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Origin of the matching effect in a superconducting film with a hole array

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We investigate the origin of the matching effect observed in superconducting Nb films containing regular arrays of holes near the zero-field critical temperature. We find "dips" in the resistance vs magnetic field curves at matching fields where the magnitude of the magnetic flux threading each unit cell is an integer number of the flux quantum. By comparing the magnetic field dependences of the resistance and critical temperature in perpendicular and parallel magnetic field directions, we find that the matching effect in Nb films containing triangular hole arrays originates from hole-induced suppression of the critical temperature rather than the widely assumed flux pinning enhancement.

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Superconducting films containing periodic hole arrays have been the subject of much interest in recent years. They provide a unique platform to study generic problems appearing in many physical systems, for example, frustration[1,2] and interaction between a periodic elastic medium and an array of obstacles.[2,3] Rich novel vortex phenomena such as the existence of composite vortex lattices,[4] the rectification and phase locking of vortices,[5] commensurate pinning effect,[6,7] vortex domain formation,[6] and the appearance of multiquanta vortices[8] have been revealed via magnetization,[4] computer simulation,[5] and vortex imaging at temperatures well below the zero-field critical temperature, T_{co}.[6–8] At temperatures near T_{co}, transport measurements show an intriguing "matching effect" which appear as "dips" in the magnetic field dependence of the resistance, $R(H)$, or "peaks" in the field dependence of the critical current $I_c(H)$ when an integer number of flux quantum, $n\Phi_0$, is commensurate with the unit cell of the hole-array superconductor.[9–11] This effect has been widely attributed to a pinning enhancement where the entire vortex lattice is commensurately pinned by the hole lattice.[9–14]

However, similar resistance dips have also been observed in superconducting wire networks[2,15,16] when the width w of the superconducting strips circumventing a square hole is comparable to the superconducting coherence length ξ. Here, the resistance minima which occur at integer flux quantum matching fields are due to the additional suppression of the superconducting critical temperature T_c by magnetic field at noninteger flux quantum values arising from the fluxoid quantization effect (Little-Parks effect).[1,17] Since the superconducting coherence length $\xi \sim (1-T/T_{co})^{-1/2}$ is temperature dependent, a superconducting film containing a periodic hole array should resemble a superconducting wire network at temperatures close to T_{co}, where $\xi \sim w$, and Little-Parks effect induced resistance minima at matching fields should be observed. A review of the literature shows that all transport measurements[9,10,13] related to induced dips in $R(H)$ or peaks in $I_c(H)$ curves were carried out at temperatures very close to T_{co}. Thus it is not clear whether the matching effect observed in superconducting films containing periodic hole arrays originates from hole-induced pinning enhancement at the integer flux quantum matching fields or hole-induced T_c suppression at noninteger flux quantum fields or even both.

Here we present an experimental approach, as displayed in Fig. 1, to investigate the origin of the matching effect. We will focus on the dips in $R(H)$ curves which can also translate to peaks in the $I_c(H)$ curves since the conventional critical current I_c $(=V_c/R)$ is defined with a voltage criterion V_c. The solid circles in Fig. 1 represent a typical $R(H)$ curve obtained in a superconducting film with a periodic hole array at a fixed temperature near T_{co}. Dips in the resistance vs magnetic field curves appear at matching fields H_n where the magnitude of the magnetic flux threading each unit cell is an integer number of the flux quantum, $n\Phi_0$. If the dips in the $R(H)$ curve are due to pinning enhancement at integer flux quantum matching fields, the resistance curve without the

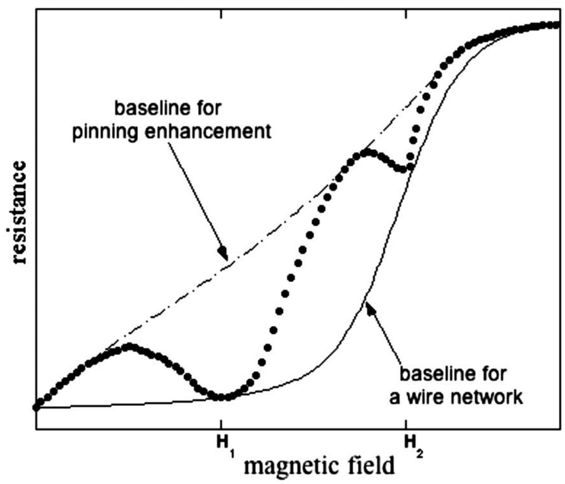

FIG. 1. A schematic outlining an approach to identify the origin of the resistance dips in $R(H)$ curves at integer flux-quantum matching fields which appear in a superconducting film with a regular hole array. The solid circles represent typical experimental observations. The dashed and solid curves are reference baselines expected for hole-induced pinning enhancement at matching fields and hole-induced T_c suppression at noninteger flux quantum fields (wire network), respectively.

influence of the hole array should be larger than or equal to the measured values (dashed line in Fig. 1). On the other hand, the fluxoid quantization effect induces additional T_c suppression at noninteger flux quantum fields, resulting in excess resistance at those field values in the $R(H)$ curve obtained at a fixed temperature. Consequently, the $R(H)$ for a wire network in the absence of the hole-induced Little-Parks effect should lie below the measured curve except at integer flux quantum matching fields where they have the same values. This is demonstrated schematically by the solid curve in Fig. 1. Developing a way to determine the baselines for the two separate effects (pinning enhancement vs Little-Parks effect) in the absence of the influence of the hole array is crucial for understanding the origin of the resistance minima in $R(H)$ curves.

In order to demonstrate the commensurate pinning induced by the hole array in a superconducting film, one usually compares a patterned film with a reference continuous film.[11,18–20] It is difficult to reach a reliable conclusion since T_{c0} of the patterned film often differs from that of the reference film.[20] A comparison is typically carried at the same reduced temperature T/T_{c0}.[20] At temperatures close to T_{c0}, however, the critical field H_{c2} of the patterned film at the same T/T_{c0} is larger than that of the reference film.[20] This difference in H_{c2} cannot be understood with pinning enhancement and is actually an indication that a patterned film may become a new system which has different characteristics from a continuous film. In fact, the experimental $H(T)$ phase line near T_{c0} for a patterned film was found to resemble that of a wire network.[19–22] That is, it follows a parabolic background augmented by T_c oscillation[19–22] rather than the two-dimensional continuous thin film behavior $H \sim (1-T_c/T_{co})$. In this case, it is inappropriate to derive the influence of the hole array by comparing a patterned film with a reference continuous film since it assumes that the hole array does not alter the properties of the continuous film except inducing the commensurate pinning. On the other hand, a wire network in a perpendicular field can be treated as a superconducting strip along with the hole-induced T_c suppression derived through coupled superconducting islands at the nodes of a wire network.[21] Thus at temperatures close to T_{c0} a film with a regular hole array should be compared with a superconducting strip to derive the contribution of the hole array to the properties of the film, e.g., to the $R(H)$ curve. However, it is difficult to obtain a strip with exactly the same quality (T_{co}, transition width) as that of a film with a hole array due to potential damage or degradation caused by the patterning process, as demonstrated by the difference in T_{c0} between an Al strip and an Al film containing a hole array.[21]

Both theory[21] and experiments[21,23] have demonstrated that the Tinkham formula $H_{c2}=\sqrt{3}\Phi_0/(\pi t\xi)$ (Ref. 24) for the critical field of a thin film with a thickness t in parallel fields can be applied to a strip with a width of w in perpendicular field by replacing the t with w (when t/ξ and w/ξ are less than 1.84), as the area exposed to the magnetic field has the same geometry. If the finite width of the zero-field superconducting transition is due to a critical temperature distribution, a thin film in parallel magnetic field will have the same magnetic field dependence of the resistance as a strip. This implies that if a film containing a hole array behaves like a wire network, $R(H)$ curves in parallel fields can be used to derive the baselines of those in perpendicular fields. That is, comparing $R(H)$ curves in perpendicular and parallel field directions can give clues to the origin of the matching effect. As demonstrated below, by using this approach we can identify the Little-Parks effect as the sole origin for the matching effect observed in our Nb films containing triangular hole arrays.

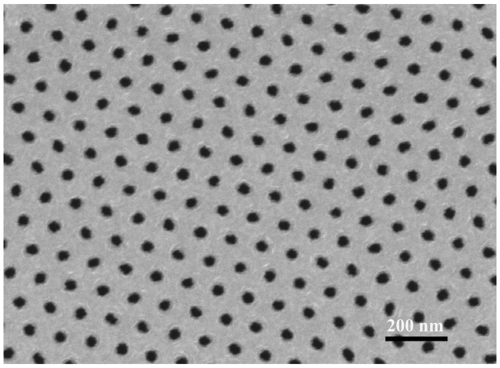

FIG. 2. SEM micrograph of a 60 nm thick Nb film deposited on an AAO substrate containing a triangular channel array (sample A).

We carried out experiments on superconducting niobium films with periodic hole arrays fabricated by depositing niobium onto substrates containing triangular channel arrays.[19] The anodic aluminum oxide (AAO) membrane substrates were fabricated by anodizing high-purity Al foils in an acid solution at 40 V. The diameter of the channels and the separation between them are about 60 and 103 nm, respectively. More details on the fabrication and a cross-section view of the membrane showing nanoscale channels can be found in Ref. 19. Niobium was deposited onto AAO substrates in an ultrahigh vacuum chamber via dc magnetron sputtering. The hole diameter decreases with increasing Nb film thickness and can range from less than 10–60 nm. Five samples with various thicknesses and hole diameters were investigated with four-probe dc transport measurements using a constant current mode. A criterion of $0.5R_N$ was used to define the critical temperature T_c and the critical field H_{c2}, where R_N is the normal state resistance. Similar to the thickness behavior of continuous films T_{co} of our perforated Nb films increases with film thickness, ranging from 5.10 to 7.45 K. The $R(H)$ data from three samples are presented here. Samples A and B are 60 nm thick and their T_{co} is 5.133 and 5.354 K, respectively. The thickness of sample C is 100 nm and its T_{co} is 7.310 K. $R(H)$ curves were measured at fixed temperatures with stability better than 1 mK.

Figure 2 shows a top-view scanning electron microscopy (SEM) micrograph of sample A. A regular triangular array of holes with diameter of about 30 nm, spaced 103 nm apart, can be identified. The solid circles in Fig. 3 represent the $R(H)$ curves obtained at 5.04 K ($0.982T_{co}$) and 5.25 K ($0.98T_{co}$) in perpendicular fields for samples A and B, respectively. Resistance dips occur at a field of 0.222 ± 0.002 T and 0.219 ± 0.007 T in samples A and B, respectively. These

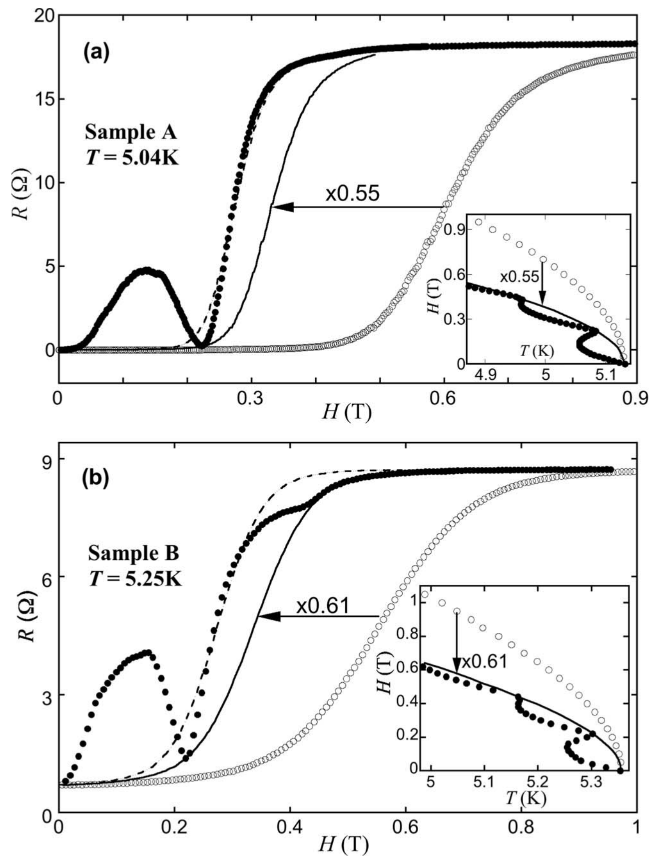

FIG. 3. $R(H)$ curves and $H(T)$ phase lines (insets) for samples A and B. Solid and open circles are experimental data obtained in perpendicular and parallel fields, respectively. The dashed and solid curves represent baselines derived based on commensurate pinning and wire network analysis, respectively. See text for more details.

values are consistent with the calculated first matching field of $H_1=0.225$ T at which each hole traps one flux quantum.[19] The dips are consistent with the characteristics reported for films containing hole arrays,[2,9–11] though a smaller number of dips are observed in our samples due to the much larger first matching field H_1. In order to obtain "reference" baselines for the sample as suggested in Fig. 1, we measured the related $R(H)$ curves for samples A and B in the parallel field direction (open circles in Fig. 3). The shift in the superconducting transition to higher magnetic fields shows that the critical field $H_{c2\parallel}$ in the parallel field direction is larger than the value of the perpendicular field $H_{c2\perp}$.

If the resistance dips were induced by pinning enhancement at the matching field, the dashed baseline suggested in Fig. 1 could be derived by scaling the $R(H)$ curve at parallel fields with a factor of $H_{c2\perp}/H_{c2\parallel}$ which represents the anisotropy of the film geometry. The dashed curves in Fig. 3 were obtained this way, where scaling factors $(H_{c2\perp}/H_{c2\parallel})$ of 0.455 and 0.495 were used for samples A and B, respectively. It is clear that this scaling approach does not produce the wanted baselines for hole-induced commensurate pinning. In the case of a wire network, on the other hand, supercurrents circling the holes contribute an additional T_c suppression mechanism in the presence of a magnetic field.[17,20,21] This mechanism is not accounted for when we use the scaling factor of $H_{c2\perp}/H_{c2\parallel}$ (except at the temperature where $H_{c2\perp}=H_1$) to obtain a baseline. The $H(T)$ phase diagrams for both the perpendicular and parallel field directions are shown in the insets of Figs. 3(a) and 3(b) for samples A and B, respectively. T_c oscillations with the same field period as that observed in the $R(H)$ curves can be clearly identified in the perpendicular field data. By multiplying $H_{c2\parallel}$ with a scaling factor of 0.55 (sample A) and 0.61 (sample B), respectively, the data (solid curves) transforms into a uniform baseline which forms an upper bound to the phase diagram of the perpendicular field direction. The remarkable overlay of the scaled $H_{c2\parallel}$ data on the $H_{c2\perp}$ line indicates that close to T_{co}, a film containing a hole array behaves like a wire network whose phase diagram follows that of a strip (or a thin film in parallel field) augmented with a hole-induced T_c suppression at noninteger flux quantum fields. This result also implies that we should use these scaling factors to derive the baselines for the $R(H)$ curves in the perpendicular field direction if the resistance dips originate *purely* from hole-induced T_c

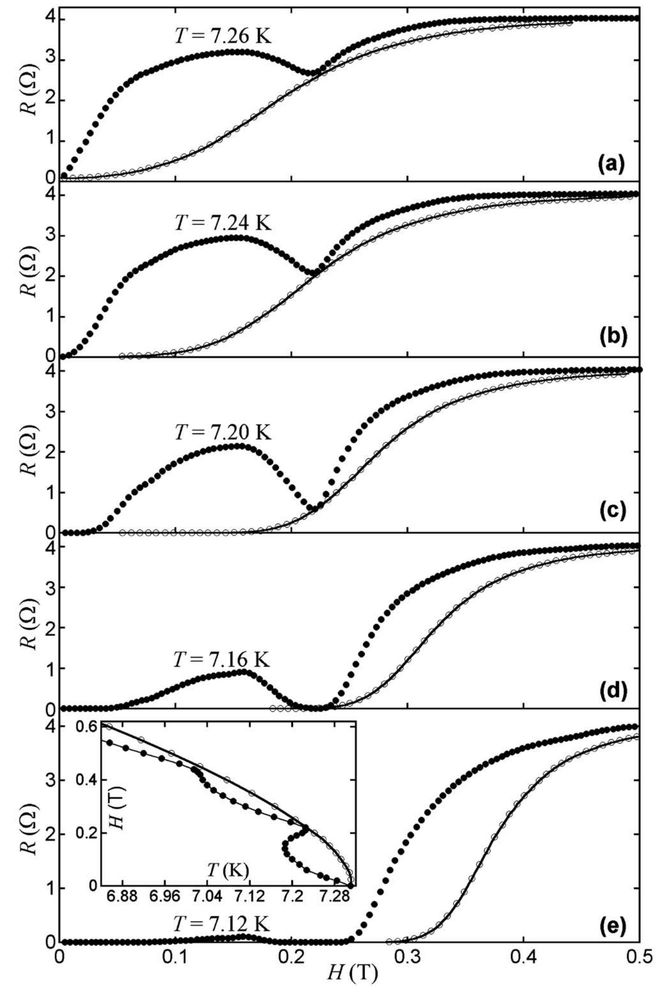

FIG. 4. $R(H)$ curves at various temperatures and $H(T)$ phase line [inset of (e)] for sample C. Both $R(H)$ and $H(T)$ curves obtained in parallel fields (open circles with solid lines) form the wire network baselines for those in perpendicular fields (solid circles) without additional scaling manipulation.

suppression at *noninteger flux quantum* fields. The solid curves in Figs. 3(a) and 3(b) represent the $R(H)$ curves obtained by multiplying the $H_{\parallel}$ of the $R(H)$ curves in parallel field direction with a factor of 0.55 and 0.61 for samples A and B, respectively. They coincide remarkably with the baselines hypothesized in the wire network scenario.

As discussed above, the critical field of a thin film in parallel fields and of a strip in perpendicular fields is inversely proportional to its thickness t (Ref. 23) and width w,[20] respectively. The width w of the "strip" for a wire network is the width of a superconducting section between two neighboring holes. For sample A, the width w is ~70 nm (please refer to the SEM image in Fig. 2). The calculated ratio (t/w) between the baselines (solid lines) of $H_{c2\perp}$ and $H_{c2\parallel}$ for sample A is ~0.86 which is larger than the experimental value of 0.55. This discrepancy can be caused by surface oxidation of the Nb film (usually a few nanometers), which reduces the actual thickness t of the film. It is also difficult to precisely determine the thickness of the film through imaging the cross section of Nb/AAO, where the charging effect from AAO blurs the boundary between Nb and AAO substrate. With increasing film thickness, however, the influence from both surface oxidation and the error in determining t decrease and the ratio determined by $R(H)$ scaling should approach the estimated value based on the measured thickness and hole diameter. This is indeed consistent with the experimental finding that the scaling factors approach the estimated t/w values in thick films. $R(H)$ data for a thick sample (sample C) are given Fig. 4 and a discussion is given below.

Sample C is about 100 nm thick and with a hole diameter of less than 10 nm. The estimated t/w ratio is less than 1.1. $R(H)$ curves obtained at various temperatures close to T_{co} (=7.310 K) in perpendicular and parallel fields are presented as solid circles and open circles with solid lines, respectively. The data are similar to those obtained for samples A and B where the dips in the $R(H)$ curves are observed in the perpendicular field direction. The most striking feature observed in this sample is that the measured $R(H)$ curves for the parallel field direction coincide with the values of $R(H)$ for the perpendicular fields at the *matching fields* [see Figs. 4(a)–4(d)] without additional scaling manipulation, i.e., with a scaling factor of 1. This scaling behavior is further confirmed by the $H(T)$ phase diagrams shown in the inset of Fig. 4(e). The "baseline" phase diagram obtained from the parallel field direction overlays nicely onto the data for $H_{c2\perp}(T)$, forming an upper bound which intersects the latter at the matching fields. Comparison of the $R(H)$ data to the schematic description in Fig. 1 demonstrates that the open circles with solid lines in Fig. 4 directly form the baselines for the $R(H)$ curves of a wire network in perpendicular fields. Thus we conclude that our Nb films containing arrays of holes behaves as superconducting wire networks where the baseline for the $R(H)$ curve in a perpendicular field can be obtained from the parallel field direction.

In conclusion, we developed an approach to determine the origin of the matching effect in superconducting Nb films containing periodic hole arrays where dips and peaks appear in the magnetic field dependence of the resistance and critical current. By comparing the field dependence of the resistance and the critical temperature in perpendicular and parallel directions, we found that in superconducting Nb films with triangular hole arrays the "matching effect" where the resistance exhibits a minima at an integer flux quanta matching field originates from hole-induced T_c suppression at noninteger flux quantum fields.

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