Vortex motion rectification in Josephson junction arrays with a ratchet potential

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By means of electrical transport measurements we have studied the rectified motion of vortices in ratchet potentials engineered on over-damped Josephson junction arrays. The rectified voltage as a function of the vortex density shows a maximum efficiency close a matching condition to the period of the ratchet potential indicating a collective vortex motion. Vortex current reversals where detected varying the driving force and vortex density revealing the influence of vortex-vortex interaction in the ratchet effect.

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The rectification of motion by asymmetric periodic potentials, so called ratchet effect, has been addressed extensively in recent years [1–3]. The suggestion that directed motion in biological systems is driven by this effect have largely triggered the research in this subject [4]. In this letter we address this subject by studying superconducting vortices which has been proven to be a paradigm for testing a number of statistical phenomena due to the ability of controlling density and interactions. The ratchet effect on superconducting vortices has been studied for numerous vortex pinning potentials [5–8] and suggested as a method to reduce vortex density or even generate lensing and guidance of vortices [9, 10]. In Josephson junction arrays (JJA) and SQUIDs, asymmetric potentials for vortices and fluxons were also proposed and studied [11–13]. In this letter we present measurements on JJAs where asymmetric periodic pinning potential were created. We were able to detect rectification in the vortex motion and study the ratchet effect. By changing the periodicity of the potential we were able to study collective effects in this phenomena.

Our JJAs were fabricated by e-beam lithography and Ar⁺ ion milling starting from a 2000 Å/2000 Å Lead-Copper bi-layer. The gap between Pb islands was modulated with a sawtooth function across the arrays from 0.2 to 1 µm, while keeping 5 µm as the center to center distance between islands. In all cases sample size were 100 × 100 islands. Different samples with periods of the ratchet potential $P = 7, 10$ and 15 array cells were built maintaining the overall width of the array constant (hereafter called V7, V10 and V15 respectively). In Fig. 1 we show a scanning microscope picture of a representative region of one of the samples.

Due to the discreteness of the JJA the energy associated with a single vortex is position dependent [14]. This feature is responsible for the existence of a finite critical force for the vortex motion (made evident through a critical current) and is responsible for the guiding of vortices [15]. To obtain an insight on the energy landscape for a vortex in these ratchet JJAs
we performed a series of numerical simulations. We modeled a square array of superconducting islands connected by ideal Josephson junctions of coupling energy $E_J$. No resistive or capacitive terms were considered. Every junction energy can be summed to give the Hamiltonian

$$H = \sum_{<i,j>} E_{ij}^j[1 - \cos(\varphi_i - \varphi_j - A_{ij})],$$

where $\varphi_i$ stands for the phase of the superconducting order parameter in the island $i$, the sum is taken over nearest-neighbor pairs, $A_{ij} = \frac{2\pi}{\Phi_0} \int_{A} A \, d\vec{r}$, $A$ is the vector potential, and $E_{ij}^j$ embodies the modulation of the coupling energy to build the ratchet potential. This Hamiltonian assumes an infinite penetration depth of the magnetic field, $\lambda_\perp = \infty$ (no self fields are taken into account). Within this model the arctan approximation has been used to construct the phase configuration of a vortex in a homogeneous JJA, and from there, the energy landscape is calculated [16]. It is difficult to generalize this arctan procedure to an inhomogeneous JJA, where coupling energies vary from one junction to the other. For our ratchet arrays we used a variation of a numerical relaxation technique [16, 17] to calculate the potential energy of the vertex. First we introduce a vortex by using the arctan approximation as an initial condition. Then, we let the phases $\varphi_i$ to relax to the equilibrium configuration following a Metropolis algorithm. As a result we obtain the phase configuration and energy of a state corresponding to a vortex located on the bottom of a potential well [17]. To obtain the energy of states other than these local minima, we introduced a variation to the previous procedure [18], in which we fix and control the phase of two islands, adjacent to the vortex center, while allowing all other phases in the system to relax. In this way, we are able to pull and push the vortex uphill, as we are forcing the center of rotation of the vortex currents to be in a defined location, allowing us to calculate the potential energy of a vortex located in any arbitrary position. Using this method we have numerically calculated the single vortex potential for a linear sawtooth coupling energy dependence across the array, for zero magnetic field. The result of this calculation shows clearly the almost ideal ratchet landscape, as seen in lower part of Fig. 2, supporting the idea of using gap-modulated JJA to create a ratchet potential.

The temperature dependence of the coupling energy for a superconductor-normal-superconductor (S/N/S) Josephson junction is well described by the de Gennes expression:

$$E_J(T) = \frac{\hbar}{2e} I_0 (1 - T/T_0)^2 \exp(-d/\xi_N(T)),$$

where $I_0$ represents the zero temperature critical current, $T_0$ the critical temperature of the superconducting electrodes, $d$ the distance between superconductors, and $\xi_N(T) = \xi_0/\sqrt{T}$ the coherence length in the normal metal. In our sample design, where the parametrized magnitude is $d$, the landscape of the vortex potential is temperature dependent. However, due to the dependence of the coupling energy with the gap between islands, the asymmetry of the ratchet-like potential is preserved for all non-zero temperatures.

In order to test the rectifying efficiency of the designed samples, we have performed I-V measurements with the force exerted by the current either forward or backward to the sawtooth potential. In Fig. 3 we show V/I data of the sample V10 as a function of the magnetic flux in the sample, for both current directions, for a temperature of 3.2 K and an applied current of 0.4 mA. The magnetic flux is expressed as frustration $f$, defined as the applied magnetic flux in units of flux quan-

FIG. 3: V/I as a function of the frustration of the sample V10 for a temperature of $T = 3.2$ K and for positive and negative dc current $I = 0.4$ mA. The difference in the resistance between both current directions is evident, indicating the rectification of the vortex motion in the array.
the sign terms of vortex excitations it can be explained by considering resistances each half period. This is a direct consequence of evident from the plot, indicating the rectification of the vortex motion in the array. A distinguished result of this measure-difference in the resistance between both current directions is of a single junction is about 5-20% of the array cell area. The junction effect due to the design of our arrays where the area decreases a positive voltage, a negative vortex moving to the will generate a negative voltage. The mirrored effect happens This means that if a positive vortex moving to the same direction by the ratchet potential. However the in-
crease in speed and the signal-to-noise ratio of the acquisi-
tion. In Fig. 4 we plot as two dimensional graph the magnitude of the rectified voltage as a function of the frustration and ac current (driving force).

At higher currents a periodic in field complex response is observed with voltage reversals as varying magnetic field (vortex density) and ac current (driving force).

At low vortex densities a pronounced structure is observed, for frustration $f \approx \pm 1/7$ labeled $\text{c}$ and $\text{d}$ in Fig. 4. It is also seen at $f \approx (n \pm 1/7)$, with $n = \pm 1$. Similar feature is found for the V10 and V15 samples with position of the maximum located in $f = 1/P$. This is clearly shown in Fig. 5 where the rectified voltage is plotted as a function of frustration times $P$ for the three samples investigated. The applied ac current selected for each sample was chosen to cross the absolute maximum at the given temperature. For example, the sample V7 and $T = 3.8\,\text{K}$ we present data for $I_{ac} = 3\,\text{mA}$, as could be estimated from Fig. 4. The overlap of the curves is remarkable indicating that there is an optimal rectification of the vortex motion when there is a matching condition between the moving vortex structure and the periodic ratchet potential.

Based on the matching condition for a peak at $f_{max} = 1/P$ for a sample of period $P$ of the ratchet potential, we can speculate that the moving structure would be similar to a row of adjacent vortices located at the bottom of every tooth of the sawtooth potential. It is difficult to predict which is the vortex configuration as a function of frustration for such ratchet arrays. Therefore it is not trivial to describe which is the matched state responsible of the observed rectification and dynamical numerical simulations would be required to elucidate this issue.

A more complex interpretation is required to analyse the sign reversal observed at lower currents in the regions indicated as $\text{a}$ and $\text{b}$ in Fig. 4. The fact that this feature is observed for high densities can be taken as an indication that vortex-vortex interactions overcome the geometrical potential landscape and effectively change the shape and asymmetry of
the ratchet potential. A change in the structure of the vortex system occurs on dynamical phases[21], changing the vortex-vortex interactions. As a result a sign reversal of the rectified motion can arise at high vortex velocities. More experiments complemented with dynamical simulations are required to give a more detailed explanation of these features.

In conclusion we have presented a design of Josephson junction arrays that generates a sawtooth-like potential for vortices and antivortices. Transport measurements indicate a rectified motion for these excitations. These experiments also clearly identify for the first time the sign of the transported vortices which changes as a function of frustration. Measurements performed in samples with different periodicities of the sawtooth potential show that there is a maximal rectification of the vortex motion for a matching condition of the vortex density to the ratchet periodicity. Our results indicate that collective effects are relevant for understanding the motion of particles in ratchet potentials. It was suggested [9] that the ratchet effect can be used to reduce the vortex density in superconductors. Our results widen this suggestion showing the possibility of the utilization of potentials with different periodicities for density separation.

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