Effect of Pr scattering on the penetration depth λ_{ab} in $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ single crystals

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Four superconducting single crystals near the optimum-doped region ($x=0$, 0.11, 0.17, and 0.28) for the $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ system were chosen for detailed structural and magnetic measurements, in order to study the effect of Pr scattering on the temperature dependence of the ab-plane penetration depth λ_{ab}. The penetration depth for these incommensurate modulated single crystals follows a T^2 behavior at low temperature, and then crossover to a linear T dependence at the characteristic temperature T^*. Variation of linear T region and T^* with increasing Pr content indicates that Pr acts as a strong scattering center that modifies the local density of states of the system. The present result is consistent with the prediction for disorder-affected d-wave superconductors. [S0163-1829(98)01326-5]

I. INTRODUCTION

It is extremely important to understand the symmetry of high-T_c superconductors. Studies on the electromagnetic penetration depth λ at a temperature well below T_c are beginning to yield a consistent picture on the pairing state of high-T_c systems.[1–11] For example, recent penetration depth measurements on high-quality single crystals of $YBa_2Cu_3O_{7-y}$ and $Bi_2Sr_2CaCu_2O_{8+\delta}$ gave strong support to d-wave symmetry.[2] In $YBa_2Cu_3O_{7-y}$, the temperature dependence of the penetration depth was found to be linear in a wide temperature range,[1,2] while some other experiments often show a T^2 dependence[3–9] instead of the linear T characteristic expected for a clean d-wave superconductor. The discrepancy can be interpreted qualitatively as due to impurity or disorder scattering for a dirty d-wave superconductor. Particularly, Hirschfeld and Goldenfeld[10] predicted that there exists a crossover temperature T^* at which the dependence changes from the T to T^2 law due to impurity defect and disorder scattering. Recently, the temperature dependence of the penetration depth on T_c in $Bi_2Sr_2CaCu_2O_{8+\delta}$ was reported.[11] Samples with a maximum T_c show a linear behavior, while those with significantly reduced T_c follow a quadratic law. Since only the oxygen content δ is changed, it is not clear why the penetration depth follows a linear law in some samples, but not in all samples.

In order to study the effect of disorder substitution on the temperature dependence of the penetration depth, the $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ system is a good candidate due to the similar ionic radius of Pr^{3+} of 1.126 Å compared with Ca^{2+} of 1.12 Å. There have been many previous studies on the Pr-substituted systems.[12–14] However, previous studies are all on polycrystalline samples, which present very strong impurity scattering. In this paper, impurity-free clean single-crystal penetration depth data on the Pr-substituted $Bi_2Sr_2Ca_{1-x}R_xCu_2O_{8+\delta}$ system are reported.

II. EXPERIMENTS

Single crystals of the $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ system were grown using the standard self-flux method. High-purity Bi_2O_3, $SrCO_3$, $CaCO_3$, Pr_6O_{11}, and CuO powders with the off-stoichiometric ratio were mixed, ground, and calcined in air for 1 day. The reacted powders with excess Bi_2O_3 included as a flux were then used for crystal growth. The details for crystal growth will be described elsewhere.[15] The actual composition of the as-grown single crystals was determined from an energy dispersive x-ray (EDX) analysis using a Leica Steroscan 440 scanning electron microscopy. The average size of the single crystals was 4 mm×2 mm×0.04 mm. All single crystals were post-annealed at 360 °C in air for 3 days to ensure sample homogeneity.

Single-crystal x-ray data were obtained with a Rigaku Rotaflex 18-kW rotating anode x-ray diffractometer using graphite monochromatized Cu $K\alpha$ radiation with a scanning rate of 0.5°–1° in 2θ per minute. For the a-axis and b-axis x-ray diffraction measured in the transmission fashion, a fiber sample attachment with a divergence slit of 1/6° was used. All x-ray diffraction data were collected through careful alignment of the a, b, and c axes of the crystals. The anisotropic magnetic susceptibility $\chi_{ab}(T)$ and magnetization $M_{ab}(H)$ measurements were carried out with a μ-metal-shielded Quantum Design $MPMS_2$ superconducting quantum interference device (SQUID) magnetometer down to 5 K in an applied magnetic field from 1 G to 10 kG.

III. RESULTS AND DISCUSSION

Four superconducting single crystals near the optimum-doped region ($x=0$, 0.11, 0.17, and 0.28) for the

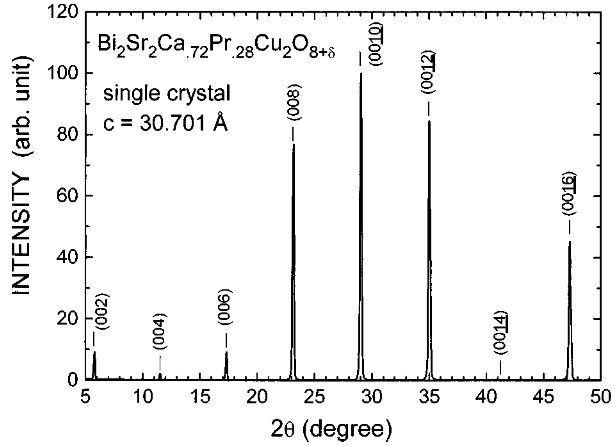

FIG. 1. X-ray diffraction pattern of orthorhombic (00l) lines for $Bi_2Sr_2Ca_{0.72}Pr_{0.28}Cu_2O_{8+\delta}$ single crystal.

$Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ system were chosen for detailed studies. Figure 1 shows a typical c-axis x-ray diffraction pattern for the single-crystal $Bi_2Sr_2Ca_{0.72}Pr_{0.28}Cu_2O_{8+\delta}$. No impurity lines were observed, and the Bi-2212-type (00l) diffraction lines give an orthorhombic c parameter of 30.701 Å. The b-axis diffraction pattern in Fig. 2 gives a b parameter of 5.439 Å and an incommensurate modulation along the b axis with period $s=4.56$. No modulation was observed along the orthorhombic a axis ($a=5.435$ Å).

The orthorhombic unit-cell volume increases from 902.3 Å^3 for $x=0$ to 907.6 Å^3 for $x=0.28$ and 912.1–922.5 Å^3 for $x=1$,[16] due to extra incorporated oxygen and a slightly larger ionic radius of Pr^{3+} of 1.126 Å compared with Ca^{2+} of 1.12 Å. The incommensurate modulation period along b axis decreases from $s=4.76$ for $x=0$ to 4.56 for $x=0.28$ and 4.16 for $x=1$, and the c parameter decreases monotonically from 30.849 Å for $x=0$ to 30.701 Å for $x=0.28$ and 30.267–30.363 Å for $x=1$.[16] The decreasing c parameter is probably due to one or more of the following reasons: (i) With increasing Pr content, the incorporated oxygen with positive charge in the Bi_2O_3 double layers increases and, consequently, causes the slab sequence SrO-BiO-BiO-SrO to shrink. (ii) With Pr doping, an additional band crosses the Fermi level, grabbing holes from the Cu-O d_σ-p band. The attractive interaction should result in the decrease of the separation between two CuO_2 layers. (iii) With predominant Pr^{3+} character, there may still exist some Pr^{+4} character[16] with a smaller ionic size compared with Ca^{2+}.

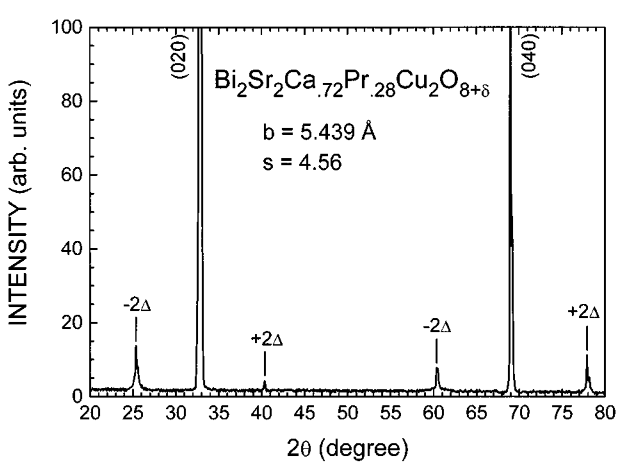

FIG. 2. X-ray diffraction pattern of orthorhombic (0k0) lines for a $Bi_2Sr_2Ca_{0.72}Pr_{0.28}Cu_2O_{8+\delta}$ single crystal. Incommensurate modulation lines are denoted by $\pm 2\Delta$.

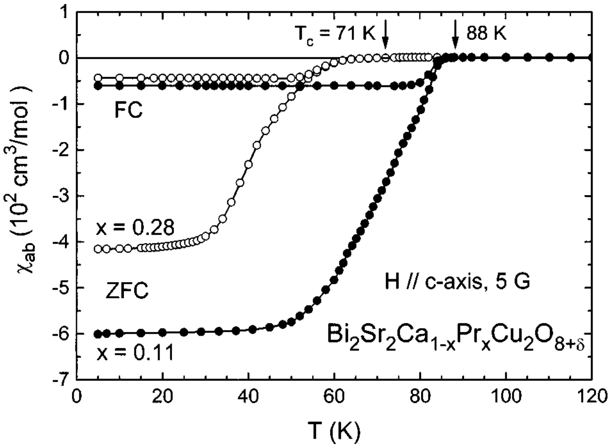

FIG. 3. Molar magnetic susceptibility $\chi_{ab}(T)$ with low applied magnetic field parallel to the c axis of superconducting $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ single crystals ($x=0.11,0.28$) in field-cooled (FC) and zero-field-cooled (ZFC) modes.

The ab-plane magnetic susceptibility $\chi_{ab}(T)$ with a 5-G low field parallel to the c axis of $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ single crystals as shown in Fig. 3 gives a superconducting transition temperature T_c of 88 K for $x=0.11$ and 71 K for $x=0.28$. Since a T_c of 86 K was observed for $x=0$ and 84 K for $x=0.17$, the optimum-doped composition is near $x=0.1$. Single crystals with $x=0.17$ and 0.28 are in the underdoped region and $x=0$ is already in the overdoped region. A metal-insulator transition occurred around $x=0.6$, and $Bi_2Sr_2PrCu_2O_{8+\delta}$ ($x=1$) is an insulator without long-range Pr ordering down to 0.5 K.[16] The diamagnetic response signal decreases systematically with increasing Pr concentration due to the damaging effect on the coherence of the two CuO_2 layers by the randomly distributed Pr ions between these two layers. Smaller field-cooled (FC) signal as compared with the zero-field-cooled (ZFC) signal indicated the flux trapping by single-crystal defects during the field-cooled process.

The ab-plane magnetization curves $M_{ab}(H,T)$ for four single crystals were measured with $T<T_c$. Figure 4 shows $M_{ab}(H,5\ \text{K})$ for four samples at 5 K. The ab-plane lower critical field H_{c1}^{ab}, defined as the field at which flux first penetrates, can be estimated from the $M(H)$ curves as a deviation from the linear M-H behavior corresponding to the Meissner state. For $H<H_{c1}$, the magnetization is reversible and no hysteresis loop was observed. For $H>H_{c1}$, the fact that the observed hysteresis loops for these single crystals are near symmetrical denies the effect of surface barriers on the determination of H_{c1}.[17,18] The ab-plane H_{c1}^{ab} (5 K) thus estimated are 255 G for $x=0$, 170 G for $x=0.11$, 130 G for $x=0.17$, and 95 G for $x=0.28$. For $x=0.11$, increasing temperature gives a lower H_{c1}^{ab} of 74 G at 10 K, 42 G at 15 K, 22 G at 20 K, and 12 G at 30 K (Fig. 5). Due to the low H_{c1}^{ab} values, a zero-field de-Gaussing procedure is thoroughly applied before every measurement to ensure the data quality.

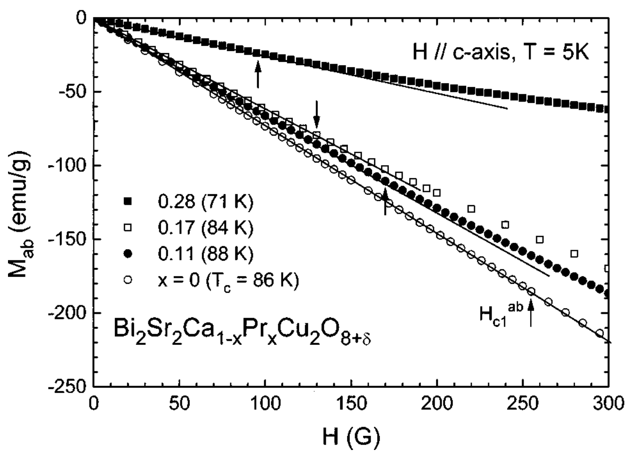

FIG. 4. Magnetization curves $M_{ab}(H)$ for $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ single crystals ($x=0$, 0.11,0.17,0.28) at 5 K. The lower critical field is denoted as H_{c1}^{ab}.

The ab-plane lower critical field H_{c1}^{ab} allow one to estimate the ab-plane penetration depth λ_{ab} using he equation $H_{c1}=\Phi_0 \ln\kappa/4\pi\lambda^2$, where Φ_0 is the fluxoid and κ is the Ginzburg-Landau parameter. Using κ of 130 from the parent compound $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Ref. 11) for all compounds, the estimated λ_{ab} (5 K) is 1800 Å for $x=0$, 2200 Å for $x=0.11$, 2500 Å for $x=0.17$, and 2900 Å for $x=0.28$. The extrapolated λ_{ab} (0 K) of 1650 Å for the parent compound $Bi_2Sr_2CaCu_2O_{8+\delta}$ is very close to the value reported using other measurement techniques.[3]

The temperature dependences of the penetration depth $\lambda_{ab}(T)$ for four single crystals with a magnetic field perpendicular to the CuO_2 layers are shown collectively in Fig. 6. At lower temperature $[T<(0.2\text{–}0.3)T_c]$, all samples show a T^2 behavior. However, a crossover from a T^2 to T dependence was observed at the crossover temperature $T^* \sim (0.2\text{–}0.3)T_c$. When the temperature is approaching T_c,λ_{ab} diverges as expected. The linear T region is extremely long from T^* of 16.5 to 55 K for the undoped parent compound $Bi_2Sr_2CaCu_2O_{8+\delta}$, and this linear region shrinks sharply with Pr doping as shown in Fig. 6.

For the clean d-wave superconductors with line nodes on the Fermi surface, theory predicts a linear T dependence penetration depth $\lambda \propto T^p$ $(p=1)$ at all temperatures.[10] However, in the present study using impurity-free clean single crystals, the presence of structural modulation and defects for the Bi-2212-type phase and the Pr random disordering effect in the Ca site, the defect and disorder scattering will force the clean-limit picture with linear T dependence to be observed only at higher temperature range, and a crossover to a scattering dominated T^2 dependence $(p=2)$ is expected at lower temperature.[10] Such a behavior was observed in the present studies. As shown in Fig. 7, regardless of the T_c variation from the overdoped to underdoped region, T^* monotonically increases from 16.5 K for $x=0$ to 18.9 K for $x=0.11$, 21.6 K for $x=0.17$, and 24.0 K for $x=0.28$. The T^* values of $(0.19\text{–}0.33)T_c$ are consistent with the theoretical predicted range of (0.12–0.27) T_c.[10] The reduction of linear T region and the variation of T^* with increasing Pr content indicates that Pr acts as a strong scattering center in the Pr-doped $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ system, which modifies the local density of states in the system and is consistent with the prediction for disorder-affected d-wave superconductors.

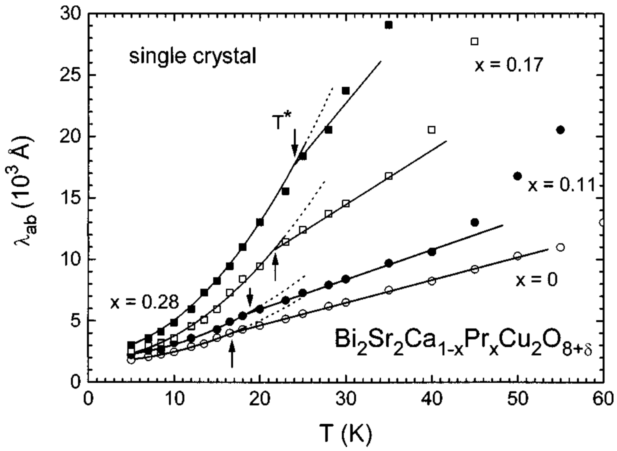

FIG. 6. Temperature dependence of the penetration depth λ_{ab} for $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ single crystals ($x=0$,0.11,0.17,0.28). The crossover temperature from a T^2 behavior to T dependence is denoted by T^*.

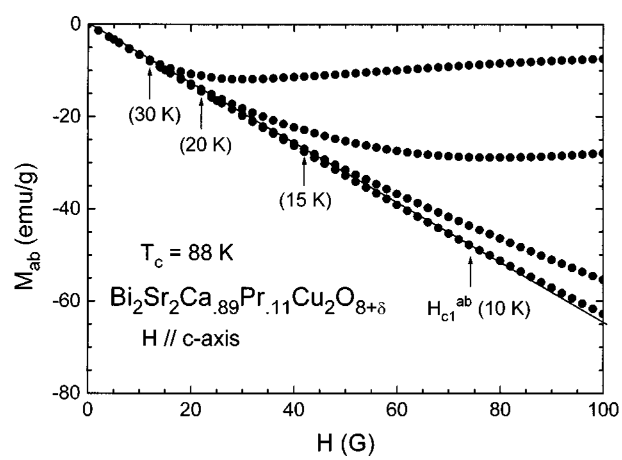

FIG. 5. Magnetization curves $M_{ab}(H)$ for a $Bi_2Sr_2Ca_{0.89}Pr_{0.11}Cu_2O_{8+\delta}$ single crystal at 10, 15, 20, and 30 K.

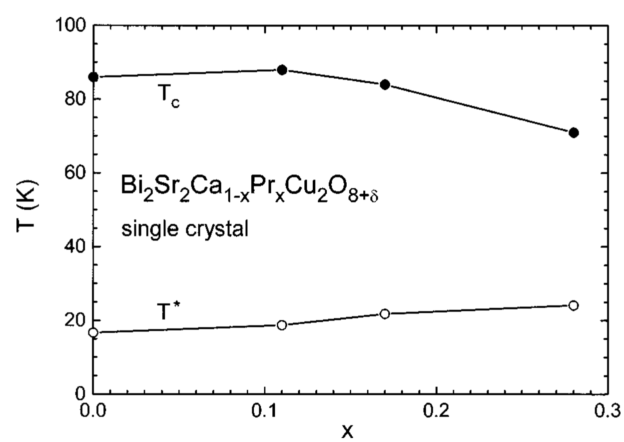

FIG. 7. Variation of the superconducting transition temperature T_c and crossover temperature T^* for the $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ system.

IV. CONCLUSIONS

In conclusion, using impurity-free clean single crystals, the Pr disorder in the $Bi_2Sr_2Ca_{1-x}Pr_xCr_2O_{8+\delta}$ system acts as the scattering center and increases the crossover temperature T^* from a quadratic to linear temperature dependence of the penetration depth λ_{ab}, which is consistent with the theoretically predicted behavior in defect and disorder-affected d-wave superconductors.

ACKNOWLEDGMENTS

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