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# Vortex ratchet effect in a niobium film with spacing-graded density of pinning sites

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The vortex propagation exhibits rectification effect in Nb superconductors with spacing-graded density of holes. A rectified dc voltage is obtained when the vortex lattice is driven by ac current. The asymmetric geometry of the pinning array produces a significant influence on the vortex motion. The rectified voltage depends considerably on the amplitude of the applied ac current and the magnetic field. The experimental results reveal a drastic change of the vortex rectification for magnetic field above/below the first matching field. The reason may be that the interstitial vortices are formed in the film above the first matching field. A reversible vortex motion is induced by the interstitial vortices for the field above the first matching field. © *2007 American Institute of Physics*.
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## I. INTRODUCTION

Nanolithographic technologies allow the preparation of well-controlled ordered arrays of pinning sites on the scale which is comparable to the characteristic length of superconductor. Magnetotransport properties in type II superconducting film are determined by the motion of the vortices. The vortex-vortex and vortex-pin interactions in the superconductor give rise to a rich variety of static and dynamical phases in vortex lattice.[1–17] The periodic pinning array enhances the critical current and the vortex lattice is stabilized at integer matching fields $H_n=nH_1$ ($H_1$ is the first matching field where one vortex is confined in one pinning site). Experimental[8,9,11] and theoretical studies[10,12] focus on analyzing the motion of vortices in superconducting films in recent years. Several schemes were proposed to control vortex motion and studied the ratchet effect in superconducting films. In the case of vortex dynamics in superconductors, several research groups have reported vortex rectification on periodic asymmetric pinning potentials, for example, two interpenetrating square pinning sites,[11,12] boomerang shape pinning sites,[2,10] and triangle pinning sites.[8,9] In these systems the symmetry of the vortex pinning potential is broken by the asymmetric pinning centers. The ratchet effect is found under ac current driving. The ac-driven vortices become rectified under the influence of the asymmetric potential.

Similar observations were obtained for samples with gradient in spacing between the symmetric holes in our research. We studied several effects produced by the spacing-graded arrays of pinning sites in Nb films. The lattice-constant variation results in the change of the pinning site's density. Since the pinning strength of pinning site can balance the elasticity of vortex lattice, the vortex lattice distorts to match the hole array at matching fields. However, the commensuration effects were eliminated by introducing graded concentration of hole distributions. Two different amounts of gradient of the hole have been fabricated, with the changing rate of the number density of defect in $y$ axis defined by $\Delta n_p/n_p$, where $\Delta n_p$ is the difference of the number density between the top row and bottom row and $n_p$ is the average number density. The changing rates of smaller gradient sample and the larger one are 7.96% and 69.02%, respectively. At least four matching fields are found in magnetoresistance (MR) curves for the small gradient sample. The rectified voltage shows complicated dc response at different magnetic fields as an ac current is applied. Detailed results of the small one can be found elsewhere.[15] In this paper, we present experimental results on the larger spacing-graded array of pinning sites. MR curves show a kink around the first matching field and no higher-order matching field is observed. The gradient structure breaks the symmetry of the vortex pinning potential and results in vortex motion rectification. The experiments indicate that the first matching field ($H_1$) is a borderline of two different types of vortex motions. The rectified voltage in the dc response increases as the magnetic field increases below $H_1$. As the magnetic field is further increased, the number of vortices is more than the number of pinning sites for magnetic field above $H_1$. The rectified voltage decreased monotonically and a reversal rectified voltage formed at the low current density region because of the appearance of interstitial vortices. The opposite

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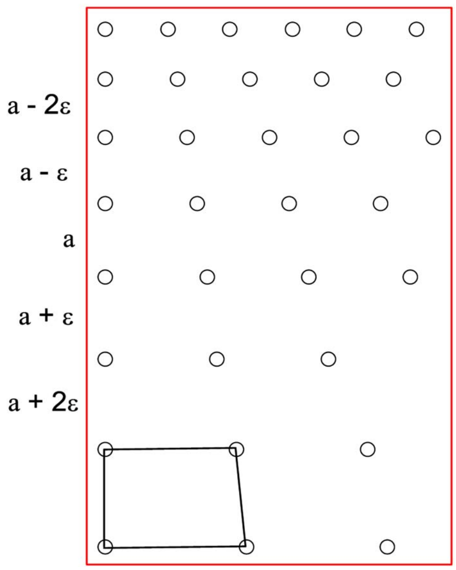


FIG. 1. Schematic presentation of the spacing-graded array configuration.

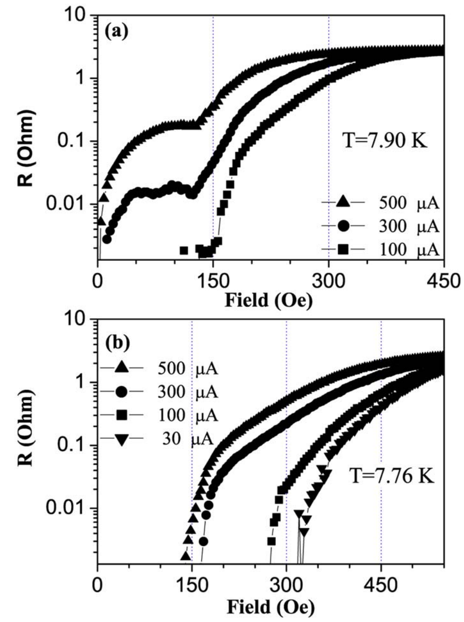


FIG. 2. Magnetoresistance curves MR of a niobium film with spacing-graded array of holes in two opposite direction of dc current: (a) $T=7.90$ K and (b) $T=7.86$ K.

flow of interstitial vortices may correspond to the repulsive interactions from the pinned vortices beyond the first matching field.

## II. EXPERIMENT

The samples used in the experiments were prepared by electron beam lithography combined with a reactive ion etching technique. The detailed process is similar to that published in our previous reports.[16,17] In brief, the hole array was defined on polymethyl-methacrylate (PMMA) positive electron resist using scanning electron beam, and then hole array was transferred into $Si_3N_4$-coated Si wafer through a reactive ion etching. The trench that covers the hole array was created, and then the niobium film with a thickness of about 100 nm was dc sputtered on the patterned substrate.

The diameter of the circular holes is approximately 200 nm. The hole array covers a total area of $30 \times 50\ \mu m^2$. The geometry of the defects is with a constant hole separation in the $x$ direction and a graded separation in the $y$ direction which increases from the top to the bottom, as sketched in Fig. 1. The lattice constant of the top row is 326 nm, and that of the bottom one is 443 nm. The intervals of the hole gradually increase in an increasement of $\varepsilon = 1$ nm. These are $\ldots, a-2\varepsilon, a-\varepsilon, a, a+\varepsilon, a+2\varepsilon, \ldots$, etc., where $a$ is the lattice constant. Thus, the number density of the pinning sites increases gradually along the $y$ direction and keeps constant along the $x$ direction. The average number density of the pinning sites for the whole sample is equal to a regular triangular lattice of pinning sites with spacing of 400 nm. In the spacing-graded array the 150 Oe may be identified as the first matching field $H_1$ where every pinning site can pin just one vortex.

Magnetoresistance measurements were performed in the mixed state of the sample using a quantum design model MPMS-5S superconducting quantum interference device (SQUID) system with a low temperature fluctuation within 3 mK. The external magnetic field was applied perpendicular to the plane of the film and the transport current. The current was injected along the $x$ axis and gave the vortices a $y$ direction driving force, that is, along the graded direction. The Nb films show a superconducting transition temperature equal to 8.02 K with a sharp superconducting transition width of 0.10 K.

## III. RESULTS AND DISCUSSIONS

MR curves measured at 7.90 K are plotted for several different current densities for applying current along the $x$ axis, as shown in Fig. 2(a). The pinning properties for the graded array of pinning sites are less effective than those for regular ones because the vortices cannot be stabilized in such a quasiregular hole array. Periodic minima at matching fields are absent in the MR curves. Two kinds of MR curves can be found in Fig. 2(a). For injected high current, vortices are moving and the resistivity increases below the first matching field. There are little dips in the MR curves at $H=68$ Oe ($I=300\ \mu A$) and 124 Oe ($I=300$ and $500\ \mu A$). The reduction in dissipation, however, is visible in a tiny range of temperature and for high injected current. It is noticeable that the flux density at 124 Oe has a relation to the pinning density, that is, the lattice constant of the bottom row is 443 nm. When the magnetic field is increased, portion of the vortices seems to be locked into the bottom pinning row. However, at the magnetic field of 172 Oe, which corresponds to the lattice constant of the top row (326 nm), the reduction of dissipation is not seen. Vortex lattice is more effectively pinned at low density of pinning sites than at high density of pinning sites.

For injected low current, MR curve shows a sharp onset of the resistivity for an applied magnetic field close to the first matching field, i.e., 150 Oe at 7.90 K, and the resistivity increases monotonic until normal state. The onset of the resistivity is also observed at matching fields in many MR curves for superconductor with regular periodic array of pin-

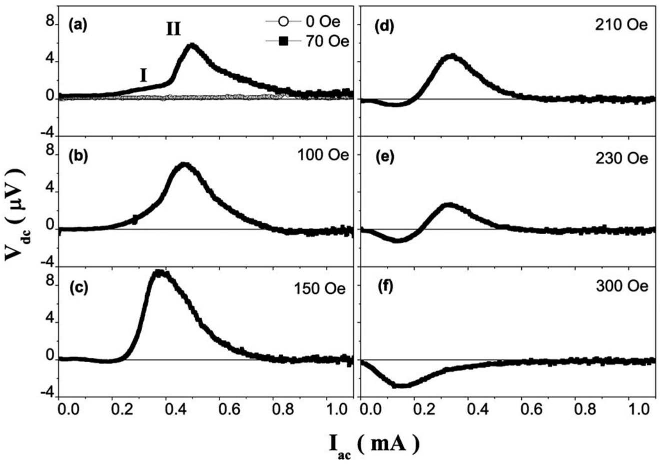


FIG. 3. dc voltage drop $V_{dc}$ as a function of ac current $I_{ac}$ for different magnetic fields. Panels (a)–(b): $H < H_1$. Panel (c): $H = H_1$. Panel (d)–(f): $H < H_1$. $H_1$ is the first matching field and is equal to 150 Oe.

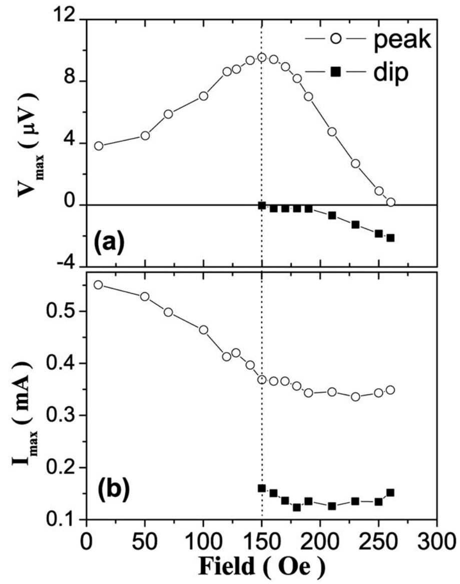


FIG. 4. (a) The dependence of the maximum/minimum rectified voltage ($V_{max}$) in the $V_{dc}(I_{ac})$ curves of the peak/dip for different applied magnetic field. (b) The position of peak (open symbols) and dip (filled symbols) as a function of applied magnetic field.

ning sites for low temperature or low injected current on matching fields.[3] Figure 2(b) shows a set of MR curves measured at lower temperature of 7.86 K with different current strengths. The curves show two separate groups where the sharp onsets of resistivity exhibit at field equal to 150 and 300 Oe, respectively. The flux densities at those onset fields are related to the average density of pinning sites, which is in agreement with lattice constant of 400 nm for regular array. This means pinning force is strong enough at low temperature to distort the vortex configuration which matches the quasiregular pinning array. As the magnetic field is further increased above the matching fields, as soon as the interstitial vortices appear, the pinned vortices start to be pushed out of the hole array. The pinned vortices start to move and avalanches take place. Then the dissipation of resistivity shows a monotonic flux-flow behavior without any characteristic features.

The ratchet effect is obtained because of ac-driven vortices being rectified in asymmetric potential. The transport properties are carried out using an ac current $I = I_{ac}\sin(\omega t)$ through the Nb superconducting film along the $x$ axis, where $\omega$ is an ac frequency (1 kHz) and $t$ is time. The ac current yields an ac-Lorentz force on the vortices. The time averaged Lorentz force is zero, i.e., $\langle F_L \rangle = 0$. According to the expression of the electron field $E = B \times \nu$, the dc voltage drop $V_{dc}$ is proportional to the average velocity $\langle v \rangle$ of vortices in the direction of the ac driving force. The dc voltage drop $V_{dc}$ is then recorded along the $x$ axis by a dc nanovoltmeter. Figure 3 clearly shows a nonzero dc voltage $V_{dc}$ for $T = 7.90$ K. It should be noted that the dc voltage as a function of ac current shows an important feature of the ratchet effect at a fixed applied field. This means that a net vortex flow toward the $y$ direction arises. The dc voltage strongly depends on the amplitude of the applied ac current.

By comparing the results obtained for our sample, we notice markedly the difference in the rectified voltage below/above the first matching field. Figures 3(a)–3(f) show the rectified voltages for several selected magnetic fields. Basically, the $V_{dc}$ increases monotonically up to a maximum value and then decrease smoothly. The positive rectified voltage corresponds to the motion of vortices from a region of high density pinning sites to a low density region. As the magnetic field is increased, the maximum rectified voltage ($V_{max}$) increased until a field $H = 150$ Oe, as shown in Fig. 3(c). In addition, the curves shift toward the low current density value as the magnetic field increases below the first matching field. Another important effect shown in Figs. 3(a) and 3(b) is that two types of ratchet phases labeled as I and II are being observed. Such a behavior takes place under the first matching field, that is, the number of pinning sites is more than that of the vortices. In phase I, a portion of vortices near the vacant pinning sites are first rectified by the ac injected current. In phase II, the whole vortices are being rectified. With the number of the empty pinning sites decreased, phase I disappears close to the first matching field. The rectified voltage abruptly increases and presents a maximum enhancement in the rectification at the first matching field. For magnetic field above the first matching field, the maximum rectified voltage starts to drop and a negative voltage forms in the rectified curve, as shown in Figs. 3(d)–3(f).

As can be seen in Fig. 3(c), the first matching field is a borderline of two different vortex motions. To emphasize the borderline at first matching field, the maximum in the rectified voltage ($V_{max}$) is depicted as a function of the applied field, as shown in Fig. 4(a). $V_{max}$ at the first matching field is the largest. The increase of the $V_{max}$ is due to the fact that more and more vortices penetrate into the film and are getting involved with the rectification with the increase of magnetic field. When the maximum number of pinned vortices is rectified, the value of $V_{max}$ is largest. All vortices trapped at the pinning sites may collectedly contribute to the rectified voltage. Above the first matching field, the interstitial vortices appear and are rectified. The interstitial vortices do not directly interact with pinning sites; however, they are repelled by vortices trapped at the pinning sites. The interstitial vortices were rectified in the opposite direction to the pinned vortices. The reversal drift of the interstitial vortices leads to a negative signal at low drives. Similar results are also reported by Nori and co-workers in Refs. 13 and 14. The rectified value of the interstitial vortices increased with increased applied field, as shown in the filled-square curve of Fig. 4(a). The interstitial vortices would block the motion of the pinned vortices, thus the rectified voltage of pinned vortices begins to decrease at high applied magnetic field.

It is interesting to note that the ac current amplitude at which the maximum of the dc rectified voltage ($I_{\rm max}$) decreased with increasing applied field until the first matching field. Then maximum rectified voltage decreased and $I_{\rm max}$ keeps constant at the same current around 350 $\mu$A. Meanwhile, the value of the negative rectified voltage increased and the ac current of the dip keeps constant at the same current around 150 $\mu$A for every curve above the first matching field. These trends are illustrated in Fig. 4(b). $I_{\rm max}$ strongly depends on the magnetic field amplitude below the first matching field. It should be noted that the vortex-vortex interaction plays an important role in this situation. The vortex-vortex interaction force is larger for vortices in the high concentration side than in the low concentration side. Thus the effective pinning potential is small for vortices in the high concentration side, and vortices prefer to locate at pinning sites in the low concentration region. The increase of the vortex-vortex interaction causes the vortices to be pushed out of pinning sites easily. The average effective pinning potential would decline with the increase of the vortex density, so $I_{\rm max}$ decreases towards a lower value as magnetic field increases until the density of pinning sites is equal to the density of vortices, i.e., the first matching field.

$I_{\rm max}$ for the positive/negative rectified voltage, however, is located at the same applied current equal to 350 $\mu$A [open symbols in Fig. 4(b)]/150 $\mu$A (filled symbols) for magnetic field above the first matching field. The interstitial vortices are confined between the pinned vortices and are balanced by the pinned vortices. Thus, the interstitial vortices were more easily influenced by the applied current than the pinned vortices. The constant current of 350 $\mu$A indicated that every pinning center that catches a vortex will hold onto it up to a certain maximum pinning force and depins at a certain applied current.

## IV. CONCLUSIONS

In summary, we have studied the rectification of vortex motion on a Nb superconducting film with spacing-graded array of submicrometer-scaled holes. The arrangement of the pinning sites controls the distribution of the vortices. Vortex-vortex interaction changes the effective pinning landscape of vortices and asymmetric potential is formed. The ratchet effect of vortices is created on spacing-graded array of pinning landscape. The mobility of two kinds of vortices is found with ac injected current through a superconducting thin film. One is pinned vortices and the other is interstitial vortices. The pinned vortices drift from a region of high density pinning sites to a low density region. Sharp peak in the typical rectified voltage was found as a function of ac current $V_{\rm dc}(I_{\rm ac})$. The interstitial vortices are rectified in the direction opposites to the pinned vortices. The $V_{\rm dc}(I_{\rm ac})$ shows a reversed polarity of the dip above the first matching field.

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