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Matching effect in superconducting NbN thin film with a square lattice of holes*

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A square hole array is fabricated over a micro-bridge of NbN thin film by electron beam lithography and reactive ion milling. Magneto-resistance is measured across the micro-bridge filled with a hole array near the superconducting transition temperature. It is found that magneto-resistance minima occur when the number of vortices is an integer multiple or a fractional multiple of the number of holes. The temperature and the current dependences of the matching effect are studied.

Keywords: flux pinning, superconducting thin film, matching effect
PACC: 7460G, 7400, 7475

1. Introduction

Vortices in type II superconductors exhibit a wide variety of interesting phenomena.[1,2] When the size of the superconductor is compatible with its coherence length ξ or penetration depth λ, a lot of interesting effects arise from the flux quantisation and confinement of the vortices. With the progress in microfabrication technology, it has become possible to fabricate structures with dimensions of the same order of the coherence length or the penetration depth. During the past years, artificial periodic pinning array has aroused a lot of research interest.[3,4] The interactions of vortices with each other and with holes in these superconductors with mesoscopic structures result in a variety of static and dynamic phenomena.[1,5] Superconducting films with different geometries of arrays and different types of materials like Nb, Pb and Al have been extensively explored by many research groups.[3,6,7] In such superconducting thin films with artificial arrays, because of the flux quantization as well as the reduction in the condensation energy, vortices can be confined either inside the holes, or in the interstitial regions between the holes. At magnetic fields below an upper critical field, the holes act as strong pinning centres for the vortices, and it is possible for the holes to contain multi-quantum vortices. However, the energy of such multi-quantum vortices increases rapidly with the number of vortices increasing.[8] The maximum possible number of the vortices trapped by a single hole with diameter D is determined by the saturation number $n_s \approx D/[4\xi(T)]$, where $\xi(T) = \xi(0)/(1 - T/T_c)^{1/2}$.[9] Because of the quantisation of the flux quantum for the superconducting vortices, matching effect will take place when the number of the vortices is an integer multiple or a fractional multiple of the number of holes. The first experimental observation of the matching effect was performed by Baert *et al* who observed jumps in the magnetisation when the number of vortices was an integer multiple of the number of holes.[3] Later on, Metlushko *et al* observed fractional matching effect at down to a filling factor of 1/16.[10] In other experiments, fractional matching was seen at filling factors of 1/2 and 3/2.[11] These fractional matching effects are generally less pronounced than those at the integer matching fields. Recently the vortex configurations in various fractional matching fields have also

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been directly visualised by Lorentz[12] and scanning-Hall probe microscopy.[13,14]

The previous studies were carried out mainly on Nb, Pb and Al thin films where the residue pinning effect is assumed to be small. It is of great interest to carry out a similar study on superconducting samples with strong residue pinning. NbN is a type-II superconductor with a bulk T_c of 16.00 K. It has coherence length $\xi(0)$ of about 5 nm and penetration depth $\lambda(0)$ of about 200 nm, and therefore the value of κ is about 40.[15] The residue pinning in NbN is much larger than that in Nb or Pb, it is an ideal material for studying the effect of residue pinning on the matching between superconducting thin films and artificial hole arrays. In the present paper, we explore the vortex pinning effect by the artificial hole array in superconducting NbN thin films. We observe the interplay between the vortex quantization and the artificial hole array. Magneto-resistance minima in integer matching fields up to five times the field strength of H_1 (the first matching field corresponding to one vortex inside each hole) and in fractional matching fields of $1/2H_1$, $3/2H_1$ and $5/2H_1$ are observed.

2. Sample preparation

High quality NbN thin films with a thickness of about 100 nm were grown on MgO substrates by magnetron sputtering. To prepare the sample for the transport measurements, standard lift-off processes were utilized to carry out the micro-fabrication. First, a micro-bridge with dimensions of 60 μm×60 μm in the centre of the NbN film was fabricated with ultraviolet photolithography. And then, a square hole array was patterned with electron beam lithography, followed by reactive ion etching. In the electron beam lithography process, care was taken to avoid the damage to the sample. The sample reported in this paper had a square hole array with hole diameter $D = 175$ nm and period $L = 200$ nm. For these geometric parameters, the first matching field corresponding to one vortex threading each hole should locate at $H_1 = \Phi_0/L^2 = 517.5$ Oe (1 Oe=80 A/m), where superconducting flux quantum $\Phi_0 = hc/2e = 2.07 \times 10^{-7}$ Gs·cm^2 (1 Gs=10^{-4} T). Shown in Fig.1 is the scanning electron microscopic (SEM) image of the square hole array. It can be clearly seen that well-defined pattern is obtained. After the micro-fabrication, the sample has a superconducting onset transition temperature $T_c = 15.35$ K with a narrow transition width. This fact suggests that no degradation in sample quality occurred in the micro-fabrication process.

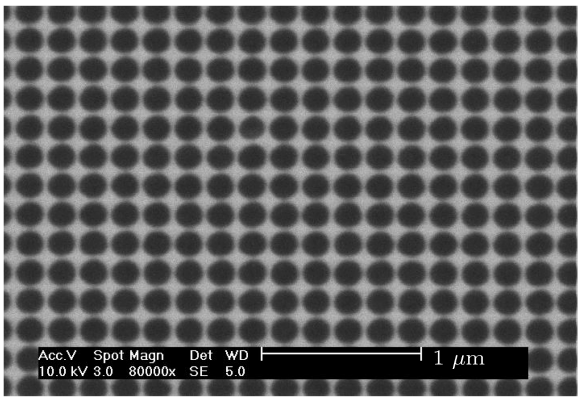


Fig.1. Scanning electron microscopic image of the square array of holes (diameter $D = 175$ nm and period $L = 200$ nm).

To study the pinning effects by the artificial hole array, magneto-resistance measurements were carried out near the superconducting transition temperature. The standard four-probe technique was utilised with the four contacts arranged near the micro-bridge. The measurements were performed using a Quantum Design Physical Properties Measurement System (PPMS) with an applied magnetic field perpendicular to the film plane. The temperature stability was better than 2 mK during the measurement.

3. Results and discussion

Figure 2 shows the magneto-resistance of NbN film with a square array of holes at several representative temperatures. During the measurement, the magnetic field was swept from +3100 to –50 Oe with a rate of about 1 Oe/s. The applied current was 700 μA, corresponding to current density $J = 9.33 \times 10^4$ A/cm^2. Sharp minima in the magneto-resistance are clearly visible when there are integral numbers of vortices threading each hole. The first pronounced minimum occurs at $H_1 \approx 503.80$ Oe when there is one vortex threading each hole. There is a small difference between the calculated H_1 and the observed one. This difference comes from the deviation of the actual period of the lattice after micro-fabrication from the designed period. The resistance minimum repeats itself with a period of H_1, i.e. the sharp resistance minima also occur when the applied magnetic fields are

$2H_1$, $3H_1$, $4H_1$ and $5H_1$ separately. It was shown earlier that the number of observed matching fields varied with the temperature and the lattice constant of the hole array.[3,16] When the lattice constant is fixed, more periods of matching are visible at lower temperatures, which is attributed to the change in the maximum number n_s of flux quanta trapped by a single hole due to the strong temperature dependence of $\xi(T)$ close to T_c.

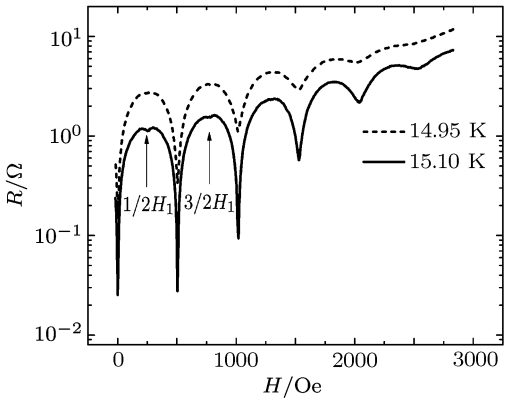


Fig.2. Curves for resistance vs. applied magnetic field for NbN thin film with a square array of holes (D = 175 nm) at different temperatures and an applied current I = 700 μA. For the geometric parameters of this hole array, the first matching field H_1 is 517.5 Oe. Arrows indicate the fractional matching fields at $1/2H_1$ and $3/2H_1$.

It is also noticed that between the integer matching fields, less pronounced minima in the magnetoresistance occur at the magnetic fields which are fractional multiples of H_1, i.e. $1/2H_1$, $3/2H_1$, and $5/2H_1$. The fractional matching fields at filling factors of 1/2 and 3/2 have also been observed in previous work on Nb and Pb films.[11,13] An analysis of our experimental data can be based on the flux pinning by holes which is strongly dependent on the number of vortices actually sitting in each pinning site.[17] When the holes are sufficiently large, they can pin multi-quantum vortices[6] with the number of the flux quanta n, increasing up to a saturation number n_s, given by

$$n_s \approx D/[4\xi(T)].$$

Here D is the diameter of the hole and $\xi(T)$ the temperature-dependent coherence length. In our case, with D = 175 nm, $\xi(0)$ = 5 nm, $\xi(T) = \xi(14.95\ \text{K})$ $\approx$ 31 nm, and $n_s \approx 1.42$. This is consistent with the result that the fraction filling begins at H_1.

After the magnetic field has reached H_1, there is one vortex inside each hole; additional vortices are forced to stay at the interstitial area between the holes. As a result, the whole system is composed of two different types of vortices: (i) multi-quantum vortices strongly pinned by holes and (ii) weakly pinned, single-quantum vortices at the interstitial sites. For field $H > H_1$, vortices are pushed into the interstitial area where the pinning potential is weaker than in the hole. Their motion results in the increasing of background resistance with the applied magnetic field increasing.

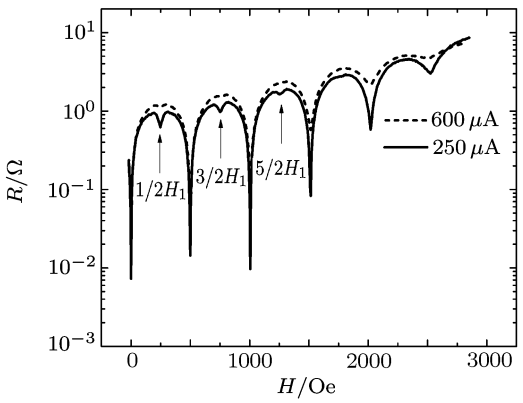


Fig.3. Curves for resistance vs. applied magnetic field for NbN thin film with a square array of holes (D = 175 nm) at different currents for T = 15.12 K. Arrows indicate the fractional matching fields at $1/2H_1$, $3/2H_1$and $5/2H_1$.

To further study the matching effect from the artificial hole array, we change the Lorentz force exerted on the vortices by varying the applied current. Shown in Fig.3 are the results measured at different transport currents at T = 15.12 K. We can see that when the applied current is 250 μA, the minima resulting from the fractional matching effect can be clearly seen. As the applied current increases, the drop-off of the resistance becomes less pronounced because of the enhanced Lorentz force acting on the vortices. When the applied current is 600 μA (current density $J = 8.00 \times 10^4$ A/cm^2), the featured minima at fractional multiples of H_1 disappear. This can be understood as follows: at the fractional matching fields, there are integral numbers of vortices inside each hole, and the remaining vortices are located at the interstitial sites because of its residue pinning. Below the critical current density, the residue pinning can provide an effective pinning of the vortices. When the applied current is larger than the critical current density, the residue pinning will be smeared out and there is no pinning of the vortices at the interstitial sites. As a result, the minima diminish at higher applied currents.

4. Conclusions

We study the matching effect in a superconducting NbN film perforated with a square array of holes. Pronounced resistance minima are observed when the magnetic fields are integer multiples of the first matching field H_1. The matching effect up to five periods has been observed. At these specified magnetic fields, the vortices are confined inside the holes, and there are integral numbers of vortices threading each hole. Besides the matching effect at integer multiples of H_1, less pronounced resistance minima are also observed when the magnitude of the magnetic fields is fractional multiples of H_1. At these magnetic fields, there are integral numbers of vortices inside the holes and one half of vortices at the interstitial sites. When the applied current is larger than the critical current of the NbN film, the resistance minima at fractional matching fields are smeared out.

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