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RAPID COMMUNICATION

Wire network behavior of superconducting films with lower symmetrical mesoscopic hole arrays

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Superconducting films with the same hole density but different geometric symmetry have been designed and fabricated. The $R(H)$ curves show obvious periodic oscillations with several dips at fractional matching fields. It is found that the period of the oscillations in the low field is not necessary equal to that derived from the hole density, but consistent with that from the corresponding wire networks when the large disk-like film regions are regarded as nodes. The experimental results of $R(H)$, $T_c(H)$ and $j_c(H)$ at fractional matching fields within the first oscillation also support the rationality of considering films with large-diametered hole arrays as wire networks. Our results demonstrate that the connectivity of superconducting films with large-diametered hole arrays plays a more important role in the oscillations of $R(H)$ curves.

Keywords: fluxoid quantization, wire network, matching effect

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1. Introduction

Superconducting films with periodic artificial pinning sites have been investigated for decades[1–8] since it provides a potential platform for realizing specilized quantum states by controlling individual vortex. A commonly observed phenomenon is that there are dips in the magnetoresistance $R(H)$ or peaks in the field dependence critical current density $j_c(H)$ when the number of flux quantum Φ_0 is an integer multiple of the pinning sites, known as the matching effect or the commensurate effect.[2–7] The most widely accepted explanation of the matching effect is the pinning enhancement when the vortex lattice is commensurate with the pinning sites.

Similar effects have also been observed in other systems like superconducting wire networks[9–14] which may arise from quite different origins. For superconducting wire networks with a line width ω comparable to the superconducting coherence length ξ, the origin of the oscillations is very close to the well-known Little–Parks effect.[15,16] This is a consequence of the supercurrent induced suppression of the superconducting critical temperature T_c at non-integer flux quantum fields, which is closely related to the fluxoid quantization effect.[17]

However, the multiple connected nature of superconducting wire networks makes the coherence of different paths of vital importance. This is reflected in the integer or fractional matching fields of the periodic oscillations, which is closely related to the lattice geometry. The oscillations in superconducting wire networks such as the phase boundary $T_c(H)$ can be calculated from the linearized Ginzburg–Landau equations,[18,19] which is expressed in the form of superconducting order parameters of the nodes. These problems can be mapped into the eigenvalue problems of tight binding electrons in the same lattices, with the results of the upper limits of the Hofstadter butterfly[20] like spectrums being the $T_c(H)$ boundary of the corresponding wire networks. The eigenvalue problems can be also solved by an analytical approach based on multiple-loop Aharonov–Bohm Feynman path integrals,[21–23] and this provides a more systematical process to obtain the phase boundary $T_c(H)$.

As for superconducting films with large-diametered hole arrays where ΔW is comparable to ξ, the origin of the oscillations is not clear yet. Interestingly, for superconducting films with different kinds of pinning arrays, transition from pinning mechanism to wire network behavior has been observed when the edge-to-edge separation of the nearest holes ΔW is gradually decreased to near ξ.[4] Furthermore, the fluxoid quantization induced T_c decline at non-integer flux quantum fields is determined when the $R(H)$ curves of the films with hole arrays are compared to that of continuous reference film.[8]

Most previous results are given in films with square or triangle hole arrays[4,24–26] whose structures are very close to the corresponding wire networks. Thus it is straightforward that these arrays can be simplified to wire networks. While for other films with periodic hole arrays with large-areaed remaining film, such as Kagomé or honeycomb hole arrays, the simplification is no longer appropriate. Nevertheless, the simplification from a film with hole arrays to wire networks can still be done in the low field if the disk-shaped film regions are regarded as nodes.[27]

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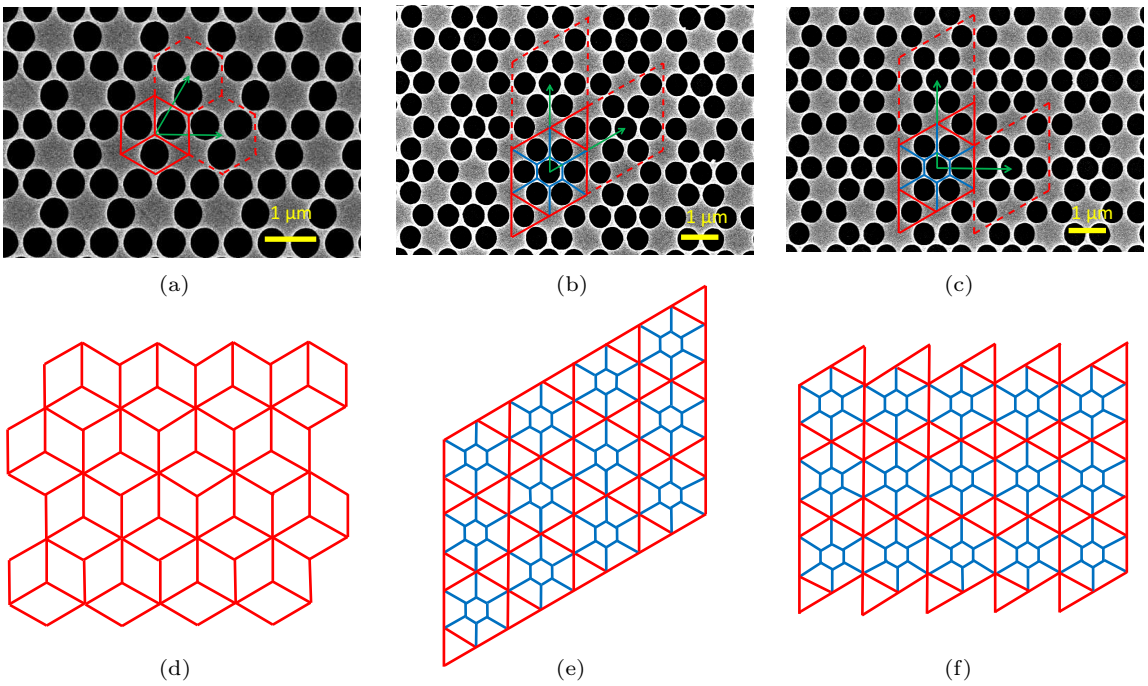


Fig. 1. SEM images and unit cells of sample Kagomé, FH3 and FH2 are presented in (a), (b) and (c), respectively, and their corresponding wire networks are shown in (d), (e) and (f), respectively. These samples share similar parameters, with the distance of the center of the nearest holes $a = 600$ nm, and the edge-to-edge separations of the nearest holes $\Delta W \approx 60$ nm.

It is worth noticing that the theoretical values of the period of the oscillations that derived from the hole density and those derived from the corresponding wire networks are accidently the same, which makes it inconvenient to figure out whether the connectivity of the system is the true origin of the oscillations. A possible reason is that the commonly used lattices including square, rectangle, triangle, Kagomé and honeycomb are all consist of holes with the same distribution of neighboring holes. One exception is the diluted square hole array which has two different types of holes,[28] but the experiment value of the oscillation period in the low field is still the same as the theoretical value derived from the hole density, and the corresponding wire network is also too complicated to be determined.

In order to further clarify the origin of the oscillations, three different samples named Kagomé, FH3 and FH2 have been fabricated. They are all diluted triangle arrays with the same hole density but different configurations of holes. The latter two samples have been fabricated with specially designed hole arrays by adding some holes to the honeycomb hole array, and their symmetries are lower than that of the Kagomé hole array. Periodic oscillations of $R(H)$ curves have been observed in these samples with different intervals of oscillations, especially in the low field region. It is found that the experiment results of intervals of oscillations in the low field are not necessarily equal to the theoretical ones that derived from the hole density. In addition, the results of dips or peaks of $R(H)$, $T_c(H)$ and $j_c(H)$ at fractional matching fields within the first oscillation are also consistent with those derived from the corresponding wire networks if the large disk-like film regions are regarded as nodes. All these results suggest that the oscillations are determined by the connectivity of the samples rather than the hole density. So we find a strong evidence to support that for superconducting films with large-sized hole arrays where w_s is comparable to ξ, the periodic oscillations are determined by the connectivity of samples rather than the hole density.

2. Experiments

The samples with desired nanostructures were fabricated and measured as follow. First, Nb film of about 60 nm was deposited on the surface of Si substrate which was covered with a 300 nm-thick SiO_2 layer using DC magnetron sputtering. Next, a micro-bridge consisted of a 60×60 μm^2 area and four leads was fabricated using ultraviolet lithography and reactive iron etching. Then, superconducting films with designed hole arrays were fabricated on the 60×60 μm^2 area using electron beam lithography and reactive ion etching. Finally, the transport properties of the samples were measured using a physical properties measurement system (PPMS) connecting with a LS370 AC bridge, a model 6221 current source and a model 2182 nanovoltmeter.

Three different samples were fabricated to investigate the origin of the oscillations, which are all 3/4 diluted of the same triangle hole array but with different arrangements of holes. The distance between the center of the nearest holes a is 600 nm, and the diameter of the hole d is about 540 nm, which leaves the edge-to-edge separation of the nearest holes ΔW about 60 nm, very close to the superconductor coherence length ξ.[29] The scanning electron micrograph (SEM) images

and unit cells of sample Kagomé,[22,23,30] FH3 and FH2 are shown in Figs. 1(a), 1(b) and 1(c), respectively.

They are all obtained by removing a quarter of holes from the triangle hole array but with different distributions of holes. The latter two are obtained by adding extra holes to the honeycomb hole array. It is shown in Figs. 1(b) and 1(c) that, both samples FH3 and FH2 share the same rhomboid primitive cell while there is a difference in one of the two basis vectors, which are marked with green color. It is easy to see that there is a shift of half the length of the primitive cell in the vertical direction. The film with Kagomé hole array is used as a reference sample, which has already been investigated elsewhere.[27]

3. Results and discussion

The $R(H)$ curves of samples Kagomé, FH3 and FH2 are shown in Figs. 2(a), 2(b) and 2(c), respectively, the temperatures are selected at which the oscillations are the most pronounced. For convenience, the magnetic field is presented in both the original form and the reduced one normalized by the period of the first oscillation, and the resistance is also displayed in the reduced form $R/R_{\rm N}$, where $R_{\rm N}$ is the resistance at 10 K. Obviously, there are two different field regions with different intervals of the oscillations in all these samples. The intervals of the oscillations are extracted and displayed in Fig. 3(a), and the averages of the intervals are shown in Fig. 3(b).

The critical field is $H_{\rm c} = 145.7$ Oe in sample Kagomé. For field lower than $H_{\rm c}$, there are three complete oscillations with sharp dips at fractional matching fields, and the average value of intervals is $\Delta H_1 = 48.6$ Oe. However, for field higher than $H_{\rm c}$, the average value of intervals increases to $\Delta H_2 = 65.9$ Oe, and dips at fractional matching fields are slowly washed out. Similar behaviors have been observed in samples FH3 and FH2. These results change into $H_{\rm c} = 129.6$ Oe, $\Delta H_1 = 43.2$ Oe and $\Delta H_2 = 64.7$ Oe for sample FH3, excluding an exception of the interval in the high field region, and $H_{\rm c} = 128.9$ Oe, $\Delta H_1 = 43.0$ Oe and $\Delta H_2 = 64.4$ Oe for sample FH2.

It is surprising that ΔH_1 of samples FH3 and FH2 are nearly the same, but different from that in sample Kagomé. The theoretical value of the oscillation period ΔH_1 in the triangle hole array corresponding to the hole density with $a =$ 600 nm and $d = 540$ nm is 66.3 Oe obtained by the equation

$$\Delta H_1 = n_0 \Phi_0 / S_{\rm u}, \tag{1}$$

where $S_{\rm u}$ is the area of the unit cell and n_0 is the number of holes in the unit cell. Since samples Kagomé, FH3 and FH2 are all $3/4$ diluted triangle hole arrays, the theoretical values of ΔH_1 corresponding to the hole density are all $3/4$ of that in the triangle hole array, which equals to 49.8 Oe. This is very close to the experimental result in sample Kagomé, but different from that in FH3 and FH2, which is shown in Fig. 3(b). Thus the oscillations periods in the low field region are not determined by the hole density, which has not been clearly shown in previous works.

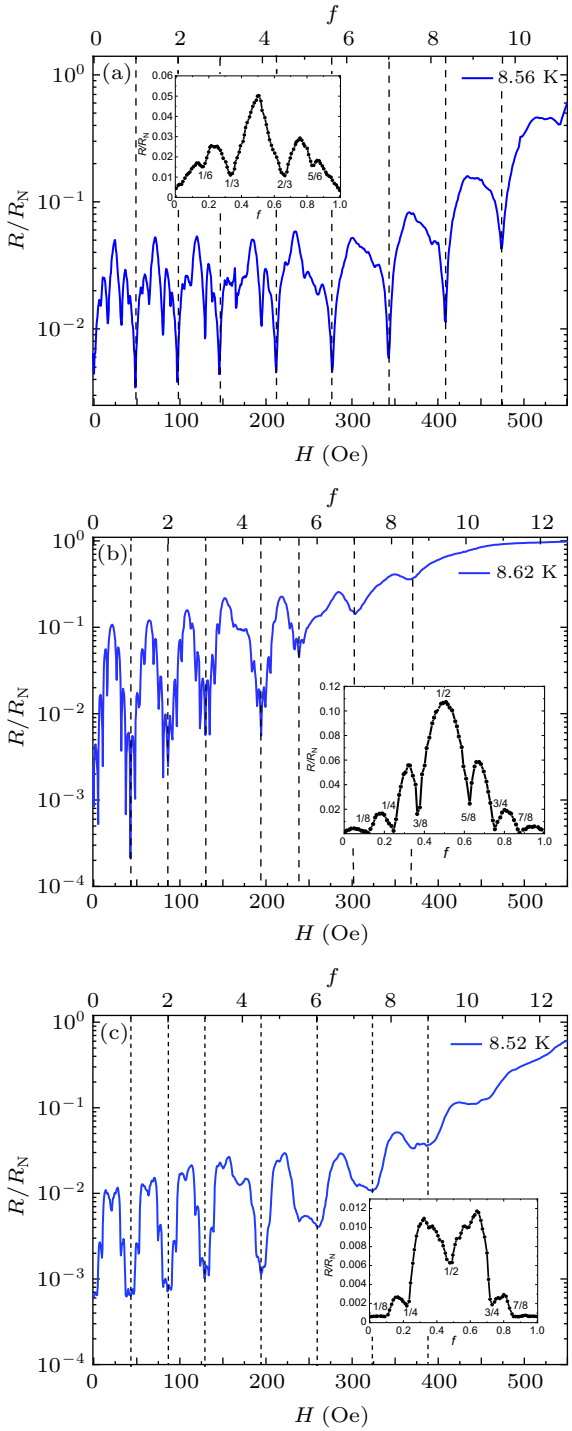


Fig. 2. (a)–(c) The most pronounced $R(H)$ oscillation curves of samples Kagomé, FH3 and FH2 measured with a current of 10 μA, respectively. For each curve, the magnetic field is both displayed in the original form and the reduced one normalized by the period of the first oscillation, and the insert shows the dips at fractional matching fields of the first oscillation.

At field above $H_{\rm c}$, the intervals of the oscillations increase, except for the fifth oscillation of sample FH3, which retains the same interval as that in the low field. The experiment results of ΔH_2 of all these samples are very close to the theoretical value of the oscillation period ΔH_1 in film with triangle

hole array corresponding to the hole density. The changes of the intervals have been mentioned in many articles as a result of the reconfiguration effect of vortices,[29,31–34] which exist in the form of fluxiod in the low field, and both fluxoid and Abrikosov vortices[35] in the high field. Nevertheless, more details are needed to obtain the exact distributions of the vortices in these samples.

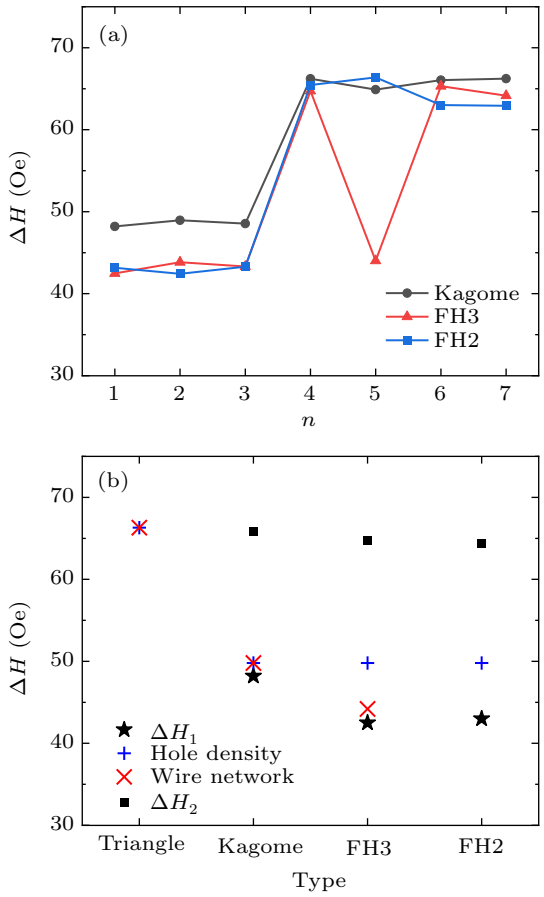


Fig. 3. (a) The separations of field of $R(H)$ oscillations in samples Kagomé, FH3 and FH2 extracted from Fig. 2. (b) The average separations of field in the low field ΔH_1 and those in the high field ΔH_2 in samples Kagomé, FH3 and FH2 are compared with the theoretical value of the oscillation period derived from the hole density and the corresponding wire networks respectively.

Films with different hole arrays can be simplified to the corresponding wire networks if the disk-like film regions in these samples are considered as nodes, which highlights the importance of the connectivity of superconducting films with large size of hole arrays. In this way, the corresponding wire network of the film with Kagomé hole array is T_3 wire network,[36–38] which is shown in Fig. 1(d). In fact, the dips of the first oscillation at fractional matching fields in sample Kagomé are located at $f = 1/6$, $1/3$, $2/3$ and $5/6$, and a distinctive sharp peak is found at $f = 1/2$, as shown in the insert of Fig. 2(a). These are just the fingerprint of the T_3 wire network, which has already been investigated elsewhere.[27] Furthermore, the experiment results of ΔH_1 in sample Kagomé are also consistent with the oscillation period derived from the corresponding T_3 wire network. However, the oscillation periods calculated from the hole density and the wire network are exactly the same, and this makes it impossible to decide whether the hole density or the connectivity of the wire network is the true origin of the oscillation.

The corresponding wire network of sample FH3 shown in Fig. 1(e) is much more complicated. In fact, there are two different kinds of disk-like film regions which are simplified as the nodes of the wire network, and the wire network is just exactly the Kagomé lattice if the small disk-like pieces of film regions are ignored and only the connectivity of the large pieces is considered, shown as the red lines in Fig. 1(e). Interestingly, the experimental dips at fractional matching fields within the first oscillation in sample FH3 shown in the insert of Fig. 2(b) are located at $f = 1/8$, $1/4$, $3/8$, $5/8$, $3/4$ and $7/8$, and there is also a distinctive peak at $f = 1/2$. These features are exactly the same as that in Kagomé wire network.[12,22,23] Furthermore, the experiment value of the oscillation period of sample FH3 ΔH_1 is also consistent with the theoretical one derived from the Kagomé wire network, and this is not the same as that derived from the hole density of sample FH3, which is shown in Fig. 3. These results suggest that the oscillation of the $R(H)$ curves in sample FH3 is originated from the connectivity of the film.

For sample FH2, the experimental dips at fractional matching fields within the first oscillation changed to $f = 1/8$, $1/4$, $1/2$, $3/4$ and $7/8$, which is shown in the insert of Fig. 2(c). Simplification of sample FH2 can be also done in the same way of FH3, shown as the red lines in Fig. 2(f).

It is unexpected that precise results are obtained while large simplification is considered in sample FH3, where the contribution of the small disk-like film regions is ignored. In fact, the transitions of the films with Kagomé and honeycomb hole array to T_3 and triangle wire networks respectively[27] are also surprising since the disk-like film regions are simply considered as nodes of wire networks. It is worth noticing that the large disk-like film regions are directly connected to each other in the film with honeycomb hole array, but they are connected to each other by the small disk-like film regions in the film with honeycomb hole array.[27] While for sample FH3, the large disk-like film regions are directly connected to each other without passing through the small ones. Therefore, a possible explanation is that, the coherence between the large disk-like film regions in sample FH3 is strong, which dominates the connectivity of the sample.

The phase boundary $T_c(H)$ of superconducting wire networks can be theoretically calculated from Ginzburg–Landau theory.[18,19] Based on the linearized Ginzburg–Landau equations, the relationship between the order parameter of a given node and that of other nodes directly connected to it can be derived, which is also called the Alexander equations.[18] Each of the order parameter of the nearest node in these equations

has a phase factor related to the external magnetic field, and the superconducting coherence length, as a function of temperature, is a parameter of these equations. Hence the phase boundary $T_c(H)$ can be obtained by solving the eigenvalue problem of these equations under periodic boundary conditions. Interestingly, the mathematical means used here is very similar to that of tight binding electrons in the same 2D lattice, which gives the famous Hofstadter butterfly energy spectrum[20] when the lattice is a square. Thus the calculation of phase boundary $T_c(H)$ can be mapped into the eigenvalue problem of tight binding electrons under the same lattice. In fact, this eigenvalue problem can be solved by an analytical approach based on the multiple-loop Aharonov–Bohm Feynman path integrals,[21–23] which provide a systematically method to calculate the phase boundary.

The experiment results of $T_c(H)$ provide a more direct approach to determine whether films with hole arrays can be regarded as wire networks in the low field, comparing with the theoretical ones of the corresponding wire networks. The blue line in Fig. 4 shows the $T_c(H)$ boundary of sample FH3 within the first oscillation with the criteria of $0.1R_N$, where R_N is the resistance of the sample at 10 K, and T_c is displayed in the form of $(T_c(0)-T_c(f))/T_c(0)$ for convenience.

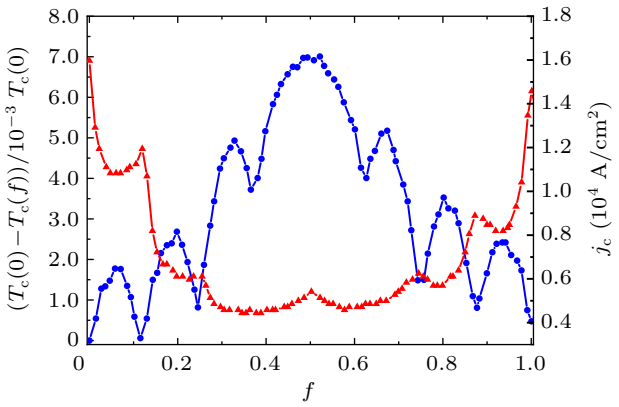


Fig. 4. The $T_c(H)$ curve within the first oscillation with the criteria of $0.1R_N$ (blue line) and the $j_c(H)$ curve measured at 8.48 K with the criteria of $0.02R_N$ (red line) of sample FH3.

The $T_c(H)$ curve of the oscillation displayed here shows the similar behavior of the $R(H)$ curve with the dips located at fractional matching fields including $f = 1/8$, $1/4$, $3/8$, $5/8$, $3/4$ and $7/8$ while there is a peak at $f = 1/2$, and this is consistent with that calculated from the Kagomé wire network based on the multiple-loop Aharonov–Bohm Feynman path integrals.[13,22,23]

Nevertheless, the behavior of fractional matching fields of the $j_c(H)$ curve measured at 8.48 K with the criteria of $0.02R_N$ is not exactly the same as that in $T_c(H)$ curve, which is shown in Fig. 4 by the red line. There is a peak at $f = 1/2$ while the peaks at $3/8$ and $5/8$ disappear. Considering that the $j_c(H)$ curve is obtained well below the critical temperature, the pinning effect of holes is enhanced with the transition from the film with hole array to wire network invalid. Thus the matching effect of the $j_c(H)$ curve is dominated by vortex–vortex interactions as well as the interactions between vortices and pinning landscape, with the long-range order of vortex configurations of vital importance.[39–41] In fact, similar behavior has been observed in superconducting Kagomé wire network, but it is a transition from peak to small dip at $f = 1/2$ in $T_c(H)$ curve when the criteria of critical resistance changes to lower values.[11] Therefore, the method of treating sample FH3 near T_c as a Kagomé wire network is reasonable in the low field.

4. Conclusions

The magnetoresistance oscillations of superconducting films with the same hole density but different configurations of holes have been investigated here. It is found that when the edge-to-edge separations of the nearest holes are comparable to the superconductor coherence length, the periods of the magnetoresistance oscillations in the low field are not necessarily determined by the hole density, but rather by the connectivity of corresponding wire networks. Also, the experimental details at fractional matching fields in $R(H)$, $T_c(H)$ and $j_c(H)$ curves within the first oscillations also support the rationality of simplifying films with hole arrays into wire networks. Thus we can conclude that the magnetoresistance oscillations of films with large-sized hole arrays are determined by the connectivity of these systems rather than the hole density.

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