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Experimental adiabatic vortex ratchet effect in Nb films with asymmetric pinning trap

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Abstract. Nb films grown on top of an array of asymmetric pinning centers show a vortex ratchet effect. A net flow of vortices is induced when the vortex lattice is driven by fluctuating forces on an array of pinning centers without reflection symmetry. This effect occurs in the adiabatic regime and it could be mimiced only by reversible DC driven forces.

Keywords. Vortices; asymmetric pinning; rectifier; adiabatic ratchet.

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1. Introduction

It is well-known that particles driven by fluctuating forces could not show a net flow. But if these particles are moving in potentials without reflection symmetry, then a net flow could happen. Even when the average of driving forces is zero, a direct motion of particles could be induced. This effect is called the ratchet effect. In summary, the ratchet effect occurs when we have 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. Two ingredients are needed to induce ratchet effect: (a) Periodic structures that lack reflection symmetry and (b) input signal yielding fluctuating motion of particles with zero-average oscillation. A state of the art of ratchet effect and the related topic of Brownian motors can be found in [1]. Experimental ratchets are found in many realms in nature and in the laboratory; for instance, biological motors [2], particle separation [3], vortex motion rectification [4], etc.

During the last few years, the interplay between superconductivity and ratchet effect has been addressed from very different points of view [5–10]. Recently, a reversible vortex motion rectification has been reported in [4]. In this experimental superconducting ratchet, the vortex lattice moves on an array of periodic asymmetric pinning centers. The samples are Nb films grown on arrays of Ni triangles. Injecting AC current in the film parallel to the Ni triangle base induces the vortex motion rectification. A DC vortex net flow is induced in the direction of the triangle tips. On increasing the input current amplitude or the applied magnetic field, the net direction of the vortex flow could be reversed. Villegas *et al* [4] explained this reversible rectification by taking into account two types of vortices: the vortices pinned in the Ni traps and the interstitial vortices outside the Ni triangles. These two types of vortices feel opposite ratchet potentials. Another crucial point of this experimental vortex ratchet effect is its adiabatic behavior. Villegas *et al* [4,11] have shown that the effect is non-frequency dependent. That is, we are dealing with an adiabatic ratchet. Van de Vondel *et al* [12] have studied this vortex ratchet effect in Al films with antidots for magnetic field only up to one vortex per pinning center and they found an adiabatic behavior too. In this paper we will show that this adiabatic regime spans for any applied magnetic field and that the ratchet effect could be mimiced using DC driving forces.

2. Experimental results and discussion

Arrays of nanometric Ni triangles have been fabricated by sputtering on (1 0 0) Si substrate by electron beam lithography technique. A Nb film was deposited on top of this array. Photolithography and ion etching techniques were used to define a cross-shaped bridge for magnetotransport measurements. The Nb films are superconducting with critical temperature between 8.1 and 8.4 K. Magnetic force microscopy (MFM) shows that the magnetizations of the Ni islands are plane-aligned. The side of the Ni triangles is around 620 nm and the array period is around 770 nm. Measurements have been done with the applied magnetic field perpendicular to the substrate direction and in a He liquid cryostat. An injected AC current applied parallel to the triangle base (x-axis) is the vortex driving force. Therefore, the vortex lattice moves in the perpendicular direction (y-axis) and the output signal in this direction (y-axis) is a DC voltage. That is, a very clear DC vortex motion occurs along the y-axis and the vortex motion is rectified. Figure 1 shows the ratchet effect close to critical temperature for the attainable frequency range in our experimental set-up. We experimentally observe that this vortex ratchet effect is not frequency dependent.

Another important point that should be underlined is that we could choose the number of vortices per unit cell of the Ni triangles' array at will. Magnetoresistance measurements allow us to choose the number of vortices per unit cell. If we applied a magnetic field for which vortex lattice parameter matches the array unit cell, we enhance the stopping forces on the vortex motion and, therefore, we slow down the vortex motion and a sharp minimum occurs in the dissipation curve [4,13]. In summary, an inspection of the magnetoresistance data, at constant temeprature, shows equi-spaced minima that correspond to the commensurability of the vortex lattice with the unit cell of the pinning centers, the first minimum corresponds to one vortex per unit cell, the second to two vortices per unit cell and so on. Finally, the maximum number of vortices that are pinned in the Ni triangles could be estimated with the so-called filling factor [14]. In our case, the filling factor is three vortices per triangle (see ref. [4]). Therefore, in the case of four vortices per array unit cell three vortices are pinned at the Ni triangle and the fourth one is an

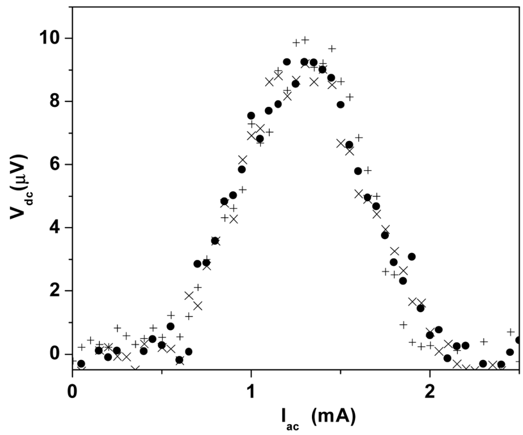

Figure 1. The DC voltage vs. AC current for an applied field of $H = 34$ Oe ($n = 1$, one vortex per unit cell of the array) $T = 0.99T_c$. The AC frequencies: 0.5 kHz (×), 1 kHz (+) and 10 kHz (•).

interstitial vortex. As was stated before, under AC driving forces, the interstitial vortices move first because they are feeling a weaker pinning than the vortices in the Ni triangle. Once the driving forces are increased, and they are strong enough to unpin the pinned vortices, they move, but in the opposite direction. Interstitial vortices and pinned vortices are feeling opposite ratchet potentials.

In summary, we are able to fix the number of vortices per unit cell of the array and using asymmetric pinning traps the motion of AC-driven vortices is rectified and a DC net flow of vortices happens. We have found a reversible ratchet effect that is frequency independent. This ratchet effect could be mimiced using DC driving forces. That is, in the following we will show that this effect occurs in the pure adiabatic regime.

The pure adiabatic regime will be obtained by means of a DC experimental simulation of the AC real experiment. The (I, V) characteristic curves have been measured at constant applied magnetic field and temperature close to the superconducting critical temperature. We need to measure close to T_c because the pinning force increases with decreasing temperature and the driving forces needed to unpin the vortices are very large. The (I, V) curves are extracted as follows: first a DC current is applied in the $+x$-axis, and the output DC voltage is recorded, keeping the temperature and the applied magnetic field constant. The (I,V) curve is recorded again but now the DC current is applied in the $-x$-axis direction. Both curves are subtracted and the net average voltage is obtained: $V_{DC} = \{V(I_{+x}) - V(-I_{-x})\}/2$. Figure 2 shows this net average voltage in a log scale when the sample has one vortex per unit cell, and figure 3 shows the results when the applied field corresponds to two vortices per unit cell of the array. In both cases, we observe a clear *DC ratchet effect* that mimics the real one. The experimental windows and the amplitude of the effect are very similar in the AC ratchet effect than in our experimental simulation *DC ratchet effect.*

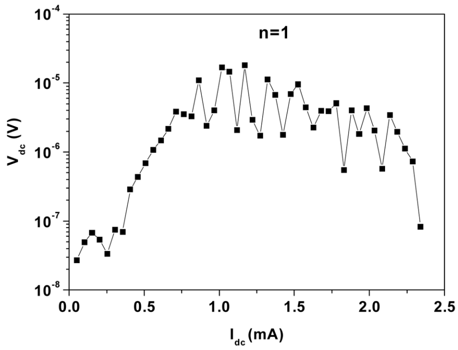

Figure 2. The DC ratchet effect (adiabatic limit, see text) for $n = 1$ (one vortex per unit cell). $T = 0.98T_c$.

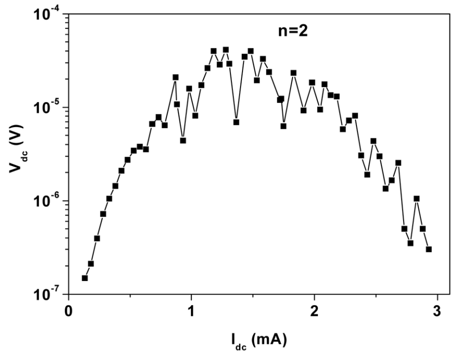

Figure 3. The DC ratchet effect (adiabatic limit, see text) for $n = 2$ (two vortices per unit cell). $T = 0.98T_c$.

More striking is the observation that if we increase the applied magnetic field above $n = 3$ (this is more than three vortices per pinning centers) the *DC ratchet experiment* shows the same trends as in the real ratchet effect. In refs [4,11], a reversible ratchet effect is shown when interstitial and pinned vortices are present in the sample. The interplay between these two types of vortices is the key factor to have a reversible vortex motion rectification. The interstitial vortices are, of course, weaker pinned than the pinned vortices in the Ni triangles; therefore less input current strength is needed to move them than that needed for the stronger pinned vortices, and they are in a virtual ratchet potential that is inverted in comparison with the Ni triangle potentials (see ref. [4]). On further increasing the driving force, the pinned vortices in the triangles finally start to move, but experiencing a real ratchet potential in the opposite direction. In summary, we have a polarity change. This behavior could be mimiced using pure DC driving forces as can be seen in figures 4 and 5. In these two cases we are subtracting the (I_{+x}, V) and the (I_{-x}, V) curves and the net average voltage is plotted in linear scale and a cross-over from a negative polarity to a positive polarity is observed in this *pure DC ratchet effect*. In these cases, the number of vortices n per array is 6 and 8, taking into account that the filling factor in our film is $n = 3$. The sample has interstitial and pinned vortices and therefore two types of vortices which are experiencing two ratchet potentials with opposite polarities.

3. Conclusion

In closing, we have shown that the experimental superconducting vortex ratchet effect is purely adiabatic. The experimental data could be mimiced using DC-driven vortices. This DC experimental method allows us to mimic even the polarity change in the ratchet effect that happens when the number of vortices per array unit cell is higher than the filling factor of the pinning asymmetric traps. The pure

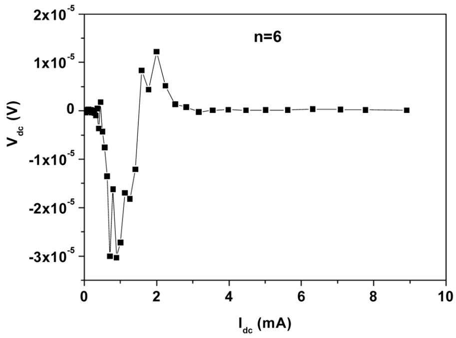

Figure 4. The DC ratchet effect (adiabatic limit, see text) for $n = 6$ (6 vortices per unit cell, three pinned vortices and three interstitial vortices). $T = 0.98T_c$.

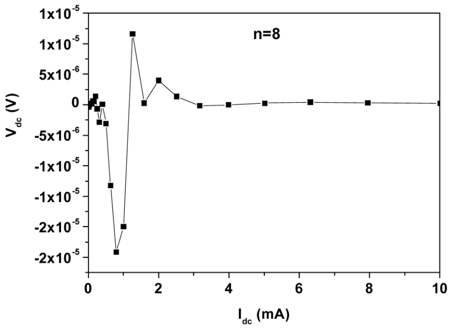

Figure 5. The DC ratchet effect (adiabatic limit, see text) for n = 8 (three pinned vortices and five interstitial vortices per unit cell). $T = 0.98T_c$.

DC (adiabatic) experiment reproduces the interplay between the interstitial and the pinned vortices that leads to the rectification polarity reversed which could be tuned at will with the value of the applied magnetic field.

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