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Amplification of the c-axis vortex correlation by twin-boundary pinning at the vortex liquid-solid phase transition

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Transport measurements using the dc flux transformer configuration together with c-axis resistance data in clean and twinned $YBa_2Cu_3O_{7-\delta}$ single crystals show that vortices are localized by the twin-boundary potential. The results support the existence of a divergent tilt modulus [D. R. Nelson and V. M. Vinokur, Phys. Rev. B **48**, 13 060 (1993)] in a liquid that freezes into a Bose glass.

Vortex-lattice melting and the presence of a vortex-liquid phase in the mixed state of high-temperature superconductors have stimulated extensive experimental and theoretical investigation. The influence of disorder on the properties of the liquid phase and on the nature of the transformation from a vortex solid to a vortex fluid is not yet well established.[1]

Recent transport measurements[2] using the transformer configuration[3] in clean (untwinned) and twinned single crystals of $YBa_2Cu_3O_7$ (YBCO) have shown that the vortex liquid phases in these two materials have intrinsically different characteristics. In untwinned crystals the well established[4,5] melting transition at $T_m(H)$ takes place from a crystalline long-range ordered solid[6] into a liquid which is uncorrelated in all directions. In this sense the vortex liquid can be considered as a highly entangled[7] liquid with entanglement distances much shorter than the sample thickness.[8,9] Quite different is the situation for twinned crystals, where the vortex solid transforms[3] into a liquid of disentangled vortex lines at the temperature $T_i(H)$. The vortex velocity correlation in the c direction is lost[10] at a higher sample-thickness dependent temperature $T_{\rm th}(H)$. The difference in the hydrodynamic response of the liquid state of both types of crystals indicates that twin boundaries act as correlated defects.[11,12] As such, we expect them to influence not only the dynamics[13] of the liquid but also its elastic properties[2] as well as the characteristics of the solid formed at lower temperatures.[11]

In this paper we present transport measurements in YBCO (clean and twinned crystals) in the vortex liquid regime using a multiterminal contact configuration. We present additional evidence[2] which supports that in clean YBCO samples, the melting transition occurs from an ordered solid into an entangled liquid. In the presence of correlated disorder (twinned crystals), there is a disentangled vortex liquid separating the solid phase from the entangled high-temperature liquid. We show that the thickness dependence of $T_{\rm th}(H)$ is caused by the presence of twin boundaries acting as correlated defects,[11] promoting disentanglement and stabilizing a liquid of vortex lines.

The samples used in this study are seven twinned samples of different thicknesses, ranging from 10 to 90 μm, two untwinned crystals (15- and 35-μm thick) and one detwinned sample (100 μm). Typical dimensions in the ab plane are 0.8×0.5 mm. Electrical contacts with low resistance were obtained following the procedure described in Ref. 3. The transport measurements were performed using standard dc techniques.

In Fig. 1(a) we plot typical results for the top and bottom voltages, $V_{\rm top}$ and $V_{\rm bottom}$, as a function of reduced tempera-

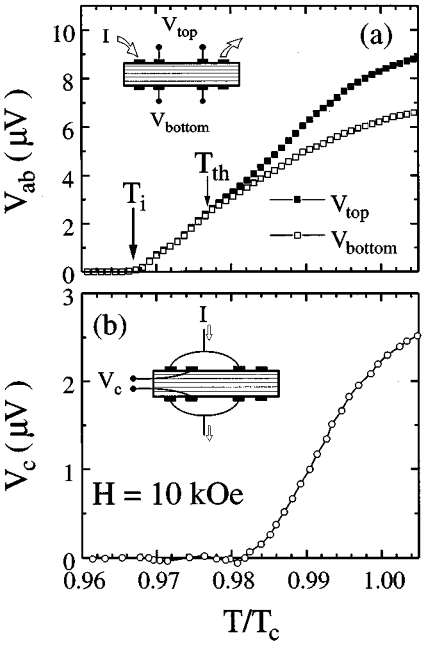

FIG. 1. (a) $V_{\rm top}$ and $V_{\rm bottom}$ as a function of reduced temperature for a twinned $YBa_2Cu_3O_{7-\delta}$ single crystal. (b) Temperature dependence of the voltage in the c direction for the same sample. The inset in each figure shows the respective contact configuration. The sample is 40-μm thick and the magnetic field is applied along the c axis.

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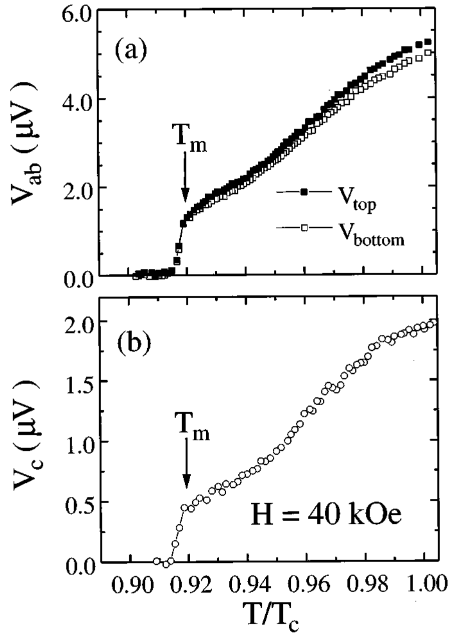

FIG. 2. Results obtained using the same contact and field configuration as in Fig. 1 for an untwinned $YBa_2Cu_3O_{7-\delta}$ crystal. The sample is 15-μm thick.

ture, T/T_c, using the transformer configuration [inset of Fig. 1(a)] for a twinned YBCO sample 40-μm thick. In this particular case the data has been taken at a field of 10 kOe parallel to the c axis. Similar results have been obtained in crystals of different thicknesses and magnetic fields ranging from 0 to 80 kOe. The current used in the measurements is 1 mA. The arrows in the figure indicate the two characteristic temperatures $T_i(H)$ and $T_{\text{th}}(H)$. The temperature $T_{\text{th}}(H)$ is determined[14] by measuring the temperature-dependent current density, $J_{\text{cut}}(T)$, necessary to induce vortex cutting. The temperature $T_{\text{th}}(H)$ is defined[14] as that where J_{cut} becomes zero. The temperature $T_i(H)$ is essentially that corresponding to $\rho_{ab}(T_i)=0$. Measurements of I-V characteristics[3] show in-plane linear response for $T>T_i$ and nonlinear behavior at temperatures below it. More experimental details and discussions on the definition of the different temperatures used in this work can be found in Refs. 3 and 10. Figure 1(b) shows the reduced-temperature dependence of the voltage in the c direction using the configuration shown in the inset of the same figure. The current used in this experiment is 1 mA, corresponding to a current density of 0.5 A/cm^2. Although the geometrical factor of the single crystals is not adequate[10] to measure resistivity in the c direction it is interesting to verify that the measured voltages reconfirm the behavior expected from the data using the transformer configuration. The I-V characteristics in the c axis are nonlinear[10,3] for $T<T_{\text{th}}(H)$ indicating that $T_{\text{th}}(H)$ marks the onset of coherence in the c direction. As was shown[10] previously, the vortex liquid has linear resistivity $\rho_{ab}\neq 0$ and $\rho_c=0$ (disentangled liquid) in the temperature range $T_i<T<T_{\text{th}}$.

In Fig. 2 we present the same measurements for an untwinned YBCO crystal in the presence of an external field of 40 kOe perpendicular to the ab plane. The arrows in the figures indicate the temperature $T_m(H)$, below which the I-V characteristics become nonlinear.[2] The experimental results show that the sharp drop of the in-plane resistance [Fig. 2(a)] observed in clean crystals coincides with the loss of c-axis coherence [Fig. 2(b)]. This indicates that in clean samples (with no correlated disorder) the melting transition takes place between a vortex solid and a highly uncorrelated vortex fluid (entangled liquid).

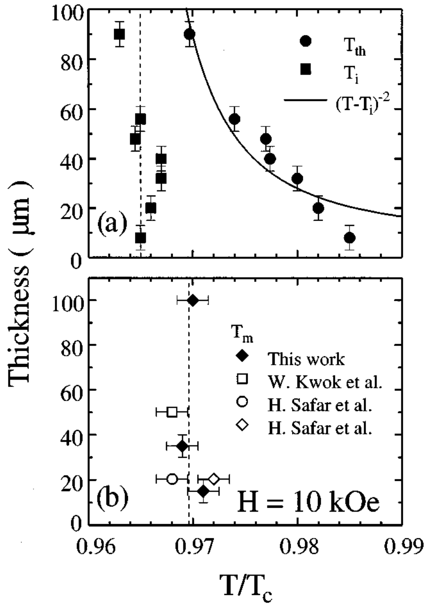

FIG. 3. (a) Thickness dependence of T_{th} and T_i for twinned samples. The solid line is a fit using Eq. (2). (b) Melting temperature T_m for several twin-free samples.

The results of Figs. 1 and 2 show quite clearly that there is no disentangled vortex liquid behavior in the clean samples. That is, the liquid has no vortex velocity correlation in the c direction and, consequently, it has a linear response with a finite resistivity in that direction, $\rho_c\neq 0$.

Figure 3(a) shows the thickness dependence of $T_{\text{th}}(H)$. In this case we have extended the results previously reported[10] to larger thickness values. In the same figure we have plotted the corresponding $T_i(H)$ for all samples. The melting temperature $T_m(H)$ for the detwinned and untwinned samples measured in this work is plotted in Fig. 3(b). For completeness we have included some data obtained from the literature.[4,5] The results in Fig. 3 make clear some relevant conclusions about the main characteristics of the vortex liquid state. The results indicating that the liquid in the clean samples is an entangled vortex liquid with a small cutting energy have been already discussed.[2] However, it is interesting to note the thickness independence of $T_m(H)$, within experimental resolution, for samples of different origin.

From its definition we see that $T_{\text{th}}(H)$ is the maximum temperature where vortex velocities across the sample are correlated. Following Ref. 9 the velocity correlation is lost when the sample thickness coincides with the vortex cutting length, defined as

$$l_c(T)\simeq l_o e^{U_x/kT}, \tag{1}$$

where l_o is the distance along the field direction between vortex encountering and U_x is the cutting energy. In this sense, the thickness dependence of $T_{\mathrm{th}}(H)$ should be the same as the temperature dependence of l_c. The large difference between the values of $l_c(T)$ for clean and twinned samples is evident from the results in Fig. 3. The thickness independence of $T_m(H)$ indicates that the vortex velocity correlation in these samples is established only after the solid phase forms at the melting temperature. Thus, the cutting length in the liquid has to be considerably smaller than the thickness of the thinnest untwinned sample measured (15 μm). On the contrary, in twinned samples the thickness dependence of $T_{\mathrm{th}}(H)$ implies a rapid increase of $l_c(T)$ when approaching $T_i(H)$.

The experimental results clearly show that the presence of twin boundaries not only modifies the nature of the liquid-solid phase transition, but also increases the stiffness of the vortices, stabilizing a disentangled phase at temperatures where the liquid of the clean system is fully entangled.

Following Nelson and Vinokur[11] the effect of correlated disorder is to stabilize a Bose glass ground state that melts at T_{BG} into a liquid with a tilt modulus that diverges as

$$c_{44}(T) \sim l_{\parallel}(T) \sim \frac{1}{|T-T_{\mathrm{BG}}|^2}, \tag{2}$$

where $l_{\parallel}(T)$ is the vortex localization length.

The full line in Fig. 3(a) is a fit of the experimental data to the temperature dependence of expression (2) and assuming $T_{\mathrm{BG}}=T_i$. Although the range of experimental data is limited the agreement with the temperature dependence indicated by (2) is good and to our knowledge is the first experimental result measuring a divergent elastic constant in a liquid that transforms into a solid through a continuous transition at T_{BG}. The results suggest that $T_i(H)=T_{\mathrm{BG}}(H)$, strongly supporting that the proposed[11] Bose glass phase is the ground state of the vortex solid in the twinned samples.

The data presented suggest the existence of a single phase transition in both clean and twinned samples when the thickness is large enough. In the first case the transition is a first-order phase transition, as supported by recent theoretical predictions[15,16] and numerical simulations.[17] In the case of twinned samples the data is consistent with a continuous transition from an entangled liquid to a Bose glass, as predicted by Nelson and Vinokur.[11] Evidence of this Bose glass transition has been obtained by W. K. Kwok *et al.*[4] through angular-dependent transport measurements.

The data of Fig. 3 can be used to estimate the amplification effect of the twin boundaries on the cutting length l_c. From Fig. 3(a) we see that at $t=0.97$, $l_c=90$ μm in the twinned sample. In the untwinned samples the cutting length has an upper limit of $l_c=10$ μm, estimated from the smallest thickness of the investigated crystals. We see that the minimum amplification factor increasing the vortex correlation in the twin boundary direction is 10. The maximum possible amplification effect is obtained assuming $U_x=0$, that is $l_c=l_o$. Using[8]

$$l_o \simeq \frac{M_\perp}{M_z}\,\frac{\phi_o \epsilon_1}{H k_B T}, \tag{3}$$

where $M_\perp/M_z$ is the mass anisotropy, ε_1 is the vortex line tension and ϕ_o is the flux quantum, with $\varepsilon_1 M_\perp/M_z \sim 0.5$ K/Å (Ref. 1), $H=10^4$ G and $T\sim 90$ K, we find that in this case the amplification factor would be $\sim 10^3$.

In conclusion, transport properties using different contact configurations have demonstrated the importance of twin boundaries as correlated defects in the determination of the equilibrium as well as the dynamic properties of the vortex liquid. The results strongly support that, in twinned crystals, the vortex matter at low temperatures has a Bose glass ground state.

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