3D-2D-like vortex transition above B_{c2} in niobium films

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Abstract

Isotropic superconducting Nb-films thicker than the penetration depth exhibit a magnetically anisotropic structure within the magnetic field range $B_{c2} \leq B_a \leq B_{c3}$, where B_a is the applied field, and B_{c2} and B_{c3} are the upper and surface superconductivity critical fields, respectively. The anisotropic structure of the films consists of three layers: two superconducting surface layers and normal layer in between. Upon tilting the field with respect to the film surface, we have found that surface vortices undergo a 3D-2D-like dimensional crossover. Vortices residing on each of both film surfaces are coupled at fields almost parallel to the surface (3D), and decoupled at larger angles (2D) within the surface superconductivity state.

Key words: Surface superconductivity; vortices; dimensional crossover

The existence of vortices in the surface superconductivity (SSC) state within $B_{c2} \leq B_a \leq B_{c3}$ was found in Nb thin samples at applied magnetic field B_a orientations within the angular range $|\theta| \leq 30^\circ$ [1,2], where θ is the angle between B_a and main film surfaces, B_{c2} is the second critical field, and B_{c3} is the SSC critical field. It was further proven [1,3] that in this angular range there are *two co-existing flux-line lattices* (FLLs): one perpendicular and the other parallel to the main film surface. There is indirect evidence [4] that the parallel FLL in films having thickness $d_p > 2\lambda(T)$ (λ is the magnetic field penetration depth) transforms into a giant vortex above B_{c2}; whereas the perpendicular FLL forms two, preferably decoupled (i.e., independent) arrays of surface vortices [5] on each of the main film surfaces. Surface vortices reside in the superconducting surface sheath [6]. In this work we provide experimental evidence for a 3D-2D-like crossover [7] experienced by surface vortices in the SSC state.

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Two Nb-films [4] of thickness $d_p \simeq 400$ (Nb400) and 1200 nm (Nb1200) larger than $2\lambda \simeq 120$ nm [1,4] were investigated by employing the vibrating reed technique [1,2] at different B_a and T. The orientation of the field with respect to the main film surface was defined with an accuracy of $\pm 0.01^\circ$ [1,3,4].

In Fig.1 we show the measured resonance frequency change $\omega^2(B_a) - \omega^2(0)$ due to pinning of vortices (a) along with its first derivative (c), as well as the damping $\Gamma(B_a)$ due to dissipation produced by vortex movement (b) together with its onset definition (d) for the Nb400-film. Hereafter, we will mainly refer to the Nb400-film unless otherwise specified. The key-point in this figure is the appearance of a singularity at $B_{\rm sing}$ for $\theta \geq \theta_{dc} \simeq 0.45^\circ$ in (c). $B_{\rm sing}(\theta)$ for both measured films is shown in Fig. 2. $B_{\rm sing}$ appears within the angular range $\theta_{dc} \leq \theta < 20^\circ$. This behavior can be explained as *decoupling of surface vortices* (see inset in Fig. 2), undergoing a transition from 3-dimensional (3D) at $B_a < B_{\rm sing}$ to 2-dimensional (2D) FLL behavior at $B_a > B_{\rm sing}$.

Indeed, above B_{c2} measured at $\theta \to 90^\circ$ (shown by the dashed line in Fig. 1), the films consist of three magnetically different layers: two SSC sheaths sepa-

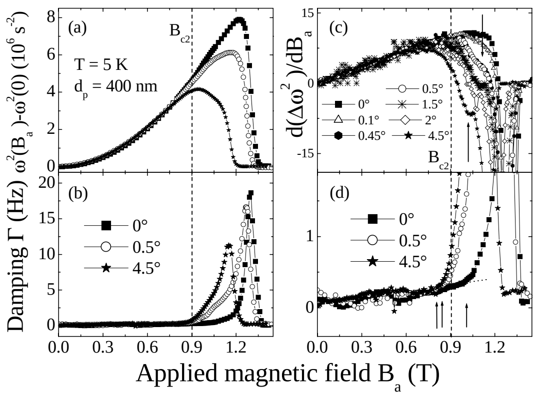

Fig. 1. The resonant frequency enhancement (a) and the corresponding damping (b) as a function of B_a for the Nb400-film. The first derivative $d(\Delta\omega^2)/dB_a$ in (c) shows the appearance of the singularity $B_{\rm sing}(\theta)$ marked by arrows. In (d) the enlarged low field damping is shown for $B_{\rm onset}(\theta)$ definition marked by arrows. The dashed lines in all figures denote B_{c2}.

rated by a normal layer. This magnetically anisotropic environment creates suitable conditions for the dimensional crossover of the perpendicular FLL. At $\theta > \theta_{dc}$ the perpendicular component of the applied field ($B_{a\perp} = B_a \sin\theta$) turns out to be larger than the 3D-2D crossover field $B_{cr} = \Phi_0/(d_p^2\gamma)$ [7], where Φ_0 is the flux quantum and $\gamma = B_{c3}/B_{c2}$. Therefore, a feature associated with a change of pinning at the decoupling is expected. For the Nb400-film the first singularity occurs at $\theta_{dc} \simeq 0.45°$ and $B_{\rm sing} \simeq 1.1\ T$, giving $B_{a\perp} \simeq$ 8.6 mT which is close to $B_{cr} = 8.4$ mT calculated with $\gamma = 1.55$ [4]. A similar agreement between experimental data and the 3D-2D theory is found for the Nb1200-film [4].

At $\theta < \theta_{dc}$ the vortices are coupled showing 3D-like behavior up to B_{c3}, and start moving only in fields significantly higher than B_{c2}. Therefore, neither vortex pinning ($\Delta\omega^2(B_a)$) nor energy dissipation due to vortex movement ($\Gamma(B_a)$) change their behavior up to the vicinity of B_{c3}, above which the superconductivity vanishes. As a consequence, the measured magnetic response of vortices behaves as if there were no transition at B_{c2}. If $\theta > \theta_{dc}$ the surface vortices decouple at $B_{\rm sing}(\theta)$. At fields below the decoupling pinning weakens. As soon as two 2D FLLs form, the weakening slows down producing the singularity in the first derivative of the resonant frequency change. Considerably vortex movement starts when pinning weakens, hence the onset of energy dissipation is correspondingly measured at lower fields.

One would expect $B_{\rm sing} = B_{c2}$, but this is not the case since the decoupling is angular dependent as follows. At $B_{a\perp} < B_{cr}$ the decoupling does not take place; as θ becomes larger $B_{a\perp}$ increases, more perpendicular vortices are created and the decoupling takes place at $B_{a\perp} \simeq B_{cr}$. The larger $B_{a\perp}$, the closer $B_{\rm sing}$ approaches to B_{c2}. $B_{\rm sing}$ behavior at $B_a < B_{c2}$ will be discussed elsewhere. Here we just note that the singularity occurs in the angular range where SSC exists.

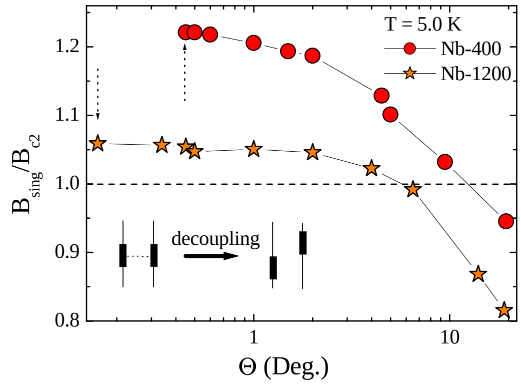

Fig. 2. Normalized singularity occurrence as a function of angle. The dotted arrows mark θ_{dc}. In the inset the decoupling of the aligned surface vortices is schematically shown.

We have shown that vortices exist within $B_{c2} \leq B_a \leq B_{c3}$, and that they can undergo a dimensional crossover. 3D FLL behavior corresponds to coupled surface vortices through the normal layer. 2D behavior implies two 2D decoupled FLL arrays existing in the SSC sheaths on both film surfaces.

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