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Pinning effects by arrays of magnetic dots on niobium film

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Abstract

The interaction between an ordered array of submicron magnetic particles and a superconducting thin film can lead to important pinning effects due to the synchronized interaction with the vortex lattice. Triangular and square lattices of submicrometer magnetic dots have been fabricated by electron beam lithography, with typical spacings in the range 400-600 nm and dot radius around 100-200 nm. The influence of these lattices of small particles on the superconducting properties of niobium films has been studied. The resistivity vs. magnetic field curves exhibit a series of sharp regular minima close to the transition temperature. These minima appear at integer multiples of the matching field, which is determined by the lattice parameter of the dot array, thus, revealing a synchronized pinning effect due to the magnetic dots.

Keywords: Small particles; Flux pinning; Vortex dynamics; Thin films

The mixed state of a type-II superconductor is characterized by the penetration of the magnetic field $\boldsymbol{B}$ inside the material forming a lattice of vortices, each carrying a quantum of flux Φ_0. The origin of the dissipation in the mixed state is related to the movement of these flux lines since, as they move with a certain velocity $\boldsymbol{v}$, an electric field is induced given by the relation, $\boldsymbol{E} = \boldsymbol{\Phi}_0 \times \boldsymbol{v}$ [1]. Therefore, under the effect of a transport current that creates a Lorentz force on the flux lines, a type-II superconductor will show a finite resistivity unless some pinning force arising from material imperfections prevents vortex motion.

The pinning effect caused by defects is most effective when their size is comparable with the superconducting characteristic lengths, either the penetration length λ or the coherence length ξ [2]. In particular, it may be expected that an ordered array of defects [3-5] would produce important pinning effects on vortex dynamics, since the flux lines are arranged in a triangular lattice of spacing a_0 (see Fig. 1a). The relation between a_0 and the magnetic field [6] is given by

$$B = \Phi_0(1.075/a_0)^2. \qquad (1)$$

Many studies of the interaction of the vortex lattice with artificial regular arrays have been done using structural defects [3, 5], while only very few experiments have been done using magnetic particles.

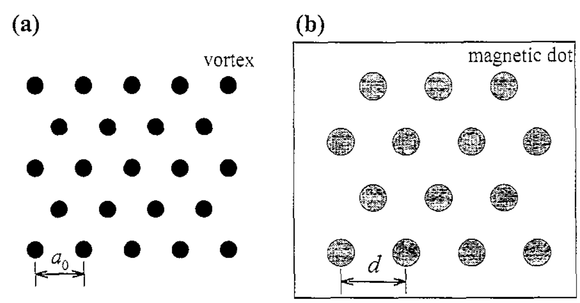

Fig. 1. (a) Sketch of the triangular vortex lattice with spacing a_0. (b) Sketch of a triangular array of small magnetic particles with spacing d fabricated by electron beam lithography to study the pinning effect on a Nb film.

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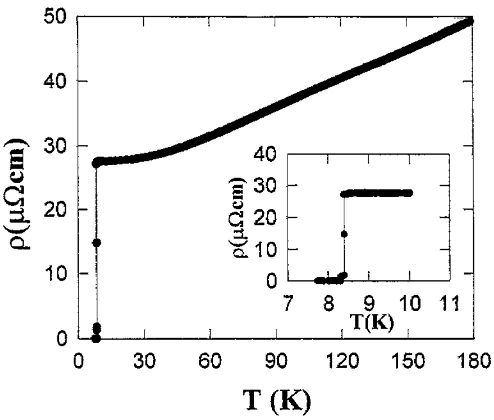

Fig. 2. Temperature dependence of the resistivity of a 100 nm thick Nb film with an array of Ni dots (d = 410 nm). Inset shows the details of the superconducting transition.

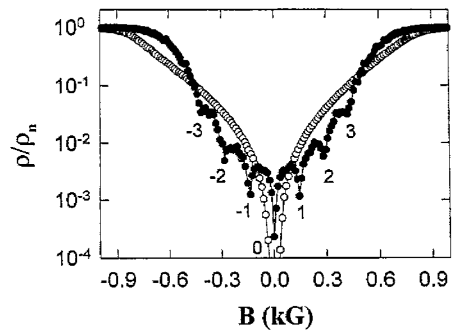

Fig. 3. Field dependence of the resistivity of a 100 nm thick Nb film with a Ni dot array of spacing d = 410 nm (filled symbols) and in a reference only Nb area (hollow symbols), both measured with $J = 2.5 \times 10^4$ A/cm^2 at 8.2 K. The resistivity has been normalized by the normal state resistivity ρ_n. The order n of the matching fields $\boldsymbol{B}_n$ are indicated.

Electron beam lithography is a powerful technique which allows the fabrication of arrays of small magnetic particles with controlled geometry. We have fabricated triangular and square lattices of submicrometric magnetic dots by electron beam lithography in order to study their pinning effect on a Nb film [7]. The magnetic dots of either Fe or Ni have been made on Si substrates. The typical dimensions of these dots are thickness t = 40 nm and radius r = 100–200 nm, which is comparable with the superconducting coherence length of Nb close to T_c. The dots form a lattice with typical spacing d in the range d = 400–600 nm, as it is sketched in Fig. 1b for a triangular lattice. Non-magnetic Ag dot arrays have also been prepared for comparison. A 100 nm thick Nb film has been grown by sputtering on top, covering the Ni dots. Then, a 40 μm bridge has been defined by photolithography and reactive ion etching for the transport measurements in the region of Nb with the magnetic dot array and in a reference area with only Nb. Fig. 2 shows the resistivity as a function of temperature for a Nb film with an array of Ni dots. It shows a metallic behavior and the superconducting transition at T_c = 8.3 K.

The effect of the ordered array of small magnetic particles is clearly present in the mixed state of the Nb film. Fig. 3 shows the field dependence of the resistivity at 8.2 K, with the magnetic field applied perpendicular to the sample plane, for the Nb with Ni dots area (filled symbols) in comparison with the only Nb region (hollow symbols). The reference Nb presents the usual monotonic increase in the resistivity as a function of the magnetic field due to the vortex motion, approaching the normal state resistivity at high fields. On the other hand, in the region with the magnetic dots array a clear structure of minima in the dissipation appears at integer multiples of the matching field $\boldsymbol{B}_n = n\boldsymbol{B}_1$ (n being an integer). Here $\boldsymbol{B}_1 = \Phi_0(1.075/d)^2$ is the first matching field at which there is exactly one vortex per unit cell of the magnetic dot array, while at $\boldsymbol{B}_n$ there are n vortices per unit cell. The measurements give $\boldsymbol{B}_1$ = 141 G, which corresponds well with the theoretical $\boldsymbol{B}_1 = 142 \pm 7$ G given by the spacing of the dot array $d = 410 \pm 10$ nm. This implies that when the artificial small magnetic particles act as synchronized pinning centers, they are more effective than the intrinsic defects always present in a Nb film. It is worth to note that this enhanced pinning at well-defined $\boldsymbol{B}_n$ is found only for the magnetic arrays but not for the arrays of non-magnetic Ag dots. This indicates that the pinning interaction between the vortex lattice and the dots array is magnetic in origin.

In summary, we have found a regular structure of minima in the magnetic field dependence of the resistivity of Nb films that can be related with the synchronized pinning effect by a periodic array of submicrometric magnetic particles fabricated by electron beam lithography.

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