large changes in the penetration depth of the evanescent fields. For each angle of incidence, therefore, the gap thickness s has to be adjusted so that the proximity of the prism will have exactly the same damping effect on the otherwise freely propagating SPW. If s is too large, the excitation will be inefficient, while if s is too small, the proximity of the prism will load and wipe out the SPW.

Reflectivity calculations with use of the same parameters as in Fig. 2 yield, for a metal thickness of 200 Å, the following results: The critical angle is 32.6244°, the angle at maximum absorption is 32.6414° and the half-width angle is 0.004°. The distance which the long-range mode propagates on the 200 Å thin film until its power decays by a factor of $1/e^2$ is therefore 300 μm, which is 27 times larger than for a SPW that propagates on the surface of a thick Ag slab. Since the range of this mode is very large, its study in the case that the surfaces are randomly rough can provide useful quantitative information about roughness-induced attenuation. As a result, this mode can be used as a probe for characterizing the properties of surfaces and thin metal films. This long-range mode can also be utilized for nonlinear interactions such as second-harmonic generation where the nonlinearity is introduced by the metal itself or by the bounding media via the evanescent fields. By imbedding the thin metal film in an (optical) power-dependent refractive-index semiconductor, one obtains for the long-range SPW a power-dependent propagation-constant which can be used for bistability studies.[12]

In summary, this theory predicts that it is possible to choose material and geometrical parameters such that a long-range SPW mode could be excited on a thin metal film, the range being more than 1 order of magnitude greater than observed before. This mode can be used for the study of rough surfaces and various nonlinear interactions where a large interaction range is desirable.

Useful discussions with G. I. Stegeman and A. Craig are acknowledged. This work is supported by the Air Force Office of Scientific Research, U. S. Air Force, and the Army Research Office, U. S. Army, under Contract No. JSOP F49620-80-C-0022.

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Collective-Flux-Pinning Phenomena in Amorphous Superconductors

P. H. Kes[(a)] and C. C. Tsuei
IBM T. J. Watson Research Center, Yorktown Heights, New York 10598
(Received 23 October 1981)

The pinning force F_p in amorphous Nb_3Ge films with $T_c \sim 4$ K has been measured as a function of perpendicular field, temperature, and thickness of the samples. As a result of the large κ and low J_c characteristic of amorphous superconductors the pinning force for the first time is found to be in good agreement with the theory of Larkin and Ovchinnikov for collective pinning extended to the two-dimensional case. Pinning-mediated renormalization of the shear modulus leads to a sharp peak in F_p near the upper critical field.

PACS numbers: 74.60.Ge, 74.70.Lp

The theory of collective pinning of the flux-line lattice (FLL) as first proposed by Larkin and Ovchinnikov[1] (LO) is based on a very attractive physical concept, which has been known in the literature for ~10 years. Until now, it has not been verified experimentally. Collective pinning should be observed in type-II superconductors with a large concentration of randomly distributed weak pinning centers, which cause the breakdown of the long-range positional order of the FLL. This leads to the formation of correlated regions in which only short-range order persists. Collective pinning is fundamentally different from single-particle pinning which requires a minimum distortion of the FLL, the threshold criterion,[2-4] to pin the lattice effectively. There is convincing experimental evidence that in most real systems the threshold does not exist.[5] Probably, one should take into account the fact that defects in the FLL, which appear in the form of dislocations, vacancies, etc., can also interrupt the long-range order of the FLL resulting in a smaller size of the correlated regions than those suggested by theory. This effect, due to disorder, may be responsible for the discrepancy between the LO theory and experiments. In view of the requirements mentioned above, we chose to search for the collective-pinning phenomena in amorphous transition-metal-based superconductors such as amorphous Nb_3Ge and Nb_3Si in the form of sputtered thin films, for the following reasons:

(1) It is experimentally established that these materials are weak coupling type-II superconductors in the extreme dirty limit with typical values for the Ginzburg-Landau parameter κ, coherence length ξ, and penetration depth λ of 100, 100 Å, and 1 μm, respectively.[6] These features simplify the analysis of the experimental data considerably because theoretical expressions in the dirty limit are readily available.

(2) Preliminary critical current (J_c) measurements indicate low pinning presumably due to the homogeneous and isotropic nature of this class of materials on the scale of ξ.

(3) Due to the large values of κ and λ and the extreme smoothness of these films [surface irregularities $\lesssim 5$ Å (Ref. 7)], the pinning behavior in a perpendicular field sufficiently large to satisfy $a_0 = 1.07(\Phi_0/B)^{1/2} \ll \lambda$ (a_0 is the FLL parameter, Φ_0 the flux quantum, and B the flux density) is believed to be insensitive to complications like pinning by surface irregularities, edge pinning,[3] and buckling of the flux lines (a form of FLL dislocation).

(4) It should be emphasized that, without buckling, the correlation length along the field direction, L_c, is much larger than the thickness (d) of the film ($L_c \sim 100d$), so that we are essentially dealing with a system of two-dimensional (2D) flux-line pinning. Therefore, the only relevant elastic modulus of the FLL is the shear modulus c_{66}.

The formulas describing collective pinning in 2D are relatively simple. By retaining the same approximations and notations as in Ref. 1, the 2D correlation function of the displacements u of the FLL[8] is

$$\langle [u(\vec{r}) - u(0)]^2 \rangle = [W(0)\rho^2/4dc_{66}^2]X^{-1}(w/\rho). \quad (1)$$

Here $W(0) = n_v \langle f_p^2 \rangle$, with n_v the number density of pinning centers and f_p the maximum elementary pinning force, $\rho = |\vec{r}|$, and w is the width of the sample. The function X, defined by

$$X(x) = 2\pi/[\ln(x) - 0.029], \quad (2)$$

depends only weakly on x and its value is of order unity. The correlation length R_c in the plane of the film is defined by $\langle [u(R_c) - u(0)]^2 \rangle \approx (a_0/2)^2$, leading to[9]

$$R_c = X^{1/2}(w/R_c)[a_0 d^{1/2} c_{66}/W(0)^{1/2}]. \quad (3)$$

The pinning force per unit volume is given by

$$F_p = BJ_c = [W(0)/dR_c^2]^{1/2}. \quad (4)$$

As expected for 2D pinning, the pinning force per unit area, $F_p d$, does not depend on d.

The a-Nb_3Ge and a-Nb_3Si samples were prepared by rf sputtering on sapphire substrates held at a temperature below 150 K. A mask provided strips with dimensions 4×20 mm. We report here on the experimental data obtained for three Nb_3Ge samples of different thicknesses selected for their very low critical current.

TABLE I. Properties of the amorphous Nb_3Ge samples.

Sample	d (μm)	T_c (K)	ρ_0 ($\mu\Omega$ cm)	$dB_{c2}/dT\|_{T_c}$ (T/K)	κ	$\lambda(0)$ (μm)	$B_c(0)$ (mT)
174B	0.62	3.86	164	2.04	65	0.68	50
175A	1.24	3.99	157	2.01	63	0.66	52
176A	2.92	4.20	165	1.83	61	0.65	52

From the critical temperature T_c, the residual resistivity ρ_0, and the slope of the upper critical field curve, $B_{c2}(T)$, at T_c, and by using well-known expressions from the literature, the superconducting parameters listed in Table I were computed. The transition width typically was 80 mK. J_c was determined by measuring I-V curves and using a 1-μV criterion for the voltage between the pressure contacts, 6 mm apart. The results for a 4-μV criterion are basically the same as those reported here. In Fig. 1(a) we show a typical plot of J_c vs $b = B/B_{c2}$ measured for sample 175A at $t = T/T_c = 0.7$. (Due to the geometry, B is equal to the applied magnetic field.) J_c, indeed, is very small. As shown in Fig. 1(a), B_{c2} is well defined. Below B_{c2} a peak in $J_c(b)$ is observed. Although the 2D-LO theory excludes such a peak, it can be explained by the renormalization of the shear modulus due to the increase in disorder when B_{c2} is approached, as we will discuss below. Thus far, this possibility of explaining the peak effect has not been discussed in the literature.

In Fig. 1(b), the volume pinning force F_p, normalized to its value at $b = 0.4$, is plotted versus b for sample 175A at $t = 0.5$, 0.7, and 0.9 and for 174B and 176A at $t = 0.7$. Three regimes can be distinguished. Below the peak (appearing at a field $b_{\rm RN}$) a universal behavior is observed independent of sample variation and temperature. This means the properties of the pinning centers of the samples are identical. Although a positive identification of the pinning centers is not possible at present, modulation of strain on a scale of about 100 Å has been discussed for similar metallic glasses.[10] The temperature scaling is proportional to $B_c^2(t)$ indicating that core interaction is the predominant pinning mechanism. The drawn line in the region below $b_{\rm RN}$ represents the 2D-LO theory applied to 175A (adapted at $b = 0.4$) on which we will concentrate our discussion below. Apart from the small discrepancies at low b for $t = 0.9$, which are probably due to some edge pinning under conditions at which $a_0 \ll \lambda$ is not obeyed, the agreement is very good. A very useful criterion for identifying the FLL dimensionality is a graph of F_p vs $1/d$. As seen from Fig. 2, where actually F_p/B_c^2 was plotted in order to account for the slightly different superconducting parameters of the samples, the pinning is indeed two dimensional in all the samples studied.

From Eqs. (3) and (4) and the experimental data, R_c/a_0 and $W(0)/(1-b)^2$ can be computed using the

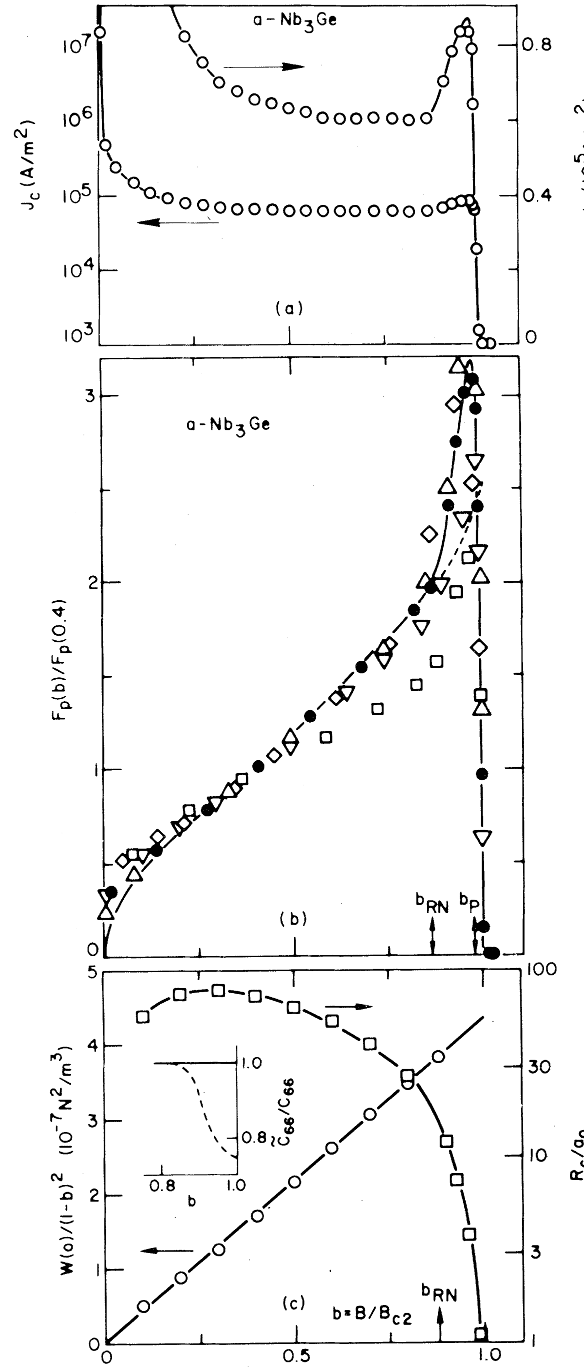

FIG. 1. (a) J_c vs b for sample 175A at $t = 0.7$. (b) $F_p/F_p(0.4)$ vs b for 175A at $t = 0.5$ (triangles), $t = 0.7$ (solid circles), $t = 0.9$ (squares); for 174B (diamonds); and 176A (inverted triangles), both at $t = 0.7$. Below $b_{\rm RN}$ the drawn line is the prediction of the 2D-LO theory adapted at $b = 0.4$ for 175A at $t = 0.7$. This prediction, extended to $b > b_{\rm RN}$, is given by the dashed line. The line drawn in this region is a guide for the eye ($b_{\rm RN}$ and b_p are defined in the text). (c) $W(0)/(1-b)^2$ and R_c/a_0 vs b for 175A at $t = 0.7$. The inset shows the relative change of c_{66} (as derived from the data) due to renormalization by pinning-mediated disorder.

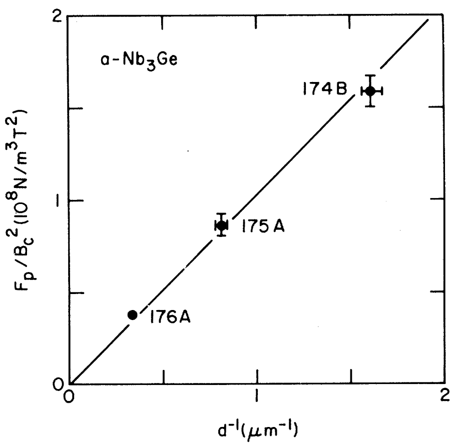

FIG. 2. $F_p/B_c^{\,2}$ vs d^{-1} at $b=0.4$ and $t=0.7$. The division by $B_c^{\,2}(0.7)$ accounts for small variations in the superconducting parameters of the samples.

analytic expression for c_{66} as given by Brandt[11] in the limit of large κ and confirmed by recent measurements[12]:

$$c_{66}=\frac{B_c^{\,2}(t)}{4\mu_0}\,\frac{\kappa^2}{\kappa_2^{\,2}}\,b(1-0.29b)(1-b)^2. \qquad (5)$$

The thin-film correction of Conen and Schmid[13] is not necessary here. The results for 175A are shown in Fig. 1(c) as functions of b. The linear dependence of $W(0)/(1-b)^2$ confirms the 2D-LO theory [in fact, this functional dependence was used to compute the theoretical curve in Fig. 1(b)]. It means $f_p\propto(1-b)/a_0$ suggesting pinning is dominated by dislocations (stress modulation) rather than point defects.[3,5] Assuming $n_v\approx10^{22}$ m^{-3}, the value of $W(0)$ at $b=0.4$ (6×10^{-8} $\mathrm{N^2/m^3}$) yields $f_p\approx3\times10^{-15}$ N, a quite reasonable order of magnitude for dislocation pinning.[3,5] The functional form of R_c/a_0 vs b reflects essentially the B dependence of $c_{66}/f_p\propto u^{-1}$ [Eq. (3)], in agreement with the expectation $R_c\propto(u/a_0)^{-1}$.

At b_{RN}, R_c has decreased to $(15-20)a_0$ (observed for all samples and at all temperatures studied). Beyond b_{RN}, the experimental data deviate from the 2D-LO prediction represented by the dashed line in Fig. 1(b) using c_{66} of Eq. (5). This expression for c_{66}, however, has been derived for a perfect FLL not taking into account the effect of disorder. We believe that, in analogy to the theoretically predicted renormalization of c_{66} due to thermally activated disorder,[14-16] the shear modulus in the region of the peak is renormalized—now due to *pinning mediated* disorder—leading to a smaller value $\tilde{c}_{66}$. With the assumption that renormalization does not affect the validity of the 2D-LO theory and $W(0)$ is not affected either, we computed $\tilde{c}_{66}/c_{66}$ and also R_c/a_0 from the experimental data in the region $b>b_{\mathrm{RN}}$, shown in Fig. 1(c). Typically, $\tilde{c}_{66}$ reduces by about 30%, comparing reasonably well with the reduction by ~20% predicted for melting.[15] Approaching b_p (the field at the maximum of F_p) R_c decreases to $\sim a_0$. In the region $b_p<b<1$, the flux lines form a 2D amorphous structure similar to the "hexatic" liquid-crystal-like phase described in Ref. 14. In this case $F_p=[W(0)/da_0^{\,2}]^{1/2}$ $\propto b(1-b)$ which is confirmed by our experiments. The values of $W(0)$, determined from the slopes, agree within a factor of 2 with those obtained previously for $b<b_{\mathrm{RN}}$.

Details about I-V curves for both Nb_3Ge and Nb_3Si, rearrangement of the FLL during flow in the peak region, and structural relaxation through annealing will be published in a subsequent paper.[8] Samples with initial relatively large J_c show domelike behavior characteristic for strong pinning. By annealing, J_c reduces by up to 2 orders of magnitude and both 2D collective pinning and the peak effect are recovered.

In conclusion, we have observed for the first time the collective pinning of the FLL as predicted by the LO theory. The fact that both the functional dependence and magnitude are in good agreement with the theory is attributed to low J_c and high κ, characteristic for amorphous superconductors. Annealing studies support the view that weak pinning is an essential requirement to observe the collective behavior. In strong pinning systems, the collective pinning is probably masked by structure defects of the FLL. By varying the sample thickness, we have experimentally demonstrated the 2D pinning of the FLL, indicating that these systems are also well suited for studying phase transition of lower dimensions. For the first time, the origin of the peak effect is explained by pinning-mediated renormalization of the elastic modulus. As an additional remark, we wish to point out that the results of this work suggest flux pinning can be used as a sensitive probe for studying structure relaxation in amorphous metallic glasses.

We wish to thank E. H. Brandt for a useful discussion, A. P. Malozemoff for a critical reading of the manuscript, and P. Leary for preparing the samples. P. H. Kes acknowledges IBM World Trade for providing a stimulating opportunity to work at the T. J. Watson Research Center.

[a]Visiting scientist from the Kamerlingh Onnes Laboratory, Rijksuniversiteit Leiden, Leiden, The Netherlands.

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[9]Essentially the same result is obtained if R_c is derived along the lines given in Ref. 1; $R_c = 2a_0 d^{1/2} c_{66} / W(0)^{1/2}$ leading to $F_p = W(0)/2a_0 d c_{66}$. This corrects an error in Ref. 1.

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