Experimental Vortex Ratchet Effect in Nanostructured Superconductors

J. E. Villegas, E. M. Gonzalez, M. P. Gonzalez, N. O. Nunez, J. V. Anguita* and J. L. Vicent

Departamento Física Materiales, Facultad Ciencias Físicas, Universidad Complutense, 28040 Madrid, Spain.
**Instituto Microelectrónica, Centro Nacional Microelectrónica, Consejo Superior de Investigaciones Científicas, Isaac Newton 8, PTM Tres Cantos, 28760 Madrid, Spain.*

Abstract. Superconducting Nb thin films were grown on different arrays of triangle-shape metallic islands. The vortex lattice dynamics could be strongly modified by these asymmetric vortex traps. These asymmetric pinning potentials lead to a rectification effect on the vortex motion: Injecting an ac supercurrent on the sample yields a net dc vortex flow. This vortex ratchet effect is adiabatic and reversible: The effect is frequency independent and the polarity of the dc voltage output could be tuned by the applied magnetic fields and the input ac currents.

Keywords: Nanostructured superconductors, ratchet effect, vortex pinning.
PACS: 74.78.Na, 74.25.Qt, 85.25.Am

INTRODUCTION

Ratchet mechanisms span inside many realms from Nature to research laboratories, from Applied Mathematics to Molecular Biology. We are alive because ratchet mechanisms are present in our cells, for example RNA polymerase moves by complex Brownian ratchet mechanisms during the crucial transcription step from DNA to RNA messenger (1). The core of ratchet mechanisms could be summarized as directional motion of out-of –equilibrium particles induced by a periodic asymmetric potential, without the need of being driven by non-zero average forces or temperature gradients.

Therefore, two ingredients are needed

a) Periodic structures which lack reflection symmetry.
b) Input signal yielding fluctuation motion of particles with zero-average oscillation.

For example, in proteins motors the room temperature induces the non-equilibrium background, and the asymmetric potential is provided by an on-off mechanism of charged and neutral proteins due to chemical reactions. Usually the biological motors belong to the so-called flashing ratchets. In this paper, we are going to deal with a different type of ratchet. In our case, the temperature is not playing the crucial role that plays in flashing ratchets. We are going to focus in a ratchet system which needs an applied zero-average driving force to be out of equilibrium and besides, in this ratchet device, the asymmetric potential (ratchet potential) is not time dependent. These types belong to the so-called tilted ratchets.

Recently, Villegas *et al.* have reported (2, 3) the fabrication and basic properties of a tilted ratchet system based on the motion of the superconducting vortex lattice in nanostructured superconducting films. They show that a Nb thin film deposited on a nanometric array of mesoscopic Ni triangles behaves as a tilted ratchet. An input ac current yields an output dc voltage and most remarkable the polarity of the dc voltage could be tuned at will with external parameters as the input signal and the applied magnetic field. The system could be easily modeled assuming that the pinned vortices in the Ni triangles and the interstitial vortices out of the Ni triangles are two repulsive particles according to the analysis of Savel'ev *et al* (4).

The temperature and field dependences of this ratchet system were reported in Ref. 2. In this paper we are going to focus in some of the main characteristic of this nanostructured device, mainly in its adiabatic behavior and the interplay between the interstitial and the pin vortices and the effect dependence with the asymmetric pinning center dimensions.

CP850, *Low Temperature Physics: 24th International Conference on Low Temperature Physics;*
edited by Y. Takano, S. P. Hershfield, S. O. Hill, P. J. Hirschfeld, and A. M. Goldman

EXPERIMENT

The samples are fabricated by the combination of different techniques, sputtering, electron beam lithography, photolithography and finally ion etching. First, the array (triangles) pattern is written on PMMA resist using an electronic microscope, after the development a Ni film is sputtered. The final lift-off step defines the array of Ni triangles. On top of this array a Nb film is grown by dc sputtering technique. On this film, using conventional photolithography, a micrometric bridge is defined, and finally ion etching on the Nb + Ni triangles sample allows obtaining the bridge for transport measurements. The thicknesses of the Nb film and the Ni nanotriangles are always the same 100 nm and 40 nm respectively. The separation between triangles and the triangle side vary from sample to sample. More experimental details, as array and bridge dimensions are reported in (2).

Magnetotransport measurements allow us to know the number of vortices per unit cell of the array and the position of these vortices. Dissipation (resistivity) sharp minima occur when the applied magnetic field (number of vortices) matches the array unit cell. Therefore, selected values of the magnetic field, which correspond to the minima positions, could be used to control the number of vortices (2, 5). More subtle is to know the position of these vortices, that is, if they are pinned in the Ni triangles or they are interstitial vortices between Ni triangles, but taking into account the so-called filling factor (6) which estimates the saturation number of vortices per defect and the sample (I,V) curves (2), this subject could be addressed. In summary, for chosen magnetic field values we know the number of vortices per array unit cell and where they are located. The only experimental data needed are measurements of resistance versus magnetic field at constant temperature. The equal spaced minima, in these data, are the crucial parameter to know the superconducting mixed state relevant properties. Data from two samples will be analysis in this work. The main characteristics are for sample A: Triangle side 620 nm, array period 770 nm, and magnetic field at first minimum H = 32 Oe (n=1 one vortex per triangle) and sample B: Triangle side 430 nm, array period 602 nm and magnetic field at first minimum H = 54 Oe (n=1 one vortex per triangle).

EXPERIMENTAL RESULTS AND DISCUSSION

In the INTRODUCTION two conditions needed having ratchet mechanisms were presented. In Figure 1 we show the results when only one of the conditions is accomplished. The out of equilibrium condition is reached injecting an ac current on the sample in the Y-axis direction, therefore the vortex lattice motion is in the X-axis direction. Since there is not broken symmetry in that direction the dc voltage recorded is zero, there is not ratchet effect, even the motion of the vortex lattice is driven by an ac force. However, Figure 2 shows a clear ratchet effect for the same sample A, for applied magnetic field of 64 Oe that corresponds to the second matching field (n=2 vortex per triangle). The ac current is now being applied in the X-axis direction, therefore the vortex lattice is moving in the Y-axis direction, and the second ratchet conditions is fulfilled, the vortices are feeling asymmetric potentials and a rectification is occurring from an ac current source to a dc voltage. Worth a while to note that the ratchet effect is not frequency dependent in the range attainable in our experiment up to 10 kHz. Villegas *et al.* (3) have explored this effect, recently van Vondel *et al* (7) has found the same behavior in superconducting Al films with array of asymmetric antidotes (holes). Both found that the vortex ratchet effect is in the adiabatic limit, but in both cases the analysis is done for n=2, (2) and n=1

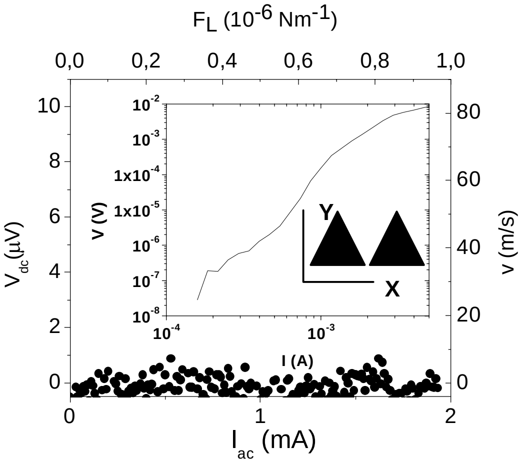

FIGURE 1. Sample A. T/T_c =0.99, H = 32 =Oe, n = 1 (one vortex per triangle). Vortex lattice motion parallel to the X-axis. There is not rectification effect. Y- axis: Left output dc voltage, right vortex lattice velocity extracted from the Josephson expression v = B x E (E, B being the electrical and magnetic fields respectively, see Ref. 2 for details). X-axis: Bottom input ac current (frequency 10 kHz), top Lorentz force on the vortex lattice, extracted from $F_L = J_{ac}$ x Φ_0 (J_{ac} being the applied ac current density and Φ_0 the flux quantum, see Ref. 2 for details). Inset shows (I, V) curve at the same temperature, we observe that the applied current is much larger than the critical current.

(7). But the most remarkable effect happens when the applied magnetic field is increase and interstitial vortices appear. According to Villegas *et al.* (2) the number of vortices tunes the polarity of the ratchet effect, because pinned vortices and interstitial vortices move on opposite ratchet potentials and the interplay between the number of interstitial and pinned vortices as well as the input current strength determine the sign of the output voltage.

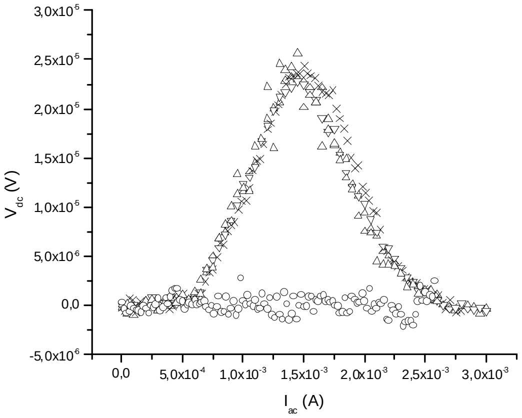

FIGURE 2. Ratchet signal for sample A at $T/T_c = 0.99$ and applied field H = 64 Oe (n=2). X-axis is the input ac current. Y-axis represents the output dc voltage. O experimental data for driving ac (frequency 10 kHz) current parallel to Y-axis (see inset Fig. 1), △, ▽, X, experimental data for driving ac current parallel to X-axis with ac frequencies of 10, kHz, 1 kHz and 1 kHz respectively.

We are going to study the possible adiabatic behavior when both types of vortices develop, that is vortices pinned in the Ni triangles and interstitial vortices.

In sample A the vortex filling factor is 3, see Ref. (2). Therefore n =6 is the situation more interesting, since the sample has 3 pinned vortices and 3 interstitial vortices. Following the analysis of Villegas *et al.* (3), the real ac driving ratchet effect could be mimic using dc (I,V) curves. First, a dc current is applied in the + X direction and the (I,V) data are recorded, after a dc current is applied in –X direction and the corresponding (I,V) curve is measured. Finally, both curves are subtracted and the net voltage is $V = V_p\text{-}V_n$. Fig. 3 shows this plot. The *dc ratchet* extracted mimics the behavior of the real ratchet. The interstitial vortices move first, because they do not feel the potential due to the Ni triangles and they need weaker driving forces. The interstitial vortices are located in *ghost and reversed* triangles among the real Ni triangles, see Ref. 2 and they move in opposite direction to the motion of the pinned vortices. The pinned vortices need stronger depinning forces (higher currents) to move, because they are *placed* in the real Ni triangles, that are pointing in the +Y direction. In conclusion this vortex ratchet is in the adiabatic limit. The frequency of the ac driving force does not play any role in this effect.

Finally, sample B is a good candidate to explore the effect of the pinning center dimensions and the interplay between interstitial and pinned vortices is crucial to understand the reversible ratchet effect.

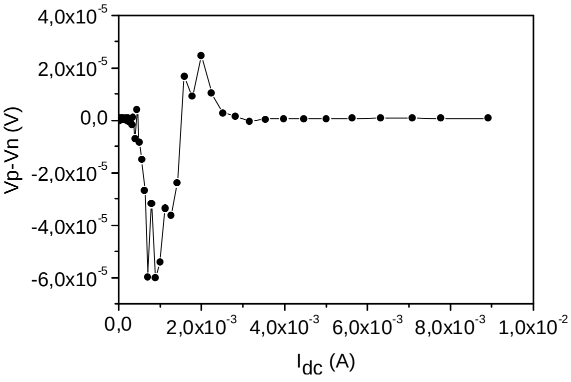

FIGURE 3. Sample A: *dc ratchet effect* extracted from (I,V) curves (see text for explanation). N = 6, applied field correspond to 3 pinned vortices and 3 interstitial vortices (H = 190 Oe). $T/T_c = 0.98$.

The magnetoresistance data of sample B allows us obtaining the matching magnetic field. At this field the vortex lattice is commensurable with the unit cell of the Ni triangle array. The matching field of sample B is 54 Oe, as well the pinning centers (triangles) are smaller than in sample A. We have larger matching field and lower pinning potential dimension. Sample B has larger separation and smaller pinning centers than sample A. The ratchet effect could be vanishing in this sample.

Taking into account the size of the defects (Ni triangles) and the expression for the filling factor (6) we obtain that in sample B the estimated filling factor is less than 3. Hence the triangles could not accommodate easily three pinned vortices as happens in sample A. The reversible rectification could be expected to occur for lower number of vortices than before. The vortex number three could be a good candidate to be an interstitial vortex. If this happens the situation n = 4 (two interstitial and two pinned vortices) could give the same result as n = 6 in sample A (see Ref. 2). Hence, the contribution of the positive (pinned vortices) and negative (interstitial vortices) could produce similar output dc voltage values, as happens in sample A for n = 6. That means that the positive and negative rectifications have similar amplitude.

Figure 4 shows that sample B is showing exactly the same trend than sample A, but with lower number of vortices per unit cell. Although sample B is not as good candidate as sample A to develop a reversible ratchet effect. The dimension of sample A are almost perfect, the real Ni triangle and the *ghost* triangles between the Ni ones are very similar. The vortex ratchet effect seems to be a very robust phenomena that could be easily observed in samples with array dimension far from ideal.

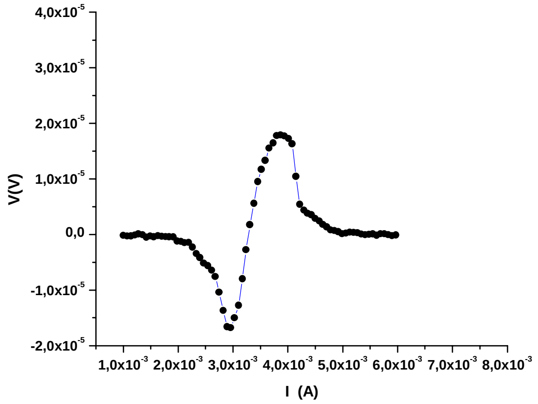

FIGURE 4. Sample B. Reversible rectification. X-axis is the input ac current. Y-axis represents the output dc voltage. N= 4: Two pinned vortices and two interstitial vortices per unit cell (H = 215 Oe). $T/T_c = 0.98$.

CONCLUSIONS

Nanostructured Nb film grown on top of array of Ni triangles rectified the vortex lattice motion. Injecting an ac current in the film an output dc voltage could be observed. This voltage is due to the net motion of the vortex lattice. This happens when the vortex lattice is moving on a landscape of asymmetric pinning potentials. The combination of zero average driving forces and asymmetric pinning centers is the clue to have a tilted vortex ratchet effect. This ratchet effect is adiabatic, that is the frequency of the zero average driving force does not play any role. The interplay between interstitial and pinned vortices governs the effect. The number of vortices per unit cell of the array can tune the polarity of the rectification effect.

ACKNOWLEDGMENTS

We want to thanks support from Spanish grants MAT2002-04543, NAN2004-09087, MAT2002-12385-E, CAM under grant 6R/MAT/0617/2002.Two of us, EMG and NON, want to thank Spanish Ministerio de Educacion y Ciencia for a Ramon y Cajal and Juan de la Cierva contracts respectively.

REFERENCES

1. G. Bar-Nahum, V. Epshtein, A. E. Ruckenstein, R. Rafikov, A. Mustaev, and E. Nudler, *Cell* **120**, 183-193 (2005).
2. J. E. Villegas, S. Savel’ev, F. Nori, E. M. Gonzalez, J. V. Anguita, R. Garcia, and J. L. Vicent, *Science* **302**, 1188-1191 (2003). E. M. Gonzalez, J. E. Villegas, M. P. Gonzalez, J. V. Anguita, and J. L. Vicent, *IEEE Trans. Appl. Supercon.* **15**, 888-891 (2005).
3. J. E. Villegas, E. M. Gonzalez, M. P. Gonzalez, J. V. Anguita, and J. L. Vicent, *Phys. Rev. B* **71**, 024519 (2005).
4. S. Savel’ev, F. Marchesoni, and F. Nori, *Phys. Rev. Lett.* **91**, 010601 (2003).
5. J. I. Martin, M. Velez, A. Hoffmann, I. K. Schuller and J. L. Vicent *Phys. Rev. Lett.* **83**, 1022-1026 (1999).
6. V. V. Moshchalkov, M. Baert, V. V. Metlushko, E. Rossell, M. J. van Bael, K. Temst, R. Jonckheere, and Y. Bruynseraede, *Phys. Rev. B* **54,** 7385-7393 (1996).
7. J. van de Vondel, C. C. de Souza Silva, B. Y. Zhu, M. Morelle, and V. V. Moshchalkov, *Phys. Rev. Lett.* **94,** 057003 (2005).