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Interstitial flux phases in a superconducting niobium film with a square lattice of artificial pinning centers

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We demonstrate that a square lattice of artificial pinning centers in a superconducting Nb film induces the formation of highly ordered interstitial vortex phases with different symmetries for external magnetic fields as high as the eighth matching field. These ''supermatching'' phases are identified by distinct differences in the behavior of their critical currents, magnetoresistivity, and magnetization. Our results are consistent with predictions of supermatching lattice symmetries by recent numerical simulations. [S0163-1829(99)51142-9]

It is well known that vortex-vortex interactions in the mixed state of a type II superconductor generally lead to the formation of a triangular flux-line lattice (FLL) that is distorted in the presence of random pinning. The introduction of a regular lattice of artificial pinning centers (APC's) into a superconducting thin film provides additional strong pinning interactions that induce prominent anomalies in the temperature and magnetic-field dependences of the magnetization, electrical resistance, and critical current I_c.[1–5] The anomalies are particularly pronounced at ''matching fields'' H_n, where the density of flux lines (FL's) coincides wit the density of the APC, and essentially all of the magnetic field inside the film resides in quantized fluxoids centered on the APC. However, there is a maximum number $n_s = D/4\xi(T)$ of flux quanta [where D is the APC characteristic size and $\xi(T)$ is a temperature-dependent coherence length] that can be trapped by the APC.[6] Further increases in the applied field above $H_n(n_s)$ lead to the formation of Abrikosov vortices within the interstices of the APC. Although these ''interstitial FL's'' (IFL's) are relatively mobile, it has been discovered recently that they can organize into stable, ''supermatching'' flux-line lattices (SL's).[7,8]

The SL symmetry in the presence of a square lattice of antidots (circular holes) was studied in numerical simulations by Reichhardt *et al.*[9] for the case $n_s = 1$. They predict that the interstitial FL undergoes a transition from a lattice of corner-sharing squares to one of triangular coordination when the number of interstitial vortices changes from 2 to 3. This transition was directly observed in a thin, perforated Nb foil by Lorentz microscopy.[7] The existence of these SL was also inferred, and their relative stability studied, in ac magnetization measurements of an amorphous $W_{0.67}Ge_{0.33}$ film with a square lattice of antidots at various ac drive levels and angular orientations of the film plane with respect to the applied dc field.[8]

However, up to now, the existence and symmetry of the SL for higher fields has remained uncertain. Calculations[9] show that for the fifth matching field (MF) the IFL again forms a square SL, and that low-symmetry SL states are formed at the sixth and seventh MF. A transition to a triangular SL at the eighth MF was also predicted. In this paper, we show that highly ordered SL at the fifth and eighth MF are clearly visible in magnetization and transport measurements on thin Nb film with a square antidot lattice, and that formation of low-symmetry SL at the sixth and seventh MF leads to a broad maximum in $I_c(H)$ which probably reflects a smooth transition between the SL for $n = 6$ and 7.

Vortex pinning by a lattice of APC competes with a background of the usual mechanisms of pinning, including thickness modulations, nonsuperconducting inclusions, grain boundaries, surface roughness, etc. In order to clearly observe matching phenomena, pinning by the APC should be stronger than other pinning interactions. This imposes strict requirements on the quality of sample films with APC. In order to dominate the pinning, the APC must have a size comparable to the superconducting coherence length $\xi(T) = \xi_0/(1 - T/T_c)^{1/2}$, which is estimated to be smaller than 100 nm for Nb at temperature relevant to this study. This small size scale restricts the techniques that can be used to fabricate such pinning centers. To date, electron-beam lithography has been used nearly exclusively to perform this task.[1–5] The main drawback of this technique is that it is expensive and too slow to pattern samples having convenient dimensions of order 0.1–1.0 mm. An effective, alternate method for producing large-area lattices of AP in superconducting thin films is based on the use of laser interferometric lithography (IL).[10–15] IL and photoresist liftoff were employed to produce a lattice of antidots of period $d = 1$ μm and diameter $D \approx 0.3$ μm imbedded in a 1000 Å Nb film deposited by magnetron sputtering on a patterned Si/SiO_2 substrate. Details of the patterning and thin-film preparation can be found elsewhere.[16] The film used in the present study had a relatively low superconducting transition temperature $T_c \approx 6.7$ K due to a residual oxygen pressure in the growth chamber.[17]

Transport measurements were accomplished by attaching Au wires directly to the Nb film using a silver epoxy and postbaking. ac susceptibility and transport measurements were performed using a Quantum Design MPMS superconducting quantum interference device (SQUID) magnetometer with the applied dc magnetic field oriented perpendicular to the film plane. We concentrated our measurements on the temperature interval near T_c where the depth (Bean) profile of the magnetic field in the sample is nearly flat.[2] In this case uncertainties concerning the penetration profile of the FL are essentially eliminated, and the observed sample behavior can be understood by considering only a few ''unit cells'' of the antidot lattice.

The critical current $I_c(H)$ was defined using a voltage criterion of 0.2 μV, and the results for the field dependence of $I_c(H)$ and $\rho(H)$ at various temperature are summarized in Fig. 1. Sharp anomalies in $I_c(H)$ and $\rho(H)$ are observed at applied fields equal to multiples of the MF, $H_m = nH_1$, where $H_1 = \Phi/d^2 \approx 20.7$ G, Φ_0 is the flux quantum and n is an integer.

It was shown earlier[2,18] that the number of observed MF varies with temperature, with more anomalies visible at lower *T*, which was attributed to the change in the maximum number $n_s = D/4\xi(T)$ of flux quanta trapped by a single antidot due to the strong temperature dependence of $\xi(T)$ close to T_c. Therefore, changes in the collective pinning interactions between the IFL, and the IFL and the fluxoid currents, with increases in the number of interstitial vortices were not considered in detail prior to the initial discovery of SL for $n > n_s$.[7,8] In contrast, in the temperature interval $\Delta T = T_c - T = 0.3$ K emphasized in our measurement, we estimate $n_s = 1$ ($D = 0.3$ μm, $T/T_c > 0.955$, and $\xi_0 \approx 160$ Å), which means that only a single Φ_0 can be trapped at each antidot. Therefore, all matching anomalies observed at applied dc fields above H_1 must be caused by the existence of relatively stable Si with different symmetries. Thermal fluctuations have less influence on the stability of SL at lower temperature, which explains why the number of well defined MF anomalies visible in Fig. 1 changes from 2 at $T = 6.68$ K $= 0.997 T_c$ to 8 at $T = 6.55$ K$= 0.978 T_c$. Moreover, there was an absence of the usual type of MF anomaly near H_6 and H_7, which was replaced by a broad anomaly in the magnetoresistance and transport critical current data for $T \leqslant 6.6$ K.

The above observations were confirmed using more sensitive measurements of complex ac magnetic susceptibility $\chi = \chi' + i\chi''$, taking care that the ac amplitude h_0 was sufficient to attain full penetration of the ac field to the sample center. The results in Fig. 2 show a broad anomaly in $\chi(H)$ for fields spanning $H_m = 6H_1$ and $7H_1$ (which cannot be separately resolved), followed by a weak anomaly at $H = H_m = 8H_1$. Taken together, the data of Figs. 1 and 2 provide strong evidence that the anomalies at $H > H_5$ reflect the intrinsic properties of the SL phases.

Numerical simulations have pointed out that dissipation

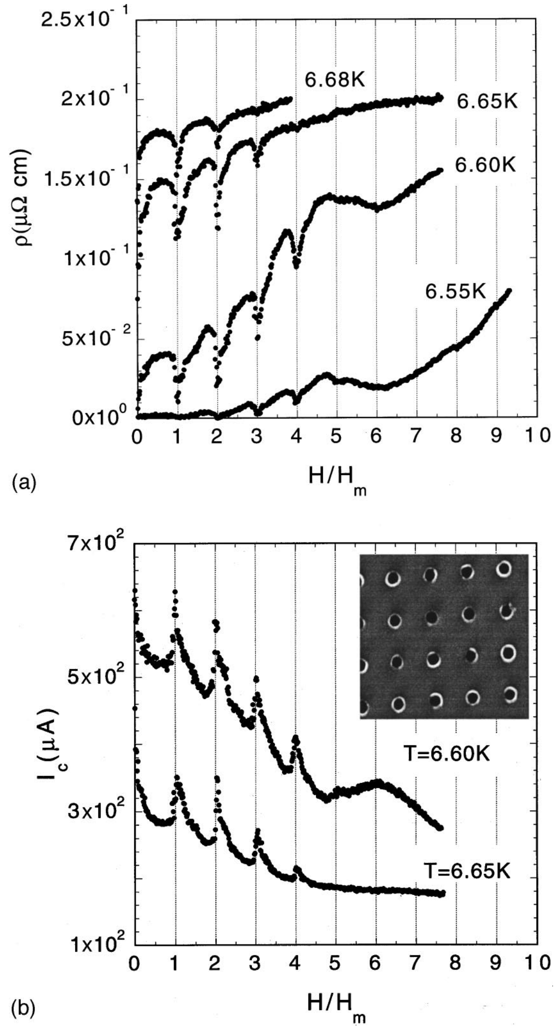

FIG. 1. (a) Magnetoresistivity (a) $\rho(H)$ vs applied dc magnetic field H for different temperatures and an applied ac current $I = 1067$ μA driven at a frequency of 23 Hz. (b) The critical current $I_c(H)$ vs H corresponding to the data of (a). Inset: SEM image of a square lattice of antidots for the sample Nb film.

by IFL is mainly due to the motion of IFL chains along the ⟨100⟩ or ⟨010⟩ directions of the antidot lattice.[9] The chart of possible IFL given in Fig. 3 indicates that for $H_5 \leqslant H \leqslant H_7$ ther are no long, straight chains of IFL which could ''slip'' along the ⟨100⟩ or ⟨010⟩ directions. This effectively places a restriction on IFL motion that would explain the suppression of dissipation which is reflected in the minima in $\rho(H)$ [Fig. 1(a)], the enhancement of the critical current $I_c(H)$ [Fig. 1(b)], and the corresponding anomalies clearly visible in $\chi(H)$ (Fig. 2) for $H_5 \leqslant H \leqslant H_7$.

The nonmonotonic dependence of $I_c(H_m)$ leads us to the conclusion that at lower-symmetry SL may yield a relatively high critical current, possibly through the suppression of mobile FL chains. The reemergence of relatively strong pinning at H_8 corresponds to the transition of the IFL to a more ideal hexagonal coordination of the IFL about the antidot sites. These data are in good qualitative agreement with numerical simulations[9] that produce matching anomalies to the second and fifth MF (corresponding to a square coordination of the IFL about the antidot sites), and the fourth and eighth MF (corresponding to roughly hexagonal coordination of the IFL

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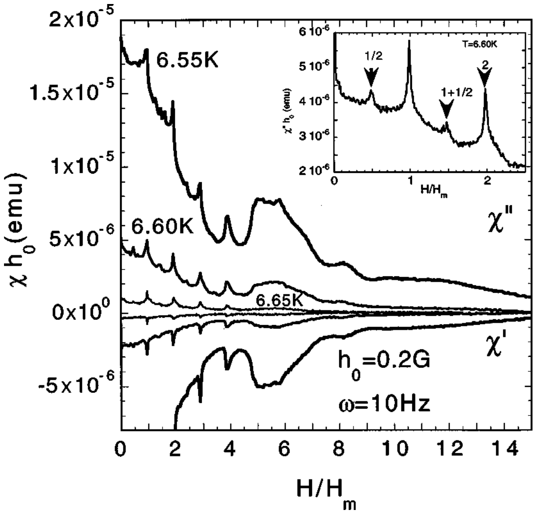

FIG. 2. Field dependences of the real (χ') and imaginary (χ'') parts of the ac magnetic susceptibility χ times the ac drive amplitude h_0 for a Nb film containing a square lattice of antidots at different temperatures T, $h_0=0.2$ G, and measuring frequency $\omega=10$ Hz. The inset: Fractional matching peaks in χ'' at $T=6.60$ K.

about the antidot site). These stable SL configurations can be realized only in the case of strong vortex-vortex interactions extending over a few intervortex separations. Indeed, it was shown that at relatively high temperatures close to T_c the effective thin-film penetration depth Λ is much higher than intervortex separation d, and one can expect collective vortex behavior.[2,3,8] The presence of long-range vortex-vortex interactions is also supported by our observation of fractional matching field ($H_{1/2}$, $H_{3/2}$, etc) for $H<H_3$ in the ac susceptibility data of Fig. 2. These MF indicate the expected existence of superstructures or lattices derived from vacancy ordering in the IFL when the vortex-vortex interactions extend beyond the antidot separation.[2,7,19]

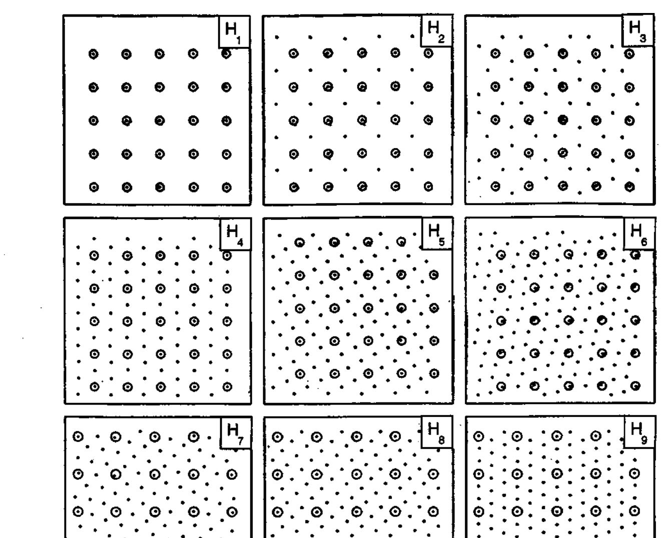

FIG. 3. Supermatching flux-line lattices SL for a square lattice of antidots, as predicted in the numerical simulations of Ref. 9.

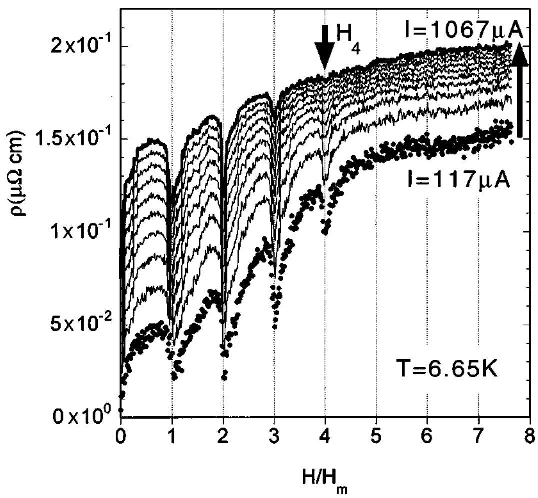

FIG. 4. Magnetoresistivity $\rho(H)$ vs applied dc magnetic field H at temperature $T=6.65$ K for different transport currents $I=117$, 223, 330, 435, 540, 645, 752, 856, 963, and 1067 μA, driven at a frequency of 23 Hz. The arrow indicates the direction of the transport current.

The $\rho(H)$ data for different transport currents and $T=6.65$ K are shown in Fig. 4, which demonstrates that the number of resolved MF in the electrical transport data is also dependent upon applied current. This is again consistent with simulation results[9] (see Fig. 3), which show that IFL tend to move in chains along linear channels perpendicular to the applied current, since an increase in current along the ⟨100⟩ direction induces an increase in the Lorentz force acting on the IFL along the ⟨010⟩ direction. This leads one to expect relatively high dissipation near $H=H_4$, where the SL consists of nearly straight lines along the ⟨010⟩ and ⟨100⟩ directions, in contrast to the case for $H=H_3$, where relatively low-density chains are broken into short segments consisting of two IFL.

In conclusion, we have demonstrated that relatively stable supermatching vortex lattice phases comprised of two different type of fluxoids—those strongly trapped at APC sites and Abrikosov vortices weakly pinned within the interstices of the APC lattice—can exist in patterned superconducting thin film in fields up to $8H_m$, much higher than the first matching field. We present evidence that rather subtle changes in the SL symmetry are responsible for the unexpected loss of distinct MF anomalies observed in our measurements. Even with a relatively simple square APC lattice, the commensurate IFL are surprisingly complex and varied. Our results show that this complexity has dramatic influence on the dynamics of the IFL, inducing large changes in the depinning threshold and in the dissipation of the moving vortices. The close connection between complexity and dynamics makes superconductors with APC lattices an attractive system for studying dynamic behavior. The complexity can be controlled easily with the applied field and the symmetry of the APC, and the depinning dynamics should be sensitive not only to the matching field but also to the Lorentz force direction. One may find, for example, a periodic variation in the critical current with angle as the Lorentz force sweeps through easy and hard depinning directions. As we have shown, the matching field behavior as seen in transport and ac susceptibility point to an unexpectedly rich spectrum of static and dynamic behavior in superconductors with periodic artificial pinning centers.

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