A critical-current jump triggered by vortex-lattice screw dislocations

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Abstract

The energy of vortex-lattice screw dislocations was computed numerically by basing upon the isotropic London approximation. Appling the computation results to the Larkin-Ovchinnikov pinning theory leads to a prediction that a vortex lattice possesses high-density screw dislocations stably for sufficiently strong pinning. In a superconducting film, penetration of the high-density screw dislocations results in a discontinuous jump of the critical current.

Key words: flux pinning; flux-line lattice; critical currents

1. Introduction

Wördenweber and Kes [1] have discovered the vortex-lattice (VL) pinning dimensional crossover accompanying a critical-current jump in $\mathrm{Nb}_x\mathrm{Ge}$ ($x \simeq 3$) films. In those samples, although two-dimensional (2-D) pinning agrees well with the Larkin-Ovchinnikov [2] (LO) theory, three-dimensional (3-D) pinning deviates far from the LO theory.

This disparity is probably because the observed crossover arises from plastic vortex-line bending, viz., VL-screw-dislocation penetration [1]; the LO theory premises elastic bending. Although pinning theory for dislocation-rich VL has been proposed by Mullock and Evetts [3], who modified the LO theory, the modified theory cannot avoid yet the disparity. I believe this attributable to deficient evaluation of the nonlocal effect in VL tilt elasticity.

Taking account of the nonlocal effect, I have computed the VL-screw-dislocation energy numerically within a framework of the isotropic London approximation. I report here the results of that computation, and predict a critical-current jump triggered by VL screw dislocations from those results. This prediction is compared with the observation in $\mathrm{Nb}_x\mathrm{Ge}$.

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2. Computation results

Suppose that VL screw-dislocation lines are spaced D_{SD} apart into a domain wall perpendicular to the flux density $\mathbf{B}$: the Burgers vectors of two adjacent slip planes are antiparallel. Then the screw-dislocation line energy density E_{SD} can be expressed as [4,5]

$$E_{\mathrm{SD}} = E_{\mathrm{SD}}^{(0)}(D_{\mathrm{SD}}) + \frac{\alpha_{\mathrm{SD}}(D_{\mathrm{SD}})}{L_{\mathrm{SD}}}, \tag{1}$$

where L_{SD} is the mean distance between the domain walls.

Figure 1 shows the results of numerical computation of $E_{\mathrm{SD}}^{(0)}/D_{\mathrm{SD}}$ and $\alpha_{\mathrm{SD}}/D_{\mathrm{SD}}$ for Ginzburg-Landau parameter $\kappa = 100$. The VL constant a_0 is set equal to $5\lambda/\kappa$. As demonstrated in this figure, $E_{\mathrm{SD}}/D_{\mathrm{SD}}$ has the minimum at $D_{\mathrm{SD}} \simeq a_0$ for sufficiently short L_{SD}.

3. Theoretical prediction

According to the Mullock-Evetts [3] argument, the volume energy density of a screw-dislocation-rich pinned VL is given by [4]

$$U = \frac{1}{2} c_{66} \left(\frac{a_0}{2R_{\mathrm{c}}}\right)^2 + \frac{E_{\mathrm{SD}}}{D_{\mathrm{SD}} L_{\mathrm{SD}}} - \frac{a_0}{2} F_{\mathrm{p}}, \tag{2}$$

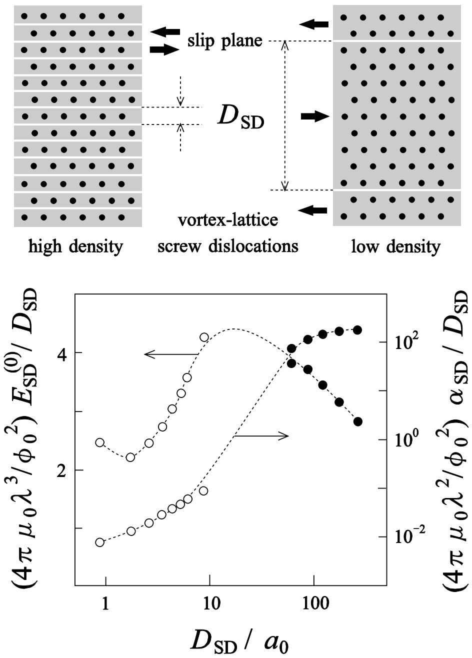

Fig. 1. VL-screw-dislocation line energy density $E_{\rm SD}$ per slip-plane spacing $D_{\rm SD}$; $E_{\rm SD}^{(0)}/D_{\rm SD}$ and $\alpha_{\rm SD}/D_{\rm SD}$ are scaled by each unit including the London length λ and the flux quantum ϕ_0. The open circles represent high-density ($D_{\rm SD}\sim a_0$) approximation [4], and the solid circles represent low-density ($D_{\rm SD}\gg a_0$) approximation [5].

where c_{66} is the VL shear modulus, $R_{\rm c}$ is the transverse short-range-order length of the VL, and $F_{\rm p}$ is the volume pinning-force density. When pinning centers with number density n exert elementary forces $f_{\rm p}$ each on vortices, we can put [4]

$$F_{\rm p}=\left(\frac{n\langle f_{\rm p}^2\rangle}{R_{\rm c}^2L_{\rm SD}}\right)^{1/2}. \qquad (3)$$

Minimizing U gives $R_{\rm c}$, $D_{\rm SD}$, and $L_{\rm SD}$ for an equilibrium state. From the result shown in Fig. 1, it follows that U is minimized for $D_{\rm SD}/a_0=\sqrt{3}$.

In a superconducting film with thickness d ($<L_{\rm SD}$), the screw-dislocation energy term is excluded from Eq. (2), and $L_{\rm SD}$ in Eq. (3) is replaced by d [1,2]. However, when U for 2-D pinning exceeds U given by Eq. (2), 3-D pinning turns more stable than 2-D pinning. Then high-density screw dislocations penetrate into the film, and the relation $d\gg L_{\rm SD}$ leads to a discontinuous $F_{\rm p}$ jump (i.e., a critical-current jump) [4].

Figure 2 shows such a dimensional crossover in a hypothetical material, which is a film superconductor with thickness $d=10$ μm and upper critical field $\mu_0H_{\rm c2}=1$ T ($\kappa=100$). The reduced flux density $b\equiv B/\mu_0H_{\rm c2}$ is set equal to 0.2, i.e., $\kappa a_0/\lambda\simeq 5$. When $n\langle f_{\rm p}^2\rangle>5.9\times10^{-7}$ N^2/m^3, the vortices form an amorphous pattern ($R_{\rm c}\to a_0$).

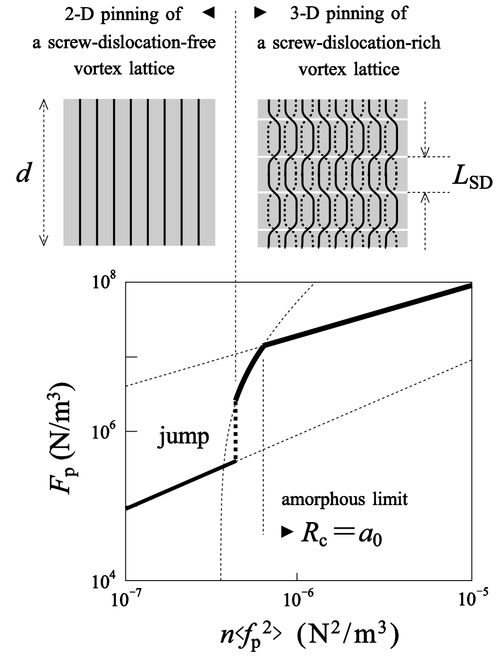

Fig. 2. A discontinuous jump of the volume pinning-force density $F_{\rm p}$ in a hypothetical material, i.e., a film superconductor with a finite thickness d [4].

4. Comparison with experiment

An experimental candidate for the above theoretical prediction is the critical-current jump in Nb$_x$Ge films [1], which have properties similar to those of the hypothetical material in Fig. 2 (e.g., $d=18$ μm, $\mu_0H_{\rm c2}=4.5$ T at 2.1 K, and $\kappa=65$). Applying the 2-D LO theory to the Nb$_x$Ge films gives $n\langle f_{\rm p}^2\rangle/b(1-b)^2\sim10^{-6}$ N^2/m^3. On the other hand, the film in Fig. 2 displays the jump at $n\langle f_{\rm p}^2\rangle/b(1-b)^2=3.4\times10^{-6}$ N^2/m^3. The two values of $n\langle f_{\rm p}^2\rangle/b(1-b)^2$ are comparable. However, we should note that the jump in Nb$_x$Ge was observed near $H_{\rm c2}$. In contrast, the jump in Fig. 2 is predicted on the premise of $B\ll\mu_0H_{\rm c2}$, which validates the London approximation.

For further decent comparison, it is necessary to compute $E_{\rm SD}$ near $H_{\rm c2}$, or to observe the critical-current jump under low flux densities in Nb$_x$Ge.

References

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[5] The details of the numerical computation will be described in a forthcoming paper.