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Reversible rectification of vortex motion in magnetic and non-magnetic asymmetric pinning potentials

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Abstract

Nb films have been grown on arrays of asymmetric pinning centers. The lattice vortex dynamics could be modified, almost at will, by periodic pinning potentials. In the case of asymmetric pinning potentials a vortex ratchet effect occurs: the vortex lattice motion is rectified. That is, an injected ac current yields an output dc voltage, which polarity could be tuned. The output signal polarity could be switched with the applied magnetic field and the ac current strength. Ratchet effect occurs when asymmetric potentials induce outward particles flow under external fluctuations in the lack of driven direct outward forces. The output signal is similar using magnetic or non-magnetic submicrometric array of pinning centers. This device works as an adiabatic rocking ratchet. This superconducting ratchet could be a model to study biological motors.

Keywords: Ratchet effect; Nanostructured superconductors; Pinning; Molecular motors; Vortex rectification

1. Introduction

One of the most relevant topics on superconducting vortices behavior is the commensurability properties of the vortex lattice, which are induced by periodic pinning potentials. Since the work of Daldini et al. [1] a flood of papers has been published on this subject. In recent years, the possibility of fabricating nanometric arrays has actually opened a new research field. Arrays of submicrometric antidots (nanoholes) allow us studying very interesting pinning matching effects [2]. Martín et al. [3] show that superconducting films grown on arrays of periodic magnetic nanodots allow us tailoring the vortex lattice dynamics. Following this approach the possibility of vortex lattice channeling effects and guided vortex motion has been proved [4–6]. Arrays of symmetric pinning defects could be used to modify the vortex lattice symmetry [7] or enhance the vortex lattice order [8]. Asymmetric pinning potentials could be useful to go deeper in the modification of the vortex dynamics.

Lee et al. [9] have suggested the use of nanostructured superconductors as a way to obtain vortex motion rectification effects, based on the ratchet effect. Ratchet effect is the 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. This effect appears in many fields from Applied Mathematics to Biology. Ratchet effect state of the art could be found in [10].

Plain superconducting thin films grown on nanostructured arrays could be a better approach than the nanostructured superconducting films as is Lee et al. [9] proposal. Nanostructured superconductors could jeopardize the basic superconducting properties, as for instance,

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critical temperature. In the case of plain superconducting thin films grown on nanostructured arrays the roughness increases is the most relevant change. This does not hinder that the superconductor main properties remain similar to the usual values reported in thin films.

In this work we will deal with Nb thin film fabricated on arrays of Ni or Cu pinning centers. Nb/Ni and Nb/Cu systems show sharp interfaces and the critical temperatures are similar to plain Nb films of the same thickness. The Cu and Ni arrays only play the role of trapping the vortices, Nb films growth on Cu array as well as Ni array show similar values of critical temperatures and upper critical magnetic fields.

Recently, Villegas et al. have reported the fabrication and basic properties of a superconducting rectifier based on the ratchet effect [11]. The interplay between superconductivity and ratchet effect has been explored from the theoretical [9,12,13] as well as from the experimental point of view [14–20]. In this paper we will address some of the basic properties of this superconducting vortex ratchet effect and we will compare it with some molecular motors, which are based on the ratchet effect.

2. Experimental

Nb films have been grown on top of arrays of Ni or Cu nanotriangles. These samples are obtained following several steps. The first step is e-beam writing on a resist (PMMA) covering the Si(100) substrate, next developing using MIBK : IPA (1:3) during 15 s, and sputtering deposition of Ni or Cu. Once lift-off is performed, only nanometric Ni or Cu triangles remain on top of the substrate, which is then covered by a thin film of Nb, also by sputtering technique. The thickness is for Ni or Cu (triangles height) 40 nm, and the Nb film is 100 nm thick. The nanotriangles side is around 600 nm. Samples were lithographed for magnetotransport measurements with a cross-shaped bridge (40 μm wide) using ion etching and standard photolithography techniques. This cross-shaped bridge allows us injecting transport current and measuring voltage drops along two perpendicular directions. All magnetotransport experiments were carried out in a commercial liquid He cryostat provided with a superconducting magnet and a variable temperature insert. The frequency of the ac applied current is always 10 kHz.

The magnetic field is always applied perpendicular to the substrate. The dc magnetoresistance of superconducting thin films with periodic arrays of pinning centers shows minima when vortex–lattice geometrically matches the periodic pinning potential induced by the array of nanostructures [3]. In our samples, square arrays of pinning centers, minima appear at applied magnetic fields, $H_m = n\Delta H = n(\varphi_0/a^2)$, where a is the lattice parameter of the square array and $\varphi_0 = 2.07 \times 10^{-15}$ Wb is the magnetic flux quanta. By this way, the number of vortices n at a given applied magnetic field can be known by simple inspection of the dc magnetoresistance R(H) curves, in which the first minimum corresponds to one pinned vortex per unit cell.

Finally, the maximum number of vortices in the pinning traps could be estimated using the filling factor expression [21].

The nanotriangles array topography has been studied by Atomic Force Microscopy technique (AFM). The array is square with periodicity of 750 nm and triangles size 600 nm, for both system Nb film on array of Ni triangles and Nb film on array of Cu triangles. In the case of Ni triangles the magnetic properties have been studied by magnetic force microscopy technique (MFM). Ni triangles show in-plane aligned magnetization with the usual magnetic domain structure for the demagnetized state (see Fig. 1).

Ratchet effect has been measured [11,20] injecting ac current in the sample and recording the output dc voltage. The ac current density yields an ac Lorentz force on the vortices that is given by $\vec{F}_L = \vec{J} \times \vec{n}\varphi_0$ (where $\vec{n}$ is a unitary vector parallel to the applied magnetic field), but the time averaged driving force on vortices is $\langle F_L \rangle = 0$. From the expression for the electric field $\vec{E} = \vec{B} \times \vec{v}$ (with $\vec{B}$ the applied magnetic field and $\vec{v}$ the vortex–lattice velocity), we get that the dc voltage drop V_{dc} measured along the direction of the injected current is proportional to the average vortex–lattice velocity $\langle v \rangle$ in the direction of the ac driving force; in particular $V_{dc} = \langle v \rangle dB$ (where d is the distance between contacts and B the applied magnetic induction). For an ac current input (or ac driving force), the output is a non-zero dc voltage V_{dc}. This means that a net vortex lattice flow ($\langle v \rangle \neq 0$) arises from the ac driving

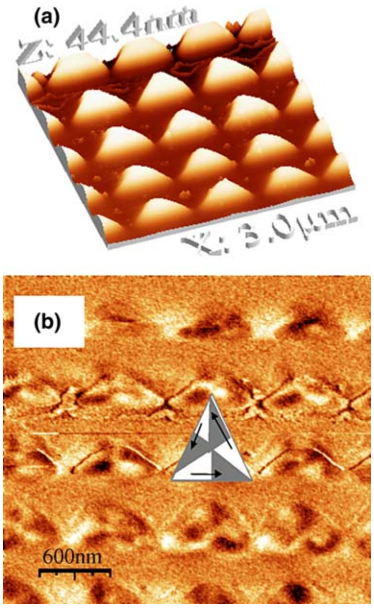

Fig. 1. (a) Atomic force microscope (AFM) picture of Ni triangle array. Z : 44.4 nm X : 3 μm. (b) Magnetic force microscope (MFM) picture of Ni triangle array. Commercial LM–MESP tip. Tip-sample distance 20–30 nm. $T = 300$ K, $H = 0$ Oe.

force ($\langle F_L \rangle = 0$), what shows that the array of Ni or Cu triangles creates a ratchet potential landscape for the vortex lattice [11].

3. Experimental results and discussion

Asymmetric pinning centers are crucial to obtain a net flow of vortices when the vortex lattice is driven by ac current above the threshold of the critical current [11,16,20]. The induced Lorentz force should overcome the intrinsic random pinning potentials and the sizes of the vortex core (that is the coherence length) should be not too large, if the vortex size is large, that is high temperature, vortex lattice will not feel the discreteness of the periodic asymmetric potentials. The competition between these two magnitudes, applied current and temperature, govern a very narrow window, closed to the critical temperature, where the ratchet effect could be measured. Another interesting point is the change of polarity of the net vortices flow (dc output voltage). The dc voltage sign changes when the applied magnetic field and ac current amplitude are increased [11,20]. The filling factor (maximum number of vortices pinned at the triangles) is the key parameter to understand this effect. The interplay between pinned vortices and interstitial vortices plays the crucial role. Interstitial and pinned vortices move in opposite direction and on different ratchet potentials, a virtual ratchet potential (space among triangles) the interstitial vortices and a real ratchet potential (nanotriangles) the pinned vortices.

Finally, this ratchet effect works in the adiabatic limit, the effect does not show any frequency dependence [11,16,20].

This adiabatic regimen has not been tested yet when both kinds of vortices are present at the same time in the sample. The data, shown in Fig. 3, have been taken for Nb film with array of Ni triangles, and for $n = 6$ (six vortices per unit cell), taking into account the filling factor of the sample [11] applied magnetic field with $n = 6$ corresponds to three pinned vortices and three interstitial vortices. Fig. 3 shows the vortex ratchet effect is adiabatic for any applied magnetic field value and the rectification polarity reversal could be mimicked with a pure dc experiment.

In detail, the data show in Fig. 2 and label dc *ratchet effect*, are extracted from the dc (I, V) curves following the analysis presented in [20]. In brief, a dc current is applied in the $+x$-axis direction and the corresponding (I_{+x}, V) curve is recorded, after a dc current is applied in the $-x$-axis direction and the corresponding (I_{-x}, V) curve is recorded. Finally, both curves are subtracted and the net voltage is plotted. This dc *ratchet effect* mimics the real ac ratchet effect (see Fig. 2). The interstitial and pinned vortices show a dc voltage reversal for similar driving force values than the real ratchet effect shows it. The dc *ratchet effect* is a very rough approach and in our opinion, it does not allow any further conclusions extracted from the difference of the current values for optimal rectification and inversion between the dc and ac experiments.

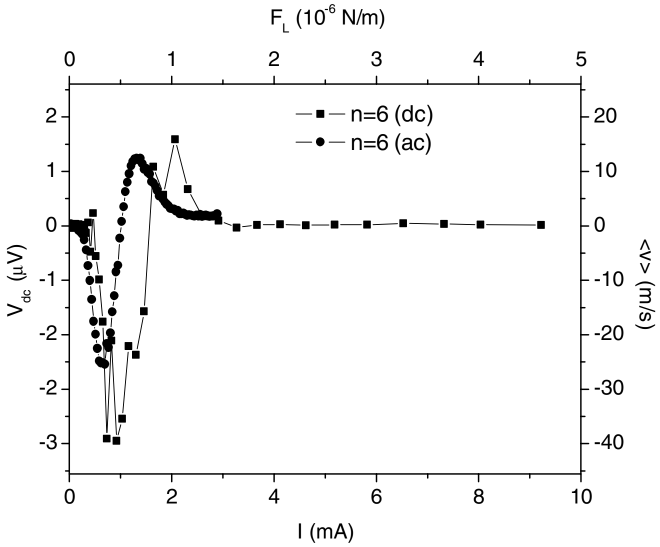

Fig. 2. Black dots ac ratchet effect for $n = 6$ (6 vortices per array unit cell). Square dots *mimic* dc ratchet effect for $n = 6$ (see text for explanation) $T/T_c = 0.98$.

Two of the most important open questions in this vortex rectifier device are whether or not the device will work with non-magnetic pinning centers and the magnitude of the background voltage in comparison with the output voltage.

To address the first topic we have fabricated a sample with the same array dimension than before; but in this new sample the Ni pinning centers were changed by Cu traps of the same dimension than the former Ni triangles. Fig. 3 shows the same behavior than in Nb film grown on array of magnetic pinning potentials. The ratchet effect in the sample with non-magnetic pinning traps shows similar values and the polarity reversal when the magnetic field

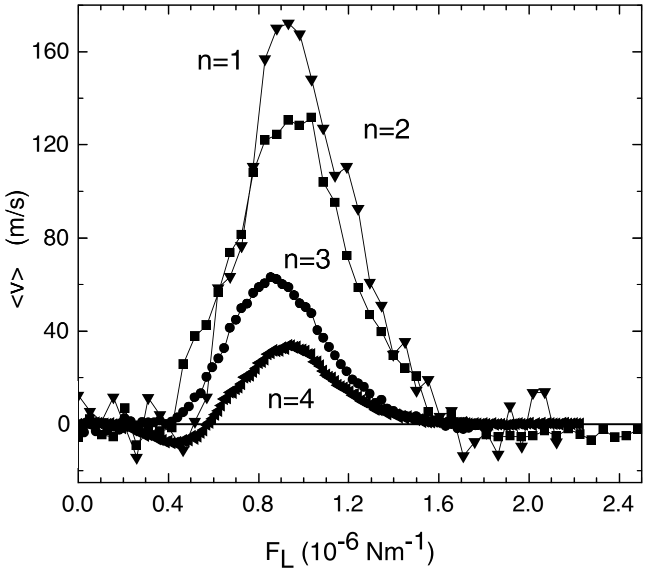

Fig. 3. Nb film on array of Cu triangles. Net velocity of vortices (y-axis) vs. Lorentz force amplitude (x-axis) for $n = 1$ to 4 (number of vortices per array unit cell). $T/T_c = 0.99$.

is increase. This result is very relevant, because the incorporation of magnetic materials in this rectifier device is not wanted, it could lead to additional noise and jeopardize its possible applications, for instance to flux removal devices. This result is not unexpected. The pinning center magnetic state plays a minor role, as was shown in [3].

A comparison of the output ratchet voltage with the magnitude of the background voltage is very easy taking into account the adiabatic behavior of the system. In Fig. 4 the background signal, that is the dc (I, V) curves are shown for applying the current in both senses ($+x$-axis and $-x$-axis). These are the raw data from the data of Fig. 4 are extracted. An estimation of the rate of rectifier signal to the background signal could be easily done comparing y-axis scales from both figures. The ratchet effect is about 10^{-2} times the background effect.

Finally, we can discuss the type of ratchet effect we are dealing with. Ratchet effects span from Nature to the laboratory as was written in the introduction. The most important ratchet mechanisms are found in Molecular biology. Recently, Bar-Nahum et al. [22] have found that at the core of transcription and translation mechanisms from DNA to proteins a very complex ratchet machine is at work. In the transcription step from DNA to RNA messenger through polymerase-RNA two ratchets motors are acting.

Many molecular motors are based in the ratchet effect. One of the most important, which is receiving a lot of attention, is kinesin. The main reason is that this ratchet molecular motor is acting in the RNA transport and the cellular track on this protein moves is a microtubulus, and this set of kinesin protein and microtubulus could be fabricated in the laboratory and in situ experiment could be done.

Molecular ratchet motors belong to the so-called flashing ratchets. Motor proteins use the energy derived from the hydrolysis of adenosine triphosphate (ATP) to take nanometer-scale steps along a cellular track.

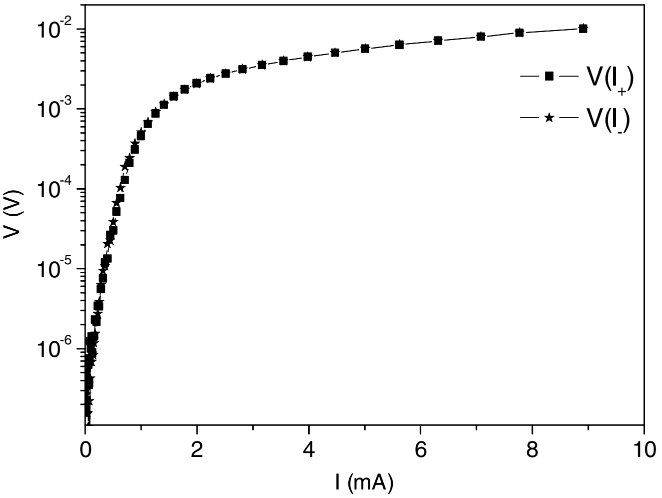

Fig. 4. dc (I,V) curves for $n = 6$ (6 vortices per unit cell). V(I_+) a dc current is applied in the $+x$-axis direction and V(I_-) a dc current is applied in the $-x$-axis direction. $T/T_c = 0.98$.

The temperature is crucial and the motor works as an on–off machine. Kinesin charged ratchet potential on. Binding of a charged ligand (ATP) to Kinesin, then the system becomes neutral (potential flat) that is, ratchet potential off. The temperature is crucial and the ratchet potential is time dependent. The microtubulus and the ATP give the asymmetric potential.

Our vortex ratchet rectifier belongs to the second type of ratchet motors: the so-called tilting ratchets. In this ratchet type the ratchet potential is not time dependent and the system needs an external zero-average driving force $F(t)$. In our case this is an applied ac current ($I_{ac} = I_0 \sin\omega t$). There are two types of tilting ratchets: rocking (deterministic) ratchet and fluctuating ratchet (stochastic). In the former the external driving force is periodic ($F(t) = -F(t + \tau/t)$) in the latter the external driving force is stochastic ($F(t) = -F(t)$). In our case we are dealing with a typical rocking ratchet.

4. Conclusions

A reversible ratchet effect has been observed in superconductors with arrays of asymmetric pinning centers. Input ac current yields an output dc voltage; that is a net motion of the vortex lattice occurs, although zero average ac forces drive the vortex lattice. At constant temperature, the polarity of this dc voltage could be switched with the applied magnetic field (number of vortices per array unit cell) and input current strength.

Magnetic and non-magnetic asymmetric pinning centers embedded in the superconductors play a similar role, in both cases a ratchet effect is obtained with similar amplitude values. The only difference seems to be that magnetic pinning centers need slightly higher driving force strength to depinning the vortex lattice.

This vortex ratchet device is an adiabatic rocking ratchet. The ratchet output voltage could be mimic by subtracting dc voltage taken from opposite driving dc currents.

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