Superconducting behavior of a square microhole lattice on Pb film

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Abstract

It is intriguing to investigate the behavior of vortices in multiply connected superconductors. A sample is a superconducting network made by the vacuum evaporating of Pb on a copper substrate. The substrate has a regular array of square lattice holes. The sample magnetization has been examined by a SQUID magnetometer under a small field regime. We found many periodic matching peaks at $H{=}nH_\phi$. At T=7.23 K, the magnetization peaks have the same polarity against the field reversal. This anomalous matching peaks cannot be understood by the extended Little-Parks effect. The vortex-vortex interaction becomes attractive in a low Ginzburg-Landau parameter κ ($\sim$0.46) superconductor. We consider that the magnetization of a polarized vortex domain caused by the attractive interaction is responsible for the anomalous matching peak.

Key words: vortex; matching effect; microhole lattice; Pb; SQUID

1. Introduction

The magnetic flux is quantized to the integral multiplies of flux quantum Φ_0=2.07 $\times$ 10^{-7} G·cm^2 in a superconducting ring with enough thickness. When a cylinder wall is thin enough to allow wall-to-wall current flow, a critical temperature T_c oscillates as a function of the applied magnetic field with the period of Φ_0. This phenomenon is called as the Little-Parks effect [1], and is caused by the enhanced kinetic energy of supercurrents at the half integers of Φ_0.

Pannetier *et al.* [2] found a T_c oscillation as a function of the magnetic field by the measurements of the electronic resistance of a superconducting square network of aluminum. In view of the kinetic energy, this phenomenon can be regarded as the extended Little-Parks effect, and is interpreted theoretically by using the network equations [3,4].

Our group also reported a periodic T_c oscillation (on the order of mK) of a triangular microhole lattice of a Pb film where a matching magnetic field H_ϕ is a period [5], and an anomalous matching effect in the magnetization [6].

We extend our work to a square microhole lattice on Pb film. In the present paper, we report the details of the sample preparation and the magnetization properties in the weak field regime.

2. Experimental

We prepared a square-microhole-lattice sample by evaporating a type-I superconductor Pb. We used a copper micromeshsieve as a substrate. This substrate includes square hole lattice with a 16.9-μm pitch while the aperture ratio is 37 %. The vacuum pressure was maintained at 1.6×10^{-4} Pa during Pb evaporation. We used an evaporation mask with a 3-mm hole diameter made of phosphor bronze. We set the substrate perpendicular to the evaporation direction. The Pb thickness of the sample was 1150 Å(The coherence length ξ of Pb is 800 Å).

We named this sample SquMHoLP (Square Micro-Hole Lattice on Pb film). Figure 1 shows a photograph of the sample. We estimate a matching field H_ϕ = 72.5

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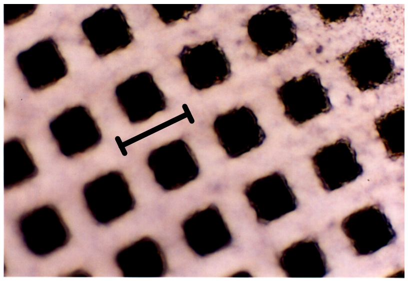

Fig. 1. The photograph of the sample taken by an optical microscope. The bar in the figure represents 17 μm.

mG of this sample by $H_\phi = \Phi_0/d^2$.

We measured the magnetization of the sample by means of a SQUID (Superconducting QUantum Interference Device) magnetometer. First, we degaussed the magnetic field twice. Second, we quenched a superconducting magnet to minimize the residual magnetic field. Third, we used a fluxgate magnetometer to measure a residual magnetic field. Finally, a residual magnetic field can be minimized as low as on the order of mG by using an option of the ultra low field mode. We used a coaxial copper cylindrical coil to generate a magnetic field upon a sample. The magnetic field is always applied perpendicular to the plane of microholes.

3. Results and Discussion

Figure 2 shows the magnetization loop of the sample at $T = 7.23$ K. The step of the external magnetic field is 2 mG. The sweep range of the magnetic field is between -0.5 G and $+0.5$ G. We applied magnetic field from 0 G to 0.5 G, from $+0.5$ G to -0.5 G, then from -0.5 G to 0.5 G. We found the sharp magnetization peaks at the period of the matching magnetic field $H = nH_\phi$. The magnetization peaks appear at the harmonic orders of the matching field H_ϕ. We estimated the actual matching magnetic field as 72.4 mG and the residual magnetic field as -20 mG. In Fig. 2, the magnetization peak has the same polarity against the field reversal. This is similar to what was observed for a triangular microholes as the novel anomalous matching effect [6]. This phenomenon cannot be understood in terms of the extended Little-Parks effect.

We interpret this phenomenon by the attractive force between the vortices. Interaction between the vortices is often repulsive from each other as was the case in high-T_c superconductors. A vortex in a superconductor ($\kappa \sim 1$) has a particular local field distribution. That is, the field changes its sign as a function of radial distance [7]. Since the vortex current is proportional to the field gradient, the current flows in a counter direction in the certain range of radius. This is the physical origin of

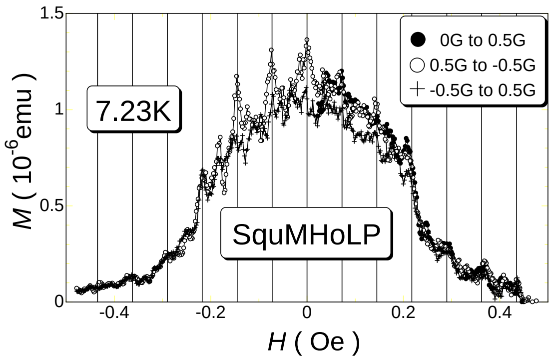

Fig. 2. Magnetization versus applied magnetic field of SquMHoLP at $T = 7.23$ K. The vertical lines represent $H{=}nH_\phi$.

the attractive vortex interaction. The reversal current may change the sign of the vortex interaction [8].

The reversal magnetic field regime appears at the distance of $\sim r/\lambda_L$ where the penetration depth λ_L depends on T. We consider that the attractive force acts between vortices when the reversal region reaches the neighbor microhole.

In conclusion, we observed the anomalous matching effect on SquMHoLP, which cannot be explained by the extended Little-Parks effect. The attractive interaction may be responsible for the anomaly.

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