SUPERCONDUCTING WIRE NETWORK UNDER SPATIALLY MODULATED MAGNETIC FIELD

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A two-dimensional (2D) superconducting square network under spatially modulated magnetic field is studied. The super/normal phase boundaries were measured with field modulation varied. The dependence on the strength of field modulation exhibited the behavior reproducing the calculation we had done before. In addition, *I-V* characteristics measurements were also conducted.

Keywords: superconducting network; modulated magnetic field; Little-Parks oscillation; Hofstadter butterfly; vortex glass transition

1. Introduction

The super/normal phase boundary of a two-dimensional (2D) superconducting wire network exhibits characteristic Little-Parks oscillation[1,2] as a function of the magnetic frustration α (perpendicular magnetic flux piercing the unit cell). The fine structure of the $T_c(H)$ curve reflects the edge of the so-called Hofstadter butterfly spectrum[3] which represents the Bloch band of tight binding electrons on a corresponding 2D lattice under a perpendicular magnetic field. Thus the $T_c(H)$ curve has local maxima at simple fractional values of α, which correspond to stable vortex configurations.[4] In this work, we address the case in which superconducting network is subjected to both a spatially modulated magnetic field and a uniform magnetic field. We measured the dependence of the $T_c(H)$ curve on the field modulation amplitude β (expressed in terms of flux per plaquette) and compared the results with the corresponding Hofstadter butterfly spectra calculated by the matrix diagonalization method.[5]

The nature of super/normal transition in 2D superconducting wire networks and Josephson junction arrays has been a subject of extensive studies. The transition at zero magnetic field is generally understood in terms of Kosterlitz-Thouless (KT) transition[6], the hallmark of which is a "universal jump" at $T=T_{KT}$ of the exponent in the power law current-voltage (*I-V*) characteristics. The super/normal transition in magnetic fields is governed by subtle competition between the vortex-vortex interactions and the interaction of a vortex with the pinning potentials both periodic and random. In particular, the overall interaction of the vortex system with the periodic potential should be sensitive to the value of α. Various models of phase transitions including, melting and floating of a vortex solid, vortex glass (VG) phase transition, and formation commensurate domains have been theoretically proposed[7] and experimentally pursued[6,8]. However, there still remain ambiguities in the comparison of the experimental data and theoretical models, so that the nature of superconducting transition in networks has so far been elusive. In order to shed light on the issue, we conducted *I-V* characteristics measurement in the present system with spatially varying magnetic field which is different from the usually studied case of uniform applied field.

2. Experiment

Figure 1 shows the scanning electron microscope (SEM) image of the sample used in this study. The sample is a square network of Al wire decorated with an array of ferromagnetic Co dots. The Al wire network consists of 120×120 unit cells with lattice period 500nm. The Al wires are 70 nm wide and 35 nm thick. The Co dots are oval shape with lateral size 130nm×200nm and thickness 80nm. The Al wires and Co dots are separated by an intervening layer of 35nm thick Ge. The role of this Ge layer is to prevent oxidation of Al network and to keep it from direct contact with Co dots. Thus the effect of ferromagnetic Co dots in the present system is solely through the local magnetic field generated by them (no pair-breaking effect).

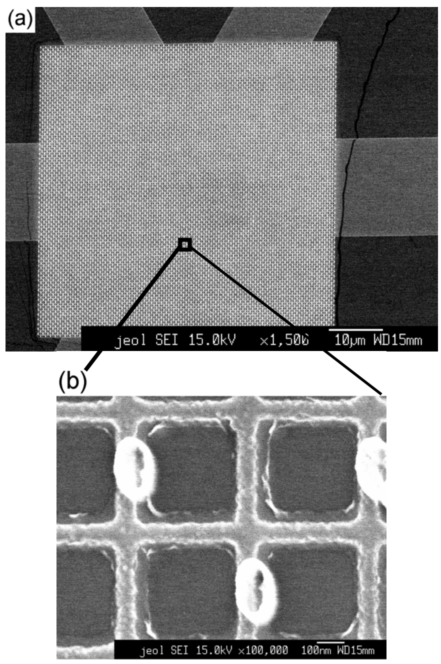

Figure 1. SEM image of the sample. (a) The whole network consisting of 120×120 squares. (b) Enlarged image showing arrangement of Co dots.

Figure 2(a) shows the schematic side view of the sample structure. When a sufficiently strong magnetic field is applied parallel to the sample, the Co dots are fully magnetized and the stray field from the Co dot array creates a spatially alternating magnetic field. The arrangement of the Co dots shown in Fig. 2(b) creates a checkerboard-patterned magnetic field whose strength β can be controlled by changing the direction of magnetization by changing the azimuthal angle φ of the parallel field. In addition to the checkerboard field β, a uniform perpendicular magnetic field α is applied, creating the flux pattern shown in Fig.2(b).

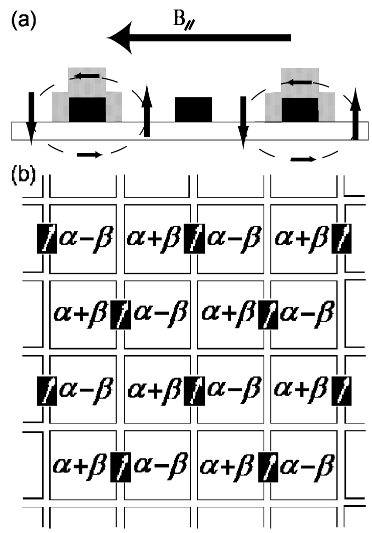

Figure 2. (a) Schematic picture of sample from side view. (b) Arrangement of Co dots and checkerboard patterned field modulation.

Measurements were conducted with a cross coil superconducting magnet system which enabled us independent control of the parallel and perpendicular field components. The experiment consisted of two steps. The first step was the determination of the super/normal phase boundary $T_c(\alpha)$ for different values of β. The magnetoresistance was measured by a standard ac method for different settings of the azimuthal angle φ, and the data was converted to $T_c(H)$. The second step was the measurement of the *I-V* characteristics with a programmable dc current source at different temperatures in the vicinity of the transition point. Temperature stability throughout the experiment was better than 1 mK.

3. Result

3.1. *Critical temperature*

Figure 3(a) shows the Little-Parks oscillation of T_c as a function of the uniform perpendicular field for different values of β. Each trace is vertically offset by 0.05K for clarity, and the azimuthal angle φ was rotated by 5° for each trace. Horizontal shift of the traces is a spurious effect due to a small angular misalignment of the sample relative to the horizontal plane. Figure 3(b) is the comparison between the experiment (solid curves) and the calculation (dotted curves) over a single period, which corresponds to the region between the dotted lines in Fig. 3(a). The traces cover the range from β=0 (bottom) to β=1/2 (top).

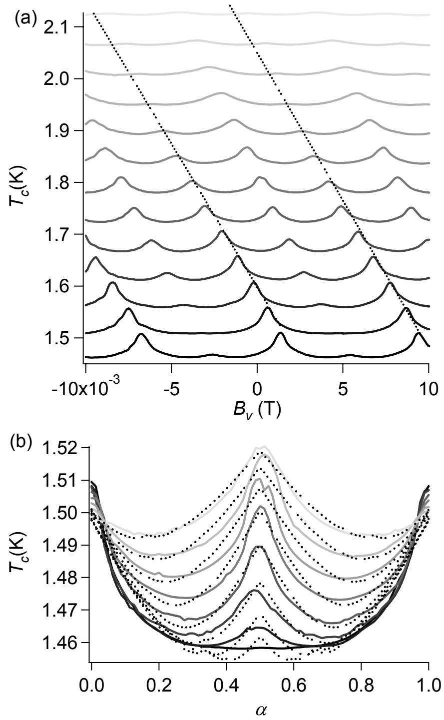

Figure 3. (a) $T_c(H)$ of the Al wire network as a function of the perpendicular magnetic field for different settings of φ which controls the amplitude of the checkerboard field. Each trace is vertically offset by 0.05K. (b) Comparison between the experiment (solid curves) and the calculation (dotted curves). The value of the parameter β is changed from 0 (bottom) to 1/2 (top).

It is seen that as β is changed from 0 to 1/2, the peak at α=1/2 become pronounced relative to those at integer α[5]. They crossover at β=1/4. These features are in common between both results. But the fine structures seen in the calculated curves disappeared in the experimental results. This discrepancy is presumably attributable to lithographical irregularity, in particular imperfect registration between the Co dot array and the Al network.

3.2. *I-V characteristics*

Figure 4 shows the *I-V* curves at different temperatures for α=0 and (a) β=0 and (b) β=0.5. We conducted measurements for α=0, 0.618, 0.5. But, contrary to our expectation, the *I-V* characteristics for these different values of α have turned out to be virtually indistinguishable.

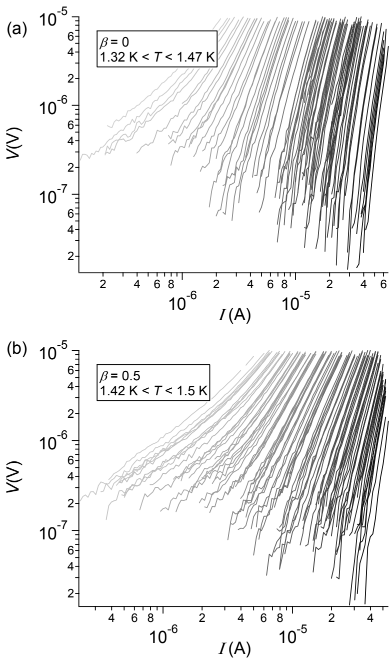

Figure 4. *I-V* curves for α=0 and (a) β=0 and (b) β=0.5.

The overall behavior of the *I-V* characteristics, *i.e.* the transition from upward-curvature to downward one with decreasing temperature, is reminiscent of the VG transition[9]. Figure 5 shows the results of scaling analysis for α=0 and (a) β=0 and (b) β=0.5. It is seen that in both cases, reasonably good scaling plot is obtained. Thus, the superconducting transition at these values of parameters α and β is consistent with the VG transition, although it does not constitute an exclusive proof.

The most puzzling feature of the present result is that the *I-V* characteristics for different values of α do not differ very much and it appears to fit the VG scaling even in the $\alpha=\beta=0$ case where the KT transition is expected. The overwhelming VG-like behavior suggests importance of disorder. It is conceivable that the requirement for the lithographical perfection is more stringent in the study of dynamics than that of the phase boundary, because ever increasing length scale is involved as the transition is approached. It is conceivable that imperfect registration between the Al network and the Co dot array over long range distorts the *I-V* characteristics and masks the features of the underlying transition.

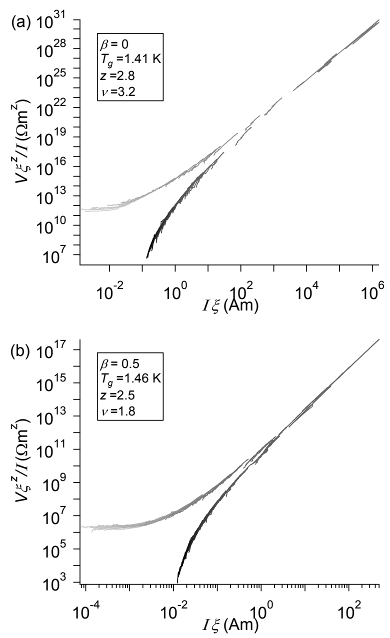

Figure 5. VG scaling plot of the *I-V* curves in Fig.4. (a) β=0 and (b) β=0.5.

4. Conclusion

In conclusion, the superconducting wire network under a spatially modulated magnetic field exhibits behavior reflecting the corresponding Hofstadter spectra. The observed *I-V* curves are consistent with the vortex glass scaling over the whole parameter range investigated, leading us to suspect overwhelming influence of disorder.

Acknowledgements

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