Dislocation-Mediated Vortex-Lattice Melting in Thin Films of a-Nb_3Ge

P. Berghuis, A. L. F. van der Slot, and P. H. Kes

Kamerlingh Onnes Laboratorium, Leiden University, P.O. Box 9506, 2300 RA Leiden, The Netherlands

(Received 9 July 1990)

Resistivity and I-V measurements have been performed on thin amorphous Nb_3Ge films in perpendicular fields. In the vicinity of the mean-field-transition line, pure flux-flow behavior occurs due to melting of the vortex lattice. The dependence of the melting field on temperature and thickness is well described by the melting theory for a two-dimensional lattice. In the narrow crossover regime between melting and weak pinning, dislocation-mediated flux creep occurs prior to melting.

PACS numbers: 74.60.Ge, 74.60.Ec

The unusual resistive and magnetic behavior of the high-temperature superconductors (HTS) in a magnetic field has greatly stimulated the interest in the properties of the vortex lattice (VL). Some key questions arising here are the following: (i) Is there a real phase transition when the temperature of a VL with pinning centers is increased, and (ii) what is the nature of the low-temperature phase (vortex glass)? Ignoring the effect of pinning, theory predicts a melting line between a low-temperature solid phase and a high-temperature liquid for both a three-dimensional (3D) VL [1] and a 2D VL.[2] Hebard and Fiory[3] experimentally confirmed the latter case in Al films at very low fields. By taking pinning into account, Fisher[4] predicted in the case of a 3D disordered VL a second-order phase transition to a low-temperature vortex-glass state characterized by a true zero resistance for $J \rightarrow 0$. Experimental support for this theory came from I-V measurements on Y-Ba-Cu-O films by Koch *et al.*,[5] and very recently on Y-Ba-Cu-O single crystals by Gammel, Schneemeyer, and Bishop.[6] However, the situation remains controversial as evidenced by new theoretical[7] and experimental[8] work.

For a 2D disordered VL, which occurs when the parallel correlation length L_c is larger than the sample thickness d, a vortex-glass phase is not expected to exist.[9] Lorentz-force-driven vortex creep is governed by an activation barrier $U(J) \sim J^{-\nu}$, with $\nu < 1$.[10] This barrier for *elastic* creep arises from the collective hopping of flux bundles. At small currents in 2D the increase of $U(J)$ is cut off by plastic motion of VL defects, i.e., small edge-dislocation pairs (*plastic* creep). Now U no longer depends on J, thereby creating a situation which is describable by the model for thermally assisted flux flow[11] (TAFF) with Ohmic behavior at low J. Here only a fraction of the VL moves and contributes to the resistivity according to[9]

$$\rho \approx \rho_f \exp(-U/kT)\,, \qquad (1)$$

where ρ_f is the resistivity for uniform flux flow.

The implications of the Kosterlitz-Thouless melting transition for a 2D disordered VL were discussed by Fisher.[2] At the transition the VL becomes unstable to the unbinding of thermally created dislocation pairs. The shear modulus c_{66} drops sharply to zero when the vortex-lattice melting (VLM) criterion is fulfilled:[2]

$$Ac_{66}a_0^2 d/kT = 4\pi\,, \qquad (2)$$

where $a_0 = 1.075(\phi_0/B)^{1/2}$ is the VL spacing. The renormalization of c_{66} due to nonlinear lattice vibrations and VL defects is absorbed in the parameter A which is of order unity. An expression for c_{66} was obtained by Brandt,[12]

$$c_{66} = \frac{B_c^2(t)}{4\mu_0} b(1-0.29b)(1-b)^2\,, \qquad (3)$$

with $B_c(t) = B_c(0)(1-t^2)$, $t = T/T_c$, and $b = B/B_{c2}$. In weak-coupling amorphous superconductors $B_c(0)$ can be written in terms of S, the slope $-dB_{c2}/dT$ at T_c, and ρ_0, the residual resistivity at $T=0$,[13] viz. $B_c(0) = 1.15 \times 10^{-5} T_c (S/\rho_0)^{1/2}$. Note that Eqs. (2) and (3) then determine the melting field $B_m(T)$.

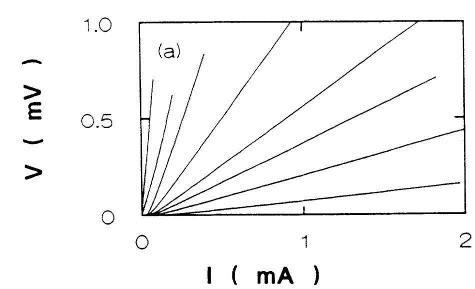
A first indication of vortex-lattice melting in low-T_c, amorphous, composite In/InO_x films was recently reported by Gammel, Hebard, and Bishop.[14] A peak in the dissipation of a high-Q quartz oscillator, on which the film was deposited, was interpreted in terms of VLM. In this Letter we employ a different approach and system. We have studied the I-V response and resistivity of thin amorphous $Nb_{1-x}Ge_x$ films ($T_c \approx 3$ K) in magnetic fields perpendicular to the film surface. The advantages of this system are twofold: (i) The behavior of the critical-current density J_c with B and T is well described by the theory of collective pinning[15] (CP) which provides essential information about the elementary pinning strength and the VL disorder. For thin enough a-$Nb_{1-x}Ge_x$ films it has been shown[13,16] that $L_c > d$ and, therefore, 2D VL melting could be observable upon approaching B_{c2}. (ii) J_c in these films is orders of magnitude smaller than in the HTS (in a-$Nb_{1-x}Ge_x$, $J_c \lesssim 10^5$ A/m^2). Hence the ratio U/kT governing the flux creep might be small enough to observe plastic-creep effects. The salient results of our measurements are the following: (a) In a regime in the vicinity of B_{c2} the critical currents are zero, and the resistivity equals the flux-flow resistivity ρ_f. Therefore we inferred that VL melting is indeed observed. (b) At the transition from a pinned ($J_c \neq 0$) to a melted VL, TAFF occurs. The corresponding analysis of the flux creep yields a criterion for the determination of the melting field B_m. A detailed discussion of the pinning will be the subject of a separate paper.

A series of thin amorphous $Nb_{1-x}Ge_x$ films with $x \approx 0.3$ was prepared by rf sputtering. The samples had thicknesses of 205 (sample I), 565 (II), and 2350 nm (III). The amorphousness was confirmed by x-ray diffraction. A four-point geometry was constructed by photolithography and used for the resistivity and I-V measurements. Typical dimensions were 1×20 mm^2, with a voltage-probe distance of 5 mm. The normal resistivity ρ_n in zero field was measured down from room temperature. It yields $\rho_0 \simeq 2\ \mu\Omega$ m. T_c was determined from the midpoints of the resistance transitions; ΔT_c was less than 20 mK. We obtained $T_c = 3.37$, 2.93, and 3.00 K, respectively.

Various I-V curves for sample II at $T = 2.49$ K, displaying the typical behavior of our films, are plotted on a linear scale in Fig. 1(a) and a double-logarithmic scale in Fig. 1(b). Three different B-T regimes can be distinguished: (1) a high-field regime with zero critical current and linear I-V characteristics in the entire current range; (2) a low-field regime with a finite critical current ($I_c \gtrsim 30\ \mu$A) (linear I-V response occurs only when $I \gg I_c$); and (3) a crossover regime where the I-V behavior is given by the dashed curves in Fig. 1(b). In this narrow field interval a linear I-V dependence could be detected at both small and large currents. Except from the latter observation, our results are very reminiscent of those of Worthington, Holtzberg, and Field on Y-Ba-Cu-O single crystals.[8] The field dependence of the low-current Ohmic behavior was measured more sensitively using an ac technique, with currents small enough to maintain a linear response, typically $I_{ac} < 10\ \mu$A.

In Fig. 2 we compare the differential resistivity $\rho_d \equiv dE/dJ$, determined at a flux-line velocity $v = E/B = 0.2$ m/s, with the microscopic theory for ρ_f in dirty superconductors which for various limiting cases has been given in Ref. 17. Close to B_{c2}, $\rho_f/\rho_n = [1+\alpha(1-b)]^{-1} \approx 1-\alpha(1-b)$. The dashed line in Fig. 2 displays ρ_f for $\alpha = 2.44$ and $B_{c2} = 0.911$ T. The inset of Fig. 2 shows the behavior of $\alpha(t)$ for the samples studied. The solid line represents the theoretical prediction for α as taken from Fig. 1 in Ref. 17, with the material parameter $\Gamma = 0.05$. Neglecting spin-orbit scattering, $\Gamma = h/4\pi k T_c \tau_e$, where τ_e is the inelastic-scattering time. Magnetoresistance measurements on amorphous Lu compounds[18] yield $\tau_e \approx 2 \times 10^{-10} T^{-2}$ s. Substituting $T = 2.5$ K yields $\Gamma = 0.04$. The temperature dependence of α is nicely reproduced by our data, although the absolute values are approximately a factor of 0.8 smaller, presumably due to a larger Γ value for a-NbGe.

An important consequence of this interpretation is that B_{c2} is determined by the criterion $\rho_d(B_{c2}) = \rho_n$ (solid arrow in Fig. 2) rather than by $J_c \to 0$. In Fig. 3 we give $B_{c2}(T)/B_{c2}(0)$ according to this criterion. The identification $\rho_d = \rho_f$ is further supported by the fact that



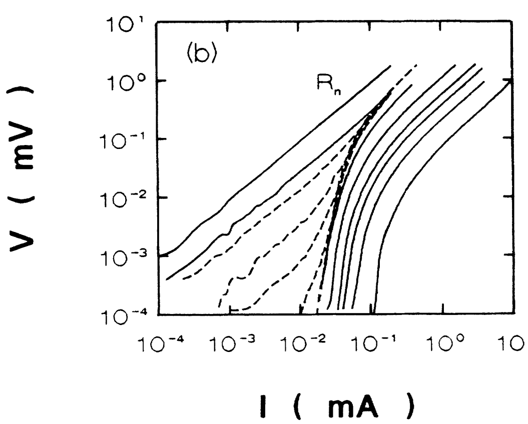


FIG. 1. I-V curves for sample II ($d = 565$ nm) at $T = 2.49$ K on (a) a linear and (b) a logarithmic scale. The solid curves were obtained at fields, increasing counterclockwise, of 0.048, 0.102, 0.152, 0.200, 0.300, 0.500, 0.700, and 0.910 T. Additional dashed I-V curves detailing the transition from superconducting to Ohmic I-V behavior are given in (b) with $B = 0.666$, 0.673, 0.680, 0.687, and 0.694 T.

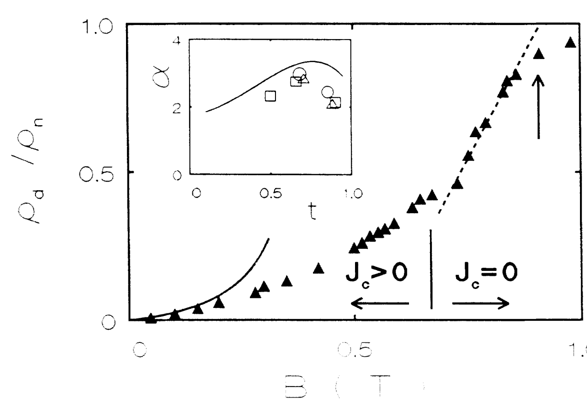


FIG. 2. The reduced differential resistivity ρ_d/ρ_n vs field for sample II at $T = 2.49$ K (solid triangles). The dashed and solid lines represent the theoretical expectation for ρ_f (see text). Inset: The theoretical expectation for $\alpha(t)$ and the values determined from ρ_d/ρ_n data close to $b = 1$: samples I (triangles), II (circles), and III (squares).

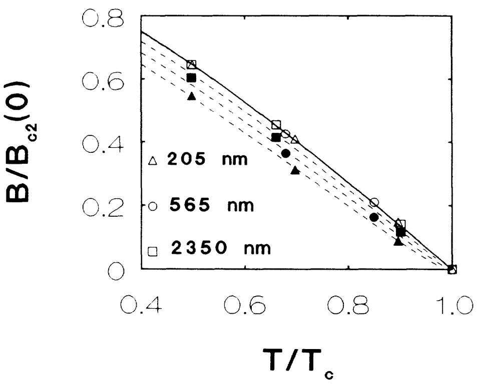


FIG. 3. Phase diagram of a-$Nb_{1-x}Ge_x$. $B_{c2}(T)/B_{c2}(0)$ data (open symbols) compared with the theoretical expectation (solid line) obtained from Ref. 19. $B_m/B_{c2}(0)$ data (solid symbols) compared with Eq. (2) (dashed lines) with $A=0.5$.

$B_{c2}(T)$ accurately follows the theoretical curve for 3D s-wave superconductors,[19] yielding $B_{c2}(0)=5.46$, 4.32, and 4.18 T for samples I, II, and III, respectively. No satisfactory fit was obtained when a more conventional criterion $\rho_d(B_{c2})=0.5\rho_n$ or $\rho_d(B_{c2})\rightarrow 0$ was used. The determination of B_{c2} allows us to evaluate the ρ_d/ρ_n data at low fields. The solid line in Fig. 2 represents the theoretical expectation for the circular-cell approximation described in Ref. 17. Note the good agreement with the nonlinear behavior valid at elevated temperatures.

We now include the $\rho_{ac}(b)$ data. In Fig. 4(a) these data (open symbols) are compared for all samples at $t=0.68$ with the ρ_d data (solid symbols) and the $\rho_f(b)$ curve (solid line). It is clearly seen that upon approaching B_{c2} all data merge with the solid line. The deviations just below $b=1$ can be attributed to paraconductive fluctuations to be addressed in a separate paper. In the field regimes where the data merge the state of the VL is characterized by $J_c=0$ and $\rho=\rho_f$. This must therefore be the vortex-liquid state. Going down in field, ρ_{ac} starts to decrease sharply, indicating the transition from the melted VL to the solid phase where pinning plays a role.

The low-resistive part of the ρ_{ac} data provides novel information concerning the transition into the melted VL. In Fig. 4(b) we show $\rho_{ac}(b)$ on a semilogarithmic scale. It is seen that the low-resistive tail of ρ_{ac} decreases exponentially. Recalling that the I-V response in this field interval (regime 3) is linear in the low-current range, we make use of the TAFF model and Eq. (1) to describe this behavior. Accordingly, Fig. 4(b) actually displays $-U/kT$ vs b at constant T. In Ref. 9 it was argued that the energy barriers for TAFF are related to the formation energy of edge-dislocation pairs. The energy for small pairs is given by $U\sim c_{66}a_0^2d$. Equation (1) shows that if $U/kT\rightarrow 0$, then ρ_{ac} equals ρ_f. Therefore, we define a field B_m as determined by the intercept of the $\rho_f(b)$ curve [dashed line in Fig. 4(b)] with the extrapolated ρ_{ac} curve and write $U\sim(1-B/B_m)^\beta$. For $\beta=1$

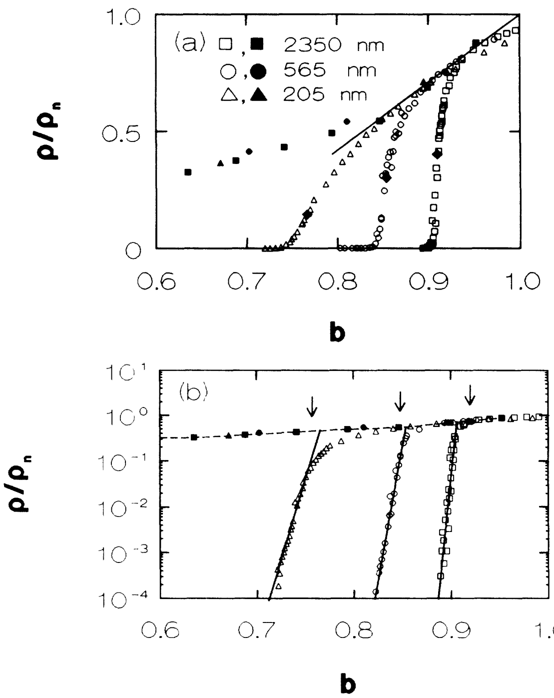


FIG. 4. The $\rho_{ac}(b)$ (open symbols) and ρ_d (solid symbols) data for a-$Nb_{1-x}Ge_x$ films at $t=0.68$ on (a) linear and (b) semilogarithmic scales. The solid line in (a) displays the prediction for $\rho_f(b)$ with $\alpha=2.9$. The solid lines in (b) determine $B_m(d)$ from the intercepts with the dashed ρ_d curve. These $B_m(d)$ values are given by the solid diamonds in (a). The arrows indicate the fields at which melting should occur according to Eq. (2) with $A=0.5$.

the B_m values, denoted by the solid diamonds in Fig. 4(a), correspond roughly with the inflection points of the resistiv- ity transitions. Although a linear approximation of $U(B/B_m)$ appears appropriate, the precise value of the exponent β is difficult to determine because of the narrow field range. Actually, the data can be fitted equally well by $\beta=2$ and slightly larger values for B_m. The dependence of B_m on *thickness* and *temperature* is well described by Eq. (2), with a constant $A=0.5$. The value $A\sim 0.5$ was also obtained in the work of Hebard and Fiory[3] and Gammel, Hebard, and Bishop.[14] The arrows in Fig. 4(b) indicate $B_m(d)$. In Fig. 3, the $B_m(t)$ data and Eq. (2) (dashed lines) with $A=0.5$ are seen to correspond very well. This, we believe, conclusively shows that B_m corresponds to the Kosterlitz-Thouless (KT) melting field. Since $U\rightarrow 0$ at B_m we conclude that U actually measures the behavior of the shear modulus c_{66} prior to melting.

The TAFF behavior we observe just below the melting line shows that in the regime where the critical current steeply decreases to zero, the zero-resistance vortex-glass picture is not valid. In 2D this is to be expected.[9] Below this regime our voltage resolution is not sufficient to make a definitive statement about the vortex state. The successful description of the 2D case might provide confidence that the 3D case is correctly modeled by the glass theory.[4] The controversy in the HTS between thin-film[5] and single-crystal work[8] might be a matter of dimensionality. Single crystals usually have much smaller critical current densities. This considerably increases the vortex-glass coherence length, presumably up to a level where it is of the order of the sample thickness leading to 2D behavior. It is interesting to note that the occurrence of 2D behavior and plastic creep is favored by the large anisotropy of the HTS, e.g. the Bi 2:2:1:2 compound.[20]

In summary, we have shown that thin films of a-NbGe can be used to study the interesting thermal properties of a 2D vortex lattice. Melting of the VL was established from the flux-flow behavior. Thermally assisted flux flow, due to mobile edge-dislocation pairs, occurs in a narrow field regime prior to melting. The melting field agrees well with the KT melting criterion. Ultrathin films or planar superconductors with weak coupling between layers are thus very sensitive to KT melting and (TAFF) creep since energy scaling with thickness occurs.

We thank J. A. Mydosh for a critical reading of this manuscript. These investigations were financially supported by the Dutch Foundation for Fundamental Research on Matter (FOM).

[1]D. R. Nelson, Phys. Rev. Lett. **60**, 1973 (1988); E. H. Brandt, *ibid.* **63**, 1106 (1989); A. Houghton, R. A. Pelcovits, and A. Sudbø, Phys. Rev. B **40**, 6763 (1989).

[2]J. M. Kosterlitz and D. J. Thouless, J. Phys. C **6**, 1181 (1973); B. A. Huberman and S. Doniach, Phys. Rev. Lett. **43**, 950 (1979); D. S. Fisher, Phys. Rev. B **22**, 1190 (1980).

[3]A. Hebard and A. T. Fiory, Physica (Amsterdam) **109 & 110B**, 1637 (1982).

[4]M. P. A. Fisher, Phys. Rev. Lett. **62**, 1415 (1989).

[5]R. H. Koch *et al.*, Phys. Rev. Lett. **63**, 1511 (1989); R. H. Koch, V. Foglietti, and M. P. A. Fisher, *ibid.* **64**, 2586 (1990).

[6]P. L. Gammel, L. F. Schneemeyer, and D. J. Bishop (unpublished).

[7]S. N. Coppersmith, M. Inui, and P. B. Littlewood, Phys. Rev. Lett. **64**, 2585 (1990); R. P. Griessen, *ibid.* **64**, 1674 (1990).

[8]T. Worthington, F. H. Holtzberg, and C. A. Field, Cryogenics **30**, 417 (1990).

[9]V. M. Vinokur, P. H. Kes, and A. E. Koshelev, Physica (Amsterdam) **168C**, 28 (1990); M. V. Feigel'man, V. B. Geshkenbein, and A. I. Larkin, Physica (Amsterdam) **167C**, 177 (1990).

[10]M. V. Feigel'man and V. M. Vinokur, Phys. Rev. B **41**, 8986 (1990); M. V. Feigel'man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, Phys. Rev. Lett. **63**, 2303 (1989); D. S. Fisher, M. P. A. Fisher, and D. A. Huse, Phys. Rev. B (to be published).

[11]P. H. Kes *et al.*, Supercond. Sci. Technol. **1**, 242 (1989).

[12]E. H. Brandt, Phys. Status Solidi B **77**, 551 (1976).

[13]P. H. Kes and C. C. Tsuei, Phys. Rev. B **28**, 5126 (1983).

[14]P. L. Gammel, A. F. Hebard, and D. J. Bishop, Phys. Rev. Lett. **60**, 144 (1988).

[15]A. I. Larkin and Yu. Ovchinnikov, J. Low Temp. Phys. **34**, 409 (1979).

[16]A dimensional crossover from a 2D to 3D disordered VL accompanied with an order-of-magnitude increase of J_c was observed in films with $d > 5$ μm. See R. Wördenweber and P. H. Kes, Phys. Rev. B **34**, 494 (1986).

[17]A. I. Larkin and Yu. Ovchinnikov, in *Nonequilibrium Superconductivity,* edited by P. N. Langeberg and A. I. Larkin (North-Holland, Amsterdam, 1986).

[18]S. J. Poon, K. M. Wong, and A. J. Drehman, Phys. Rev. B **31**, 1668 (1985).

[19]N. R. Werthamer, E. Helfland, and P. C. Hohenberg, Phys. Rev. **147**, 295 (1966).

[20]C. J. van der Beek and P. H. Kes (unpublished).