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Fluxoid quantization effects in high-T_c superconducting double networks

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We describe a study of fluxoid quantization effects in a novel superconducting network consisting of two interlaced sub-networks of small and large loops. Computer simulations show different behavior for the sub-networks in this double network. In particular, while the occupation of the large loops by fluxoids grows linearly with the external magnetic field, the small loops occupation grows in steps, similar to the occupation of a single loop. Magnetoresistance measurements in a double network made of MBE grown $La_{1.84}Sr_{0.16}CuO_4$ reveal periodic oscillations resembling that of a single loop with field periodicity as found in the Little-Parks effect. However, the amplitude of the oscillations is found to be larger by almost two orders of magnitude than that expected from this effect. We propose a new model attributing these oscillations to the interaction between moving vortices and the periodic persistent current induced in the loops by the external field. This model explains the large magnetoresistance amplitude as well as its temperature dependence.

1. Introduction

Fluxoid quantization effects have been studied extensively, both theoretically and experimentally, in a variety of superconducting networks [1-5]. In a network, the fluxoid quantization equation [6, 7], $(4\pi\lambda^2/c)\oint j\cdot d\ell+\Phi=n\Phi_0$, must be satisfied for each and every loop. (In this equation, j is the shielding current in the loop, λ is the penetration depth, Φ is the magnetic flux penetrating the loop, and Φ_0 is the flux quantum). In addition, the arrangements of fluxoids in the network must fulfill the requirement of minimum energy. In regular square networks, these two requirements give rise to periodic changes in the energy as the external field increases, and to a linear increase in the fluxoid occupation different from that observed in a single superconducting loop. Recently, we designed and

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fabricated a network composed of two interlaced sub-networks of small and large loops [8-10], see figure 1. The purpose of this design was to create a network of decoupled loops that behave like an ensemble of single loops. In this paper we describe, both theoretically and experimentally, the behavior of this unique network in the presence of an external magnetic field.

This paper is organized as follows: We first describe the fabrication of the double network and then present numerical simulations, demonstrating the uniqueness of this type of a network. In particular, the simulations show that in the limit of $L >> \ell$ the small loops in the networks are indeed decoupled. This result is then confirmed experimentally by comparing magnetoresistance measurements in a double network with that of a regular square network with loops of the same size. In the second part of the paper we analyze the magnetoresistance oscillations, concentrating on the amplitude of the oscillations and its temperature dependence. We point to the unusual large magnetoresistance oscillations amplitude, which is almost two orders of magnitude larger than that expected from the classic effect of Little and Parks [11]. Moreover, the temperature dependence of this amplitude deviates from the expectations of Little and Parks. Finally, we propose a new model attributing these oscillations to the interaction between moving vortices and the periodic persistent current induced in the loops by the external field.

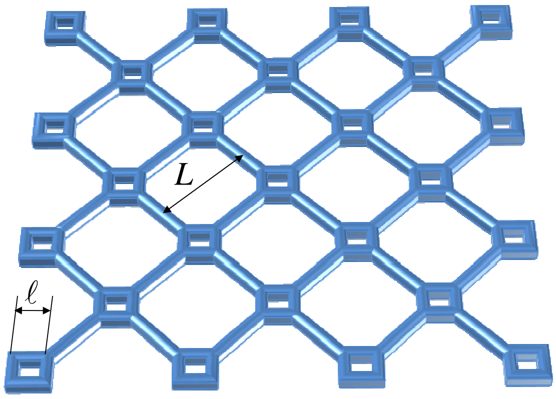

Figure 1. (Color online). Schematic illustration of the double network.

2. The double network

The 'double' network is made up of a square lattice of side L and square loops of side $\ell < L$ oriented at 45° with respect to this lattice and placed at every vertex of the large lattice. Each large loop has four short edges of length ℓ and four long edges of length $x = L - \sqrt{2}\ell$. The areas of the small and large loops are $s = \ell^2$ and $S = L^2 - \ell^2$, respectively.

A series of double networks with ℓ ranging between 75 and 150 nm and $L = 500$ nm, with wire width of 25 - 45 nm, were patterned on 26 nm thick films of optimally doped $La_{1.84}Sr_{0.16}CuO_4$ grown by Atomic-Layer-by-Layer Molecular Beam Epitaxy on single-crystal $LaSrAlO_4$ substrates polished perpendicular to the (001) direction [12, 13]. The area of the small squares is smaller by almost an order of magnitude than previously studied in high-T_c networks and rings [14-19].

3. Theoretical simulations

We performed numerical simulations in order to characterize the behavior of the two sub-networks in the double network. Our simulations are based on the fluxoid quantization equation and minimization of the network energy, which is assumed to be proportional to the average squared screening current [2, 3]. The details of these simulations are described in ref. [10]. In figure 2 we show the results of the simulation for a double network with $L/\ell = 10$, demonstrating that the behavior of the two sub-networks comprising the double network is remarkably different. Figure 2a shows that the average vortex occupation of the large loops, $< N_v >$, increases linearly with the field, whereas the average occupation of the small loops, $< n_v >$, increases in steps, resembling the behavior of a single loop. In addition, the form of the energy as a function of magnetic field (figure 2b) in the double network is similar to the energy form of a single loop (periodically replicated parabolas with upward cusps [7]). As shown in figure 2c, the energy 'waveform' of the square network is different, exhibiting downward cusps and secondary dips. (The minor asymmetry of the secondary dips with respect to $H = 0$ is due to the small size of the system, reflecting jamming of vortices at local energy minima.) These findings establish theoretically that the sub-network of the small loops in a double network with large L/ℓ behaves as effectively being an ensemble of decoupled single loops. As L/ℓ decreases, the step increase in n_v is smeared over a field range which increases approximately linearly with ℓ^2/L^2 [20]. Results for $L/\ell = 3$ are shown in figure 3. In this case, $<n_v>$ increases linearly with field in a narrow range around half integer values of $H\ell^2/\Phi_0$, see figure 3a. The period of the energy oscillation is still determined by the area of the small loops, but short period oscillations corresponding to the large loops are superimposed on these longer period oscillations (see figure 3b). Clearly, despite these differences, the behavior of the network with $L/\ell = 3$ still resembles that of a single loop.

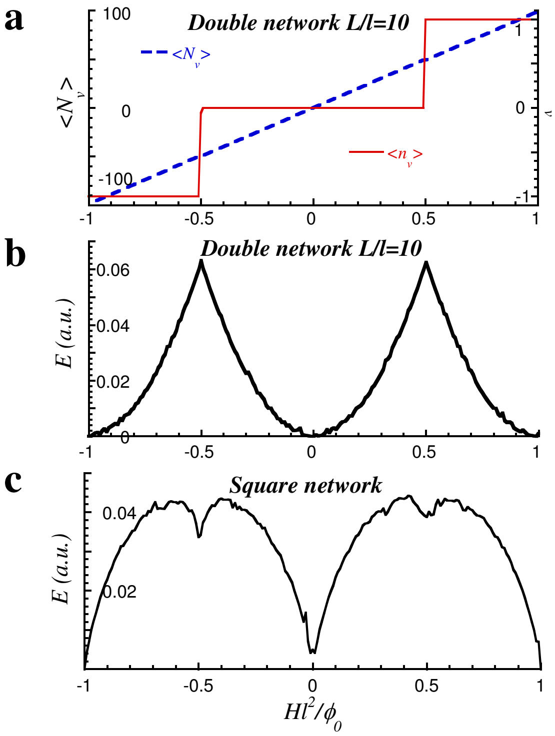

Figure 2. (Color online) Simulations for a double network with $L/\ell = 10$ **(a)** Average number of vortices per large loop, $<N_v>$, and per small loop, $<n_v>$. (b) Energy per unit cell as a function of the normalized flux through a small square loop. Simulations of the energy for a regular square network are shown in (**c**).

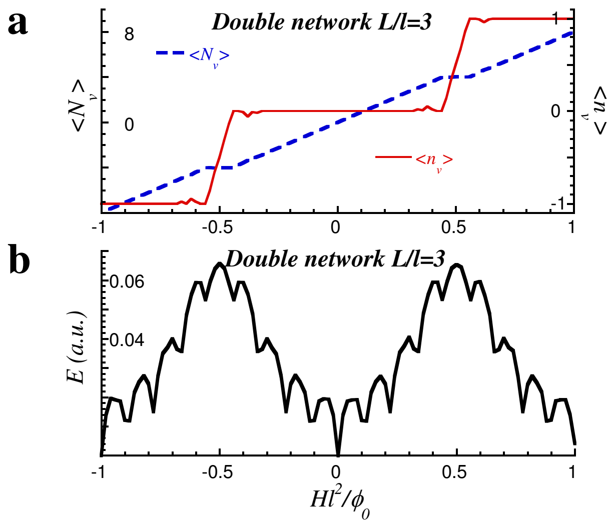

Figure 3. (Color online) Simulations for a double network with $L/\ell = 3$ **(a)** Average number of vortices per large loop, $<N_v>$, and per small loop, $<n_v>$. **(b)** Energy per unit cell as a function of the normalized flux through a small square loop.

4. Magnetoresistance oscillations in double and square networks

To confirm experimentally the results of the previous section we compare magnetoresistance oscillations measured in a double network with ℓ = 150 nm and L=500 nm and in a conventional square network with loop side of 150 nm. Magnetoresistance measurements were performed with bias current of 100 nA, corresponding to a current of 5 nA per loop.

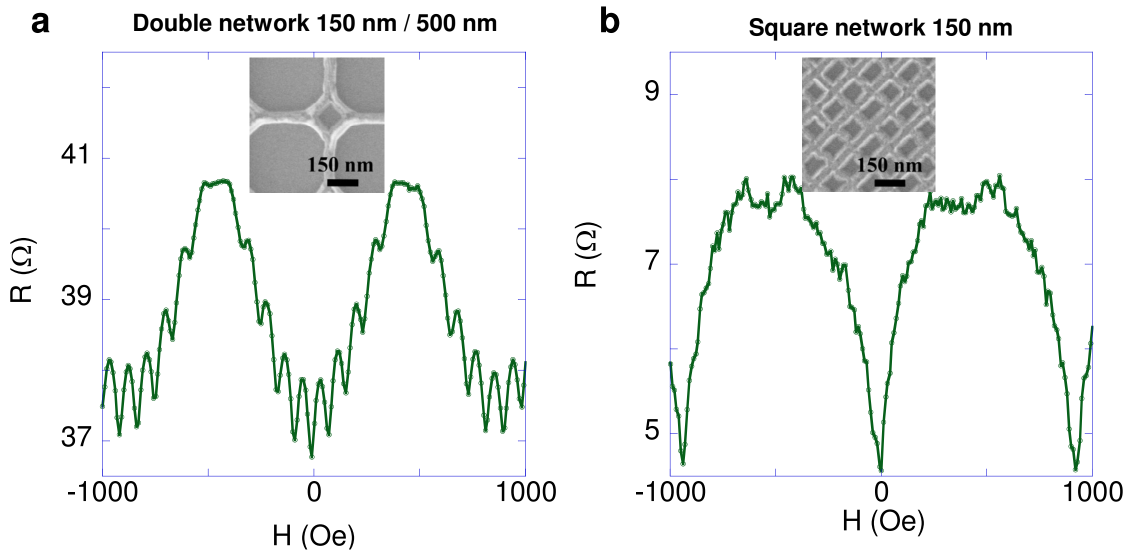

Figure 4. (Color online). Magnetoresistance oscillations in double **(a)** and regular square **(b)** networks. Insets: Scanning electron microscopy image of the square (right) and the double (left) networks patterned in $La_{1.84}Sr_{0.16}CuO_4$ high temperature film. The brighter elements are the superconducting wires composing the networks. Note that part of the cells in the inset to Fig. 4b are rectangle rather than square. Nevertheless, each side is shared by two loops and, therefore, this network exhibits features characteristics of a square network.

Figure 4 shows the magnetoresistance oscillations in the double and the regular square networks at temperatures 25.5 and 26.5 K, respectively, corresponding to the same $T/T_c \sim 0.85$. Both networks show magnetoresistance oscillations of the same period of ~ 900 Oe, corresponding to the small square loops. However, the regular square network (figure 4b) exhibits pronounced secondary dips at half integer values of Φ/Φ_0, corresponding to the checkerboard arrangement of fluxoids in this network [2, 3, 21]. In the double network these secondary dips are absent; however, oscillations of a period ~ 80 Oe, corresponding to the sub-network of the large loops, are superimposed on the longer period oscillations corresponding to the sub-network of the small square loops. These small oscillations, which are more pronounced at the minima of $R(H)$, exhibit downward cusps characteristic of the square network behavior originating from the large loops. The different magnetoresistance behavior of the two networks (figure 4) reflects the difference in energy (figure 3), confirming our prediction on the decoupled nature of the small loops in the double network.

5. Oscillations Amplitude – experiment and model

The double network exhibits oscillations of R in a limited temperature range, roughly between 22 and 31 K, indicating non-monotonic variation of the oscillations amplitude ΔR with the temperature as shown in figure 5 (blue squares). It is tempting to interpret the observed oscillations as the Little-Parks effect, reflecting oscillations with the field in the transition temperature T_c. However, no correspondence is found between ΔR and dR/dT as expected from the analysis of the Little-Parks (LP) experiment [11, 7]. More remarkable deviation from this analysis is found in the magnitude of ΔR; contrary to classical superconductors, the predicted changes in T_c in high-T_c materials are extremely small and fail to explain the large amplitude of the oscillations [8, 9]. In previous papers [8, 9] we developed a model which ascribes the magneto-resistance oscillations in high-T_c superconductors to the periodic changes in the interaction between thermally-excited moving vortices and the oscillating persistent current induced in the loops. Our analysis for a single isolated loop yielded the following expression for ΔR: $\Delta R \approx R_n \left(E_0 / 2k_B T\right)^2 \dfrac{\mathrm{I}_1(E_v / 2k_B T)}{\left(\mathrm{I}_0(E_v / 2k_B)\right)^3}$, where $R_n \approx 118\,\Omega$ is the estimated normal resistance of a small loop defined at the temperature at which the oscillations disappear; I_0 is the zero-order and I_1 is the first-order modified Bessel function of the first kind. E_v and E_0 are the two energy scales [22, 23, 8, 9] which are functions of the temperature, the two characteristic length scales, the Pearl penetration depth Λ_0, the coherence length ξ_0 at zero temperature, the geometrical parameters, and the wire width, $w = 45\ nm$. Thus, one can use Λ_0 and ξ_0 as fitting parameters for the measured temperature dependence of the oscillations amplitude. Our model is developed for a single loop. A fit to the data of ΔR is shown by the black solid line in Figure 5. This fit yields values of $\Lambda_0 = 297\ \mu m$, $\xi_0 = 1.5\ nm$.

The large magnetoresistance oscillations characterizing high-T_c superconducting nanoloops, and the large signal to noise ratio obtained in networks, suggest that double networks of high-T_c materials can be an effective tool in the search for exotic flux periodicities in unconventional superconductors; in particular, the recently predicted $\Phi_0 / 2 = hc / 4e$ [24-26] and $2\Phi_0 = hc / e$ [27] flux periodicities in striped superconductors and in superconductors with d-wave symmetry of the wave function of Cooper pairs, respectively. Efforts to discover these periodicities should continue by extending this work to higher and lower doping across the entire phase diagram, in $La_{2-x}Sr_xCuO_4$ and $La_{2-x}Ba_xCuO_4$.

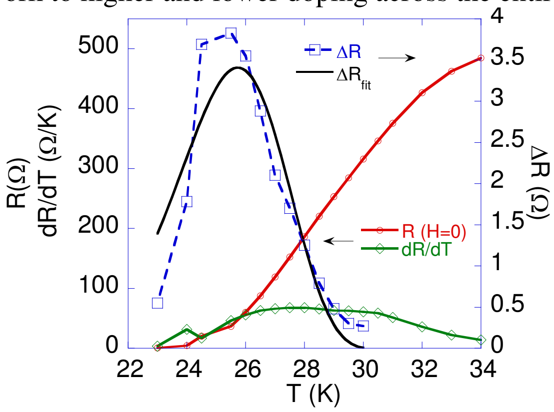

Figure 5. (Color online) Resistance (red circles), temperature derivative dR/dT (green diamonds), and oscillations amplitude ΔR (blue squares) as a function of temperature measured at zero magnetic field in the double network ($L/\ell \sim 3$). The dotted blue line and the solid red and green lines are guides to the eye. The black solid line is a theoretical fit to ΔR.

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