along the short side of the array. The geometry of this rectangular array defines an anisotropic pinning potential made up of deep potential channels along the rows of Ni dots. The most clear anisotropic behavior is found in background pinning, i.e. for fields out of matching conditions. This pinning is clearly enhanced when the vortices move perpendicular to the channels in the pinning potential, in comparison with the situation in which the vortices flow along them. This is in agreement with theoretical simulations [17] that have predicted an anisotropic background critical current even for rectangular arrays of point like pinning centers. On the other hand, the rectangular array of Ni dots also produced matching effects associated with the periodic modulation of the pinning potential inside the channels for both current directions.

It is therefore expected that if the modulation of pinning potential inside each channel is reduced (by reducing the dot separation) periodic pinning effects should disappear. Fig. 5 shows the field dependence of the resistivity close to the critical temperature ($0.99T_c$) for a Nb film grown on the array of 0.5 μm spaced Ni lines of Fig. 1(b) measured with the current perpendicular to the lines. In this case there is no modulation of pinning potential along the lines. It is clear that resistance increases monotonically with field showing no matching effect for any applied magnetic field. Experiments have been carried out in a wide current range (from 10^3 to 10^5 A/cm^2) but no periodic matching effects have been observed in any case for vortex motion along the lines, indicating that as the pinning modulation is suppressed there is not any vortex configuration that leads to an increase of the interaction between the vortex lattice

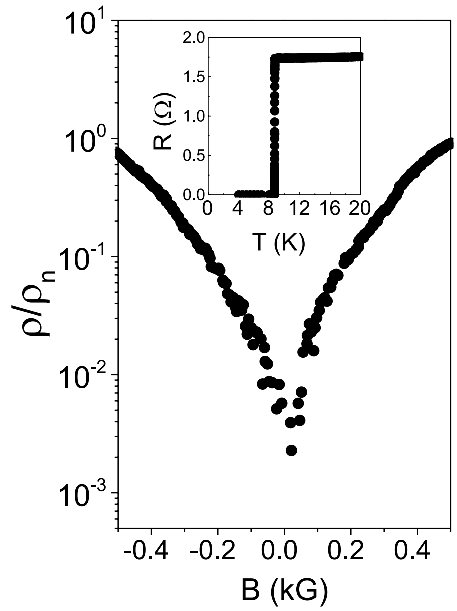

Fig. 5. Field dependence of normalized resistance of the Nb thin film with an array of Ni lines separated 0.5 μm. Temperature was $0.99T_c$ and the current was applied perpendicular to Ni lines. Current density was 1×10^4 A/cm^2. The inset shows the superconducting transition of the sample.

and the pining potential. On the other hand, if current is directed along the Ni lines (i.e. vortex motion perpendicular to the lines) matching anomalies are only observed when the vortex lattice matches the Ni line width [18]. It is worth to note that these pinning force effects at the fields of matching to line width have also been observed in experiments performed on weak-pinning channels in NbN/Nb_3Ge bilayers [19], but, in that case, when the transport current is in the perpendicular to channels configuration.

4. Conclusions

In this work we have summarized different experimental results obtained from Nb films with periodic arrays of mesoscopic magnetic pinning centers (dots or lines). Periodic pinning effects are observed in these samples when the vortex lattice matches the array of ordered dots for different array geometries (triangular, square, rectangular).

Different factors such as dot material, dot size, sample temperature and driving current are found to have an important influence on the strength of this periodic pinning, which has been used during the last years to get a further insight into the physics of vortex lattice. From these experiments it has been shown that the pinning mechanism of submicrometric Ni dots is a combination of the interaction between the vortex field and the magnetic moment of the dot and the proximity effect. This is in agreement to related experiments, which show that non-magnetic dot arrays produce weak matching effects.

The amplitude of matching peaks is also found to change with the applied current density, which can be understood in terms of a dynamic increase of the vortex lattice order for increasing vortex velocities. Finally, the current direction relative to the array principal directions is also found to play an important role in the case of low symmetry pinning arrays (rectangular arrays of dot or arrays of lines). The presence of matching anomalies is strongly dependent on the interdot separation since the periodic modulation of the induced pinning potential depends on this distance.

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