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Experimental evidence for anisotropic response of a driven vortex lattice

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Abstract

We present kinetic inductance measurements in current driven Josephson junction arrays. Measurements performed with circular coils indicate that this technique is very sensitive to the vortex mobility. Results obtained with anisotropic detection coils provide experimental evidence for the anisotropic response of a driven vortex lattice. Anisotropic behavior is obtained when rising the temperature or the mean vortex velocity as indicated by the loss of the superconducting shielding capability, first in the direction of vortex motion and then in the perpendicular direction.

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1. Introduction

The study of the dynamic behavior of elastic media in the presence of different static potentials has attracted much attention in recent years. Superconducting vortices are almost ideal for studying the phenomenology of these systems because relevant properties such as density, interactions and external force can be easily controlled.

Much work has been done on the problem of moving vortex systems. Depending on the velocity and type of static potential one can expect to have different dynamical phases. Giarmarchi and Le Doussal [1] have predicted the existence of a moving-Bragg-glass phase in a weak disordered static potential for high driving currents. The moving-Bragg-glass phase is free from dislocations, with power law decay of the positional correlations which are anisotropic with respect to flow direction. On the other hand, Balents, Marchetti and Radzihovsky [2] have argued for a smectic phase. In this phase, vortices move along well defined static channels, conserving the correlation perpendicular to the channels, but being uncorrelated along them. A number of experimental reports have presented evidence for the existence of these dynamical phases and their channel-type motion [3–6]. The case of periodic potentials has been studied by several authors [7–9]. In particular, Marconi and Domínguez [9,10] have found a transversely pinned vortex lattice with characteristics similar to those found for the disordered pinning case. This transversely pinned phase is distinguished by anisotropic Bragg peaks, quasi-long-range order, transverse superconducting coherence and zero transverse resistivity. One of the most relevant properties of all these moving vortex phases, for both disordered and periodic pinning potentials, is the existence of barriers to a small force transverse to the direction of motion. These barriers could be detected as an effective critical current in the transverse direction [11].

Kinetic inductance techniques have proven to be a valuable tool for measuring superconducting characteristics of two dimensional systems [12–14]. In this work we use a variation of this technique, which is capable of examining the anisotropic character of dynamical phases. Instead of using circular coils, we use rectangular coils with high

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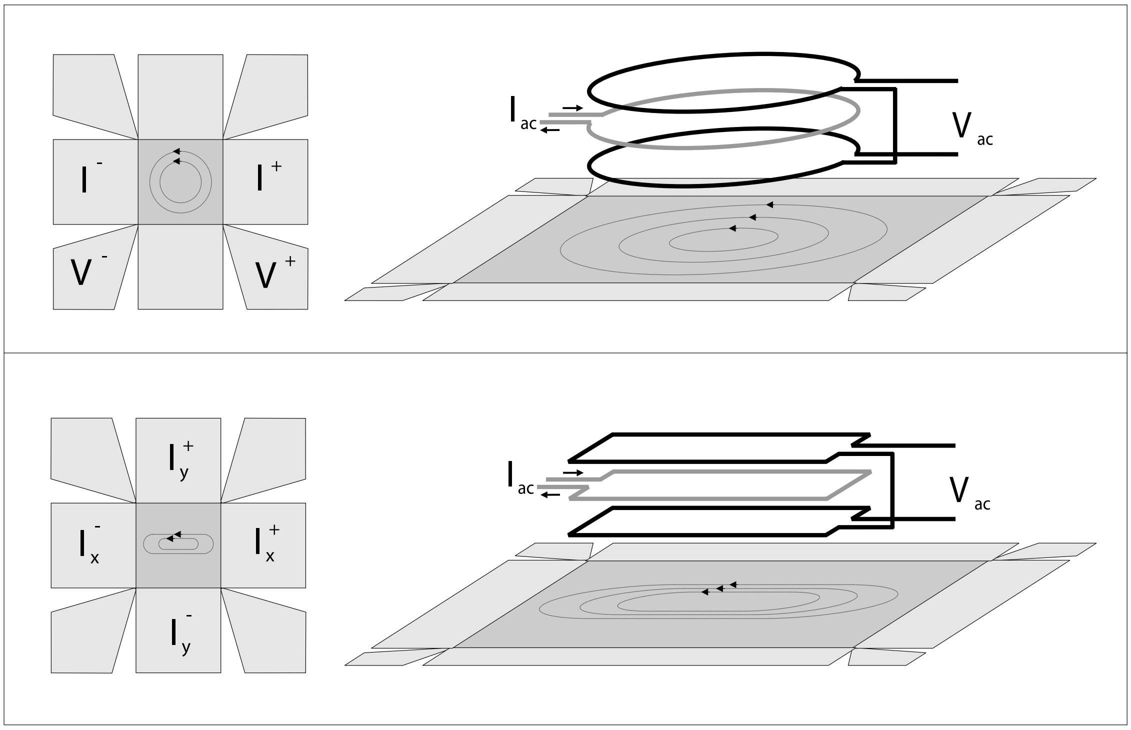

Fig. 1. Upper Part: Schematic of the circular coil setup. An ac current I_{ac} is applied to the primary excitation coil. Response, V_{ac}, is measured at the secondary reception coils. Secondary coils are set in astatic configuration. Lithographically defined contacts allow us to apply a dc transport current $I^{+,-}$ to the sample, and to measure the voltage drop $V^{+,-}$. Lower Part: Schematic of the rectangular coil setup. The main difference between circular and rectangular coil configuration is that in the latter, inductance measurement can be done in any of both directions, parallel or perpendicular to the applied dc current.

aspect-ratio, as sketched in the lower part of Fig. 1. In this geometry, the shielding currents induced in the sample by the primary coil are predominantly parallel to the long side of the coil. Consequently, the voltage generated on the secondary coil is due to shielding currents flowing in one particular direction, specified by the orientation of the coils. Measuring the response as a function of the orientation between the coils and the symmetry axis of a sample we are able to measure its anisotropic properties as, for example, the magnetic penetration depth or resistivity.

We are interested in studying the anisotropic character of vortex dynamical phases driven by externally applied dc currents. The dc current direction will determine the symmetry axis of the dynamical phases. Our experimental setup allows us to apply a dc current to the sample along two directions, parallel and perpendicular to the long dimension of the rectangular coils. Comparing the results of kinetic inductance when applying current in both directions, we should be able to detect any anisotropic character of the vortex dynamical phases.

2. Experimental details

We performed our measurements in two dimensional Josephson junction arrays. Square arrays of 1000×1000 superconducting Pb islands were patterned on top of a Cu film. The lead was completely removed from the substrate outside the islands. The cross-shaped superconducting islands formed a square lattice with a lattice parameter of 10 μm, and the gap between two adjacent arms was 1 μm. Nearest neighbor Pb islands are coupled through the underlying Cu layer, acting as a superconducting–normal–superconducting (SNS) Josephson junction. This type of junctions are known to be in the over-damped (classical) limit. The temperature of the Kosterlitz-Thouless transition of the sample presented here was $T_{KT} \approx 3$ K. Vortices in these arrays experience a static potential, periodic in nature, as a consequence of the array geometry [15,16]. Voltage and current contacts were lithographically defined on the Cu layer, as sketched in the left part of Fig. 1. Extended contacts spanning the width of the sample allow us to inject current homogeneously along both principal directions of the array. For all the measurements presented in this work vortex motion is driven to a steady state using a dc current. Voltage contacts placed in both directions let us evaluate the mean vortex velocity which is proportional to the measured electric field. A vortex density of 1/25 vortex per plaquette has been produced by means of an external dc magnetic field and used in all measurements herein reported.

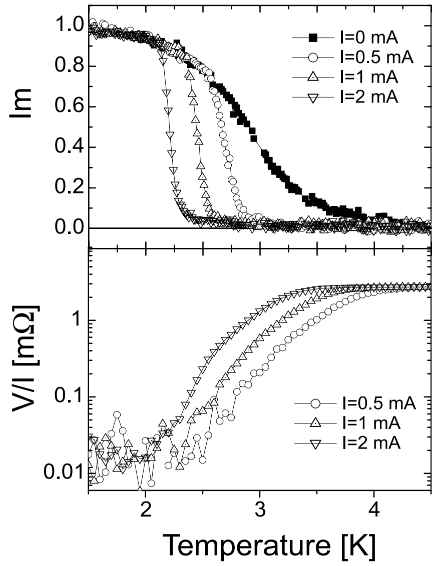

Fig. 2. Upper part: Imaginary component of the kinetic inductance measured with circular coils normalized by full screening value *Im*, as a function of temperature for different values of applied dc current to the sample. The applied currents were 0, 0.5, 1 and 2 mA. The vortex density, or frustration was $f = 1/25$. All data were taken at a frequency of 8484 Hz. Lower part: Sample resistance *V/I* as a function of temperature for the same values of applied current, measured simultaneously with inductance data. Note that the onset of finite resistance coincides with the drop on the shielding capability.

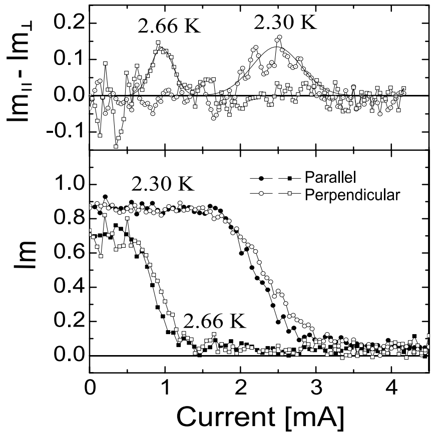

Fig. 3. Lower part: Imaginary component of the kinetic inductance measured with rectangular coils normalized by full screening value as a function of dc current in the sample for current orientations parallel (full symbols) and perpendicular (open symbols) to the coils, at two different temperatures, 2.30 K (circles) and 2.66 K (squares). Upper part: Difference between $Im_{\parallel}$ and $Im_{\perp}$ as a function of dc current for the same temperatures. Full lines are provided as a guide to the eye.

3. Experimental results

The experiment involves two novel elements: inductive measurements with current in the sample; and the use of rectangular coils. We will first briefly discuss our observations with circular coils on a current-driven sample, as sketched in the upper part of Fig. 1. These coils have a diameter of 1 mm, similar to those used in Ref. [14]. We used a frequency of 8484 Hz for all the measurements reported here. We were careful to take the data well inside the linear regime. Under this condition the largest current ac induced on the sample by the primary is much smaller than the applied dc current and than the critical current at low temperatures. Out and in-phase components of the voltage were measured using a two-phase lock-in amplifier.

In the upper part of Fig. 2 we plot the out-of-phase component of the normalized voltage, detected by the secondary coils, as a function of temperature for different currents applied to the sample. This quantity is an indication of the shielding capabilities of the sample. In the lower part of Fig. 2 we plot the longitudinal resistance of the sample (*V/I*), measured using a nanovoltmeter, simultaneously with the inductive data.

We observe that at low temperatures the longitudinal resistance is zero indicating that vortices are pinned. Moreover, in this range of temperatures the coil data are independent of the value of the applied current. From this last observation we can conclude that the injection of current on its own does not modify the inductance measurements. For a fixed current, and rising the temperature, vortices become unpinned and start to move, producing a finite resistance. Under these conditions we detected that the shielding capability of the sample drops abruptly to zero. It should be noted that this zero shielding state does not correspond to the fully dissipative (normal) phase of the Josephson network as can be recognized from the clear non-linearity in the electrical dc transport data. These results indicate that inductive measurements are very sensitive to the motion of the vortex ensemble, and as a consequence, to the depinning critical current.

Bearing in mind the previous observations we proceeded to measure the response of the system using rectangular coils. The idea behind this is to be able to distinguish the mobility of vortices in each direction, along and transverse to the dc current. The shielding current distribution in the sample is determined by the geometrical parameters of the primary coil, and the properties of the sample. Our setup consisted on a set of rectangular coils of length $l = 1.3$ mm and width $w = 0.4$ mm, with a distance between the primary and the sample of 2.2 mm. Solving the Pearl equations [17] for a superconducting film we obtained that the main part of the current distribution resembles the geometrical projection of the primary on the sample. With this geometry and the excitation current used in the primary, the maximum ac magnetic flux induced in the sample is about $10^{-3}\Phi_0$ per plaquette (where Φ_0 is the magnetic flux quantum). Since

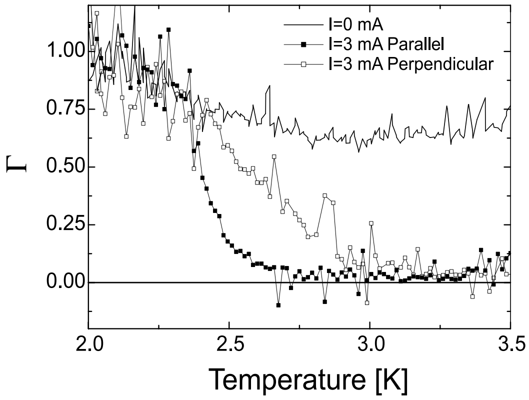

Fig. 4. Helicity modulus as a function of temperature for $I = 3$ mA parallel and perpendicular to the coils. Same features are found for other currents. On raising temperature, the superconducting capability of the vortex ensemble is lost first along the direction of motion while preserving a finite value in the transverse orientation.

the size of the sample is several times larger than the coils we can disregard any border effects in our measurements.

In the lower part of Fig. 3 we show the imaginary part of the voltage measured with the rectangular coils, as a function of the driving current for different temperatures and both current directions. The difference in the system response for both current orientations is evident. This difference is present only for currents above and close to the depinning current value. This feature is clarified on the upper part of Fig. 3, where we plot the difference between the signals in both orientations as a function of the intensity of the applied current.

The temperature dependence of the system response is composed primarily of two effects: Individual single junction response and a collective behavior contribution. In order to quantitatively compare the experimental data with numerical and theoretical calculations it is necessary to evaluate collective behavior only. This can be quantified by the helicity modulus [18], experimentally defined as the ratio between the single junction inductance to the total kinetic inductance [19]. The single junction inductance can be obtained from the inductance measurements at zero magnetic field for temperatures low enough to exclude the presence of critical 2D fluctuation effects.

In Fig. 4 we plot the helicity modulus as a function of temperature[1] for an applied current of $I = 3$ mA. Full symbols correspond to data for current parallel to the coils and open symbols to the perpendicular direction. These data represent the principal result of this work, providing evidence that the system response in the moving vortex state is clearly anisotropic. On raising the temperature, the shielding capability of the vortex ensemble is lost first along the direction of motion while preserving a finite value in the transverse orientation. This result is in good agreement with the numerical data obtained by Marconi and Domínguez [9,10].

[1] Strictly, in order to compare experiment with simulations, the experimental data needs to be plotted as a function of the reduced temperature. In this temperature scale the critical current of a single Josephson junction is constant. To perform the scaling, the determination of the temperature dependence of the single junction critical current, which in SNS Josephson junctions has a non-trivial expression is crucial. For that reason we proceeded to plot only the helicity modulus as a function of the real temperature.

4. Conclusions

In conclusion, we have used a modified kinetic inductance technique to study diluted vortex lattices on the periodic potential of a Josephson junction array. We have found different superconducting shielding capability in the directions parallel and perpendicular to applied current, providing clear evidence for the anisotropic character of current-driven vortex phases.

The anisotropic kinetic inductance technique which we have developed opens the possibility of investigating anisotropy in several vortex states. In particular, the response of dynamical vortex phases in the presence of quenched random pinning will be a subject for future research.

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