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# Vortex dynamics in spacing-graded array of defects on a niobium film

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**Abstract**

We have investigated the vortex dynamics in the niobium films having a spacing-graded array of pinning sites. The samples were fabricated by using electron beam lithography through a lift-off technique. The pinning sites of 200 nm in diameter were arranged with a constant hole-defect separation in *x*-axis direction and graded separation in *y*-axis direction from 392 nm to 408 nm. The magnetoresistance measurements and current–voltage characteristics were explored with the external magnetic field applied perpendicular to the film plane. Dc current–voltage measured at matching field revealed two distinct curves resulted from the positive and negative applied current directions, respectively. This is believed to be due to an asymmetry pinning potential formed in the spacing-graded array of holes, giving rise to asymmetry Lorentz forces. Dc voltage drop measured with respect to the ac current applied along the *x*-axis of the sample showed two separated maxima, which can be explained using the dynamics of pinned vortex lattice and interstitial vortices in the asymmetry pinning landscape.

*Keywords:* Matching field; Vortex dynamics; Thin films

## 1. Introduction

Flux pinning effect by artificial pinning arrays in a superconducting thin film has been widely studied over the past decade because of fundamental point of view as well as technological importance [1–11]. The influence of the array of defects is suggested to enhance the critical current density. Different shapes of pinning centers and arrays, different pinning sites (such as antidotes [1], holes [2], and magnetic dots [3–6]), and different materials have been explored. A rich variety of static and dynamical phases can occur due to the competition between the vortex–vortex and vortex–pin interactions. Many evidences have been used to characterize the various behaviors using channeling effects [3,7] in the vortex motion, the anisotropy pinning on the magnetization of the pinning centers [3–6], and vortex lattice ratchet effect [7–9]. Evidence for these phenomena has been observed in transport measurement when the longitudinal transport current is applied with the external magnetic field perpendicular to the film plane in the mixed state. The origin of the dissipation in the mixed state is related to the movement of these flux lines since, as they move with a certain velocity $v$, an electric field is induced given by the relation

$$E = B \times v. \tag{1}$$

Additionally, an ac Lorentz force is created to act on the vortices while an applied ac current is injected to the device. This yields time-averaged dc voltage drop along the direction of the injected current if we get none zero time-averaged vortex velocity $\langle v \rangle$

$$V_{\mathrm{dc}} = \langle v \rangle / Bd, \tag{2}$$

where $d$ is the distance between two electrode contacts and $B$ is the magnetic induction field. The device can provide one way to control vortex motion and the rectification

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can be observed in transport measurement. The dc rectification of an ac-driven system is known as the ratchet effect. In the present report, the transport measurement is performed to provide information about the pinning properties in a graded density of pinning sites. The graded density of pinning sites was made with a tiny variation of spatial distribution. This spacing-graded array of pinning sites provides tilted asymmetry potential seen by vortex.

## 2. Fabrication

We have fabricated artificial arrays of pinning sites with density gradient by electron beam lithography [10,11]. Briefly, the desired hole array of the device is produced by electron beam lithography in conjunction with reactive ion etching. 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 controlled to be 100 nm. Two kinds of geometries grown on the same substrate have been used in this work, as sketched in Fig. 1(a). One of the geometry is triangular array of pinning sites (sample A) with a lattice constant of 400 nm. The other one was arranged approximately in the shape of triangular array (sample B), with a constant hole-defect separation in *x*-axis direction and graded separation in *y*-axis direction from 392 nm to 408 nm started from the top row to the bottom row. There are 75 rows along making the row spacing increment of 0.22 nm. The size of the device is 30 μm × 50 μm. That is, the pinning site density of the film increases gradually along *y*-direction and is homogeneous distribution along *x*-direction. The average density of the sample B, however, is equal to the triangular lattice of pinning sites with the diameter of 400 nm. Fig. 1(b) shows a scanning electron microscopy (SEM) micrograph of spacing-graded array of corrugated pinning sites (sample B), with typical hole dimensions of 80 nm depth, and about 200 nm diameter, which is comparable to the superconducting characteristic length of Nb close to $T_c$. Magnetoresistance measurements were carried out by a four-probe technique in a SQUID system with a low temperature fluctuation within 3 mK, and the external magnetic field was applied perpendicular to the film plane and transport current. The onset of the superconducting transition temperature $T_{c0}$ of both the samples was 8.32 K and the superconducting transition width was about 0.1 K.

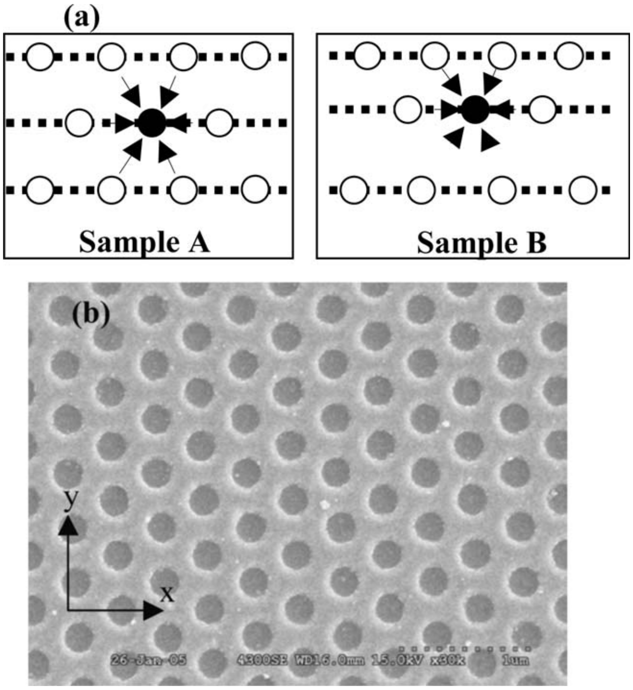

Fig. 1. (a) Sketch of the geometry of the pinning sites. Sample A is triangular array of pinning sites and the sample B is graded ones. Take first matching field for instance, the arrows are the local vortex–vortex interaction forces experienced by an individual flux line (filled circle) from its neighbors (open circle). (b) SEM photograph of the graded array of pinning sites.

## 3. Results and discussion

Due to the presence of the hole arrays, periodic pinning arrays can give rise to commensurability effects as a consequence of the geometrical matching is related to the vortex lattice and the underlying periodic structure. It was proposed that the pinning energy provided by the artificial pinning sites is larger than the elastic energy of the vortex lattice [3,4,12]. That is, the vortex lattice at integral multiples of matching field persists in strong pinning sites. Magnetoresistance (MR) curves were done with an applied field *H* perpendicular to the film plane in the mixed state and rise monotonically as the magnetic field increased until normal state, at $T/T_c = 0.992$, as shown in Fig. 2. Let us compare the magnetoresistance of an ordered array to that of an array with gradient. For both samples there are clear matching dips observed. Interestingly, these matching dips

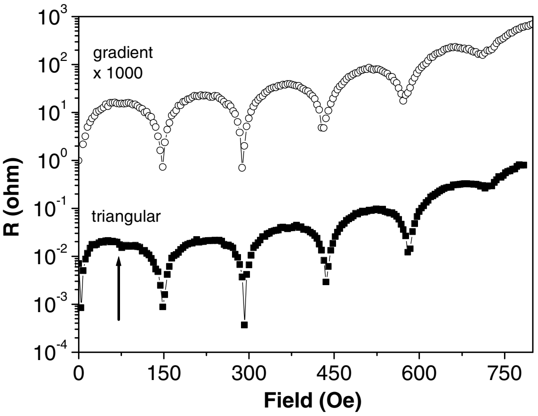

Fig. 2. Field dependent of resistance at $T/T_c = 0.992$ on two different patterns: filled square, triangular array of pinning sites: and open circles, graded array of pinning sites. The data has been normalized by normal state resistance and the top curve has been vertically displaced by a factor of 1000 for clarity.

in the resistance versus field show the same integral of matching fields. It is generally believed that the vortices arrange themselves with the same geometry as the underlying periodic pinning array. That is, the vortex lattice can be distorted by the artificial pinning center, even if the distributions of the pinning sites have small gradient. The MR exhibits commensurabile effects in which dissipation minima develop as a consequence of the geometrical matching. As can be seen in Fig. 2, these MR minima appear at equal field intervals of $H_1 = 145$ Oe. This field interval corresponds to a vortex density $n_v = H_1/\Phi_0 = 7.00\ \mu\text{m}^{-2}$, where $\Phi_0$ is the flux quanta. This is in good agreement with the pinning centers density $n_p = 7.21\ \mu\text{m}^{-2}$. This implies that the defects in the artificial regular arrays that are due to structural corrugation in the Nb thin film act as very strong pinning centers. The main differences between these two samples are that there is additional structure visible in the low part of curve for sample A and the matching dips of an ordered array are sharper than that of a graded array. This can be easily identified as the half-integer matching field for $n = 1/2$. In this situation, the vortex lattice can be more stable for half-integer matching field and integer ones in higher symmetry pinning array.

Fig. 3 shows a set of $I$–$V$ curves of sample B measured at different fields applied positive value perpendicular to the film plane with dc current applied along $x$-axis for $T = 8.20$ K. Curves with filled and open symbols correspond to positive and negative currents, respectively. Interestingly, one can clearly see the dc voltage drop in the negative current is much lower than that in the positive current at matching fields, while the dc voltage shows no quantitative difference out of matching field (for instance, applied field 120 Oe case). Notice that the quantitative differences of the $I$–$V$ curves are not pronounced in higher current regime above 0.75 mA. The $I$–$V$ curves for two opposite injected currents, however, are the same for all applied magnetic fields except matching fields. Apparently, the pinning landscape at matching fields formed by the spacing-graded pinning sites is more noticeable indication of an asymmetry in the periodic pinning potential that is seen by the vortex lattice. That is why the dc voltage drop depends on the direction of the applied current. It is important to point out that the vortex–vortex interaction should be taken into account at matching conditions, as shown in Fig. 1(a). A single trapped vortex can be extracted from an isolated pinning center by applying an external force. Because the depinning force were suggested to be independent of the direction of vortex flow out of the artificial pinning center. It is suggest that the external force to depin the vortex depends on the vortex–vortex interaction force from the other vortices. The arrows in this figure indicate the strength of the repulsive forces. For sample A, the triangular array of pinning sites, the repulsive interactions between a flux line and all its neighbors cancel each other and no net force occurs. Because of the strength of the vortex–vortex interaction force is dependent of the vortex–vortex distance. As a result, the net force may come from the nearest trapped vortices for a single trapped vortex. The situation is changed for sample B, the vortices distributed with high density exist larger vortex–vortex interaction forces than that with low density. We can expect the net force of the vortex appears in a direction opposite to that of the flux density in the presence of a flux density gradient. Here some results may be inferred from the arguments described above. First, the vortices at the graded density of pinning site may be affected by the nearest trapped vortices. Thus, the vortex motion is favorable for the applied Lorentz force along the direction of high pinning sites density. Second, the anisotropic vortices motion reflects the asymmetry in the periodic pinning potential seen by the vortex lattice at matching fields.

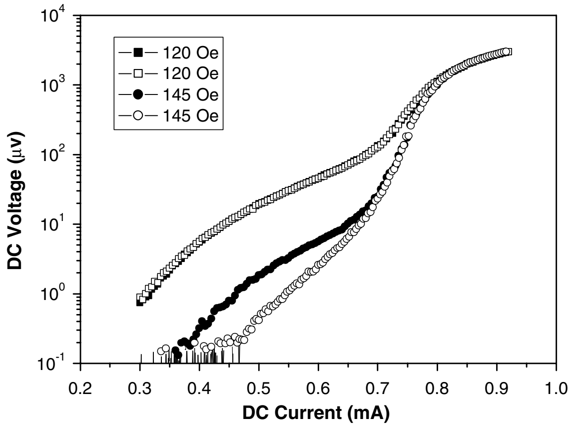

Fig. 3. The $I$–$V$ curves at $T = 8.20$ K measured for different field: square, 120 Oe; and circle, 145 Oe = $B_1$. While the applied current derived along positive direction (filled symbols) and negative direction (open symbols).

What happened if an ac current was injected? Now, it is interesting in discussing our results in terms of the applied ac current for a fixed magnetic field. The dc voltage drop $V_{dc}$ was carried out along the $x$-axis when an ac current $I = I_{ac}\sin(\omega t)$ is injected along the $x$-axis, where $\omega$ is the ac frequency (1 kHz) and $t$ is time, at $T = 8.20$ K. Then the ac current density can yield an ac Lorentz force on the vortices. Thus the ac 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 by a dc nanovoltmeter [5,6]. Dc voltage as a function of ac current shows important features of the ratchet effects in the presence of a fixed applied field for sample B, as shown in Fig. 4. The open and filled symbols correspond to $H = 145$ Oe and 33 Oe, respectively, that is, the first matching field and field not at matching fields. In Fig. 4, it shows that the dc voltage strongly depends on the amplitude of ac current and that there exists such a sharp maximum for sample B. While the dc voltage was zero for the structure with triangular lattice of pinning sites for sample A (not shown). The vortices move on the spacing-graded potential that belongs to irregular or asymmetric potential, thus the ratchet effect may be observed in the spacing-graded sample. Clearly visible peaks in the $V_{dc}$ curves, which increase steeply up to the maximum value and then decreases as the

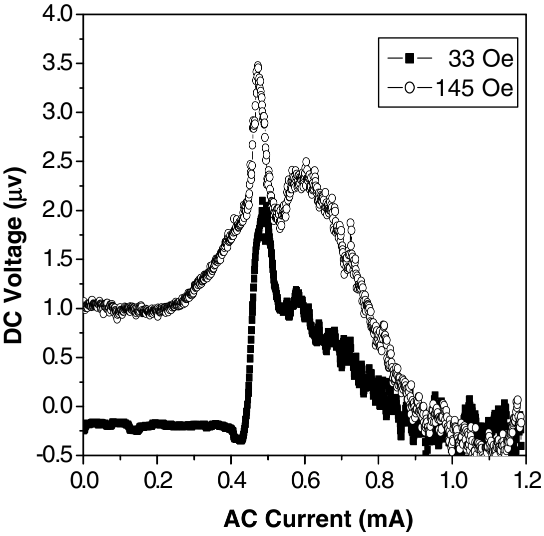

Fig. 4. Dc voltage drop $V_{dc}$ as a function of ac current density $I_{ac}$ at constant positive applied field for two applied field: filled square, 33 Oe, and open circle, 145 Oe (first matching field) at $T = 8.20$ K.

ac amplitude increase for two different applied fields, as shown in Fig. 4. Furthermore, there is an extra bump appearing in the $V_{dc}$ signal for the first matching field around 0.5–0.8 mA of ac current amplitude. The position of this extra bump just coincides with the position of peak which is computed from the data in Fig. 3 for the first matching field with the net average response of two curves, one is for dc current applied positive direction and the other is for the dc current applied negative direction at matching fields. Therefore, the ratchet effect can be easily observed by means of ac-driven vortex dynamics. The sharper jump in the rectified voltage curve, it is believed that interstitial vortices feel an asymmetry potential and stronger than the pinned vortex lattice. One can be clearly seen the asymmetric pinning effect for the vortex motion that depends on the orientation of the applied driving force.

## 4. Conclusion

We have found the asymmetry pinning by arrays of defects with modulated gradient spatial distributions on niobium film. The dc voltage as a function of applied dc current or applied ac current gives evidence that the artificial spacing-graded pinning sites induce ratchet effect, which may reasonably be suggested to control the vortex motion.

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