Suppression of dissipation in Nb thin films with triangular antidot arrays by random removal of pinning sites

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The depinning current \( I_c \) versus applied magnetic field \( B \) close to the transition temperature \( T_c \) of Nb thin films with randomly diluted triangular arrays of antidots is investigated. Our experiments confirm essential features in \( I_c(B) \) as predicted by Reichhardt and Olson Reichhardt [Phys. Rev. B 76, 094512 (2007)]. We show that, by introducing disorder into periodic pinning arrays, \( I_c \) can be enhanced. In particular, for arrays with fixed density \( n_p \) of antidots, an increase in dilution \( P_d \) induces an increase in \( I_c \) and decrease of the flux-flow voltage for \( B > B_p = n_p\Phi_0 \).

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The investigation of vortices in type-II superconductors in the presence of tailored pinning potential landscapes has attracted a lot of theoretical and experimental interest. On the one hand, vortices in superconductors may act as a model system in order to investigate general properties such as the dynamics and phase transitions in systems of interacting particles (e.g., colloidal suspensions [1, 2], Wigner crystals [3], charge density waves [4] or various types of ratchets and Brownian motors [5, 6, 7]). On the other hand, the ability to manipulate and control the static and dynamic properties of vortices is fundamental for superconducting device applications [8].

Modern lithography techniques allow the placement of artificial pinning sites into superconducting thin films with well-defined size, geometry and spatial arrangement. In case of periodic arrangements, enhanced vortex pinning was found for magnetic fields, at which the vortex lattice is commensurate with the pinning array [3, 10, 11, 12, 13, 14]. The enhanced pinning leads, e.g., to peaks in the critical depinning current \( I_c \) at multiples of a so-called first matching field \( B_p = n_p\Phi_0 \); here the density of vortices carrying one flux quantum \( \Phi_0 = \hbar/2e \) equals the density of pinning sites \( n_p \). However, at non-matching fields the vortex lattice is less pinned due to elastic deformations and formation of interstitial vortices. Hence, the question arises whether other arrangements – between the two extremes of periodic and random pinning arrangements – may lead to an enhanced vortex pinning over a broader range of applied magnetic field \( B \).

Recently, it has been shown by numerical simulations [15, 16] and experimentally [17, 18, 19] that a quasiperiodic arrangement of pinning sites produces additional commensurability effects and hence an enhanced pinning below the first matching field. A different proposal was made very recently by Reichhardt and Olson Reichhardt [20]. By molecular dynamics simulations they investigated periodic pinning arrays that have been diluted, by randomly removing the fraction \( P_d \) of pins, while keeping the pin density \( n_p \) fixed. Such arrays are very interesting, since with increasing dilution the pinning potential undergoes a gradual transition from periodic to purely random. Therefore, this model is suitable to explore the intermediate region between order and disorder, as it is usually found in real world. Interestingly, the simulations showed that the introduction of some disorder leads to an enhanced critical current above the first matching field. In periodic pinning arrays the vortices sitting at the pinning sites form easy flow channels for interstitial vortices [21], while for randomly diluted pinning arrays channeling should be suppressed [20]. This approach is also interesting from a general point of view, as the presence of disorder in competition with periodic potentials is also investigated in many other physical systems, e.g., two-dimensional conductors [22], Ising ferromagnets [23], and Josephson Junction arrays [24, 25]. For related recent work on vortex phases see [20].

In this work, we present results on the experimental investigation of vortex pinning and flow in superconducting Nb thin films containing randomly diluted triangular arrays of submicron holes (antidots) as pinning sites. We studied \( I_c(B) \) at variable temperature \( T \) close to the superconducting transition temperature \( T_c \), and we compare pinning arrays with different dilution, considering two different scenarios: (i) "Scaled lattices": For different values of \( P_d \), we fix the density \( n_p \) of pinning sites. Accordingly, the lattice parameter (smallest separation between pinning sites) scales as \( a(P_d) = a(0)\sqrt{1 - P_d} \). In this scenario a controlled transition from periodic to random arrangement of antidots is investigated. (ii) "Fixed lattices": Here, we fix the lattice parameter \( a \) for different values of \( P_d \). Accordingly, the density of pinning sites scales as \( n_p(P_d) = (1 - P_d)n_p(0) \). Here, with increasing \( P_d \) a transition to plain films (no antidots) is treated.

Our experimental results confirm essential features as
predicted in [20]: The fixed and scaled lattices show two different kind of matching effects, which differently depend on temperature. Furthermore, the scaled lattices show an enhancement of $I_c$ at magnetic fields above $B_p$ with increasing dilution $P_d$. This effect is caused by suppression of vortex channeling and can be also observed in the dynamic regime, i.e. by measuring current-voltage $(IV)$ characteristics.

The experiments were carried out on $d = 60 \text{ nm}$ thick Nb films which were deposited by dc magnetron sputtering in the same run on four separate Si substrates with $1 \mu\text{m}$ thick SiO$_2$ on top. Patterning was performed by e-beam lithography and lift-off to produce Nb bridges of width $W = 200 \mu\text{m}$ and length $L = 640 \mu\text{m}$. The bridges contain circular antidots (diameter $D = 260 \ldots 550 \mu\text{m}$), arranged in a triangular lattice that has been randomly diluted, with dilutions $P_d = 0$ ("undiluted array"), 0.2, 0.4, 0.6, 0.8, and 1 ("plain" film, without antidots). Each chip (#1 to #4) contains two or three sets (A, B, C) of bridges. Each set has six bridges with different values for $P_d = 0 \ldots 1$. The antidot diameter $D$ is kept constant within each set and varies from set to set. The chips #1 and #2 contain sets of bridges with fixed lattice parameter $a = 1.5 \mu\text{m}$. i. e. the density of vertices of the corresponding triangular lattice is $n_t = \frac{\sqrt{3}}{2} \frac{a}{D} \approx 0.5 \mu\text{m}^{-2}$, which corresponds the "lattice matching field" $B_l \equiv n_t \Phi_0 = 1.1 \mu\text{T}$ (denoted as $B_0$ in [20]). For those two chips, the antidot density $n_p$ decreases from 0.5 to $0.1 \mu\text{m}^{-2}$ with increasing $P_d$ from 0 to 0.8. The chips #3 and #4 contain sets of bridges with scaled lattice parameters $a(P_d) = 3.4 \mu\text{m}$ for $P_d = 0$ to $P_d = 0.8$, respectively, in order to have a fixed antidot density $n_p = 0.1 \mu\text{m}^{-2}$ and "pin density" matching field $B_p = 0.21 \mu\text{T}$ (denoted as $B_0$ in [20]), with $N_p \approx 12,500$ antidots in each bridge. Below we present results obtained on bridges from sets #1-B ($D = 300 \mu\text{m}$), #3-B ($D = 450 \mu\text{m}$), #4-B ($D = 360 \mu\text{m}$) and #4-A ($D = 260 \mu\text{m}$).

To characterize our devices, we first measured resistance $R$ vs. $T$ at $B = 0$ and determined $T_c$ and normal resistance $R_n \equiv R(T = 10 \text{ K})$ (with bias current $I = 2 \mu\text{A}$) of the different bridges on each chip. Due to the strong influence of the reduced temperature $t \equiv T/T_c$ (for $T$ close to $T_c$) on the characteristic length scales, i.e. the London penetration depth $\lambda(t)$ and coherence length $\xi(t)$, and on $I_c(t)$, the determination of $T_c$ plays an important role for the comparison and interpretation of the performance of pinning arrays with different $P_d$. We defined $T_c$ by linear extrapolation of the $R(T)$ curves in the transition region to $R = 0$, i. e. $T_c$ marks the onset of resistance. For all samples we find $T_c \approx 8.5 \text{ K}$ with a variation of a few mK within each set of bridges, and $R_n = 5.0 \Omega$ to $5.8 \Omega$, depending on $n_p$ and $D$. Within the sets ($D = \text{const}$) with $n_p = \text{const}$ (scaled lattices), $R_n$ varies by less than $\pm 2\%$ from bridge to bridge. The plain film (from set #4-A) has $R_n = 5.0 \Omega$, which yields a normal resistivity $\rho_n = R_n dW/L = 0.4 \mu\Omega\text{cm}$. With the relation $\rho \ell = 3.72 \times 10^{-6} \mu\Omega\text{cm}^2$ it was estimated for the mean free path $\ell = 4.0 \text{ nm}$. All $I_c$ values were determined with a voltage criterion $V_c = 1 \mu\text{V}$.

Fig. 1 shows $I_c(B/B_p)$ patterns of four randomly diluted bridges with similar antidot size at various temperatures $t = T/T_c = 0.9995 \ldots 0.9965$. $I_c$ was normalized to its maximum value at $B = 0$. Two bridges (from set #4-A) have the same antidot density $n_p = 0.1 \mu\text{m}^{-2}$ and dilution $P_d = 0.2$ (a) and $P_d = 0.4$ (c). The two other bridges (from set #1-B) have larger antidot density $n_p = 0.4 \mu\text{m}^{-2}$ with $P_d = 0.2$ (b) and $n_p = 0.3 \mu\text{m}^{-2}$ with $P_d = 0.4$ (d).

For the highest $t = 0.9995$, a clear peak in $I_c(B)$ indicates matching of the vortex lattice with the pinning array, as shown in Fig. (1b). The position of the peak is located between $B_p$ and $B_c$. This indicates that indeed "pin density matching" is observed; however, as pointed out in [20], for a diluted periodic pinning array at $B = B_p$ the vortex configuration contains numerous topological defects. Hence, commensurability effects at $B_p$ can only be observed when pinning is so strong, that the lattice distortion energy, associated with the deviation from an ideal triangular vortex lattice, can be overcome. This is most likely to be observed for the samples with higher density of pinning sites. Accordingly, for a given $P_d$, the matching peak is more pronounced in the samples with three and four times larger $n_p$.

With decreasing $n_p$ and $t$ and with increasing $P_d$ the peak in $I_c(B)$ gradually transforms into a shoulder-like structure, located close to $B_p$. Following the evolution of $I_c(B)$ with decreasing temperature shows that $I_c(B < B_p)/I_c(0)$ increases most whereas $I_c(B_p)/I_c(0)$ is almost independent of $t$. For the larger $P_d = 0.4$, this leads gradually to a transformation of the shoulder-like
structure into a triangular-shaped $I_c(B)$ pattern without any indication of matching effects, either at $B_1$ or $B_l$. Nevertheless, $I_c$ for $P_d = 0.4$ is still significantly enhanced over $I_c$ for samples without antidots, as will be shown below.

In the following, we directly compare pinning arrays with different dilution $P_d$ at the same reduced temperature. Fig. 2 shows $I_c(B)$ patterns of samples with fixed lattice parameter $a = 1.5 \mu m$ ($n_l = 0.5 \mu m^{-2}$) at $t = 0.9990$ (a) and $t = 0.9965$ (b). The $B$-axis is normalized to the lattice matching field $B_l$, which is the same for all perforated bridges within this set. The sample with $P_d = 0$ shows pronounced peaks in $I_c(B)$ which are located at $\pm B_1$ and $\pm 2B_1$, indicating a saturation number $n_s \geq 2$ [28,29] for both temperatures. In the samples with small dilution ($P_d = 0.2$ and 0.4) we also find peaks in $I_c(B)$ for the higher temperature shown in Fig.2(a). The matching peaks are significantly broader than the matching peaks of the undiluted bridge, and they are located at magnetic fields between $B_1$ and $2B_1$. This is also visible in Fig. 2(b) and (d). With increasing $P_d$ we find a gradual transition of the $I_c(B)$ patterns at $B < B_1$ from the undiluted array ($P_d = 0$) to the plain film ($P_d = 1$). Interestingly, for $t = 0.9990$ [c.f. Fig. 2(a)] the diluted sample with $P_d = 0.2$ shows a higher $I_c$ than the undiluted sample ($P_d = 0$) for $B < B_1$, and very similar $I_c$ values for all other fields, except for the matching fields $B_1$ and $2B_1$.

Fig. 3 shows $I_c(B/B_p)$ patterns of bridges with different $P_d = 0 \ldots 1$ at $t = 0.9990$ (a) and $t = 0.9945$ (b). In Fig.3(a) the data from set #4-A ($D = 260 \text{ nm}$) are complemented by results from two undiluted bridges with $D = 360 \text{ nm}$ (#4-B) and $D = 450 \text{ nm}$ (#3-B), in order to demonstrate the effect of antidot size. All bridges with $P_d = 0$ and different $D$ show qualitatively the same $I_c(B)$ patterns. The major difference is a slight increase in $I_c$ at $B < B_p$ with increasing $D$. This dependence can be explained with the increase of the pinning strength of the antidots with increasing $D$. For $B < B_p$, each vortex can be captured by an antidot, and hence the increasing pinning strength with $D$ leads to an increase of $I_c$. In contrast, for $B > B_p$, vortices occupy interstitial pinning sites where they are weakly pinned. Hence, $I_c$ is drastically reduced and determined by the motion of interstitial vortices, which should not depend on the antidot size. This is exactly what we find experimentally, i.e. $I_c(B > B_p)$ is independent of $D$ for the samples with $P_d = 0$.

With increasing $P_d$ (decreasing $a$ in order to keep the antidot density $n_p$ constant) the shape of the $L_c(B/B_p)$ patterns is strongly affected. The diluted arrays show ”lattice matching” effects around $B_l$. It is interesting to note that with decreasing $t$ the matching effects become less pronounced, and the $I_c(B)$ pattern approaches more and more a triangular shape. This shape is reminiscent of the $L_c(B)$ pattern of randomly arranged antidots [18]. This can be understood, as with increasing $P_d$ and fixed $n_p$, the antidot arrangement approaches that of a random arrangement.

For $P_d = 0$ from set #4-A we have no data for the full range of $t$, as the bridge was damaged after taking first data. Hence, to facilitate the comparison of different $P_d$ at $t = 0.9945$ [Fig. 3(b)], we also show data from another bridge with $P_d = 0$ (from set #4-B). For both temperatures ($t = 0.9990$ and $t = 0.9945$) we find a decrease in $I_c$ with increasing $P_d$ for $B < B_p$. However, for $B > B_p$ the diluted arrays show an enhanced $I_c$ as compared to the undiluted sample(s). Both observations are in qualitative agreement with the simulations in Ref. [20]. We do find that the enhancement of $I_c$ above $B_p$ persists up to the highest dilution $P_d = 0.8$. This enhancement was explained in [20] with the suppression of channeling of interstitial vortices for fields in the range $B_1 < B < B_p$. For undiluted arrays, this channeling effect causes the rapid decrease of $I_c$ with increasing $B$ slightly above $B_p$ [c.f. Fig. 3]. Our experimental data clearly confirm that this rapid drop in $I_c$ at $B_p$ is absent for the diluted arrays.

The suppression of channeling should also be visible in the current-voltage-characteristics. Fig. 4 shows the...
Fig. 4 clearly shows that with increasing pronounced slope change at \( I \) shows magnification of \( \rho = 0.1 \mu m \) and matching field \( B_m \). Upper inset shows magnification of \( V \) vs \( I \) for \( P_d = 0 \) with the critical depinning current \( I_{c,1}(B_c) \) of interstitial (pinned) vortices. Lower inset shows magnification of \( V \) vs \( I \) at small voltages; \( V(I \geq 1 \text{ mA}) \) decreases with increasing \( P_d \), except for the plain film \( (P_d = 1) \) with lowest \( I_c \).

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V(I)\text{-curves of differently diluted samples at } B = 2B_p \text{ and } t = 0.9945. \text{ The } V(I)\text{-curves directly correspond to the } I_c(B) \text{ pattern shown in Fig.4(b). For the undiluted bridge at } B = 2B_p \text{ one expects the same number of vortices sitting in the antidots and at interstitial positions. In this case we find two critical depinning currents } I_{c,1}, I_{c,2} \text{ in the } V(I)\text{-curves [c.f. upper left inset of Fig.4]. } I_{c,1} \text{ corresponds to the current above which a finite voltage appears. This voltage is caused by the motion of weakly pinned interstitials. At a higher current } I = I_{c,2} \text{ the slope of the } IV\text{-curve changes. This is due to the depinning of vortices sitting in the antidots. The value of } I_{c,2} \text{ can also be found in the } I_c(B) \text{ pattern shown in Fig.4(b). } I_{c,2} \text{ fits quite well to the critical current at the first matching field } I_c(B_p). \text{ All diluted samples } (P_d = 0.2 \ldots 0.8) \text{ have a similar } I_{c,1} \text{ but do not show a pronounced slope change at } I_{c,2}. \text{ The lower right inset in Fig.5 clearly shows that with increasing } P_d \text{ the voltage due to flux motion decreases. I. e., in the diluted pinning arrays dissipation is reduced, due to the more effective suppression of vortex channeling.}

In conclusion, we experimentally investigated Nb thin films with triangular arrays of antidots, which have been randomly diluted, by measurements of the critical current \( I_c \) vs. applied magnetic field \( B \) and current-voltage \( (IV) \) characteristics close to the transition temperature \( T_c \). The antidot lattices could be tuned to find two different matching effects, related to the antidot density and to the lattice parameter of the antidot lattice, as predicted in \[20\]. For samples with fixed lattice constant, with increasing dilution \( P_d \) a gradual transition from a periodic pinning array to a plain film without pinning sites has been observed. Obviously, with increasing \( P_d \) the critical current decreases. However, very close to \( T_c \), for small dilutions \( (P_d = 0.2) \) we do find a broad peak in \( I_c(B) \) located between \( B_p \) and \( B_l \), corresponding to an increase in \( I_c \) by removing 20% of the pinning sites. We speculate that this counterintuitive effect is due to the introduction of disorder; an understanding of this effect is still lacking, and deserves further investigations. On the other hand, for samples with fixed antidot density, an increasing dilution corresponds to a gradual transition from a periodic to purely random distribution of pinning sites. Our experiments clearly show an enhancement of \( I_c \) for magnetic fields above \( B_p \) with increasing \( P_d \). This was the main prediction in Ref. \[21\] and can be explained with the suppression of channeling of interstitial vortices. This effect is also observed in \( IV\)-measurements, i.e., the suppression of channeling causes an increasing reduction in the flux-flow voltage with increasing \( P_d \). As a consequence, the concept of introducing disorder by randomly removing pinning sites in tailored periodic pinning arrays seems to provide a feasible way for enhancing the critical current in superconductors for magnetic fields above the matching field \( B_p \).

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