Superconducting Wire Network under Spatially Modulated Magnetic Field

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Abstract. 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.

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The super/normal phase boundary of a two-dimensional (2D) superconducting wire network exhibits characteristic Little-Parks oscillation[1] against the magnetic frustration α (perpendicular magnetic flux through the unit cell). This $T_c(H)$ curve reflects the edge of the tight binding energy spectrum for Bloch electrons on a corresponding 2D lattice[2] which is known as Hofstadter butterfly.[3] Reflecting the fine structures of the edge of the Hofstadter butterfly, 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 spatially modulated magnetic field and 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 calculation we had done before[5].

In a 2D superconducting network, two types of phase transitions are expected. One is Kosterlitz-Thouless (KT) transition[6] and the other is vortex glass (VG) transition[7]. The hallmark of the KT transition is a "universal jump" of the exponent of the current-voltage (*I-V*) characteristics at $T=T_{KT}$. On the other hand, the VG transition is characterized by scaling behavior of the *I-V* curves above and below the glass transition temperature T_g. Although *I-V* characteristics of superconducting network have been studied for decades, there still remains inconsistency between these experimental results. 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.

The sample used in this study consisted of a square network of Al wire decorated with a regular array of ferromagnetic Co dots. The network pattern consisted of 120 × 120 unit cells, made of Al wire 70 nm wide and 35 nm thick. The lattice period was 500 nm. The ferromagnetic Co dots were oval and the size was 130 nm × 200 nm. This Co dots were 80 nm thick. The Co dots were arranged in such a way that the fringing field from them imposes a sign-alternating (checkerboard pattern) flux pattern to the superconducting network. Figure 1(a) shows the arrangement of the Co dots. Between these two components, Ge layer was deposited 35 nm thick. The role of this Ge layer was to prevent oxidation of Al network and to keep it from direct contact with Co dots.

Measurements were conducted using a cross-coil superconducting magnet system, which consisted of a 7T Helmholtz coil (horizontal field) and a 1T solenoid (vertical field). The vertical field defined the uniform field α for the network. The horizontal field was used to control the magnetization of the Co dots. The spatially modulated field (parameter β) was induced from the stray field from Co dots and its amplitude was tuned by the azimuthal angle φ of the horizontal field, the details of which are given in ref. 5.

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, 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. Temperature stability throughout the experiment was better than 1 mK.

Figure 1(b) shows the Little-Parks oscillation of T_c as a function of the uniform perpendicular field. Each trace is vertically shifted 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 1(c) 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. 1(b). The traces cover the range from β = 0 (bottom) to β = 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. The discrepancy between the experimental data and the calculated curves is presumably attributable to lithographical irregularity, in particular imperfect registration between the Co dot array and the Al network.

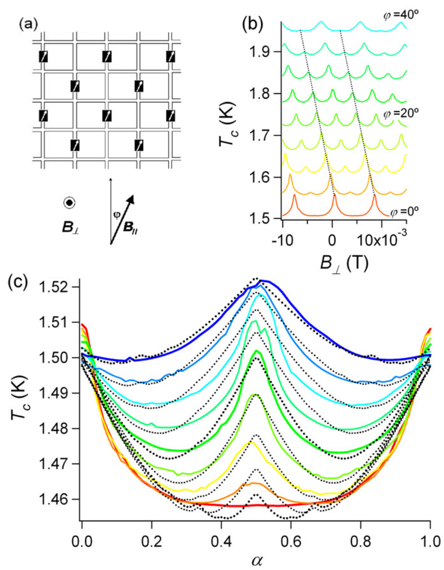

FIGURE 1. (a) Schematic picture of the sample. (b) Result of $T_c(H)$ measurements. Each trace is vertically offset by 0.05K. (c) Comparison between the experiment (solid curves) and the calculation (dotted curves). The value of the parameter β is changed from 0 (bottom) to 1/2 (top).

Figure 2(a) shows the *I-V* curves at different temperatures for α=0.61 and β=0. The inset of Fig. 2(b) shows a scaling plot of the data by the standard procedure of vortex glass model, which results in significant discrepancy for $T>T_g$. The origin of the discrepancy may be traced to the fact that T_g in this system is rather close to the mean field T_c. In order to take this into account, the correlation length ξ is multiplied by an extra factor $|T_c-T|^{-1/2}$ assuming it is scaled with the diverging length scale near T_c. The main panel of Fig.2(b) is the resulting scaling plot. Thus, the superconducting transition at these values of parameters α and β is consistent with the VG transition, although it by no means imply the only interpretation. Measurements at other values of α and β generally yielded similar results, (even for the nominally α=β=0 case, where a KT transition is expected). The requirement for the lithographical perfection is more stringent in the study of dynamics because ever increasing length scale is involved as the transition is approached.

In conclusion, the superconducting wire network under a spatially modulated magnetic field exhibits behavior reflecting the corresponding Hofstadter spectra. and the *I-V* curves are consistent with the VG scaling provided that a correction factor for diverging length scale near T_c is taken into account.

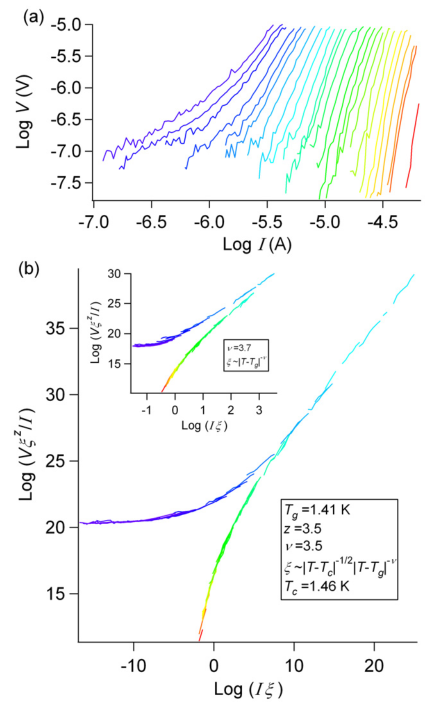

FIGURE 2. (a) *I-V* curves for α=0.61 and β=0 over the range 1.32 K < T < 1.45 K. (b) VG scaling plot with a correction factor to ξ explained in the text. The inset shows a scaling plot without the correction factor.

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