Abnormal magnetoresistance behavior in Nb thin films with rectangular arrays of antidots*

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Magnetoresistance in superconducting Nb films perforated with rectangular arrays of antidots (holes) is investigated at various temperatures and currents. Normally, the magnetoresistance increases with the increasing magnetic field. In this paper, we report a reverse behavior in a certain range of high fields after vortex reconfiguration transition, where the resistances at non-matching fields are smaller than those in the low field regime. This phenomenon is due to a strong caging effect, in which the interstitial vortices are trapped among the pinned multiquanta vortices. This effect is temperature and current dependent.

Keywords: magnetoresistance, caging effect, rectangular arrays of antidots

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1. Introduction

Superconducting thin films with periodic arrays of pinning sites have received much attention for enhancing the critical parameters[1−5] and artificially controlling the motion of vortices.[6] When the number of vortices is equal to an integer multiple or a fractional of the number of pinning centers, dips in the resistance or the peaks in critical current as a function of the applied magnetic field can be visible, which is known as the commensurate effect or the matching effect.[1,7] In Nb thin films with rectangular arrays of magnetic dots, interesting phenomena have been revealed, such as the channeling effect,[8] anisotropy in the critical current,[9] and vortex-lattice reconfiguration transition.[10−12] When the reconfiguration transition occurs, changes in the shapes of the minima and their periodicity in the magnetoresistance curves are found. Two possible models, the geometrical reconfiguration model[10] and the multivortex model,[12] have been proposed to explain this phenomenon. However, the causes of the oscillations in magnetoresistance after the transition are still unclear. In this paper, we perform transport measurements in rectangular arrays of antidots (holes) with various aspect ratios of unit cell to investigate the pinning mechanisms in the high field regime. We observe a temperature and current dependent reconfiguration transition. After the transition, a decrease in magnetoresistance is found at high fields. We attribute this abnormal behavior to a reduction in the mobility for the interstitial vortices by the caging effect, which has been predicted by theoretical simulations.[13,14]

2. Experiment

A high-quality Nb thin film is deposited on the Si substrate by magnetron sputtering. The film has a thickness of 100 nm, a critical temperature T_c of 8.870 K, and a transition width of 50 mK. For transport measurements, two four-probe microbridges are fabricated on one chip with ultraviolet photolithography and then etched by enhanced reactive ion etching. At each center of the microbridges, there is a square area of 60 μm× 60 μm for electron beam lithography.

The measurements are performed in a quantum designed physical properties measurement system (PPMS-14), with the applied magnetic field oriented

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perpendicular to the film surface. The temperature stability is 2 mK during the measurements. The superconducting coherence length $\xi(0)$ is 10.8 nm, and the penetration depth $\lambda(0)$ is 75.1 nm, which is determined from an unpatterned Nb microbridge by measuring its phase boundary $T_c(H)$.[15]

3. Results and discussion

Rectangular arrays of antidots with different aspect ratios of unit cells are, respectively, patterned on the two Nb microbridges. The related parameters of the two samples are summarized in Table 1. In Fig. 1(a), a scanning electron microscope (SEM) image shows that the overall periodicity of the antidot lattices is maintained very well. The currents flow along side b of the rectangular unit cell. Figure 1(b) shows the magnetoresitance $R(H)$ curves of patterns A and B. They are recorded at 8.746 K with a current of I = 250 μA. The magnetic field sweeps from −300 Oe to +220 Oe with a step of 0.4 Oe. Two different regimes can be clearly distinguished from the curves for both samples. In the low field regime, fractional matching minima at $1/3H_1$, $1/2H_1$, and $2/3H_1$ and sharp integer matching dips can be observed. The interval $\Delta H_A = 34.0 \pm 1.4$ Oe ($\Delta H_B = 24.8 \pm 1.0$ Oe) between the neighboring dips is in good agreement with the theoretical value Φ_0/ab (34.5 Oe for A; 24.6 Oe for B), where Φ_0 is the flux quantum. This implies that the vortex lattice is commensurate with the rectangular array of antidots. In the high field regime, broad dips ($5.4H_{1A}$, $5.1H_{1B}$, and $7.5H_{1B}$) are found corresponding to the reconfiguration of interstitial vortices to the square lattice.[10]. The interval in this regime is 52.6 ± 2.6 Oe and 57.3 ± 2.7 Oe for patterns A and B, respectively. These values are close to the theoretical period for the square vortex lattice $\Phi_0/a^2 = 57.5$ Oe.

Table 1. Sample characteristics, where ΔT_c is the superconducting transition width, R_n is the normal state resistance at 9 K, ΔW is the nearest separation between neighboring antidots along the short side of the rectangular array, and D is the diameter of the antidot.

Pattern ($a \times b$)	T_c/K	ΔT_c/K	R_n/Ω	ΔW/nm	D/nm	b/a
A (600 nm×1000 nm)	8.810	0.095	2.517	124	476	1.67
B (600 nm×1400 nm)	8.818	0.109	2.044	121	479	2.33

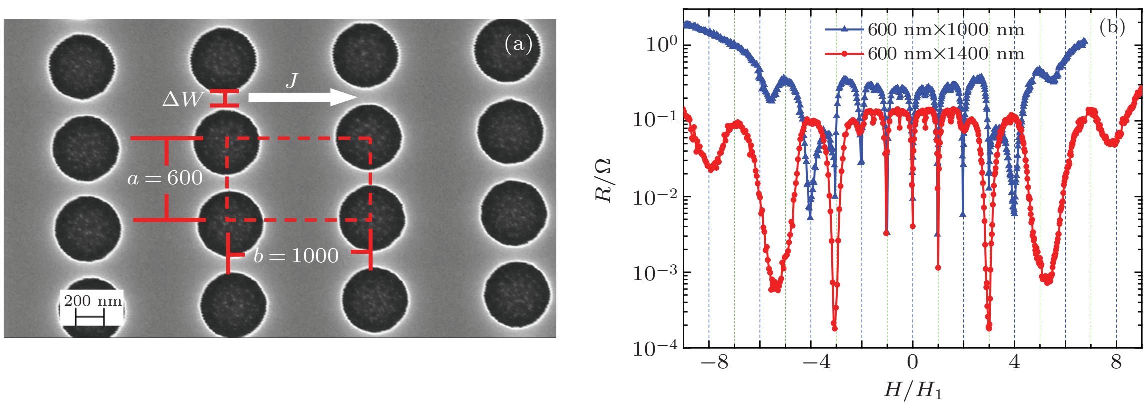

Fig. 1. (colour online) (a) SEM image of a rectangular array of antidots (holes) with a unit cell of 600 nm×1000 nm. The hole diameter is 476 nm, and the dashed rectangle indicates a unit cell. (b) Field dependences of resistance at $T = 8.746$ K with $I = 250$ μA for patterns A (600 nm×1000 nm) and B (600 nm×1400 nm). The curves are normalized by the first matching fields $H_{1A} = 34.0$ Oe and $H_{1B} = 24.8$ Oe, respectively.

In the multiquanta vortex model, the transition between the low field and the high field regimes indicates the formation of interstitial vortices.[12] Using expression $N_S = D/4\xi(T)$,[16] we roughly estimate the saturation number N_S for patterns A and B at $T = 8.746$ K to be 1. In a periodic array of antidots, N_S can be higher due to the vortex–vortex interactions.[14] In our samples, the dense array (A) has a larger N_S than the sparse one (B), $N_{SA} = 3$ and $N_{SB} = 2$, as shown in Fig. 1(b). This is the main difference between the two samples. Therefore, the saturation number depends on not only the hole size but also the geometry of the pinning array.

Since patterns A and B have a similar behavior in magnetoresistance, we shall focus on the $R(H)$ curves of pattern A. In Fig. 2(a), we show the $R(H)$ curves at several temperatures, from 8.794 K to 8.740 K with a fixed current $I = 250$ μA. The reduced temperature $t = T/T_c$ ranges from 0.998 to 0.992. Obviously, the saturation number is temperature dependent.[16] We find $N_{SA} = 2$ at $T = 8.794$ K and $N_{SA} = 3$ at $T = 8.740$ K. Different temperature dependences of the $R(H)$ curves are found for the low field and the high field regimes, suggesting that different pinning mechanisms are involved. In the low field regime, the matching behavior shows stability in a wide range of temperatures. From 8.794 K to 8.740 K, the minima at integer matching fields can always be visible due to the strong pinning by the large holes. However, the dips in the high field regime are strongly temperature dependent, indicating the high mobility of the interstitial vortices. In general, the entrance of interstitial vortices would cause a drastic increase in magnetoresistance due to their weak pinning potentials.[17] In our case, at a temperature close to T_c (such as $T > 8.776$ K), the background resistance rises with the increasing H, which is commonly seen in periodic pinning arrays.[3] However, when the temperature is below a certain value (near 8.750 K), an abnormal magnetoresistance behavior occurs. As illustrated by the horizontal dashed line in Fig. 2(a), at $T = 8.750$ K the resistances at fields out of the matching condition in the high field regime (e.g. $2.6H_1 < H < 4.3H_1$) are smaller than those in the low field regime ($H < 2.5H_1$). At a lower temperature (8.740 K), the reduction in resistance is visible in a broader range of fields ($H > 2H_1$). Similar effects can also be found in the rectangular arrays of magnetic dots,[10−12] where the complex pinning mechanisms (the proximity effect between the magnetic dot and the superconducting film, the dot stray field, etc.) are relevant. In contrast to the magnetic dots, we can discuss the results in a simple hole pinning model to revel that defect/hole pinning is responsible for the abnormal magnetoresistance behavior.

To further study the phenomenon, we examine the current dependence of magnetoreistance at a fixed temperature ($T = 8.765$ K) in Fig. 2(b). The $R(H)$ curves are recorded with currents in the range from 50 μA to 450 μA, corresponding to the current densities ranging from 4.03 kA/cm^2 to 48.36 kA/cm^2, which are well below the depairing critical current density. The current dependences of the $R(H)$ curves are much like the temperature dependence shown in Fig. 2(a). The abnormal magnetoresistance behavior appears when the current is below 200 μA, and an enhancement of the critical current at the high fields is revealed. Thus, the abnormal magnetoresistance behavior is highly affected by temperature and current.

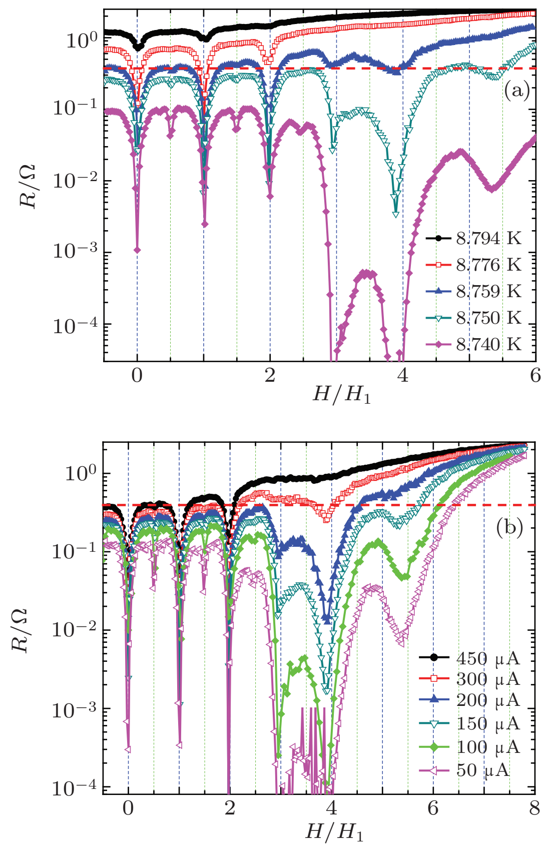

Fig. 2. (colour online) Resistances for pattern A as functions of normalized magnetic field (a) at several different temperatures with a fixed current $I = 250$ μA, and (b) at $T = 8.765$ K for several different currents. The horizontal dashed lines indicate the temperature (8.750 K) or the current (200 μA) where the resistances at the non-matching fields for the high field regime (e.g. $2.7H_1 < H < 4.5H_1$) are smaller than those in the low field regime ($H < 2.5H_1$).

The strong temperature and current dependences of magnetoresistance in the high field regime imply the competition between the pinning potentials and the driving force.[9] The pining potentials of the interstitial vortices are dominant by the strong repulsive interactions with multiquanta vortices that are confined in the holes. These potentials can cage the interstitial vortices effectively in a certain range of low temperatures with a small current density. Thus, the lowering of mobility for the interstitial vortices causes a reduction in magnetoresistance. This caging effect has been predicted by theoretical simulations[13,14] and was found to be greatly temperature dependent. In the simulation, it was discovered that the critical currents for $H_2 < H < H_3$ are higher than those obtained for $H_1 < H < H_2$.[13] In our case, a wider range of reduced resistance at 8.740 K is observed. The simulations also predicted a recovery of the normal behavior at temperatures far below T_c ($T/T_c < 0.8$). Whereas, it is difficult to check this recovering phenomenon in our magnetoresistance measurements due to the requirement of large applied currents at low temperatures. A direct measurement of $J_c(H)$ will be necessary to further confirm this effect. Another possible explanation is related to the enhanced rigidity of the vortex lattice in a high field, where the lattice cannot easily flow around the pinned vortices.[11] However, this explanation is based on the assumption that the pinning site can only trap one vortex. It would predict the sudden increase in the resistance when the interstitial vortices appear, which does not agree with our experimental results. Although many works have been done, a further study of the abnormal behavior is still necessary to reveal its nature and potential applications.

4. Conclusion

We investigated the magnetoresistance of superconducting Nb thin films containing rectangular arrays of antidots with different aspect ratios. It is found that the reconfiguration transition between the low field and the high field regimes highly depends on the saturation number N_S of antidots. The N_S is determined not only by the size of the antidots, but also by their spacing and temperature. After the transition, the resistance (critical current) becomes smaller (larger) in the high field regime, in contrast to the conventional behavior. We attribute the abnormal behavior to the lowering of vortex mobility in the high field regime, as the interstitial vortices are strongly caged by the pinning multivortices. This effect is influenced by temperature and current, which is consistent with the recent theoretical predictions.

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