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I. Sochnikov[1], I. Božović[2], A. Shaulov[1] and Y. Yeshurun[1]

[1]*Department of Physics, Institute of Superconductivity and Institute of Nanotechnology and Advanced Materials, Bar-Ilan University, Ramat-Gan 52900, Israel*

[2]*Brookhaven National Laboratory, Upton, New York 11973-5000, USA*

We study the effect of magnetic fields on the resistance *R* of a superconducting $La_{1.84}Sr_{0.16}CuO_4$ film patterned into a 'double' network comprising nano-size square loops having their vertexes linked by relatively long wires. The results are compared with those obtained in a regular network of square loops of the same size. Both networks exhibit periodic dependence of R on the ratio Φ/Φ_0 between the flux penetrating a loop and the superconducting flux quantum. However, while the regular network exhibit features characteristic of collective behavior of the loops, the double network exhibits a single loop behavior. This observation indicates uncorrelated arrangements of fluxoids in the double network, in agreement with a recent theoretical prediction.

A variety of superconducting networks have been studied, both theoretically and experimentally, aiming at revealing correlated behavior of fluxoids in such networks [1-14]. The foundation of these studies traces back to the fluxoid quantization work of Little and Parks [15-17] who demonstrated in magnetoresistance measurements the theoretical prediction of F. London [18] showing that the deviation of the magnetic flux through a superconducting loop from an integral number of flux quanta must be compensated by a circulating current, satisfying the equation

$$\frac{2\lambda^2}{c\Phi_0}\oint j \cdot d\ell = n - \frac{\Phi}{\Phi_0},$$

where the line integral is taken around the loop, λ is the penetration depth, Φ is the magnetic flux penetrating the loop, and Φ_0 is the superconducting flux quantum. In a network, the above equation must be satisfied for each and every loop. In addition, the arrangements of fluxoids in the underlying network must fulfill the requirement of minimum energy. These two requirements give rise to correlated arrangements of fluxoids in periodic networks, the most famous one being the checkerboard arrangement of fluxoids in a regular square network [8, 11, 14, 19], manifested by secondary dips of the magneto-resistance at half integer values of Φ/Φ_0.

Recently, we fabricated a novel type of superconducting network [20, 21] made by connecting the vertexes of small square loops with relatively long wires, forming two interlaced sub-networks of small and large loops. The motivation for designing such a network was to create an array of decoupled small loops that behave like isolated loops. In a previous manuscript [22] we theoretically simulated the behavior of this double network in a perpendicular magnetic field. The simulations showed that as the field increases, the vortex population in the small loops grows in steps, resembling the behavior of an ensemble of nearly decoupled loops. In addition, the loop energy E was found to be a periodic function of the ratio Φ/Φ_0, with a waveform similar to that of a single isolated loop. Features indicative of collective behavior of the loops, e.g. finite slope dE/dH at $H=0$, downward cusps in $E(H)$ and pronounced secondary dips at half integer values of Φ/Φ_0, which are found in a regular square network, were all absent in the case of a double network with large ratio between the size of the large and small loops. The purpose of the present work was to confirm experimentally the predictions of these simulations. For this purpose we fabricated a regular square network and a double network having square loops of the same size, and compared their magnetoresistance behavior.

Molecular Beam Epitaxy was used to synthesize 26 nm thick optimally doped $La_{1.84}Sr_{0.16}CuO_4$ film. The film was patterned into two different networks: a regular square network of 150x150 nm^2 loops, and a 'double' network – similar to that described previously [20] – consisting of 150x150 nm^2 square loops with their vertexes connected by ~300 nm long wires. The Scanning Electron Microscope (SEM) images of Figures 1a and 1b show a part of the square and the double networks, respectively. The wires width in both networks, as measured by the SEM, was ~45 nm. Resistance measurements were performed using a

Quantum Design PPMS® with bias current of 100 nA. Magnetic fields were applied normal to the film surface (a-b crystallographic plane), keeping the temperature constant (with stability of few mK), and then change it to a different value in the range 20–40 K for the next measurement.

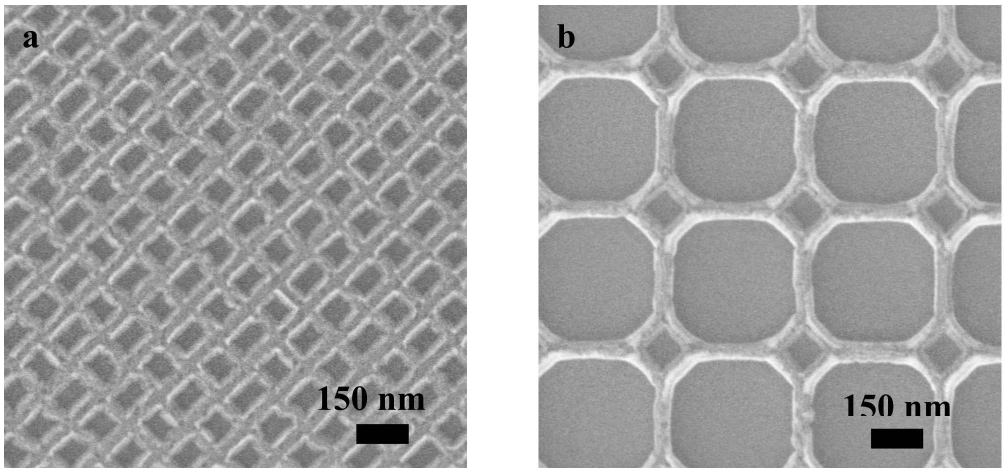

Figure 1. Scanning electron microscope images of the simple square (a) and the double-square (b) networks patterned in $La_{1.84}Sr_{0.16}CuO_4$ high temperature film. The brighter features are the superconducting wires composing the networks.

Figure 2 shows the magneto-resistance per unit cell, $R(H)$, for the simple square network (left panel) and for the double-square network (right panel) as a function of the applied magnetic field H, measured at the indicated temperatures. Both networks exhibit periodic oscillations of R vs. H with the same period of $\sim 900\,\mathrm{Oe}$, corresponding approximately to Φ_0 / A where $A = 150 \times 150\,\mathrm{nm}^2$ is the area of a single square loop. However, the oscillations waveform, $R(H)$, for the two networks is evidently different. While the regular network exhibits features characteristic of collective behavior of the loops, e.g. finite slope dR/dH at $H = 0$ and downward cusps [7], the double network behavior resembles that of a single loop, exhibiting zero slope dR/dH at $H = 0$ and upward cusps.

A closer look at the magnetoresistance oscillations reveals fine structures in the magnetoresistance of both networks. In Figure 3 we zoom on the magnetoresistance data of each network at a temperature $T/T_c \sim 0.85$. The square network (Figure 3a) exhibits pronounced secondary dips at half integer values of Φ/Φ_0 (see inset), corresponding to the checkerboard arrangement of fluxoids in this network [8, 11, 14, 19]. In the double network these secondary dips are absent; however, as shown in the inset to Figure 3b, oscillations of a period $\sim 80\,\mathrm{Oe}$, 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, shown as a parabolic-like 'envelope' in the inset to Figure 3b. These small oscillations, which are more pronounced at the minima of $R(H)$, exhibit downward cusps characteristics of the square network behavior originating from the large loops. Note that the small amplitude oscillations corresponding to the large loops could hardly be resolved in earlier experiments [20, 21] probably due to a larger size distribution in the previous samples that resulted in a distribution of field periodicities.

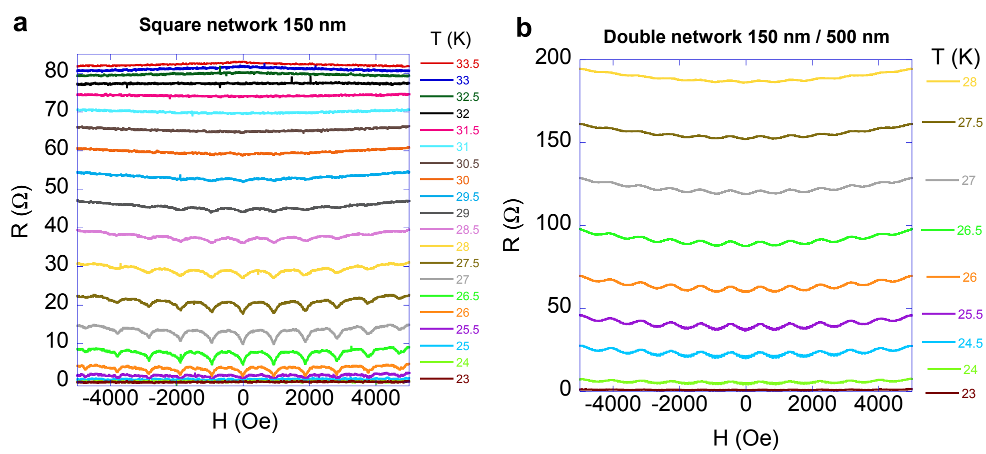

Figure 2 (Color on line) Resistance per network unit cell as a function of magnetic field measured at different temperatures in the square (a) and the double (b) networks.

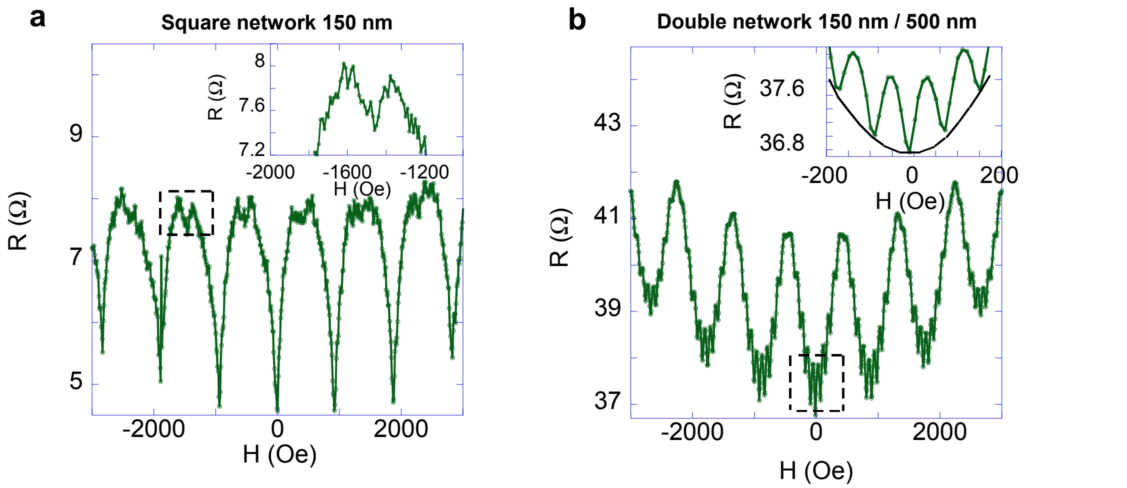

Figure 3. (Color on line) Resistance per network unit cell as a function of magnetic field measured in the square (a) and the double (b) networks at 26.5 and 25.5 K respectively. The insets zoom on the regions marked by dashed lines. Inset (a) shows a secondary dip at half period corresponding to checkerboard arrangement of fluxoids in the square network. Inset (b) shows the magnetoresistance oscillations corresponding to the large loops of the double network. The solid line in inset (b) is a guide for the eye showing parabolic-like 'envelope', describing part of the period of the small loops.

As shown in Figure 2 the oscillatory behavior of R in both networks is limited to a temperature range roughly between ~22 and ~31 K, resulting in non-monotonic variation of the oscillations amplitude ΔR with the temperature, as summarized by the squares in Figure 4. This figure also shows the temperature dependence of the zero-field resistance per unit cell $R(T)$ (circles), as well as dR/dT (diamonds), for the regular and the double networks. Evidently, $R(T)$ of the double network is significantly larger as it includes the resistance of the long wires composing the large loops. Nevertheless, the unit cell amplitude of the oscillations, ΔR, for both networks, is similar, indicating that ΔR cannot distinguish between correlated and uncorrelated behavior of fluxoids in networks of loops of the same size.

Note that there is no correspondence between ΔR and dR/dT, see Figure 4, in contrast to what one would expect if ΔR resulted from periodic changes in the critical temperature T_c, as in the analysis of the Little-Parks experiment [15-17]. A remarkable deviation from this analysis is also found in the magnitude of ΔR. Contrary to classical superconductors, in high-T_c materials the predicted changes in the critical temperature,

$\Delta T_c \propto T_c(\xi_0/r)^2$, are extremely small because of the short coherence length ξ_0, so, the standard analysis fails to to explain the large amplitude of the oscillations [23, 24]. In previous papers [20, 21] we developed a model for a single, isolated loop which explains the physics of the double network magnetoresistance, including the large oscillations amplitude and its temperature dependence. This model ascribes the magnetoresistance 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.

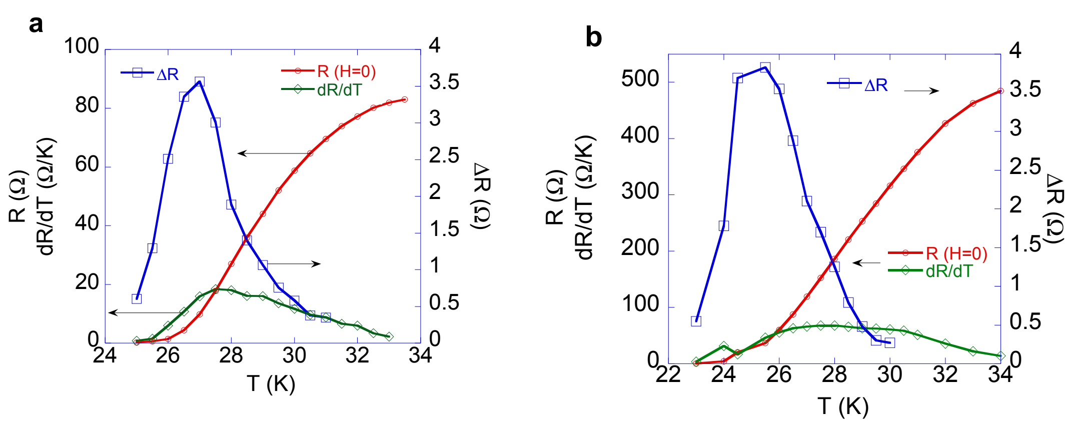

Figure 4. (Color on line) Resistance, R, measured at zero magnetic field (circles), amplitude of the magnetoresistance oscillations (squares), and the derivative dR/dT (diamonds) as a function of temperature in the square (a) and the double networks (b). Solid lines are guide to the eye.

In summary, we observed different fluxoid quantization effects in a superconducting double network as compared to a regular, square network. The regular network exhibit correlated behavior of the fluxoids, which is manifested by e.g. finite slope dR/dH at $H=0$, downward cusps, and secondary dips at half integer values of Φ/Φ_0. In contrast, the sub-network of the small square loops in the double network exhibits a single loop behavior lacking all these features. This observation indicates uncorrelated arrangements of fluxoids in the sub-network of the small loops, in agreement with our recent theoretical prediction [22]. Experimentally, the double network has an advantage over a single loop as it allows application of larger currents, thus improving the signal to noise ratio. In addition, measurements on large number of loops in the network average the effects of inhomogeneity and size distribution, allowing more precise studies of e.g. recent theoretical predictions of 'exotic' flux periodicity in unconventional superconductors [25-32].

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