Temperature dependent pinning phenomenon in superconducting Nb films with triangular and honeycomb pinning arrays

2009 J. Phys.: Condens. Matter 21 075705

(http://iopscience.iop.org/0953-8984/21/7/075705)

IOP Publishing — Journal of Physics: Condensed Matter

J. Phys.: Condens. Matter **21** (2009) 075705 (4pp) doi:10.1088/0953-8984/21/7/075705

Temperature dependent pinning phenomenon in superconducting Nb films with triangular and honeycomb pinning arrays

R Cao[1], Lance Horng[1], T C Wu[2], J C Wu[1] and T J Yang[2]

[1] Department of Physics, National Changhua University of Education, Changhua 500, Taiwan
[2] Department of Electrical Engineering, Chung Hua University, Hsinchu 300, Taiwan

E-mail: phlhorng@cc.ncue.edu.tw

Received 28 October 2008, in final form 22 December 2008
Published 23 January 2009
Online at stacks.iop.org/JPhysCM/21/075705

Abstract

The pinning phenomena in superconducting Nb films with triangular and honeycomb pinning arrays were explored. Special temperature dependent phenomena were found for both films. For the film with a triangular pinning array, the pronounced matching peaks in the critical currents as a function of magnetic field reduce from six to three within a narrow temperature range. This temperature dependent matching effect is explained by considering the dramatic change of coherent length with temperature when the temperature is close to T_c. In order to compare with the film with a triangular pinning array, we fabricated a film with a honeycomb pinning array with similar pinning site spacing and pinning size. Special prominent matching peaks at $H = 3.5H_1$ were found for this film. Molecular dynamic simulations were made to study this phenomenon. The ground state distribution of vortices obtained from simulations reasonably explains the prominent matching peaks. Pronounced temperature dependent matching effects were also found for the film with a honeycomb pinning array.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Since Abrikosov predicted the existence of vortex lattices in type II superconductors, theoretical and experimental research about these vortex lattices has made much progress. With the advancements in nanolithography techniques, artificial periodic pinning sites can be defined on the superconducting films with better precision. The interesting phenomena about the interaction between the periodic elastic vortex lattice and the underlying periodic pinning sites have captured the attention of many researchers during the past two decades [1–13]. Although a lot of experimental and simulation data have been accumulated, it seems that the understandings of these systems are still limited and some fundamental problems still need to be solved. The most important phenomenon in these systems is the matching effect. When the number of vortex is an integer multiple or a rational fraction of the number of pinning sites, the vortex lattice will match the pinning site lattice, thus the critical currents at the corresponding magnetic fields will have high peaks and the magnetoresistance will have low dips. Most experimental researches have been focusing on square, triangular and rectangular pinning arrays. We made samples with triangular pinning arrays and the honeycomb array with the same pinning site spacing and the same diameter of pinning sites. Much experimental research on triangular pinning arrays has been for samples obtained via templates made by self-assembly-techniques [6, 11, 12]. Some other experiments on samples with triangular pinning arrays used holes or magnetic dots as pinning centers [2, 10]. The pinning in our case is mainly caused by the corrugations at the edges of the pinning sites. The results obtained here show a pronounced temperature dependent phenomenon which is different from the results we obtained for a similar sample with different parameters [4]. We have explored the pinning phenomena in superconducting Nb films with honeycomb pinning arrays in an earlier work [5].

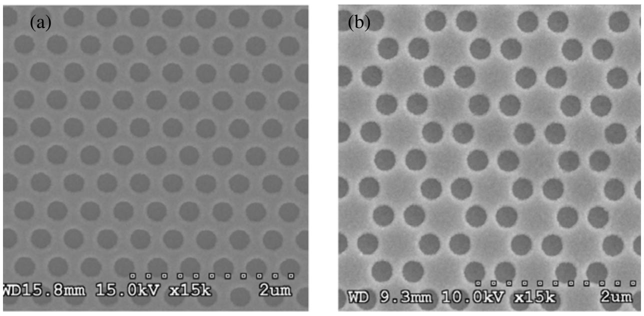

Figure 1. SEM images of the Nb film on top of (a) the triangular pinning array and (b) the honeycomb pinning array after patterning.

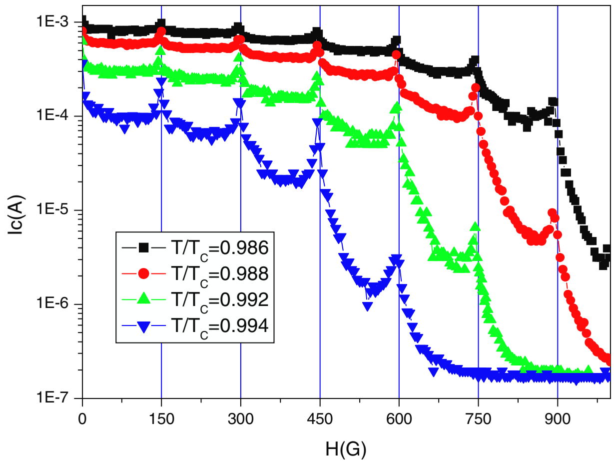

Figure 2. Critical current as a function of the magnetic field for the Nb film with a triangular pinning array at different temperatures.

In this paper, some new temperature dependent effects of the honeycomb pinning array are shown in the critical currents as a function of magnetic field curves. Simulations are made to give a reasonable explanation for the pronounced peaks found in the curves. By examining the distinct features of the pinning phenomenon found in these results, further understanding of the matching effect in this kind of system has been obtained.

2. Experiments

The scanning electron microscopy (SEM) micrographs for the films with triangular and honeycomb arrays of corrugated pinning sites are shown in figure 1. It can be seen that there is a natural relation between the triangular and honeycomb arrays. The triangular array could be regarded as the result of adding pinning sites to the honeycomb array. If the pinning site spacings for the two arrays are the same, the total number of pinning sites in the honeycomb array is 2/3 of the triangular array of the same area. We try to fabricate films with triangular arrays and honeycomb arrays with the same pinning site spacing and diameter. The final parameters were obtained with atomic force microscopy (AFM) measurements. For the triangular array, the pinning sites have a depth of about 100 nm, spacing about 400 nm and diameter about 300 nm. For the honeycomb array, the pinning sites have a depth of about 90 nm, spacing about 400 nm and diameter about 270 nm. During the fabrication process, arrays of circular holes were prepared on Si_3N_4-coated Si wafers using electron-beam lithography in conjunction with reactive ion etching. Then a dc sputtering completed the four-terminal geometry niobium films over the circular-hole array with a thickness of about 100 nm. This process is similar to that published in our previous reports [4]. MR measurements were carried out by a four-probe technique in a superconducting quantum interference device (SQUID) system with a temperature fluctuation within 3 mK and the external magnetic field was applied perpendicular to the plane of the film and transport current. The critical temperatures (T_{c0}) at zero field for the films with triangular and honeycomb pinning arrays are 8.07 K and 8.22 K, respectively.

3. Experimental results

The critical currents (I_c) as a function of the magnetic field at different temperatures for the film with the triangular pinning array are shown in figure 2. At $T = 0.986T_c$, there are six high peaks at the first to sixth matching fields and one low peak at the seventh matching field. The intervals between two consecutive maxima (H_1) are about 150 G. The experimental results of H_1 are in good agreement with the calculation $H_1 \approx B_1 = \Phi_0(1.075/a_0)^2 = 149.5$ G, where a_0 is the pinning site spacing of the triangular array. This calculation indicates that the maxima appear when every unit cell has an integer number of vortices. Therefore, the vortex pinning can be strongly enhanced when there is a geometric matching between the vortex lattice and the pinning arrays. When the temperature increases to $T = 0.988T_c$, there are five high peaks at the first to fifth matching fields and one low peak at the sixth matching field. With further increase in temperature, the number of high peaks further reduces but the single low peak still exists after the high peaks. It should be pointed out that those low peaks can be seen only when I_c is drawn in logarithmic scale and not seen if drawn in linear scale. It means that the low peaks represent a weak pinning enhancement effect.

The experimental results clearly show that the strong pinning effect is highly sensitive to temperature. The number of high peaks reduces from six to five, five to four, and finally from four to three, as the temperature increases from 7.95 K to 8.02 K ($0.986T_c$ to $0.994T_c$). This tendency is common for all our experimental results for triangular, square and honeycomb arrays. A similar pronounced temperature dependent phenomenon was reported in [14], although their results were for a film with a square array instead of a triangular array. This phenomenon was explained by the influence thermal fluctuation on the stability of the flux lattice in that research. It may not be a convincing explanation, because thermal fluctuation may not have a large influence on the stability and configuration of the flux lattice. We believe this phenomenon strongly indicates that the number of high peaks is determined by the coherent length or London penetration depth, because these parameters are divergent and change dramatically when the temperature is close to T_c. One natural explanation for this phenomenon is that the number of high peaks is the same as the number of vortices captured by the pinning sites, which was also the explanation proposed in [10]. When the vortices are all captured within the pinning sites, it is difficult for them to depin. As soon as the vortices begin to sit on the interstitial positions, the pinning becomes much weaker and the critical current peak at the matching field becomes much lower. It should be noted that the pinning sites in our experiments are not holes but close to blind holes, and the pinning is caused by the corrugations at the edge of the pinning sites. The pinning sites are also superconducting, so the multiquanta vortices in the pinning sites should be several individual vortices and not one giant multiquanta vortex. One seeming problem for this explanation is the saturation number of vortices. Usually, this number is estimated using the well known equation $n_s = D/4\xi(T)$, which will not be larger than two in our case [15]. However, it should be noticed that this number is calculated for an insulating inclusion with a diameter of D and not valid for our situation. In the periodic pinning array, the interaction between neighboring pinned vortices cannot be neglected, especially when the pinning spacing is small and the pinning sites are large. This calculated number may underestimate the number of vortices captured within the pinning sites, as already shown in a Ginzburg–Landau study [16]. Another important factor is that the pinning site in our research is not a hole and the pinned vortices should reside on the edge of the pinning site, thus the pinning sites have a much larger effective diameter.

The critical currents as a function of the magnetic field at different temperatures for the film with honeycomb array are shown in figure 3. Several phenomena are revealed in this figure. The intervals between two consecutive maxima (H_1) are 100 G, which is again consistent with the calculation based on the geometry of the array. Since the density of the pinning sites for the honeycomb array is 2/3 of the triangular array, the first matching field here is also 2/3 of the H_1 for the triangular array. One thing to be noticed is that the peaks at $H = 0.5H_1$ and $H = 1.5H_1$ are very obvious, although they are much lower than the neighboring peaks at the integer matching fields. For the half matching field at 50 G, there is one vortex for every two pinning sites and the distribution of the vortices should also be a stable triangular one. The peak at half integer matching field shows that the interaction between neighboring pinned vortices is strong and cannot be neglected in this periodic honeycomb pinning array.

Another distinguished feature in figure 3 is that the peak at 300 G (the third matching field) seems missing and the peak at 350 G is very high at $T = 0.986T_c$, even higher than the peak at the second matching field. In fact, the enhancement of critical current at 300 G still exists, but it does not appear as a pronounced peak because of the more pronounced enhancement of critical current at 350 G. This indicates that the configuration of vortices at the third and half matching field is very stable, which cannot be understood at first glance. Molecular dynamic simulations were made to study this phenomenon. The simulation methods we used here

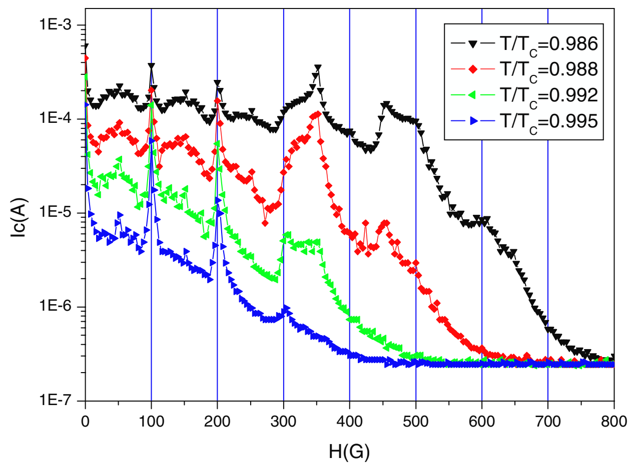

Figure 3. Critical current as a function of the magnetic field for the Nb film with the honeycomb pinning array at different temperatures.

are similar to those in [7] and our previous reports [17]. We model a two-dimensional (2D) system with periodic boundary conditions in x and y with N_v vortices interacting with N_p pinning sites. We define $n = N_v/N_p = H/H_1$, where H_1 is the field at which the number of vortices equals the number of pinning sites. We numerically integrate the overdamped equations of motion: $\eta \mathbf{v}_i = \mathbf{f}_i = \mathbf{f}_i^{vv} + \mathbf{f}_i^{vp} + \mathbf{f}_d$ Here, f_i is the total force acting on vortex i, f_i^{vv} is the force on the ith vortex due to its interaction with other vortices, f_i^{vp} is the vortex pin interaction force, f_d is the driving force and η is the viscosity, which is set equal to unity in this work. Pinning sites are modeled as

$$\mathbf{f}_i^{vp} = -\sum_{k=1}^{N_p} f_p \left(\frac{\mathbf{r}_i - \mathbf{r}_k^{(p)}}{r_p} \right)^4 H(\mathbf{r}_p - |\mathbf{r}_i - \mathbf{r}_k^{(p)}|).$$

Here, $r_k^{(p)}$ is the location of pinning site k, f_p is the maximum pinning force, r_p is the radius of the pinning site and H is the step function. This is a simple model of the pinning sites. When there are multiple vortices inside the pinning site, the vortices will reside at the edge of the pinning site. This will give a result close to our experiments, where the vortices are pinned at the edge of the pinning sites due to the corrugations of the film. The pinning sites are a honeycomb array in this work. The ground state distributions of the vortices were obtained using a numerical algorithm simulating the annealing process [7].

The ground state at the third and half matching field for the honeycomb array is shown in figure 4. Notice that there is one vortex at each center of the hexagonal unit cell in the pinning array. Every pinning site has three vortices in it. This distribution is stable, because there are many triangles of vortices in the distribution. The three vortices in every pinning site form a triangle and the vortices at the center of every hexagonal unit cell form six triangles with the neighboring vortices around them. These triangles for vortices in this distribution substantially reduce the elastic energy of the vortex system. One may still wonder why the peaks at 350 G are higher than the peaks at 200 G and almost as high as the peaks at 100 G. The consideration of the pinning energy and elastic

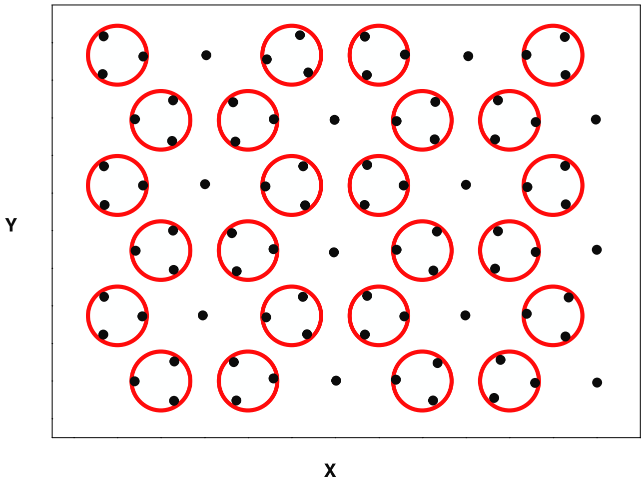

Figure 4. The simulated ground state distribution of the vortices for the Nb film with a honeycomb pinning array at the third and half matching field. The circles represent pinning sites and the dots represent vortices.

energy of the vortex system may give us some understanding of this problem. At 100 G, every pinning site has one vortex, and the pinning energy provided by the pinning array is fully exploited. However, compared to a triangular array, the honeycomb array distribution of the vortices increases the elastic energy of the vortex system, so the effect of pinning energy is weakened. At 200 G, every pinning site has two vortices and the elastic energy of the vortex system is much higher than that at 100 G and therefore caused a lower critical current. At 350 G, the elastic energy of the vortex system is close to a triangular one and is low. Only one seventh of the vortices are not pinned within the pinning sites, so the pinning energy provided by the pinning sites is almost fully used. Combining these two factors, the distribution of vortices at 350 G is very stable and the critical current is high.

In this case, the heights of the peaks in the critical currents are also sensitively temperature dependent. The peak at $H = 3.5H_1$ is high at both $T = 0.986T_c$ and $T = 0.988T_c$. However, at $T = 0.992T_c$ this peak becomes very low and extended from $H = 3H_1$ to $H = 3.5H_1$. At the higher temperature $T = 0.995T_c$, the peak is no longer at $H = 3.5H_1$ but is shifted to $H = 3H_1$. This shifting indicates that the ground state distribution of the vortices has undergone a fundamental change. This should be caused by the rapid increase of the coherent length with the increase of temperature, thus the reduction of the number of vortices within the pinning sites. The temperature dependence of the $H = 4.5H_1$ peak is also apparent. At the lowest temperature $T = 0.986T_c$, the peak at $H = 4.5H_1$ is prominent, just a little lower than the peak at $H = 2H_1$. At $T = 0.988T_c$, this peak becomes much lower, and the peaks at 100, 200 and 350 G are only a little lower than those peaks corresponding to lower temperatures. At $T = 0.992T_c$ and higher temperatures, the peak at $H = 4.5H_1$ is missing. This may suggest that more vortices are in the interstitial positions and the vortex system is no longer stable. This temperature dependence is very different from the temperature dependent phenomenon found in other periodic arrays, and will be further explored and discussed in our future work.

4. Conclusion

In this research, we have explored superconducting Nb films with a regular array of triangular and honeycomb pinning sites. The film with a regular triangular pinning array showed a pronounced temperature dependent matching effect. This effect was explained by considering the dramatic change of coherent length with temperature when the temperature is close to T_c. The film with a regular honeycomb pinning array, which has similar pinning site spacing to the triangular array, was also explored. Complex temperature dependent pinning phenomena were found. Special matching effects at $H = 3.5H_1$ were found in the experimental results and molecular dynamic simulations were made to study this phenomenon. The ground state distribution of vortices at $H = 3.5H_1$ was obtained, which gave a reasonable explanation for the prominent matching peak. Pronounced temperature dependent matching effects were also found in the film with a honeycomb array. This temperature dependence is very different from those found in other periodic arrays.

References

[1] Matin J I, Vélez M, Nogués J and Schuller I K 1997 *Phys. Rev. Lett.* **79** 1929
[2] Hoffmann A, Prieto P and Schuller I K 2000 *Phys. Rev.* B **61** 6958
[3] Patel U, Xiao Z L, Hua J, Xu T, Rosenmann D, Novosad V, Pearson J, Welp U, Kwok W K and Crabtree G W 2007 *Phys. Rev.* B **76** 020508
[4] Wu T C, Kang P C, Horng L, Wu J C and Yang T J 2004 *J. Appl. Phys.* **95** 6696
[5] Wu T C, Wang J C, Horng L, Wu J C and Yang T J 2005 *J. Appl. Phys.* **97** 10B102
[6] Welp U, Xiao Z L, Novosad V and Vlasko-Vlasov V K 2005 *Phys. Rev.* B **71** 014505
[7] Reichhardt C, Olson C J and Nori Franco 1998 *Phys. Rev.* B **58** 6534
[8] Harada K, Kamimura O, Kasai H, Matsuda T, Tonomura A and Moshchalkov V V 1996 *Science* **274** 1167
[9] Reichhardt C and Reichhardt C J O 2007 *Phys. Rev.* B **76** 064523
[10] Moshchalkov V V, Baert M, Metlushko V V, Rosseel E, Van Bael M J, Temst K, Jonckheere R and Bruynseraede Y 1996 *Phys. Rev.* B **54** 7385
[11] Vinckx W, Vanacken J, Moshchalkov Victor V, Matefi-Tempfli S, Matefi-Tempfli M, Michotte S, Piraux L and Ye X 2007 *Physica* C **459** 5
[12] Eisenmenger J, Oettinger M, Pfahler C, Plettl A, Walther P and Ziemann P 2007 *Phys. Rev.* B **75** 144514
[13] Silhanek V, Van Look L, Jonckheere R, Zhu B Y, Raedts S and Moshchalkov V V 2005 *Phys. Rev.* B **72** 014507
[14] Meilushko V, Welp U, Grabtree G W, Osgood R, Bader S D, Delong L E, Zhang Z, Brueck S R J, Ilic B, Chung K and Hesketh P J 1999 *Phys. Rev.* B **60** 12585
[15] Mkrtchyan G S and Shmidt V V 1972 *Sov. Phys.—JETP* **34** 195
[16] Berdiyorov G R, Milosevic M V and Peeters F M 2006 *Phys. Rev.* B **74** 174512
[17] Cao R, Wu T C, Kang P C, Wu J C, Horng L and Yang T J 2007 *Solid State Commun.* **143** 171