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The ac effect of vortex pinning in the arrays of defect sites on Nb films

T. C. Wu
Department of Electrophysics, National Chiao Tung University, Hsinchu 300, Taiwan

Lance Horng,[a] J. C. Wu, and C. W. Hsiao
Department of Physics, National Changhua University of Education, Changhua 500, Taiwan

Jan Koláček
Institute of Physics, ASCR, Cukrovarnická 10, 16253 Prague 6, Czech Republic

T. J. Yang
Department of Electrophysics, National Chiao Tung University, Hsinchu 300, Taiwan

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Niobium thin films with spacing-graded array of submicrometer-scaled holes had been fabricated using electron beam lithography through a lift-off technique. The magnetoresistance measurements and current-voltage characteristics were carried out with the external magnetic field applied perpendicular to the film plane, in which commensurable effects were observed in both experiments. The magnetoresistance with positive/negative directions of dc current revealed identical curves except the dips at matching fields separated. Two distinct current-voltage curves, which resulted from the positive and negative applied current directions, respectively, were discerned when the external magnetic field was fixed at the matching field, which is believed to be due to asymmetry pinning potential in the spacing-graded array of holes. In addition, ac current-voltage curve measured at matching field showed a ratchet bump along with another extra peak associated with incommensurable effect. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2176143]

Patterned superconducting thin films having a periodic array of submicrometric pinning centers have been of great interest due to their excellence for the studies of the flux pinning mechanisms in the type-II superconductors. Many systems that are being pursued for the fundamental physics as well as technological improvement have been widely studied over the past decade.[1–16] A number of theoretical simulations[17–19] and experiments[1–16] have illustrated numerous commensurable effects. It has been shown that the strong pinning effect is related to the strong influence by the presence of defects acting as pinning centers. A rich variety of static and dynamical phases are result from the competition between the vortex-vortex and vortex-pin interactions. Many evidences have been used to characterize the various behaviors using channeling effects[5] in the vortex motion, the anisotropy pinning on the magnetization of the pinning centers,[7,8] and the vortex lattice ratchet effect.[3,4,18–20] Herein, we present a spacing-graded array of submicrometer-scaled holes on the niobium thin films, and the magnetoresistance measurements and current-voltage characteristics reveal many effects due to the dc current directions and ac current.

A spacing-graded array of submicron holes was fabricated by using an electron beam lithography through a lift-off technique, as described elsewhere.[12,13] In brief, a Si_3N_4-coated Si wafer was spin coated with a polymethylmethacrylate (PMMA) positive electron resist, and the desired holes were created in the PMMA using electron beam lithography. Subsequently, hole array was transferred into Si_3N_4 using a reactive ion etching technique. A second step of electron beam lithography was then used again to create a four-terminal geometry of trench that covers the hole array. The device was completed after a dc sputtering of the niobium film over the trench and lift-off in the acetone. The film thickness was controled to be 100 nm. Figure 1 shows a scanning electron microscopy (SEM) micrograph of the spacing-graded array of corrugated pinning sites. The hole depth is around 80 nm, confirmed by atomic force microscope, and the hole diameter is 200 nm, which is comparable to the superconducting coherence length of Nb close to T_C. The geometry of the defects was arranged approximately in

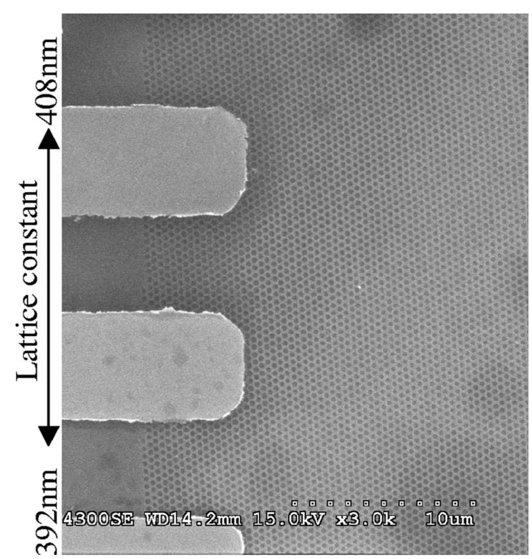

FIG. 1. SEM micrograph shows the top view of the x-y cross section of the sample. The holes are arranged in triangular array with spacing variation in the range of 392–408 nm and extended over an area of $30\times 50\ \mu m^2$.

[a]Author to whom correspondence should be addressed: FAX: 886-4-721-1153; electronic mail: phlhorng@cc.ncue.edu.tw

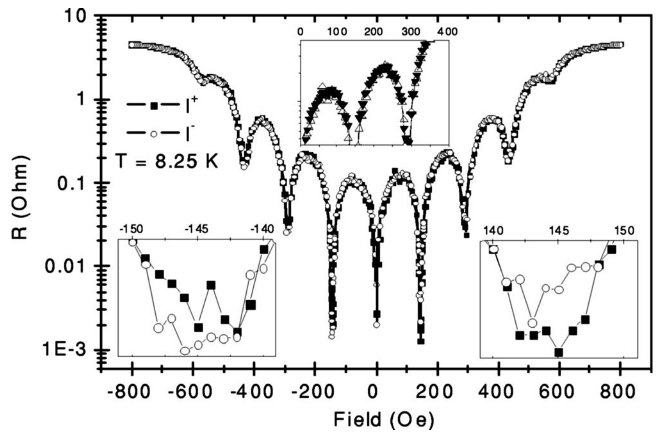

FIG. 2. Magnetoresistance (MR) curves in the mixed state. The temperature is 8.20 K and the injected dc current is 100 μA. The right and left insets show the sharp and shallow dips around the first matching field. The open cycle and filled square symbols correspond to positive and negative applied fields, respectively. The upper inset shows the applied field away from the matching condition.

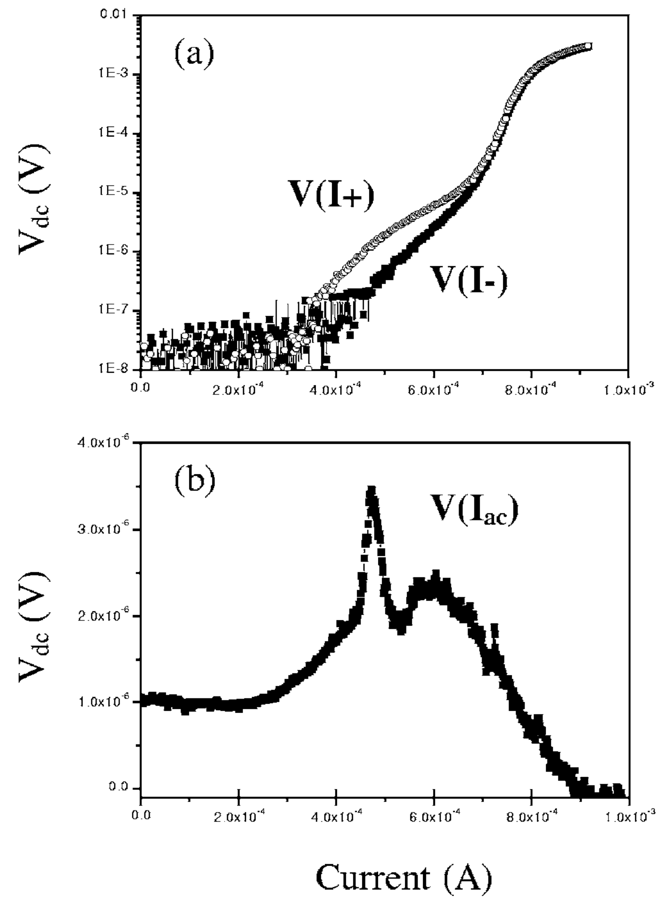

FIG. 3. (a) dc voltage vs dc applied current for a Nb film with graded pinning site's density at first matching field (145 Oe) and T=8.20 K. The open cycle and filled square symbols correspond to positive current and negative current, respectively. (b) dc voltage drop V_{dc} with an ac applied current I_{ac}.

the shape of a triangular array, with a constant hole-defect separation in x-axis direction and graded separation in y-axis direction from 392 to 408 nm starting from the top row to the bottom row. There are 75 rows making a row spacing increment of 0.22 nm. The size of the device is 30 $\times 50$ μm^2. That is, the density of the pinning sites increases gradually along the y direction and is homogeneously distributed along the x direction. The average density for the whole device is equal to a right triangular lattice of pinning sites with a spacing of 400 nm. It should be noted that the first matching field can be defined, that is, each defect contains one vortex. Magnetoresistance measurements and current-voltage characteristics were carried out by a four-probe technique in a superconducting quantum interference device (SQUID) system with a low temperature fluctuation within 3 mK, and the external magnetic field was applied perpendicular to both the film plane and the transport current. The onset of the superconducting transition temperature T_{C0} of this sample was found to be 8.32 K, and the superconducting transition width was 0.1 K.

As can be seen in Fig. 2(a), these magnetoresistance (MR) minima appear at equal field intervals of H_1=145 Oe for two opposite injected currents along the x axis. This field interval corresponds to a vortex density $n_v = H_1/\Phi_0$ =7.00 μm^{-2}, where Φ_0 is the flux quanta. This is in good agreement with the pinning centers density n_p=7.21μm^{-2}. The presence of the defects in the graded artificial arrays is due to structural corrugation in the Nb thin film and acts as very strong pinning centers. The graded array of pinning sites can give rise to commensurability effect. In addition, two well separated minima in MR curves appear clearly around the matching fields for the currents applied in two opposite directions along the x axis. Right inset of Fig. 2 shows the MR curve at the positive field in the region range from midpoint of first matching peak about 10 Oe. The overall resistivity minima values in negative currents were much lower than those in positive currents, pointing out that the asymmetric pinning effect for the vortex motion depends on the applied driving current direction. When the applied magnetic field is removed from the matching ones, the vortex lattice becomes incommensurable, as shown in the upper inset of Fig. 2. Herein, the dissipation resistivity is almost equal and independent of current directions. For more evidence of the experiment, however, the same results had also been obtained from applied negative magnetic field. In this case, two well separated minima in MR curves appear clearly around the matching condition for the two current directions, but the MR values of positive and negative currents are now reversed, as shown in the left inset of Fig. 2. Herein, the overall resistivity minima are much lower in positive current than in negative current on the negative field side.

The current-voltage (I-V) curves can show more evidence that the asymmetry pinning behavior of the spacing-graded array for the vortex lattice as shown in Fig. 3(a). The I-V curves were measured with current applied along x axis at fixed applied field equal to positive 145 Oe perpendicular to the film plane for T=8.20 K. Interestingly, the dc voltage drop in the negative current is much lower than that in the positive current at first matching field. The situation with the different dissipation resistivity for two opposite injected currents can be explained, that is, the vortex-vortex interaction should be taken into account at matching conditions. A single trapped vortex can be extracted from an isolated pinning center by applying an external driving force, because the depinning force was suggested to be independent of the direction of the vortex flow out of artificial pinning center. The external force to depin the vortex is suggested to depend on the vortex-vortex interaction force from the other vortices, owing to the strength of vortex-vortex interaction force which is strongly dependent on the distance between vortices. As a result, the net force may come from a single trapped vortex acted upon by the nearest trapped ones, since the net applied Lorentz force is opposite to the high pinning sites density direction. The vortices distributed with higher density have larger vortex-vortex interaction forces than those with lower ones. This indicated that vortices flow easier along lower pinning site density direction because of the applied Lorentz force. There are some indications that pinning site density gradient can affect the maximum depinning force and the anisotropy behavior is a clear indication of asymmetry in the periodic pinning potential seen by the vortex lattice.

Asymmetric pinning potential was studied by Nori *et al.*.[19,20] These authors found that vortex dynamics in asymmetric superconducting devices, driven by an external ac Lorentz forces, is a most promising way for an unprecedented degree of control of the motion of flux quanta.

Figure 3(b) shows the dc voltage drop V_{dc} measured along the x axis when an ac current $I=I_{ac}\sin(\omega t)$ is injected along the x axis, where ω is the ac frequency (1 kHz), and t is time, at $T=8.20$ K and $H=145$ Oe. Then the ac current density can yield an ac Lorentz force on the vortices. Thus the Lorentz force can be zero over the time averaged, i.e., $\langle F_L \rangle=0$. On the other hand, the dc voltage drop V_{dc} is measured along the x axis because of the average vortex velocity $\langle v \rangle$ in the direction of the ac driving force. Thus, the vortex lattice moves on this asymmetry pinning potential with a net velocity. From the expression for the electric field $E=B\times v$, the dc voltage drop V_{dc} can be measured by a dc nanovoltmeter. The plot in Fig. 3(b) clearly shows a nonzero dc voltage V_{dc} in the applied current range of 0.3–0.8 mA. It should be noted that the dc voltage as a function of ac current shows on important feature of the ratchet effect in the presence of a fixed applied field. The dc voltage strongly depends on the amplitude of the ac applied current and there exist two separated maxima. It has been shown that the dc voltage was kept at zero for the device having periodic triangular lattice of pinning sites (not shown). V_{dc} increases monotonically up to a maximum value and then followed by an extra bump as the ac amplitude increases around 0.5–0.8 mA of ac current amplitude at matching condition. The position of this extra bump coincides with the position extracted from the subtraction of two curves in Fig. 3(a), measured at first matching field. One can again clearly see the asymmetric pinning effect for the vortex lattice, which implies that there is a tendency for the vortex lattice to move toward the low-density side. As is clearly seen from the sharper jump in the rectified voltage curve, we conclude that interstitial vortices were subjected to an asymmetry potential, giving rise to a driving force stronger than that of the pinned vortex lattice. As a result, the first peak appears at low current density since the intestinal vortices move first resulting in a large dc voltage. Furthermore, the first peak shown in the rectified voltage curve appeared at all applied fields, and the latter extra bump only appeared at matching fields.

In conclusion, we have shown the asymmetry pinning by arrays of defects with spacing-graded pinning sites on niobium thin film. The magnetoresistance with opposite directions of dc current revealed identical curves except the dips at matching fields separated. Two distinct current-voltage curves from the positive and negative current directions were discerned when the external magnetic field was fixed at the matching field. By measuring the dc voltage drop V_{dc} with applied ac current along the x axis, the dc voltage would depend on the amplitude of the ac current. There exists a ratchet bump along with another extra peak associated with incommensurable effect. It is believed the vortex lattice and extra interstitial vortices take part in the asymmetry of the pinning landscape and induce ratchet effect, which can be suggested to control the vortex motion.

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[1] O. M. Stoll, M. I. Montero, J. Guimpel, J. J. Akerman, and I. K. Schuller, Phys. Rev. B **65**, 104518 (2002).
[2] J. I. Martin, M. Velez, J. Nogues, and I. K. Schuller, Phys. Rev. Lett. **79**, 1929 (1997).
[3] J. E. Villegas, S. Savel'ev, F. Nori, E. M. Gonzalez, J. V. Anguita, R. Garcia, and J. L. Vicent, Science **302**, 1188 (2003).
[4] M. Velez, D. Jaque, J. I. Martin, M. I. Montero, I. K. Schuller, and J. L. Vicent, Phys. Rev. B **65**, 104511 (2002).
[5] J. E. Villegas, E. M. Gonzalez, M. P. Gonzalez, J. V. Anguita, and J. L. Vicent, Phys. Rev. B **71**, 024519 (2005).
[6] V. Metlushko *et al.*, Phys. Rev. B **60**, R12585 (1999).
[7] M. Lange, M. J. Van Bael, V. V. Moshchalkov, and Y. Bruynseraede, J. Magn. Magn. Mater. **240**, 595 (2002).
[8] M. J. Van Barel, J. Bekaert, K. Temst, L. Van Look, V. V. Moshchalkov, and Y. Bruynseraede, Phys. Rev. Lett. **86**, 155 (2001).
[9] V. V. Moshchalkov, M. Baer, V. V. Metlushko, E. Rosseel, M. J. Van Bael, K. Temst, and Y. Bruynseraede, Phys. Rev. B **57**, 3615 (1998).
[10] A. Hoffmann, P. Prieto, and I. K. Schuller, Phys. Rev. B **61**, 6958 (2000).
[11] D. M. Silevitch, D. H. Reich, C. L. Chien, S. B. Field, and H. Shtrikman, J. Appl. Phys. **89**, 7478 (2001).
[12] L. Horng, J. C. Wu, T. C. Wu, and S. F. Lee, J. Appl. Phys. **91**, 8510 (2002).
[13] T. C. Wu, P. C. Kang, L. Horng, J. C. Wu, and T. J. Yang, J. Appl. Phys. **95**, 6696 (2004).
[14] L. Van Look, E. Rosseel, M. J. Van Bael, K. Temst, V. V. Moshchalkov, and Y. Bruynseraede, Phys. Rev. B **60**, R6998 (1999).
[15] U. Welp, Z. L. Xiao, V. Novosad, and V. K. Vlasko-Vlasov, Phys. Rev. B **71**, 014505 (2005).
[16] M. Baer, V. V. Metlushko, R. Jonckheere, V. V. Moshchalkov, and Y. Bruynseraede, Phys. Rev. Lett. **74**, 3269 (1995).
[17] C. Reichhardt, J. Groth, C. J. Olson, and F. Nori, Phys. Rev. B **54**, 16108 (1996).
[18] C. J. Olson, C. Reichhardt, B. Janko, and F. Nori, Phys. Rev. Lett. **87**, 177002 (2001).
[19] B. Y. Zhu, F. Marchesoni, V. V. Moshchalkov, and F. Nori, Physica C **404**, 260 (2004).
[20] F. Marchesoni, B. Y. Zhu, and F. Nori, Physica A **325**, 78 (2003).