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Symmetric dynamic behaviour of a superconducting proximity array with respect to field reversal

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Abstract
As the complexity of strongly correlated systems and high temperature superconductors increases, so does also the essential complexity of defects found in these materials and the complexity of the supercurrent pathways. It can be therefore convenient to realize a solid-state system with regular supercurrent pathways and without the disguising effects of disorder in order to capture the essential characteristics of a collective dynamics. Using a square array of superconducting islands placed on a normal metal, we observe a state in which magnetic field-induced vortices are frozen in the dimples of the egg crate potential by their strong repulsion interaction. In this system a dynamic vortex Mott insulator transition has been previously observed. In this work, we will show the symmetric dynamic behaviour with respect to field reversal and we will compare it with the asymmetric behaviour observed at the dynamic vortex Mott transition.

Keywords: superconductivity, vortex, critical dynamics, supercurrent pathways, Mott physics

(Some figures may appear in colour only in the online journal)

1. Introduction

In spatially inhomogeneous systems carriers create complex spatial pathways and their band-structure becomes more difficult to connect with the physical properties of the material [1, 2]. High temperature superconductors belong to this latter class of materials where a non-Fermi liquid is observed [3].

Most of the manifestations of non-Fermi liquid behaviour occurs in material with a very high degree of inhomogeneity which is quite difficult to control [4, 5]. Although disorder and inhomogeneities in strongly correlated electron systems could be considered an annoyance, it seems on the other hand that they are unavoidable as shown in several experiments with atomic scale resolution [6–10].

In prototypical cuprate superconductors, x-ray images have considered that correlated disorder could be actually beneficial [11, 12]. It has been experimentally observed that nanostructures of the quenched disorder within the spacer layer are anti-correlated with the charge density puddles accompanied by local lattice distortions of the active layer [13–15] [17] [18]. Moreover, the tuning of the superconducting properties in the active layers is inseparably given by the properties of the spacer layers that can also be controlled through a continuous light illumination [16]. As a result of the tuning, an optimal mix of anti-correlated fractal nanostructures between the active and the spacer layer has been suggested to determine an optimal spatial pathways for supercurrents [14, 18].

However, the morphology of these spatial pathways of supercurrents and their collective behaviour is considered an open problem [19]. In superconducting networks the superconducting critical temperature is dependent on the geometrical

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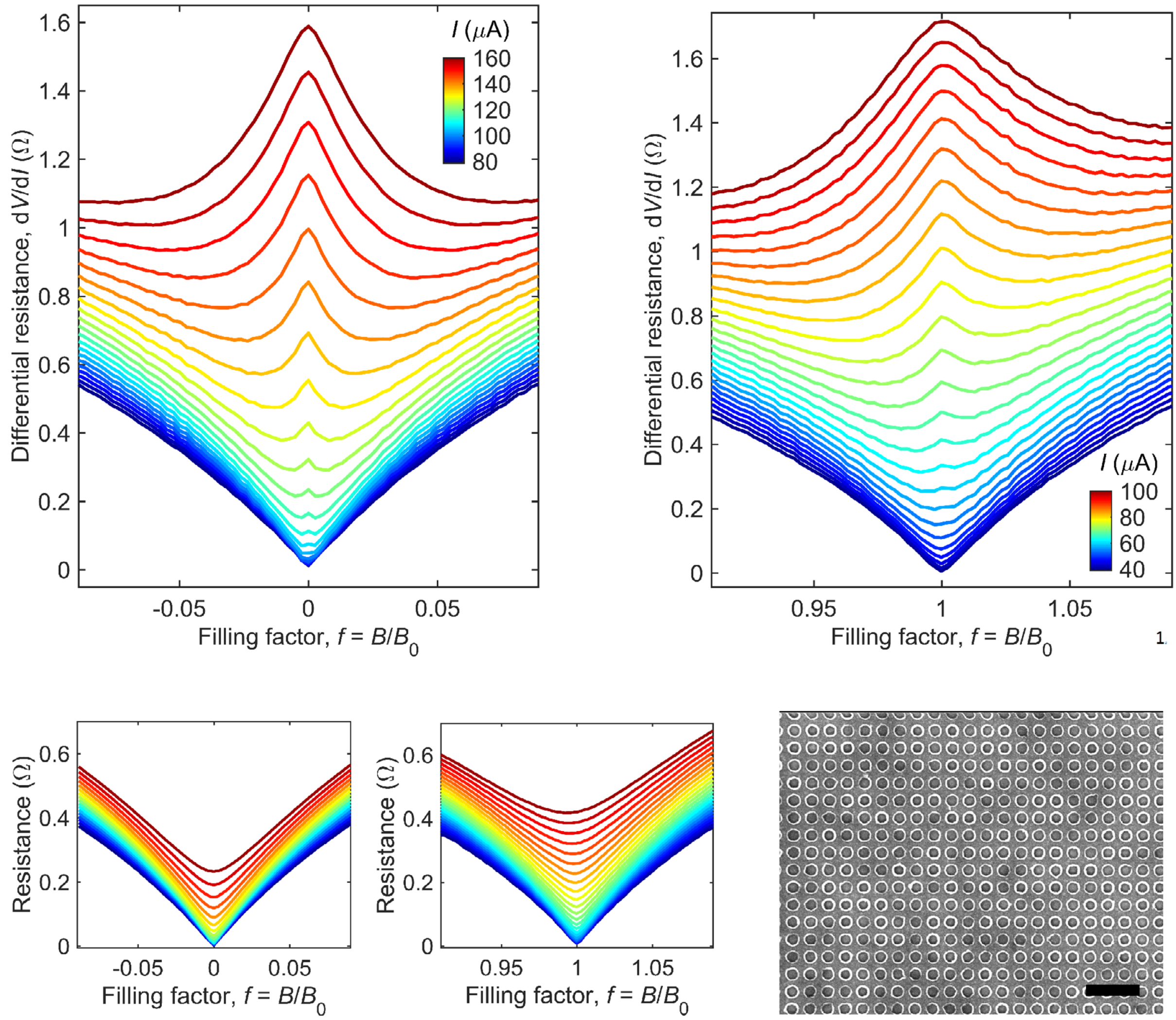

Figure 1. Comparison of the critical behavior around $f = 0$ and $f = 1$. The upper left panel shows the differential resistance, dV/dI, around $f = 0$. The lower left panel shows the corresponding resistance around $f = 0$. The upper right panel shows the differential resistance, dV/dI, around $f = 1$. The lower center panel shows the corresponding resistance around $f = 1$. The color bar shows the external current, and the resistance panels have the same current range as their respective dV/dI panel. The lower right panel shows the SEM image of a portion of the superconducting proximity array. The scale bar is 1 μm.

parameters of the network [20–23]. The relevance of the geometry for the spatial pathways of supercurrents is shown by a recent experiment on an artificial man-made superconducting proximity array where supercurrents can flow in regular and well controlled pathways [24]. In this array of superconducting islands, the supercurrents pathways form vortices that are trapped between the islands in the areas of weaker proximity-induced superconductivity. Since the Feyman pathways interpretation of quantum mechanics [25] and of continuous quantum phase transitions [26], this system can be mapped to a Mott insulating state that forms when the particle concentration matches the density of the regular potential minima [27]. Via the vortex-particle mapping, in fact, the vortices sitting at the sites between the islands take the role of electrons in an electronic Mott insulator. With the application of an electric field, a collective dynamic phase transition between a vortex-Mott-insulator and a vortex-metal is observed [24].

In this weakly coupled superconducting proximity array, a classical critical dynamics of the vortex lattices is observed. We will show the transition upon magnetic field reversal, discussing the symmetrical aspects in comparison with its asymmetric counterpart observed at integer fillings of the vortex lattice.

2. Experimental method

A square array of 270-by-270 Nb islands was grown on a 40 nm thin layer of gold on top of a Si substrate. The gold layer was fabricated with photolithography and DC sputtering. The Nb islands were fabricated with e-beam lithography and DC sputtering. The islands have a diameter of 180 nm and the array has a lattice constant of 250 nm. A four-point probe measurement was done to obtain the voltage and differential resistance as a function of a transverse magnetic field. The

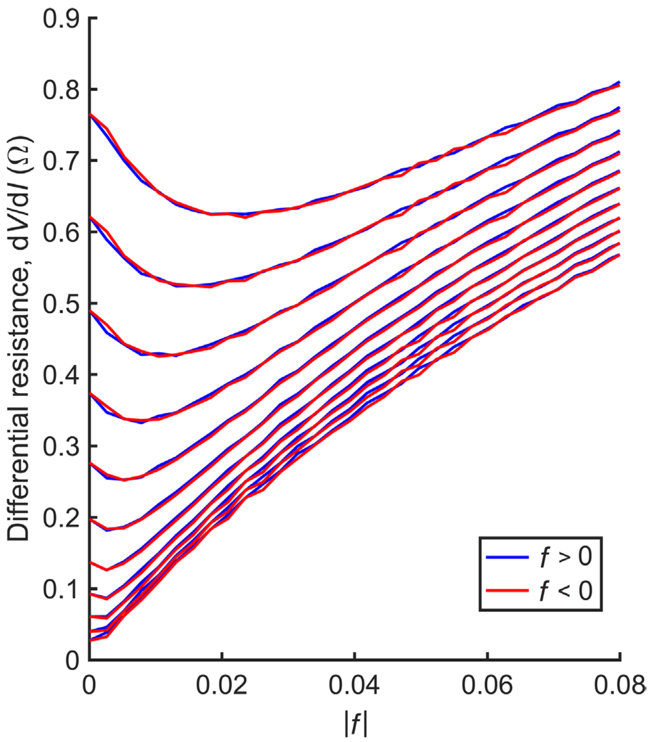

Figure 2. Symmetric dynamic behaviour with respect to field reversal. The same differential resistance around $f = 0$ as in figure 1, but now as a function of $|f|$ instead of f. The curves for negative f and positive f fall on top of each other, showing that around $f = 0$, the differential resistance is symmetric upon mirroring the magnetic field about the critical point. This is in contrast to the data around $f = 1$, where this mirror symmetry clearly does not hold.

transport measurements were done in a liquid helium bath cryostat at 4.14 K.

3. Results and discussion

Vortices occur in superconductors because the phase of the superconducting order parameter around a closed loop can pick up an integer times 2π. In contrast to Abrikosov vortices, where this loop encircles a normal core, the loop contains the weak links between the superconducting islands. If one forms a closed path between four such links along the Josephson junctions, the sum of the phase difference picked up in the junctions must add up to an integer times 2π. This integer counts the number of Josephson vortices.

The number of Josephson vortices in the square array is proportional to the perpendicular external magnetic field. The magnetic field at which the number of vortices matches the traps in our square array is $B_0 = \Phi_0/a^2$, with $\Phi_0 = \pi\hbar/e$ being the magnetic flux quantum [28]. The vortex filling fraction is defined as $f = B/B_0$. This means that $f = 1$ corresponds to one vortex per lattice cell. The vortices repel each other, and the in the ground state the vortices form a periodic pattern. If the filling factor is a rational value p/q, the ground state vortex configuration is a q by q superlattice. The ground state energy energy versus f is described by the Harper equation [29]. The minima in the magnetoresistance as described in [24] are resulting from a Hofstadter-type energy spectrum [30]. In this experiment, we apply an external current and measure the regime where a finite voltage is measured, so phase slips occur and the Josephson vortices are not stationary.

Figure 1 shows a scanning electron microscopy image (SEM) of the superconducting array of Nb islands, the measurements done around $f = 0$ and $f = 1$ for comparison upon the application of a current. The resistances corresponding to the differential resistance, dV/dI are shown. The resistance around $f = 0$ and $f = 1$ show pronounced dips indicating strong pinning at rational f. The minima remains even at the currents where dV/dI shows profound maxima. The vortex phase pinned around $f = 1$ is a vortex Mott insulator [31], and the transition is a dynamic vortex Mott transition [24].

In this superconducting proximity array the dip to peak reversal for $f = 0$ occurs in the range of 80 to 160 μA. Visual inspection of the shape of this current driven transition shows a symmetry around the magnetic field reversal. The nature of this symmetry is further shown in figure 2. Here the two side of the transition are plotted one on the top of each other. The superposition shows the symmetric behaviour. Around $f = 1$, this mirror symmetry around $f = f_c$ is clearly broken. In the analogy with the electronic Mott insulator proposed in [24], the asymmetry is explained by noting that the $f < 1$ regime corresponds to a hole doped Mott insulator, while the $f > 1$ regime corresponds to an electron doped, which need not have the same physical behaviour.

In conclusion, we have showed the differential resistance in a superconducting proximity array and compared its symmetric behaviour at $f = 0$ with the dynamic vortex Mott insulator to metal transition, observed at $f = 1$. Further experimental and theoretical investigations are under way to determine the origin of this difference and its implication for the strongly correlated electronic systems.

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