Properties of vortex propagation in a niobium film with spacing-graded density of pinning sites

Lance Horng, T. C. Wu, J. C. Wu, R. Cao, and T. J. Yang

Citation: Journal of Applied Physics **101**, 09G113 (2007); doi: 10.1063/1.2712323
View online: http://dx.doi.org/10.1063/1.2712323
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/101/9?ver=pdfcov
Published by the AIP Publishing

Properties of vortex propagation in a niobium film with spacing-graded density of pinning sites

Lance Horng[a)]
Department of Physics, National Changhua University of Education, Changhua 500, Taiwan

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

J. C. Wu and R. Cao
Department of Physics, National Changhua University of Education, Changhua 500, Taiwan

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

(Presented on 10 January 2007; received 31 October 2006; accepted 21 December 2006; published online 3 May 2007)

The vortex propagation has been investigated in Nb superconductors with one dimension spacing-graded density of submicrometer-scaled holes in this research. A rectification effect can be discerned because the applied ac is transformed into a net dc voltage. These results demonstrate that the rectification is mainly characterized by the asymmetric pinning landscape and the rectified voltage depends considerably on temperature and the amplitude of applied ac. The dc voltage increases steeply up to the maximum value and then decreases to zero dc voltage with the increase of ac. The shape of peaks in the dc voltage signal become steeper and move to higher applied ac regime with the decrease of temperature. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2712323]

I. INTRODUCTION

Magnetic flux penetrates type-II superconductor in the mixed state in the form of quantized vortices, which have the tendency to form a periodic lattice. When the current is injected into the superconductor, vortices will start to move if no defects exist to pin the vortices. The flux pinning effect is a fundamental characteristic for the superconductors with defects. The vortex-vortex and vortex-pin interactions in the superconductor give rise to a rich variety of static and dynamical phases.[1] A series of experiments[3,4] and numerical simulations[2,4–6] has analyzed the motion of vortices in recent years. Several schemes were proposed to control vortex motion and have attracted attentions to study ratchet effects in superconductor.[3–8] Several groups have reported the behavior of the vortex rectification on an array of periodic asymmetric pinning potentials.[3–5] The net vortex flow under ac drive will give rise to dc responds. Similar results have been obtained for quasiregular array of symmetric pinning centers in our research.[7,8] A spacing-graded array of submicrometer-scaled holes on the niobium thin films was studied by our group. The appearance of the vortex rectification can be caused by long range interaction between vortices which change the threshold of pinning energy at every pinning site. In this work, we want to investigate the rectified motion of the vortices under the influence of thermal effect. The rectified voltage, however, decreases in the dc response as the temperature increases. High temperature induces vortex fluctuations, which reduces the magnitude of the ratchet effect. The rectification effect is monotonically enhanced with the decrease of temperature.

II. EXPERIMENT

The spacing-graded array with circular holes was prepared using electron beam lithography (EBL) as described in Refs. 7 and 8. The circular holes approximately 200 nm in diameter and 80 nm in depth were created on Si_3N_4-coated Si wafer using reactive ion etching technique. Niobium films were then grown on top of arrays of hole by a dc sputtering in a shape of four-terminal trench. The film thickness is 100 nm and the total area of measuring bridge is $30 \times 50\ \mu m^2$. The lattice constant of the hole array in the y direction varied with small gradient. The defects were arranged with a constant hole separation in the x-axis direction and graded separation in the y-axis direction which increases from 392 to 408 nm. The distance between holes would be $\ldots, a-2\varepsilon, a-\varepsilon, a, a+\varepsilon, a+2\varepsilon, \ldots$ (a=400 nm and ε=0.22 nm). The number density of the pinning sites increases gradually along the y direction and is kept constant along the x direction. The average number density of the pinning sites for the whole device is equal to that of a regular triangular lattice of pinning sites with spacing of 400 nm. This type of holes effectively pins vortices in Nb, because the corrugation of the Nb film results in a lower T_c superconductor area. Magnetoresistance (MR) was measured using a four-probe technique in a superconducting quantum interference device (SQUID) system with a low temperature fluctuation within 3 mK. The external magnetic field was always applied perpendicular to the plane of film and the

[a)]Electronic mail: phlhorng@cc.ncue.edu.tw

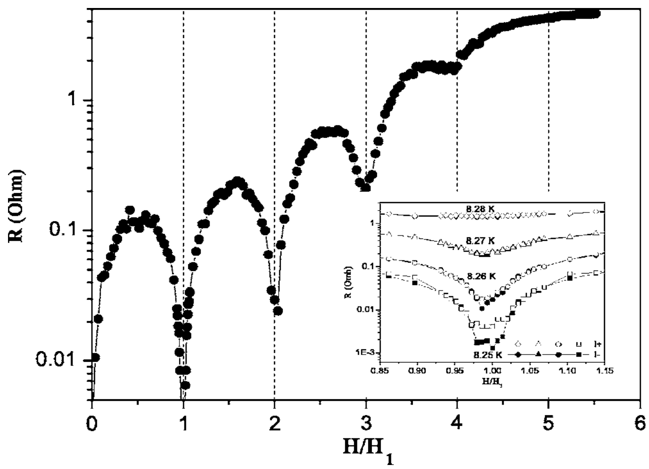

FIG. 1. Magnetoresistance curves $R(H/H_1)$ of a niobium film with spacing-graded array of holes at $T=8.25$ K and the injected dc is 100 μA. The inset shows the dip injected positive/negative current around the first matching field for different temperatures. The open and filled symbols correspond to positive and negative applied currents, respectively.

transport current in the mixed state of the sample. The current was injected along the x axis and gave the y direction driving force along the graded direction. The onset of the superconducting transition temperature T_{c0} of the device was 8.32 K and the superconducting transition width was about 0.1 K.

III. RESULTS AND DISCUSSION

As can be seen in Fig. 1, the MR curves reveal very sharp dips at matching fields for applying positive current along the x axis at 8.25 K. Periodic minima appear in the MR curves at equal field intervals, which are related to the average density of pinning sites. Similar curves were obtained for all the studied temperatures. This commensurability effect, which was found up to the fourth matching fields in the quasiregular array, indicates that the pinning is strong enough that a vortex lattice that matches the pinning array is formed. The reductions in dissipation corresponding to positive/negative current, however, are remarkably different around the first matching field for different temperatures, as shown in the inset of Fig. 1. The matching dips are much more pronounced at lower temperature. The difference of the minima for opposite applied current begins to be smeared out for higher temperature, while the reduction in dissipation decreased. Although the pinning of the hole array becomes dominant around matching fields, a deformation of the vortex lattice was formed in the spacing-graded pinning sites. A net force may act on a single trapped vortex by the nearest trapped ones. The graded pinned vortices result in a ratchet effect that is based on the change of the depinning threshold energy. The depinning force is asymmetric. Thus, the total force that acts on the vortex is large for injected positive current. As a result, the MR curves for two opposite directions along the x axis have well separated minima in the region around matching fields. For higher temperature, thermal effect results in vortex motion fluctuation which reduces the difference of the separated minima.

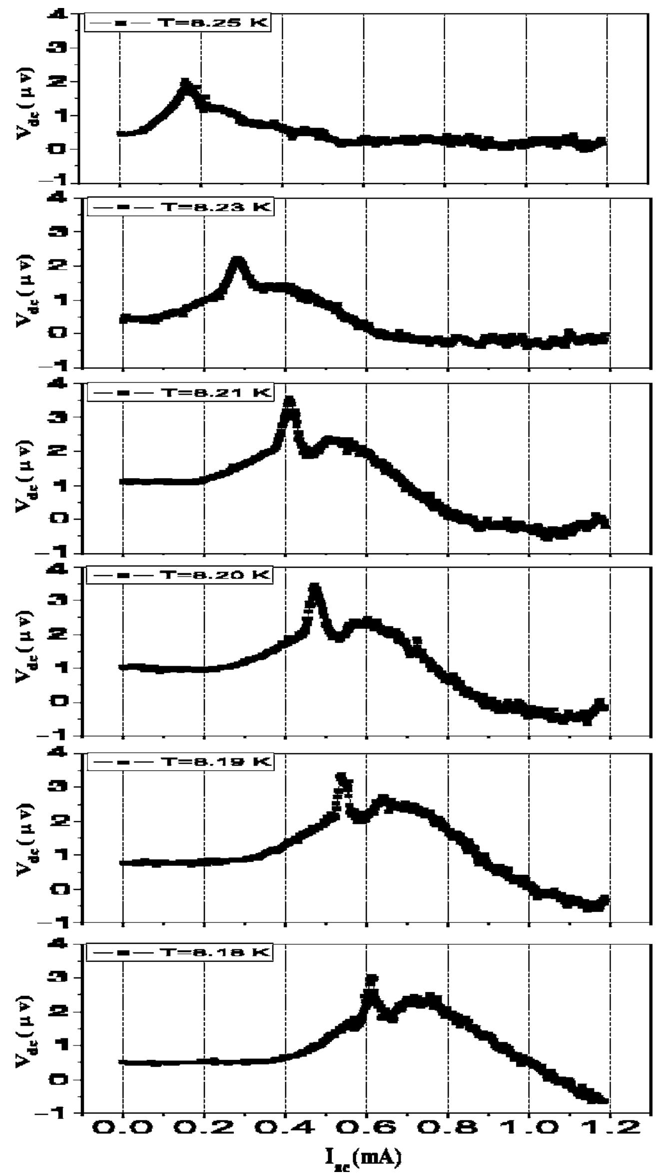

FIG. 2. dc voltage drop as a function of ac for different temperature.

Ratchet effect has been measured by injecting ac into the sample and measuring the dc voltage by a dc nanovoltage meter. We injected ac of 1 kHz along the y axis in the sample. The ac density give rise to an ac Lorentz force acting on the vortices. The dc voltage drop V_{dc} recorded along the y axis is governed by the average lattice velocity $\langle v \rangle$ caused by the ac driving force. The vortex motion is on asymmetric potential and a ratchet effect occurs. The rectification of ac-driven vortices as a function of applied ac at the first matching fields for different temperatures are shown in Fig. 2. For all curves, one sharp and one broad peak in the V_{dc} curve are clearly seen, the V_{dc} first increases steeply up to the maximum value and then decreases, with an extra broad peak appearing in the V_{dc} signal for the first matching field. It should be noticed that the position of the broad peak in these curves coincides with the position of the peak in the difference of the two curves (one is for dc applied in positive direction and the other is for negative direction for the first matching field) in the IV curves, as shown in Fig. 3. The IV

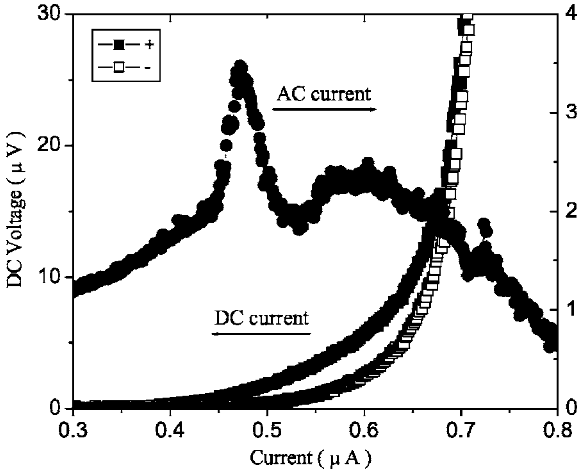

FIG. 3. The comparison between $V_{dc}(I_{ac})$ and $V_{dc}(I_{dc})$ curves at the first matching field and T=8.20 K.

curves for opposite injected currents show difference only at matching fields. This infers that these asymmetric *IV* curve characteristics can be correlated with long range order of vortex-vortex interactions of pinned vortices. The sharp jump in the rectified voltage curve is the predominant feature in the $V_{dc}(I_{ac})$ curve and is related to weak pinned disorder vortices, as our sample is quasiregular array of pinning sites and should have some random vortices. As a result, the sharp peak appears at low current density regime since the vortices are weakly pinned and move first.

Figure 2 shows the temperature dependence of the ratchet effect. The thermal noise also affects the rectification. The whole peaks are shifted to the low current density region with the increase of temperature. That is, the jump of V_{dc} occurs at lower value of I_{ac} and the magnitude of jump also decreases. Apparently, the net flow of vortices is developed when the vortex lattice is driven by ac above the threshold of the critical current. The critical current is temperature dependent, because the thermal fluctuations are favorable for the depinning and melting of the vortex lattice. The sharp jumps in the rectified voltage become broader and shallower as the number of random vortices increase which is induced by thermal fluctuation. It is interesting that the broad peak is less pronounced while the temperature is increased. We can expect that the broad peak comes from the pinned vortices sensing the asymmetric pinning energy. As the temperature is close to critical temperature, vortices cannot easily be pinned on graded array of pinning sites. Thus, the appearance of a dc component of the voltage no longer contributes to the $V_{dc}(I_{ac})$ curve and is absent at high temperature.

IV. CONCLUSIONS

In summary, we have studied the rectification of vortex motion for spacing-graded array of submicrometer-scaled holes. Both applied dc and ac were injected in superconductor and strong asymmetry in dissipation was observed. For both cases the thermal effect exhibit quantitative impact on the movement of the vortices when the temperature is high enough.

ACKNOWLEDGMENTS

This work was supported by the National Science Council of Taiwan of the Republic of China under Grant Nos. NSC 94-2112-M-018-004 and NSC 94-2112-M-009-001.

[1]C. Reichhardt, C. J. Olson, and F. Nori, Phys. Rev. B **58**, 6534 (1998).
[2]A. V. Silhanek, L. Van Look, R. Jonckheere, B. Y. Zhu, S. Raedts, and V. V. Moshchalkov, Phys. Rev. B **72**, 014307 (2005).
[3]B. Y. Zhu, F. Marchesoni, V. V. Moshchalkov, and F. Nori, Physica C **404**, 260 (2004).
[4]J. Van de Vondel, C. C. de Souza Silva, B. Y. Zhu, M. Morelle, and V. V. Moshchalkov, Phys. Rev. Lett. **94**, 057003 (2005).
[5]J. E. Villegas, S. Savel'ev, F. Nori, E. M. González, J. V. Anguita, R. Garcia, and J. L. Vicent, Science **302**, 1188 (2003).
[6]J. E. Villegas, E. M. Gonzalez, M. P. Gonzalez, J. V. Anguita, and J. L. Vicent, Phys. Rev. B **71**, 024519 (2005).
[7]T. C. Wu, L. Horng, J. C. Wu, C. W. Hsiao, J. Koláček, and T. J. Yang, J. Appl. Phys. **99**, 08M515 (2006).
[8]T. C. Wu, L. Horng, J. C. Wu, C. W. Hsiao, J. Koláček, and T. J. Yang, Physica C **437**, 353 (2006).