Reconfiguration and hysteresis in superconducting Nb film with honeycomb arrays

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Abstract. Superconducting Nb films with honeycomb array of holes are studied using transport measurements. The oscillating magneto-resistance curves are observed up to large flux density. Two types of resistance minima with different field intervals are observed, indicating the reconfiguration of the overall flux lattice from honeycomb to triangular arrangement. Moreover, hysteretic effects are found in a very large field span from \( H = 2H_1 \) to \( H = 8.5H_1 \). It is revealed that the hysteresis is related to the presence of interstitial vortices.

1. Introduction

Superconducting films with artificial pinning arrays have been intensively studied for decades and a rich variety of static and dynamic vortex phenomena have been revealed.[1, 2] Vortices are pinned and match the pinning arrays when the density of vortices equals an integer multiple of the density of pinning sites. Critical current peaks and resistance dips are observed at field values \( H = n\Phi_0/S \) (where \( \Phi_0 = \hbar/2e \) is the flux quantum, and \( S \) is the area of the unit cell of the periodic pinning arrays.)

However, if \( n \) exceeds the so called saturation number \( n_s[3] \), extra vortices would nucleate at interstitial regions. The locations of these interstitial vortices are determined by vortex-vortex interaction and pinning potential. In imaging experiments such as electron-beam microscopy,[4] scanning Hall probe microscopy[5] and scanning tunneling microscopy[6] the coexistence of pinned vortices with interstitial Abrikosov vortices have been confirmed. However, most of these images were taken at temperatures far below \( T_c \), where the temperature dependent coherence length \( \xi(T) = \xi(0)/\sqrt{1-T/T_c} \) is small. At temperatures close to \( T_c \), transport measurements[7, 8] also shown that interstitial vortices can arrange in ordered configurations. We notice that previous works are mainly targeting on vortex configurations with small vortex densities. The distribution of interstitial vortex with large flux density is unclear. A honeycomb array is a special case of triangular array in which 1/3 of the sites are removed. Attention has been paid for its large interstitial region.[9, 10, 11, 12] In this work, we choose honeycomb array of holes with large diameter and small inter-hole spacing which enable us to investigate vortex configuration in a much wider field range. The magneto-resistance(MR) curves measured in increasing field and decreasing field allow us to gain more insight into the vortex configurations in such system.
2. Experiment
The nanostructured superconducting films were prepared as follows. First, the superconducting Nb film with a thickness of 100 nm was deposited by magnetron sputtering on SiO$_2$ substrate. Next, micro-bridge for transport measurement were fabricated by ultraviolet photolithography followed by reactive ion etching. Then the desired honeycomb array covering the whole bridge area of 60 $\times$ 60 $\mu$m$^2$ was patterned by electron-beam lithography (EBL) on a polymethylmethacrylate (PMMA) resist layer. The pattern was transferred to Nb film by magnetically enhanced reactive ion etching. After etching, the remaining resist was removed using warm acetone. Scanning electron micrograph (SEM) picture of the sample is shown in figure 1(a). The lattice constant is 600 nm and the diameter of the hole is about 540 nm. Two samples were fabricated in one chip, one with the current flowing along the Y axis (geometry A) and the other one with the current flowing along the X axis (geometry B), as illustrated in figure 1(b) and (c).

The transport measurements were carried out in a commercial Physical Properties Measurement System (PPMS) manufactured by Quantum Design. The magnetic field was applied perpendicular to the film surface. The superconducting transition temperature of both samples are 8.73 K (using a criterion of half normal-state resistance) with a transition width of about 0.2 K. Reference film without any pattern has a higher $T_c$ of 8.87 K and the transition width is only 50 mK. We measured the $T_c(H)$ phase boundary of the reference sample and obtained an extrapolated$[13]$ zero-temperature coherence length $\xi(0) = 10.8$ nm.

3. Results and discussion
The normalized MR curves for both samples at 8.60 K ($T/T_c = 0.991$) with a probing current of 30 $\mu$A are shown in figure 2. The magnetic field is increased from zero to about 0.1 T. The field axis is given in unit of $H_1$, the value at which the first resistance minimum is observed. For honeycomb array with a lattice constant 600 nm, the theoretical value of $H_1$ equals to 44.3 Oe at which the number of flux quanta equals the number of holes.

First we concentrate on the sample with geometry A. Two types of minima are clearly identified in figure 2(a). For fields smaller than $4H_1$, sharp dissipation minima occur at every integer multiple of the first matching filed. However, when the field is larger than $4H_1$, the minima become broader and the intervals between two consecutive ones are about $1.5H_1$ which is in excellent agreement with the matching field of a triangular array with the same lattice constant. Up to seven minima belong to this region are observed. The field dependent resistance for geometry B is shown in figure 2(b). Two regimes that have been observed in sample A can be identified clearly. Both the position and shapes of the integer matching minima show no significant difference. The difference between sample A and sample B can only be found in sub-matching located between integer matching minima. The insets of figure 2(a) and figure 2(b) highlight the fractional matchings of geometry A and geometry B respectively. For
Figure 2. Normalized magnetoresistance curves for Nb film with honeycomb array of holes in increasing field at $T=8.60$ K and $I=30 \, \mu A$. The data for (a) geometry A and (b) geometry B are plotted. The fractional matchings are highlighted in the inset.

geometry A, the half integer matching effect is very strong that the depth is comparable to the integer matching minima. This is consistent with findings in Ref [9]. Much shallower but also pronounced dips occur at $\frac{1}{4}H_1$ and $\frac{3}{4}H_1$. However, for geometry B, the dip occurs at half integer field is very weak but sharp dips at $\frac{1}{4}H_1$ and $\frac{3}{4}H_1$ can be easily identified. The origin of this dissipation anisotropic is probably related to the six-fold rotational symmetry of honeycomb array.

Similar phenomenon of crossover from low field to high field has been observed in rectangular array of magnetic dots [7, 14] and explained in terms of reconfiguration of the vortex lattice from rectangular to square geometry. Note that in our samples with large holes, circular current is induced around the holes to satisfy the fluxoid quantization condition when subjected to external fields. At low field regime, the interstitial region is in Meissner state. The circular current also acts as shielding current. The system behaves like wire networks so energy minima exist when the external flux density is an integer multiple of the flux quantum. At high field regime ($H > 5.5H_1$), interstitial Abrikosov vortex are generated to minimize the total energy and the overall symmetry of the flux lattice is triangular. The presence of one interstitial vortex in each interstitial site of the honeycomb array has been reported[9] The wide high field range(seven minima)in this study provide evidence for ordered interstitial vortices with high flux density.

Until now we have discussed the MR curves measured with increasing fields. If the magnetic field is first increased from zero to a maximum value ($H_{max}$) and then decreased back to zero, hysteretic effect is observed in both geometries. The MR curves obtained in decreasing fields of geometry B are plotted in figure 3. Four different values of $H_{max}$ are chosen. A direct comparison between the decreased field curve and the increased one (the same curve in figure 2(b)) allows us to identify the hysteretic effect. When $H_{max} = 3.8H_1$ and $H_{max} = 5.0H_1$, the MR curve is fully reversible as shown in figure 3 with filled square and circle. However, with a medium field value $H_{max} = 10.3H_1$, the minima position in decreasing field is different from the increasing one. The irreversible region is between $8.5H_1$ and $2H_1$. The curve with $H_{max} = 15.3H_1$ is shown with down- triangle. The hysteretic effect is observed in the same field region form $8.5H_1$ to $2H_1$. Therefore, the region between the two dotted lines in figure 3 shows hysteretic effect and does not change for $H_{max}$ larger than $10H_1$. This is a very large field span compared to previous studies in rectangular array.[15]

From the first part of our discussion, we know that the first ordered configuration with
interstitial vortices appears at $H = 5.5H_1$. The decreased field MR curves with different $H_{\text{max}}$ suggest that the hysteresis is related to the presence of interstitial vortices. Vortices formed at interstitial sites can be pinned by the intrinsic pinning of the film so they do not leave the film following the reverse sequence they enter.

4. Conclusion
In conclusion, we have performed transport measurements in perforated superconducting Nb film up to large flux density. The MR curves include two parts and can be distinguished according to the intervals of the minima. Besides, hysteretic effect is observed in a large field span. These observations confirm the presence of interstitial vortex in high field region. The results also indicate that the flux lattice reconfigure from honeycomb in low field region to triangular arrangement in high field region.

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