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Temperature dependence of vortex configuration by honeycomb hole arrays in a superconducting Nb film

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A honeycomb array of submicrometer holes in a Nb superconducting thin film has been fabricated to investigate the flux pinning effect. It is found that the minima positions reveal two regimes characterized by the matching fields and the fractional ones. It is believed that the complex behavior may come from more than one vortex being captured per pinning site. Furthermore, the temperature dependence of the saturation number of vortices per pinning site together with vortex-vortex interaction gives the complex vortex configurations. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1849511]

I. INTRODUCTION

In type II superconductor, magnetic fields can penetrate into the superconductor inhomogeneously as an array of vortices. The interaction of these vortices and vortex-pin interactions in the superconductor give rise to a rich variety of static and dynamical phases. Recently, vortex lattice states in periodic pinning arrays have been attracting considerable attention as they represent ideal examples of an elastic lattice interacting with a periodic substrate.[1] Nanolithography based on electron-beam direct writing[2–6] has been used to prepare submicrometric structures with geometries specified. Herein, one important aspect for the pinning mechanism is that the artificial pinning center is occupied by either one vortex or multivortex. Experiments[4] and numerical simulations[7] have shown the excess vortices can be pinned to the weaker pinning sites at interstices. Ordered vortex lattice structure with various symmetries has been imaged using Lorentz microscopy by Harada *et al.*[4] The vortex positions observed in these experiments were then well reproduced by numerical simulations by Reichhardt, Olson, and Nori.[7] Another possibility at the matching fields is that multiple vortices can occupy individual pinning sites. For an isolated pinning center the saturation number of vortices is $n_s \approx d/[4\xi(T)]$,[8] the maximum possible number of the vortices trapped by the single insulating, where d is the diameter of a defect and ξ is the superconducting coherence. One the other hand, a Bitter decoration technique was used by Bezryadin, Ovchinnikov, and Pannetier[9] to investigate multivortex states. That work demonstrates that the size of the pinning sites can influence the number of the vortices trapped at a single site. Furthermore, it is supported by numerical simulations[10,11] of scaling of the critical current for varied pinning strength. In this work we study a periodic pinning of magnetic flux quanta in a Nb film with a honeycomb array of submicrometer holes. The situation for our sample is based on the corrugation of Nb film. The main effect of the corrugation is that the Nb film effectively has a reduced thickness along the perimeter of the defect causing lower T_c superconductors. The magnetoresistance (MR) curves of our sample can show the matching and the fractional matching properties that allow us to study the configuration of the vortices.

II. EXPERIMENT

Honeycomb arrays of submicrometer holes with 80 nm depth, a spacing of about 400 nm and a diameter close to 300 nm have been prepared on Si_3N_4-coated Si wafers using electron-beam lithography in conjunction with reactive ion etching. Then a dc sputtering completed the four-terminal geometry niobium films over the circular-hole array with a thickness of about 100 nm. This process is similar to that published in our previous reports.[5,6] Figure 1 shows an scanning electron microscopy (SEM) micrograph and an atomic force microscopy (AFM) image for a honeycomb array of corrugated pinning sites. MR measurements were carried out by a four-probe technique in a superconducting quantum interference device (SQUID) system with a temperature fluctuation within 3 mK and the external magnetic field was applied perpendicular to the plane of the film and transport

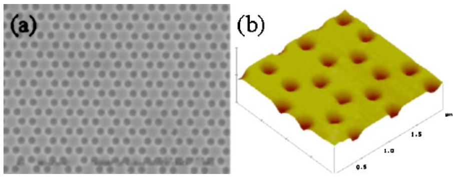

FIG. 1. (a) SEM micrograph of honeycomb array of holes. (b) AFM three-dimensional image of the patterned sample.

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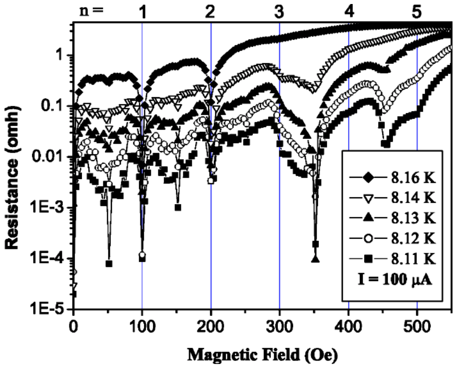

FIG. 2. Magnetoresistance curves with the driving current of 100 μA at different temperatures; n indicates the number of vortices per unit cell of hole array under matching field.

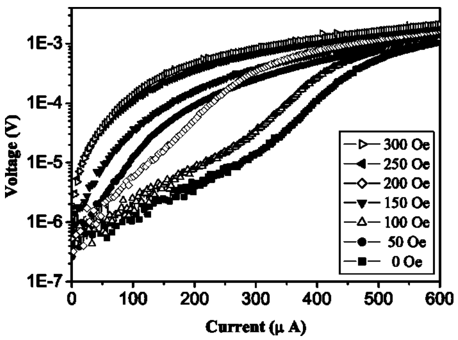

FIG. 3. *I-V* characteristics for a honeycomb array of the pinning sites at $T = 8.16$ K under various half integer and integer matching fields applied perpendicular to the film plane.

current. The superconducting transition temperature, T_{C0}, of the sample at zero field is 8.28 K and the superconducting transition width was 0.1 K.

III. RESULTS AND DISCUSSION

The experiments with either square or triangular anti-dot arrays of pinning sites do not show much of a qualitative difference. However, as one with honeycomb arrays suggests, the lack of defects in the central position of a triangular array transforms the pinning arrays into honeycomb ones. Figure 2 shows the magnetoresistance (MR) curves within the various temperature range $T = 8.11-8.16$ K. As can be seen, these curves show a set of minima of magnetoresistance at specific value of external fields. These intervals between two consecutive minima (ΔB_0) are about 100 Oe. This is in good agreement with the calculation based on the geometry of honeycomb unit cell of the pinning sites. Therefore, the vortex pinning can be strongly enhanced when there is a geometric matching between the vortex lattice and the pinning arrays. In particular the occurrence of the first matching field corresponds to the vortex density $(n_v = \Delta B/\Phi_0 = 4.831\ \mu\text{m}^{-2})$ being equal to the pinning center density $(n_p = \Delta B/\Phi_0 = 4.811\ \mu\text{m}^{-2})$, where Φ_0 is the flux quantum.

Most remarkably, two types of sharps at the minimum of resistance are clearly present; one is narrow and deep at low fields, and the other is broad at high fields (above 300 Oe). On the other hand, additional structures are visible to the whole part of the curves called fractional matching fields. A detailed analysis of the minima positions reveals two regimes characterized by the matching fields and the fractional ones. In the low field regime, the half integer matching effects $(n = 1/2, 3/2, 5/2)$ are weaker than the integer ones. This indicated that there is less energy loss at integer matching fields. However, we can find that the minima of the half integer matching field at high magnetic fields are distinct. It is believed that the complex behavior may come from more than one vortex being captured by an individual pinning site. Due to the temperature dependence of coherence length, the coherence length become larger and then the number of vortices in one pinning center become fewer when the temperature is close to critical temperature T_c. This is because the saturation number that depends on the coherence length gives the maximum number of vortices. As can be seen from Fig. 2, more than one vortex can be pined by one defect at lower temperatures, such that it indicates that vortex configurations should be correspondingly changed, and magnetoresistance becomes larger markedly.

Figure 3 shows *I-V* curves at integer and half-integer matching fields. The reduction in the energy dissipation can be observed at integer matching field. At higher driving force an ordinary monotonic behavior can be observed, that is, the voltage drop increases with magnetic field. However, the *I-V* curves measured at each integer matching field cross with its half integer matching field in lower driving force regime. The voltage drop at integer matching fields becomes smaller than that at half integer ones. These crossovers indicate a different pinning mechanism as a function of the current. In addition, the integer matching curve (100 and 200 Oe) has quite a similar shape as the zero field curve. It is suggested that the multivortex could be stabilized at each artificial pinning center. The vortices in one pinning site repel one another and move to the edges of the pinning site. The interactions between the vortices in the pinning sites and other pinning sites give rise to some orientation ordering. The excess vortices can be pinned in interstitial sites with weaker pinning. Since the vortex-vortex distance varies with applied field, the weak pinned interstitial vortices easily move through the vortices at the pinning sites where the pinning potentials are stronger. As a result, the integer matching effects are stronger than the half integer ones, as shown in MR datum.

Herein, for more discussion we sketch out the contour plot of the vortex-vortex interaction force strength created by a honeycomb array of pinning sites, and each pinning site captures three vortices, as shown in Fig. 4. The reason for making this assumption is that the length scale of the hole diameter can be compared with the temperature dependence of characteristic lengths of the superconductor. The vortex-vortex interaction energy was calculated with the following parameters: $d = 280$ nm, $a = 400$ nm, $\lambda = 790$ nm, and $\xi = 95$ nm,[12] where d is hole diameter and a is the lattice distance of a array. The interaction force strength between two vortices with the distance of r_{ij}[13] is

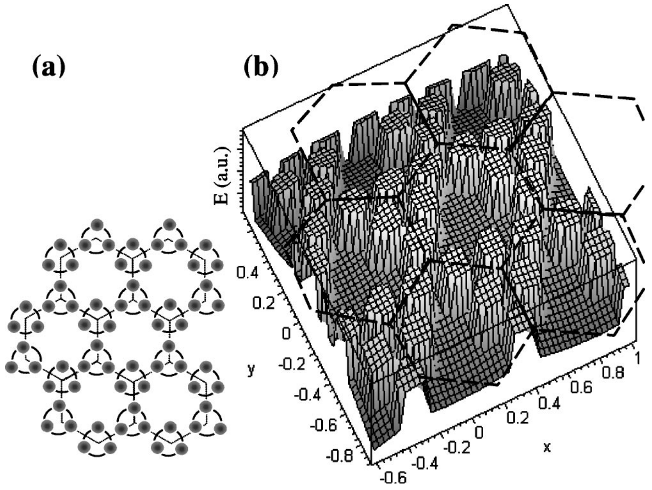

FIG. 4. (a) Schematic drawing shows three vortices captured by one pinning site in a honeycomb array. The vortices distribution (filled circles) for every pinning site (open circles) captures three vortices in a honeycomb array of pinning sites. (b) Sketch of the vortex-vortex interaction force strength created by the three-vortex distribution.

$$F_{ij} = \frac{\Phi_0^2}{8\pi^2\lambda^2} K_0\left(\frac{r_{ij}}{\lambda}\right),$$

where K_0 is a zero-order Hankel function with an imaginary argument and the λ is the magnetic penetration depth. The behavior is illustrated in Fig. 4(a), in which there are three vortices captured by one pinning site, and forming a regular vortex state. When the external fields are increased to $n = 3.5$, the excess vortices can be caged at interstices, such that the overall vortex lattice still remains ordered. This behavior causes the vortex lattice to become stiffer at higher fields. As vortices interactions become stronger, the interstitial lattice cannot easily flow around. As a result, at higher magnetic fields (above 300 Oe) the half integer matching effects are even much stronger than integer ones. Unfortunately, the third matching effect is less noticeable in the behavior of the MR, as shown in Fig. 2. This is because the total vortex-vortex interaction force almost overcomes the pinning force of the pinning sites. As a whole, the vortex-vortex interaction between the three-vortex at pinning sites and interstitial vortices can make a contribution to more stable pinning structure that is in agreement with the less energy loss on the magnetoresistance.

IV. SUMMARY

Flux-line confinement by a honeycomb array of submicrometer holes has been studied in a superconducting Nb film. The integer and half-integer matching effects observed in the MR curves are related to the flux pinning caused by the honeycomb array of defects. When the magnetic fields are equal to the integer matching fields or half integer ones, the vortices would be arranged in good order. The vortex lattices configuration in a honeycomb array of defects forms a coexistence of the multivortex at one pinning site and the vortices at the interstice. This leads to a much broader and deeper half integer matching effect in higher field range.

ACKNOWLEDGMENTS

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