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The upper and lower critical points are investigated in untwinned $YBa_2Cu_3O_{7-\delta}$ single crystals with dilute columnar defects. Dilute columnar defects raise the upper critical point, indicating that the transition near the upper critical point is a vortex entanglement transition. The lower critical point is very sensitive to columnar defect disorder and its position can be described by a Lindemann-like criterion similar to that for melting. Dilute columnar defects induce non-linear behavior in the I-V curves of the vortex liquid state above the lower critical point, which we interpret as a vestige of the critical region associated with the Bose glass transition below the lower critical point.

1. INTRODUCTION

The existence of a first order vortex melting transition in clean single crystals of $YBa_2Cu_3O_{7-\delta}$ (YBCO) has been well established through transport [1], magnetic [2], and thermodynamic measurements [3]. One of the salient features of the melting transition is the termination of the first order transition at an upper critical point [4] at high magnetic fields where the transition becomes higher order. The upper critical point has been widely discussed as a signature of increasing point pinning, first diminishing and finally destroying the first order character of the melting transition [5]. Supporting experimental evidence for this picture comes from the observation of a line of second magnetization peaks in the vortex solid phase in the vicinity of the upper critical point [6]. The second peak line reflects fundamental changes in the critical current and pinning of the solid, as would be expected at the onset of a disordered glassy state. The upper critical point can vary from a few Tesla up to 26 Tesla [3] in nominally clean YBCO crystals, suggesting that residual point disorder is a dominant factor in determining its value. Theoretical studies propose that vortex entanglement is a key element of the disorder in the glassy state above the upper critical point [7].

More recently, a lesser noticed *lower* critical point has been reported where the first order vortex melting transition disappears with decreasing field [3, 8]. Similar to the upper critical point, the lower critical point in nominally clean YBCO crystals varies widely, from a few hundred gauss to several Tesla. The nature of the lower critical point and the disordered phase below it are still largely unexplored.

In this paper we investigate the nature of the upper and lower critical points and the disordered phases associated with them by carefully introducing controlled densities of columnar defects via high-energy heavy ion irradiation. We find that columnar defect disorder has a dramatic effect on the lower critical point, shifting it from approximately 0.5 T in an unirradiated crystal to 4 T with a dose equivalent matching field B_ϕ of 1000 G. We identify the disordered phase below the lower critical point as a Bose glass [9]. Above the lower critical point, where a clear first order transition occurs, columnar defects introduce non-Ohmic behavior in the liquid state, which we interpret as a remnant of the critical behavior associated with the Bose glass transition at lower fields. Surprisingly, dilute columnar defects have a clear effect on the upper critical point even at 100 times the matching field B_ϕ, raising it from 9 T in the unirradiated crystal to 11 T in the irradiated one. We attribute this effect to the reduction of vortex wandering by the columnar defects, experimentally confirming that entanglement is a key feature of the disordered state above the upper critical point.

2. EXPERIMENT AND RESULTS

A single crystal of YBCO with dimensions 780μm (l) x 740μm(w) x 19μm (t) was grown and detwinned under uniaxial stress. The crystal was cleaved into four pieces, three of which were irradiated with 1.4 GeV $^{208}Pb^{56+}$ ions at Argonne's ATLAS heavy ion irradiation facility to dose matching fields B_Φ=100G, 1000G, and 1 Tesla, while the fourth was kept as a reference. Transport measurements with current directed in the ab plane of the crystal were performed using the standard four probe method with both ac and dc techniques in magnetic fields parallel to the c-axis up to 17 T at the National High Magnetic Field Laboratory. We present data comparing the B_Φ=1000G crystal and its unirradiated reference.

Figure 1 shows the superconducting resistive transition for H || c before and after irradiation normalized to the zero field transition temperatures of T_{co}=94.10K and 93.85K for the unirradiated and irradiated crystals respectively. The sharp kink in the resistivity for the unirradiated crystal is associated with the first order vortex lattice melting transition [1] and is observed from 0.5T up to about 9T where it disappears. For the irradiated crystal, we observe a similar kink in the resistivity starting near 4T and extending to beyond 10 Tesla, as shown by the arrows in Figure 1. First order melting is clearly demonstrated in the inset to Figure 1 where we show the temperature derivative of the resistivity for the irradiated crystal. The peaks in dρ/dT reflect the kink in the resistivity at the first order melting transition.

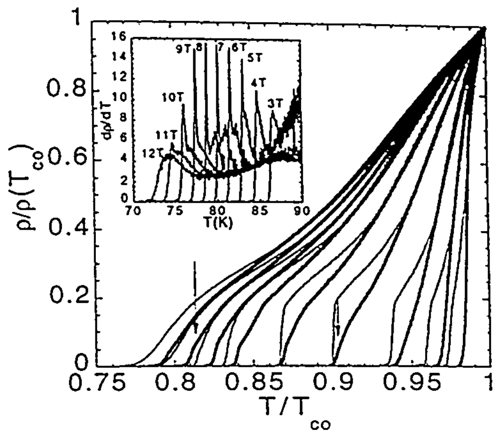

Figure 1. Temperature dependence of the resistivity for the unirradiated (thin lines) and irradiated (thick lines) crystals for H=0.5, 1, 2, 4, 6, 8, 9, 10, and 11T parallel to the c-axis. Inset: Temperature derivative of the resistivity for the irradiated crystal.

Figure 2 shows the phase diagram of the melting transition determined from the temperature derivative of the resistivity. First order vortex melting occurs in the region between the upper and lower critical points and is shown by triangles indicating the location of the peak in dρ/dT; above the upper critical point there is no peak in dρ/dT and the squares represent the locations of the resistive zeros. Comparison of the unirradiated and irradiated crystals shows a dramatic upward shift in the lower critical point from H_{lcp}=0.5T to H_{lcp}=4T. We interpret this shift as a disordering effect of the randomly placed columnar defects. At low fields comparable to the matching field B_ϕ, strong pinning of the columnar defects randomizes the positions of the pinned vortex lines and prevents formation of the lattice and first order melting. At fields well above the matching field, there are many unpinned vortices between columnar defects which are free to take up the lattice structure which minimizes their vortex interaction energy. At sufficiently high field the randomizing effect of the columnar defects is of little importance, and first order melting sets in as the ordered lattice structure becomes dominant.

In this picture, the lower critical point provides a quantitative measure of the degree of disorder needed to destroy first order melting. Our observation of the lower critical point at 4T for B_Φ=1000G indicates that randomizing the positions of B_Φ/B~2.5% of the vortices is enough to suppress first order melting. This condition for the loss of first order melting can be related to a Lindemann-like criterion for the onset of glassy behavior. The expected squared displacement of a randomly placed vortex from its equilibrium position is $a_0^2/2$. If we assume that 2.5% of the vortices are randomly displaced while the others are not displaced at all, the average square displacement is $<u^2> = 0.025\ a_0^2/2$. The average fractional displacement is then $(<u^2>/a_0^2)^{1/2} = (.0125)^{1/2} = 0.11$, remarkably similar

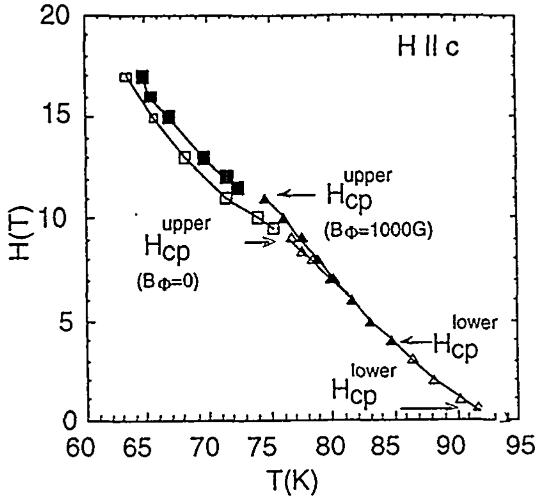

Figure 2. Superconducting phase diagram depicting the upper and lower critical points of the first order vortex melting transition in the unirradiatied (open symbols) and irradiated (closed symbols) crystals.

to the Lindemann criterion for melting by thermal disorder [10].

The picture presented above might suggest that the effect of dilute columnar defects is lost above the lower critical point where the first order melting transition is recovered. Remarkably, there are measurable effects of the columnar defect disorder even well above the lower critical point. The lower inset of Figure 3 shows the tail of the superconducting resistive transition for H=1T for the irradiated crystal, taken with two different measuring currents of 0.1mA and 1.0mA. Notice the absence of a kink defining the first order melting transition for this field which lies below the lower critical point. Instead, the two curves display a smooth monotonic decrease with decreasing temperature. The onset of non-ohmic behavior is clearly observed by the deviation of the two resistivity curves at T_{onset}. The upper inset of Figure 3 shows the same measurements taken above the lower critical point at H=8T. A distinct kink in the resistivity is observed, indicating the presence of a first order melting transition. However, unlike in pristine crystals where the onset of nonlinearity coincides with the kink in the resistivity, here the non-ohmic behavior sets in above the melting transition.

The main panel in Figure 3 compares the onset of non-ohmic behavior with the first order melting transition for the irradiated crystal. The shaded area indicates the region of non-Ohmic behavior in the liquid state above the first order melting transition. Non-ohmicity in the liquid state has also been observed in very dilute twinned crystals [11] where the twin boundaries act as correlated defects similar to the columnar defects presented here. Below the lower critical point non-Ohmic behavior can be understood as a signature of the critical behavior associated with the Bose glass transition. Elsewhere [12] we confirm the presence of a Bose glass below the lower critical point and extract the scaling exponents and Bose glass transition temperature from the non-Ohmic I-V curves. However above the lower critical point, the existence of both non-Ohmic behavior in the liquid *and* first order melting is anomalous. Non-Ohmic

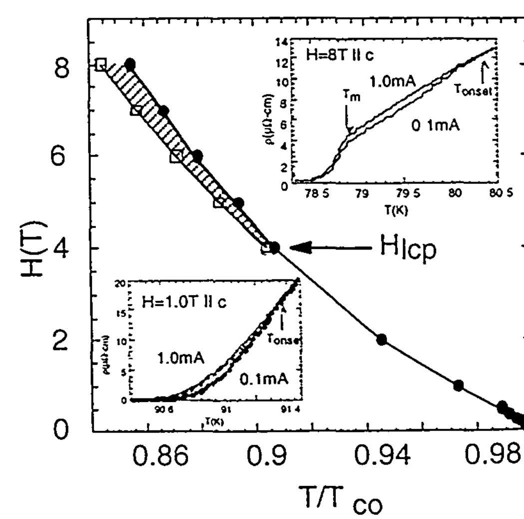

Figure 3. Phase diagram showing the onset temperature for non-ohmic resistivity (filled circles) and the first order vortex melting line (open squares) for the B_Φ=1000G irradiated crystal. Insets: Tail of the resistive transition measured with 0.1mA and 1.0mA for $H<H_{lcp}$ (lower) and $H>H_{lcp}$ (upper).

behavior does not occur in the liquid phase of untwinned, unirradiated crystals displaying first order melting. We interpret the non-Ohmic behavior as a vestige of the Bose glass transition below the lower critical point. It represents the high temperature onset of the critical region associated with the Bose glass transition, but above the lower critical point the critical region is abruptly cut off by the first order freezing transition. Non-Ohmic behavior is still visible above the lower critical point, because the Bose glass transition and its critical region always occurs at *higher* temperature than the bare first order melting transition in an undefected crystal [12]. This anomalous combination of non-Ohmic critical behavior and first order melting illustrates the subtle nature of the evolution from continuous Bose glass transition to first order vortex lattice melting with increasing vortex density.

There is a second high field effect of columnar defects that occurs at the upper critical point. Figure 2 shows that columnar defects raise the upper critical point of the irradiated crystal from 9T to 11T. This remarkably strong effect cannot be due to the randomization of the vortex line positions, since the randomization effect is lost at the lower critical point where first order melting is recovered. Rather, we interpret this effect as due to the line-like longitudinal geometry of the columnar defect, which reduces the transverse wandering and entanglement of the vortices. This effect tends to increase the order of the lattice state, and stabilizes it against entanglement to higher fields. The increase in the upper critical point by columnar defects provides direct experimental evidence that entanglement is a key feature of the high field disordered state.

3. SUMMARY

We have investigated the upper and lower critical points in untwinned single crystals of $YBa_2Cu_3O_{7-\delta}$ with a low dose-matching field of columnar defects. We demonstrate an enhancement of the upper critical point with a few columnar defects. The columnar defects suppress vortex line meandering due to the inherent point defects at high fields, thereby shifting the upper critical point to a higher field and give strong support for a vortex entanglement transition near the upper critical point. We find the lower critical point to be remarkably susceptible to correlated disorder. A simple picture relating the loss of first order melting at the lower critical point to the average displacement of vortices from their equilibrium positions by columnar pins yields a Lindemann-like criterion for glassy behavior remarkably similar to that for melting by thermal disorder. We show an anomalous region of non-Ohmic behavior in the vortex liquid above the lower critical point, and interpret it as the onset of a critical region associated with an incipient Bose glass transition which is interrupted by first order freezing.

4. ACKNOWLEDGEMENT

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