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Dimensional crossover in collective flux pinning

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Critical-current experiments on thick ($d=5-18$ μm) films of amorphous Nb_3Ge or Mo_3Si reveal a dramatic increase of the pinning force F_p at fields around $0.8B_{c2}$. The onset of this peak is triggered by a crossover from two- to three-dimensional disorder of the flux-line lattice, which occurs when the longitudinal correlation length L_c is approximately $d/2$. The large pinning force and the unusual nonlinear V-I characteristics show that in the three-dimensional regime L_c is determined by defects of the flux-line lattice which are extremely unstable.

Two-dimensional collective flux pinning (2DCP) has recently been observed in a variety of weak-pinning, thin-film amorphous superconductors.[1-4] For such systems the long-standing summation problem of flux pinning has been solved theoretically[5,6] and confirmed experimentally. In addition, recent experiments[7] and computer simulations[8] on 2D systems have shown that the concepts of CP apply as well for an elastically as for a plastically distorted flux-line lattice (FLL). In the latter case, the theory of Larkin and Ovchinnikov (LO) (Ref. 5) loses its applicability,[7] and the experimental results are better described by a model in which the transverse correlation length R_c follows from a spatial distribution of edge dislocations.[9,10] For stronger pinning and thicker films the FLL disorder along the field direction, represented by the longitudinal correlation length L_c, becomes important.

The situation for 3DCP is totally unresolved regarding the nature of the disorder. For a basic understanding of flux pinning in technologically important, strong-pinning superconductors, it is crucial to obtain a clear insight into the character and amount of the FLL disorder in 3D. Our present experiments on thick amorphous films provide for the first time lucid evidence for a sharply defined dimensional crossover (DCO) from 2DCP below to 3DCP above the crossover field.[11] The DCO is accompanied by a dramatic increase of the bulk pinning force and a related collapse of the size of the correlated regions. This behavior yields the first indication that in 3D the FLL is unstable with respect to the formation of screw dislocations. The results of flux-flow measurements further support this point of view.

In the collective-pinning theory the bulk pinning force is given by

$$F_p=[W(0)/V_c]^{1/2}, \tag{1}$$

with V_c the volume of the correlated regions, and in our samples[7] $W(0)=C_{\rm dl}(T)b(1-b)^2$, where b is the reduced field B/B_{c2} and $C_{\rm dl}$ a pinning strength parameter related to quasidislocation loops (dl) to be determined from experiment.[1] Expressions for the correlation lengths were derived for an elastically deformed FLL in Ref. 5. For 2DCP, R_c is given by[1]

$$R_c=a_0c_{66}[2\pi d/W(0)\ln(R_c/w)]^{1/2}, \tag{2}$$

with a_0 the FLL parameter and w the width of the sample. The corresponding L_c, obtained from the logarithmic term in the LO theory, is[5]

$$L_c=(\tilde{c}_{44}/c_{66})^{1/2}R_c\approx 3[b/(1-b)]^{1/2}R_c \tag{3}$$

for large values of κ and λ, and $b>0.5$.[8] Here $\tilde{c}_{44}$ and c_{66} are the nonlocal tilt modulus and the shear modulus, respectively.[12]

Theoretically, the DCO is expected at a field for which $L_c=d/2$,[13] where d is the sample thickness. When $L_c>d/2$, 2DCP is observed with essentially straight flux lines and $V_c=R_c^2d$. For $L_c<d/2$, the FLL disorder develops in all directions and thus we have the case of 3DCP with $V_c=R_c^2L_c$. Note that R_c and L_c in both situations can be determined from the experimental F_p using the formulas given above. Note also that in 2D, $R_c\propto d^{-1/2}$, so that $F_p\propto d^{-1}$, whereas in 3D, F_p is independent of d. For R_c of the order of a_0 the FLL becomes amorphous and a further decrease of R_c is impossible. This occurs just before B_{c2} is attained. In the case of 2DCP this means that V_c remains constant and F_p decreases linearly with $1-b$ and has a slope $dF_p/db\propto[C_{\rm dl}/d]^{1/2}$. In the case of 3DCP, the LO theory for the amorphous limit gives[5]

$$L_c=\left(\frac{\pi\hat{c}_{44}^2k_h^4a_0^6r_f^2}{W(0)}\right)^{1/3}, \tag{4}$$

with $k_h=(1-b)^{1/2}/\lambda$, $\hat{c}_{44}$ the local tilt modulus, and r_f the range of the elementary pinning interaction, approximately $a_0/2$. Similar to the 2D case, this results in a linear decrease of F_p with b, but with a much steeper slope that is *independent* of d. The different power laws of F_p with respect to d provide a unique and unambiguous tool to determine the dimensionality of the CP.

To observe the DCO, thick films and large $W(0)$ are needed. Samples of Nb_xGe and Mo_xSi with x about 3 and d ranging from 5 to 18 μm were prepared by rf (magnetron) sputter deposition either on liquid-nitrogen- or water-cooled substrates of sapphire or Si. In changing the sputter conditions, $C_{\rm dl}$ could be varied by a factor of 5, which, for instance, is accounted for by a 50% increase of the diameter of the quasidislocation loops.[1] In spite of the long sputter runs the samples were homogeneous as indicated by the sharp resistive transition at T_c with typical widths less than 50 mK. The amorphousness was checked by means of x-ray diffraction. Four-probe V-I measurements were carried out using superconducting contacts in order to avoid Joule heating. The bulk pinning force follows from $F_p = |\mathbf{j}_c \times \mathbf{B}|$, where j_c is defined by a 1-μV criterion over 5 mm sample length. The typical features for thick samples are represented by the results of a Nb_3Ge film with $d = 7.9$ μm, $T_c = 3.4$ K, $\rho_0 = 190$ $\mu\Omega$ cm, and $-dB_{c2}/dT|_{T_c} = 1.96$ T/K. The Ginzburg-Landau parameter κ, coherence length ξ, and the penetration depth λ are 70, 7, and 800 nm, respectively. A complete list of the superconducting properties of several thick Nb_3Ge and Mo_3Si samples that show the DCO close to B_{c2} will be given in a forthcoming paper. The superconducting parameters of a thin ($d = 93$ nm) reference sample (Nb_3Ge, sample No. 7) can be found in Ref. 7. Only experiments on samples with different d are able to reveal the dimensionality. In order to avoid difficulties with sample preparation at these long sputter times we mounted the samples under different angles with respect to the external field. Defining the angle as that between the applied current and field directions and taking it 90° and 45°, the effective thickness is changed by a factor of $\sqrt{2}$. The voltage criterion is adapted accordingly to 0.7 μV over 5 mm for an angle of 45°. The experiments on the thin Nb_3Ge reference sample serve as a test of the validity of this method, but they also illustrate the 2DCP scaling laws, which are then compared with the results for the thick sample.

Typical results on the thin sample are given in Fig. 1(a) (data points). The solid line represents the theoretical 2DCP curve adapted at $b = 0.4$ from which the parameter $C_{dl}(0.4)$ follows. As discussed in Ref. 7, b_{ST} marks the structural transition from elastic to plastic disorder. It should shift according to $(1 - b_{ST}) \propto d^{-1/2}$, which is indeed observed (see Fig. 1). The inset shows the ratio of $F_{p\perp}/F_{p\measuredangle}$ [the symbols denote the mounting angles of 90° ($\perp$) and 45° ($\measuredangle$)] for $b = 0.4$, $b = b_p$ (at the peak value of F_p), and $b \approx 1$ (above the peak) at different temperatures. According to the 2DCP theory $F_p \propto d^{-1}$ up to b_p and $\propto d^{-1/2}$ above b_p. The corresponding value of $F_{p\perp}/F_{p\measuredangle}$ should thus be $\sqrt{2}$ up to b_{ST} and at b_p, and $(\sqrt{2})^{1/2} = 1.19$ above b_p. This is indeed the behavior observed in the inset, and proves that d can be effectively varied by a rotation of the sample with respect to the external field.

The experimental results for the thick sample are shown in Fig. 1(b). Note here the *logarithmic* scale of the normalized pinning force. For temperatures above $t = 0.83$, F_p exactly follows the 2DCP theory (solid curve), as is displayed in Fig. 1(b) for $t = 0.95$. Up to the amorphous limit no peak can be seen.[14] The thickness dependence displayed in the inset shows that for $T > 0.83$, 2DCP is present over the whole field range [compare with Fig. 1(a)]. A totally different behavior is found below $0.83T_c$. At a field b_{CO}, a step in F_p is observed which increases considerably when T is decreased. Below $b = 0.5$, F_p agrees for all temperatures with the 2DCP theory. Accordingly, the ratio $F_{p\perp}/F_{p\measuredangle}(0.4) = \sqrt{2}$ at all t (see inset). The deviation from the theory between $b = 0.5$ and b_{CO} is attributed to a decrease of R_c as a precursor of the DCO (Ref. 13) due to the increasing effect of tilt distortions.

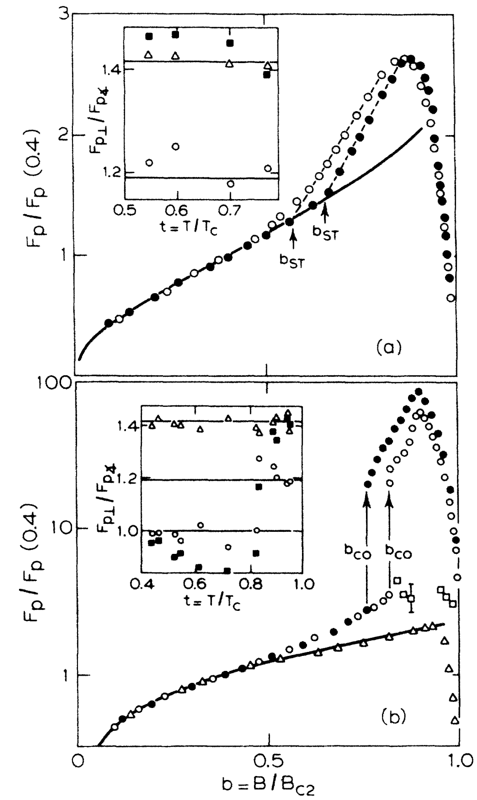

FIG. 1. Normalized volume pinning force $F_p/F_p(b = 0.4)$ vs b. (a) Nb_3Ge at $t = 0.6$ for $d_{eff} = 93$ nm (circles) and $d_{eff} = 131$ nm (solid circles). (b) Nb_3Ge at $t = 0.44$ for $d_{eff} = 7.9$ μm (circles) and $d_{eff} = 11.2$ μm (solid circles), and at $t = 0.95$ for $d_{eff} = 7.9$ μm (triangles). Note the logarithmic scale used in (b). The solid lines represent the 2DCP theory. The arrows b_{ST} and b_{CO} denote the onset of the peak in 2D and the crossover to 3D, respectively. The insets of (a) and (b) depict a plot of $F_{p\perp}/F_{p\measuredangle}$ at $b = 0.4$ (triangles), $b = b_p$ (solid squares), and $b \simeq 1$ (circles) for different temperatures. From these plots the dimensionality of the CP follows unambiguously. The squares with error bars in (b) denote the data determined from the extrapolated flux-flow regime in Fig. 3.

The magnitude and range of the deviation decrease for higher temperatures. Therefore, below b_{CO} the pinning is 2D. The shift of b_{CO} is opposite to that of b_{ST} for the thin sample which indicates a different mechanism for the peak. If a DCO takes place at b_{CO}, pinning should be 3D above b_{CO} with F_p independent of d, and thus, $F_{p\perp}/F_{p\measuredangle} = 1$. As can be seen in the inset of Fig. 1(b) this is exactly the behavior observed within the experimental accuracy for $t < 0.83$. Strong evidence for the presence of 3DCP in the peak is provided by the slope of $F_p(b)$ in the amorphous regime. Evaluating C_{dl} via Eqs. (1) and (4), taking $R_c = 2a_0$ yields for $t < 0.83$ values within 30% of $C_{dl}(0.4)$. *At this stage we conclude that the peak in F_p for our thick samples originates from a DCO at b_{CO} from 2D to 3DCP.*

The DCO is expected well below the amorphous limit for $L_c(b_{CO}) = d/2$. Using Eqs. (1)-(3) and the F_p values just below b_{CO}, $L_c(b_{CO})$ can be determined and compared to d_{eff} which is d or $d\sqrt{2}$, depending on the mounting angle. The results for $t < 0.83$ are shown in the inset of Fig. 2. They agree very well with the condition for the DCO. Actually, this is a surprising result, since the LO theory is supposed to be only qualitatively correct with the prefactors requiring computer simulations.[8] The good numerical agreement, here and in our previous reports on CP, indicate that these prefactors must be of order unity. The fact that the DCO disappears above $t = 0.83$ is related to the scaling of R_c and L_c with a_0 and the growth of a_0 at fixed b with increasing temperature. Therefore, b_{CO} increases monotonically until at $0.83T_c$ it becomes equal to b_p.

At the DCO, F_p increases sharply indicating a collapse of the correlated volume. Depending on d and T the decrease of V_c amounts up to four orders of magnitude. In Fig. 2 V_c/a_0^3 vs b is shown for the thick sample at $t = 0.44$. The data are obtained from Eq. (1) using $C_{dl}(0.4)$ and the experimental values of F_p. Also R_c/a_0 and L_c/d obtained from V_c are plotted. Below b_{CO}, $V_c = R_c^2 d$, and above b_{CO}, $V_c = R_c^2 L_c$ is used in combination with Eq. (3). In the 2D regime, L_c only has a formal meaning. In the 3D regime, the correlation lengths decrease rapidly between b_{CO} and b_p. Above b_p they become almost constant at $R_c/a_0 \approx 1.8$, $L_c/d \approx 0.055$, and $V_c/a_0^3 \approx 50$. The drop of R_c and L_c shows that at b_{CO} an elastically deformed FLL, that is stable in 2D, is unstable in 3D. So in 3D, flux-line dislocations (FLD's) are mainly responsible for the disorder of the FLL and it could be that the "elastic" LO theory can never be observed in 3D. From a comparison with the peak effect in the 2D case, caused by edge FLD's, it necessarily follows that the much larger F_p in the 3D case must come from topological defects that destroy the order along the field direction, e.g., screw FLD's.[15] Apparently, the screw dislocations move into the FLL as soon as the DCO condition is fulfilled. The Peierls potential of screw FLD's is zero, so that they can only exist in equilibrium with pinning centers. The tilt distortions also contribute to the disorder in the x-y plane which causes the drop of R_c at b_{CO}. A description in terms of the 3D FLD model[9] does not lead to a satisfactory agreement.

The screw FLD's turn out to be very unstable as follows from the I-V characteristics that are depicted in Fig. 3. The curves for $b < b_{CO}$ show the usual behavior found in the case of 2DCP, i.e., no voltage below I_c, followed by a gradual transition to the final flux-flow state. Above b_{CO} the transition to the flux-flow state is preceded by a history-dependent, sharp increase of the voltage at I_c. The hysteresis and size of the jump are largest for fields close to b_{CO}. The flux-flow resistances as a function of field display the usual characteristic behavior and no discontinuity at b_{CO}. Linear extrapolations from the flux-flow regime to zero voltage along the dashed lines gives I_c values [depicted by the squares in Fig. 1(b)] that one should expect, if there still were 2DCP above b_{CO}. In the case of the first current sweep at b_{CO}, coming from a lower field, a hump ≈ 0.3 mV is observed at the current value expected for the I_c of the 2D situation, followed by noise of a few microvolts. The extrapolation from the flux-flow regime exactly coincides with the first voltage rise. No such behavior is seen when the current is decreased or cycled.

We propose an explanation for the above behavior within the context of the DCO. Above b_{CO} the pinned FLL is distorted in all 3 dimensions. When the buckled vortices begin to move at I_c, the effect of the pinning centers diminishes and the screw dislocations are removed from the moving FLL, that now obey the 2DCP rules. The transition from 3D to 2D deformations (buckled to stretched FLL) sets in immediately at I_c demonstrating the zero Peierls potential. The hysteresis can be ascribed to edge FLD.[7,9] At b_{CO} the first formation of 3D areas from the 2D FLL is triggered by vortex motion up to a velocity of about 2 cm/s corresponding to the 0.3 mV. Apparently, the situation is very unstable resulting in the microvolt noise observed. Once the 3D configuration is established, it is stable below I_c but easily removed becoming 2D above I_c.

In conclusion, we studied the dimensionality of the collective flux pinning in amorphous Nb_3Ge and Mo_3Si sam-

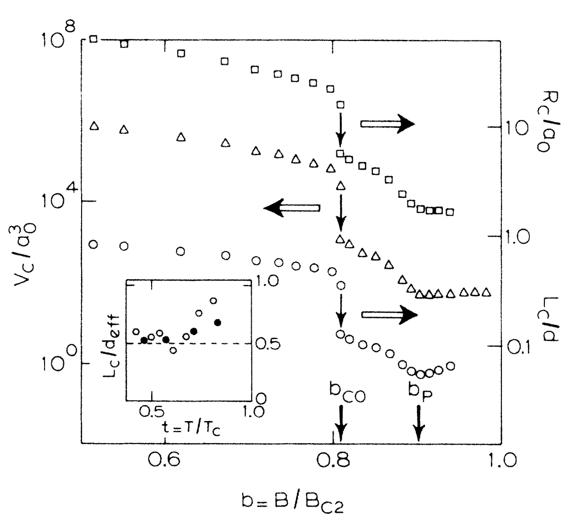

FIG. 2. V_c/a_0^3 (triangles), R_c/a_0 (squares) and L_c/d (circles) vs b for the thick sample at $0.44T_c$. The DCO and the maximum of F_p in the peak are denoted by b_{CO} and b_p. The inset gives the value of $L(b_{CO})/d_{eff}$ for $d_{eff} = 7.9$ μm (circles) and $d_{eff} = 11.2$ μm (solid circles) at different temperatures.

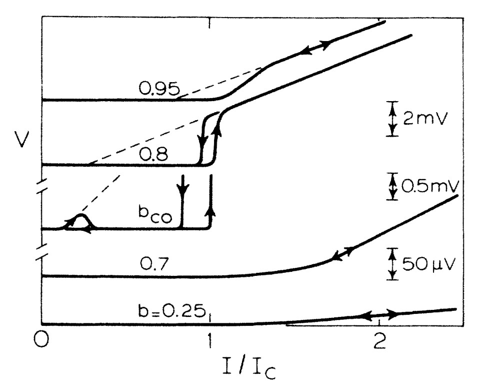

FIG. 3. Representative $I-V$ curves labeled by the reduced field b for the thick sample at $t = 0.44$. The dashed lines give the extrapolation from the linear flux-flow regime.

ples by means of thickness variation. A DCO, characterized by a huge enhancement (up to a factor of 100) of the pinning force, takes place at a field defined by $L_c \approx d/2$. In our samples this criterion is met for $d > 5\ \mu$m at temperatures well below T_c and fields above $0.7B_{c2}$. The 3D distorted FLL appears to be unstable when it is set into motion. It stretches itself to become eventually 2D distorted. This is ascribed to the role screw FLD's play in establishing the 3D disorder and their property of having no Peierls potential so that they are basically unstable.

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[12]Since $R_c < k_h^{-1}$, the dispersion of c_{44} is important for $b > 0.5$.

[13]E. H. Brandt (unpublished); P. H. Kes and R. Wördenweber (unpublished).

[14]In these cases b_p is defined as the field where the maximum value of F_p is reached.

[15]Other defects that destroy the order along the field direction, like twists of flux-line bundles, may be responsible as well.