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Transverse rectification in superconducting thin films with arrays of asymmetric defects

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Superconducting Nb films have been grown on top of arrays of Cu nanotriangles. These asymmetric pinning centers strongly modify the vortex lattice dynamics. Two rectification effects have been observed: (i) longitudinal ratchet effect when the input currents are injected perpendicular to the triangle reflection symmetry axis and (ii) transverse rectification effect when the input currents are injected parallel to the triangle reflection symmetry axis and the output voltage drop occurs perpendicular to the triangle reflection symmetry axis. Increasing the applied magnetic field, the former shows a change of the output voltage polarity, the transverse output voltage does not show any polarity reversal. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2767199]

Arrays of nanodefects embedded in superconducting thin films are a powerful tool to control the vortex lattice motion. Superconducting films fabricated on arrays of periodic and symmetric pinning potentials show, for instance, vortex lattice channeling effects[1] that allows us to guide the vortex lattice motion. Superconducting films with arrays of periodic and asymmetric pinning centers show vortex motion rectification effects.[2] This rectification is based on the ratchet effect, that, is the net motion of particles induced by asymmetric potentials, without the need of being driven by nonzero average forces or temperature gradients.[3] This vortex ratchet effect could be used for improving the performance of existing superconducting devices, for instance, diminishing the noise in superconducting quantum interference devices coming from trapped magnetic flux as has been proposed by Lee *et al.*[4] Furthermore, the vortex ratchet effect shows very interesting properties; for example, the output signal polarity could be tuned with external parameters (for instance, applied magnetic fields).[2,5] Moreover, this vortex ratchet is an adiabatic ratchet; i.e., the effect shows a nonfrequency dependence that allows us to study and mimic the vortex ratchet effect by $I(V)$ curves.[6,7]

The possible transverse rectification of particles has been theoretically studied by several authors.[8,9] The transverse ratchet effect for vortices moving in arrays of triangular pinning sites was specifically studied by Reichhardt-Olson and Reichhardt.[10] The transverse effect could be used for fabricating devices whose aim should be particle separation (DNA sorting, ion channeling, and so on). In this letter, we will deal with transverse and ratchet rectifier devices based on Nb films grown on top of an array of Cu nanotriangles. We will experimentally show that the same device could exhibit longitudinal ratchet rectification and transverse ratchet rectification. In the longitudinal ratchet configuration the driving current is applied perpendicular to the triangle reflection symmetry axis (tip to base axis) and the output voltage signal is recorded on the same direction. The Lorentz force induces vortex motion parallel to the triangle reflection symmetry axis, but the output (dissipation) voltage arises, following the Josephson expression,[11] in the direction perpendicular to the triangle reflection symmetry axis, i.e., the voltage drops in the direction of the injected current, and therefore, perpendicular to the vortex lattice motion direction. On the other hand, in the case of transverse rectification, the input current is applied parallel to the triangle reflection symmetry axis, and the output voltage is measured perpendicular to the input current direction, i.e., perpendicular to the triangle reflection symmetry axis. In the following, we are only taking into account the applied current and the voltage drop directions, but we have to keep in mind that the voltage drop in one direction probes the vortex motion along the perpendicular direction. Figure 1 shows ratchet [Fig. 1(b)] and transverse rectification [Fig. 1(c)] layouts in our experimental configuration. In the following, we are going to use the ratchet effect for the longitudinal rectification and the transverse effect for the transverse rectification.

Electron beam lithography, magnetron sputtering, and etching techniques were used to fabricate Nb films on top of arrays with periodic pinning centers (Cu nanotriangles). The system is grown on Si (100) substrates. The triangle sides are around 600 nm and the periodicity around 750 nm; the Cu triangle and Nb film thicknesses are 40 nm (Cu) and 100 nm (Nb) in all the samples. These triangle dimensions and array periodicity are similar to samples reported by Villegas *et al.*[2] (Nb films on top of Ni arrays). Figure 1(a) shows a picture of the cross-shaped bridge (40 μm wide), which was ion etched on the Nb films; this bridge allows us to inject the current either parallel (I_x) or perpendicular (I_y) to the triangle base. Magnetic field was applied perpendicular to the films. Magnetoresistance was measured with a commercial cryostat. These ratchet effects are pure adiabatic, as was commented

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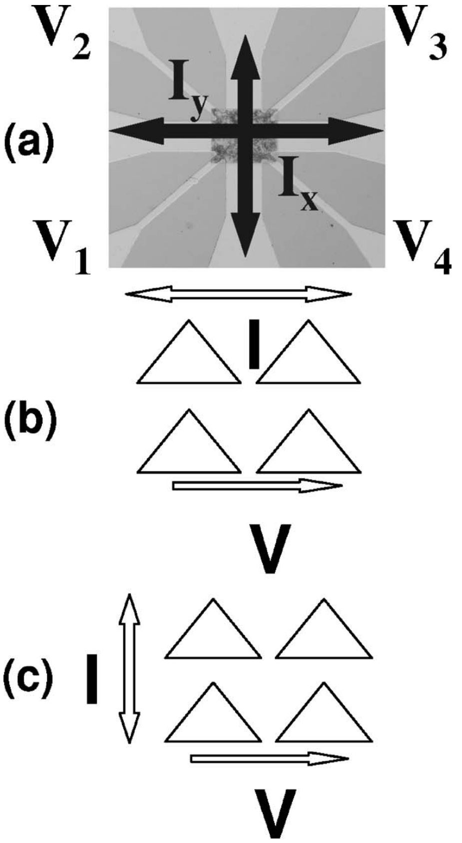

FIG. 1. (a) Micrograph of the cross-shaped bridge used for the measurements. The darker central area is the array of triangles. (b) Longitudinal ratchet measurement layout. Injected current direction: I_x; output voltage: V_1 and V_4 or V_2 and V_3. (c) Transverse ratchet measurement layout. Injected current direction: I_y; output voltage: V_1 and V_4 or V_2 and V_3.

before. Vortices were driven by direct injected currents (dc) as well as alternative injected currents (ac) up to 10 kHz, which is our experimental upper limit. The same behavior is found in both cases (ac and dc driving forces).[6] The experimental data shown in Figs. 2 and 3 are taken in the adiabatic limit. More experimental details could be found in Refs. 2 and 6.

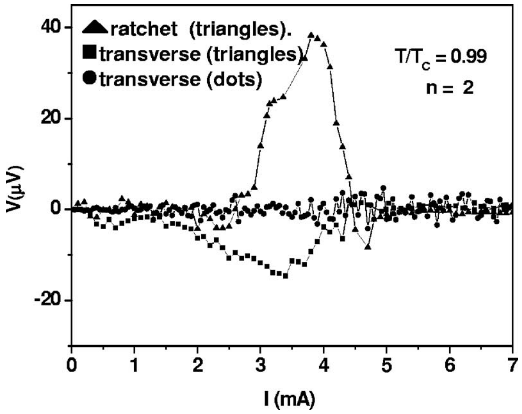

FIG. 2. Ratchet and transverse effects in thin film of Nb with array of Cu triangles (T_c=8.6 K). Transverse effect in Nb thin film with array of Cu dots (T_c=8.2 K). In both samples the applied magnetic field is 68 Oe (n=2). Samples Nb film and Cu triangles: period of 750 nm and triangle side of 625 nm. Sample Nb film with Cu dots: period of 770 nm and Cu dot diameter of 620 nm.

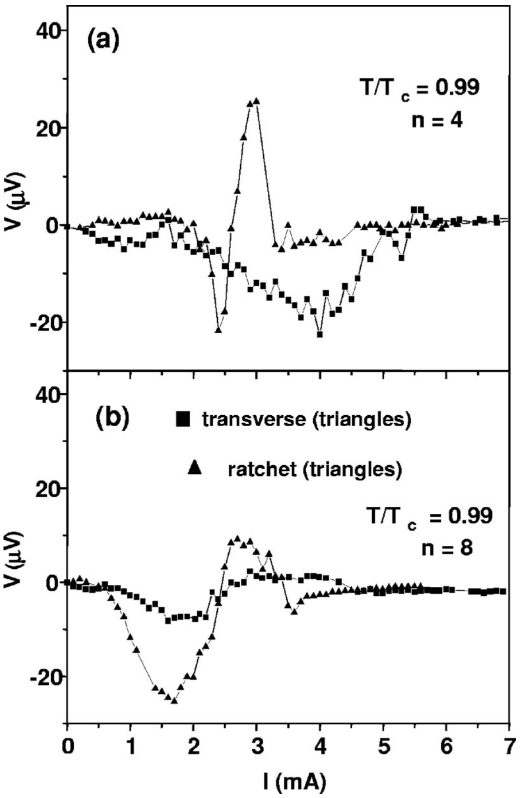

FIG. 3. Ratchet and transverse effects in Nb thin film with array of Cu triangles. The sample is the same as that in Fig. 2. (a) Four vortices per array unit cell (applied magnetic field is 136 Oe). (b) Eight vortices per array unit cell (applied magnetic field is 272 Oe).

Figure 2 shows ratchet and transverse rectification measurements. First of all, we have to be sure that we are measuring the transverse rectification signal, i.e., the voltage due to contact misalignments is negligible in comparison with the transverse effect due to the asymmetric potentials (triangles). For checking this point, we have fabricated Nb film on top of an array of Cu dots, i.e., the same system but with symmetric (Cu dots) pinning potentials. The dot size and the array periodicity are the same than the triangle size and periodicity in the array of Cu nanotriangles. In the Nb film with dot array the magnetotransport measurements were done within the same cross-shaped bridge than in the triangle samples [see Fig. 1(a)]. Since this sample (Nb film with Cu dots) does not show any ratchetlike effects, any recorded dc voltage drop will be due to the misalignment of the contacts. Figure 2 shows the transverselike [experimental configuration as Fig. 1(c)] measurements for the Nb film with array of Cu nanodots. We have applied dc and also ac (10 kHz) input currents and we have measured the dc output voltages for both cases (ac and dc injected currents); the output dc voltage is negligible in comparison with the transverse rectifier voltages which appear in Nb film with array of Cu nanotriangles.

The interplay between interactions is crucial to figure out the experimental results. First of all, we have to realize that we are dealing with a collective ratchet effect and the interactions between particles (Abrikosov lattice) play a crucial role. Furthermore, vortices are moving on two different potentials: the weak but periodic pinning potential (Cu triangles) and the strong but random intrinsic potential (Nb films). The interplay and competition between these two pinning potentials and the vortex-vortex interaction govern the vortex lattice dynamics.[12] The geometrical matching between the vortex lattice and the periodic structure induces dissipation minima at equal spaced values of the applied magnetic field, $H=nH_1$, being H_1 the first matching field and n the number of vortices per array unit cell. The suitable temperatures and driving forces for exploring ratchet and matching effects have been discussed elsewhere.[6,13] In summary, the temperature should be very close to the superconducting critical temperature and the driving forces (currents) should be between the two current values. Below a threshold current value the vortex lattice velocity is too low and the intrinsic and random potentials overcome the periodic pinning, therefore the periodic pinning effect vanishes; above a second threshold current value (high driving force) the vortex lattice velocity is enhanced and the vortex lattice does not undergo the periodic potentials.[13] The competition between the vortex-vortex interaction and the asymmetric potentials could be explored by increasing the applied magnetic field, which means more vortices per array unit cell. Figure 3 shows ratchet and transverse effects when the number of vortices increase to 4 [Fig. 3(a)] and to 8 [Fig. 3(b)] vortices per array unit cell. The ratchet effect shows a reversed signal. This effect is related with the number of vortices placed inside and outside (interstitial vortices) the Cu triangle traps. This change of polarity has been already reported,[2] and it could be explain as a reversal in vortex lattice motion due to a reconfiguration of the vortex lattice when the number of vortices per unit cell is larger than the saturation number (maximum number of vortices which can be placed inside the Cu traps).[2,14] Increasing the number of vortices, i.e., increasing the number of interstitial vortices [$n=8$, Fig. 3(b)], the inverse voltage of the ratchet effect is enhanced.

Concerning the transverse ratchet effect its behavior is very different: (i) the transverse ratchet effect does not show any change of polarity, and (ii) increasing the number of vortices, i.e., increasing the number of interstitial vortices [$n=8$, Fig. 3(b)], the transverse effect is vanished. The vortex lattice dynamics simulations quoted in Ref. 10 could be a hint to figure out the transverse effect behavior. According to these works, taking into account that the asymmetric potentials are attractive potentials, the vortex trajectory is deflected for the triangles always in the same way, for instance, downwards. The asymmetric potentials (triangles) do not distinguish whether the vortices are coming from the left or from the right sides when the vortex lattice is moving perpendicular to the reflection symmetry axis of the triangle. Finally, increasing the number of vortices per unit cell, the number of interstitial vortices increases and the collective behavior of the vortex lattice overcomes the vortex-periodic potential interaction smearing out the transverse ratchet effect.

In summary, we have measured a transverse vortex ratchet effect. In comparison with the usual vortex ratchet effect, the transverse rectification does not show a output dc reversed signal, and the rectification polarity does not change. The transverse rectification effect is enhanced for applied magnetic field values around the saturation number, i.e., the maximum number of vortices, which could be placed inside the asymmetric potential.

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