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Dichotomy of photoinduced quasiparticle on CuO_2 planes of $YBa_2Cu_3O_7$ directly revealed by femtosecond polarization spectroscopy

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The dichotomy of photoinduced quasiparticle dynamics in the anisotropic high T_c superconductors ($YBa_2Cu_3O_7$) is revealed by using the orientation-resolved femtosecond reflection spectroscopy in the specially designed thin films. The transient reflectivity $\Delta R/R$ along the *ab* diagonal and *b* axis are totally different in the slow relaxation process which relates to the opening of the superconducting gap. In addition, the distribution of the temperature evolution of $\Delta R/R$ on the CuO_2 planes of $YBa_2Cu_3O_7$ may indicate the *d*-wave symmetry of the superconducting gap in high T_c superconductors. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2764237]

I. INTRODUCTION

Optical characterizations have become an important tool in modern materials research. For instance, polarized light may be used to investigate the anisotropic optical responses in anisotropic materials.[1] Recently, a great deal of research related to the dichotomy phenomena of quasiparticles (QP) has been reported and discussed in the community of strongly correlated electron. By the standard time-resolved measurements, the dichotomy between coherent nodal QP excitations and incoherent antinodal excitations has been associated to the abrupt change in the sign of transient reflectivity (ΔR) and the kinetics of QP decay in $Bi_2Sr_2Ca_{1-y}Dy_yCu_2O_{8+\delta}$ crystal.[2] However, the conclusions of dichotomy in $Bi_2Sr_2Ca_{1-y}Dy_yCu_2O_{8+\delta}$ crystal are not directly from femtosecond spectroscopy. Additionally, it is extremely difficult to measure the nodal characteristics in a small size single crystal by optical light. A natural alternative is to use thin film for such investigations. Here we demonstrate a method which combines both polarized femtosecond spectroscopy and thin films with specific orientations to reveal the dichotomy of photoinduced QP dynamics directly.

II. EXPERIMENT

In order to study the dichotomy of QP dynamics in the strongly correlated electron system, the polarization of pulses in the nearly collinear polarized pump-probe scheme (as shown in Fig. 1) should be controlled to probe the optical responses along each axis individually. The femtosecond pulses from a mode-locked Ti:sapphire laser, which produced a 75 MHz train of 20 fs pulses with a central wavelength of 800 nm, were prechirped via two prisms and split to two parts (i.e., pump and probe beams) by a beam splitter. One of both was modulated at 87 kHz by an acousto-optic modulator (AOM) and served as a pump beam. The intensity and polarization (electric field, **E**) of pulses can be adjusted by a $\lambda/2$ plate and a polarizer. The reflective intensity changes (ΔR) and the reflective intensity (R) of the probe beam were, respectively, measured via a lock-in amplifier and a multimeter as a function of delay time (t). Moreover, the $\Delta R/R(t,\ \phi_{\text{pump}},\ \phi_{\text{probe}},\ \theta)$ curves along various directions on the surface of a sample can be obtained by rotating the polarization of pulses at nearly normal incidence ($\theta \sim 0°$). If the polarization of pulses is perpendicular to the *c* axis of (110) films (see the inset of Fig. 1), one is able to measure the responses $\Delta R/R(t,\ 90,\ 90,\ \theta)$ along various directions on the *ab* plane by changing the angle θ. Thus, the three-dimensional polarization-dependent (or orientation-resolved) femtosecond time-resolved spectroscopy in the layered-structure materials could be doubtless carried out. Under this idea, the typical layered-structure material, $YBa_2Cu_3O_7$ (YBCO), was the testing sample in this study. Additionally, three types of the oriented YBCO thin films, i.e., (001), (100), and (110), were prepared by the pulsed laser deposition. For (001), (100), and (110) YBCO films, the zero resistance transition temperature (T_c) are 90.2, 89.7, and 88.2 K, respectively. All of them are the well characterized oriented thin films with >97% in-plane alignment, of which detail could be found in Refs. 3–5.

III. RESULTS AND DISCUSSION

The method combining both polarized femtosecond spectroscopy and specific thin films with various orientations

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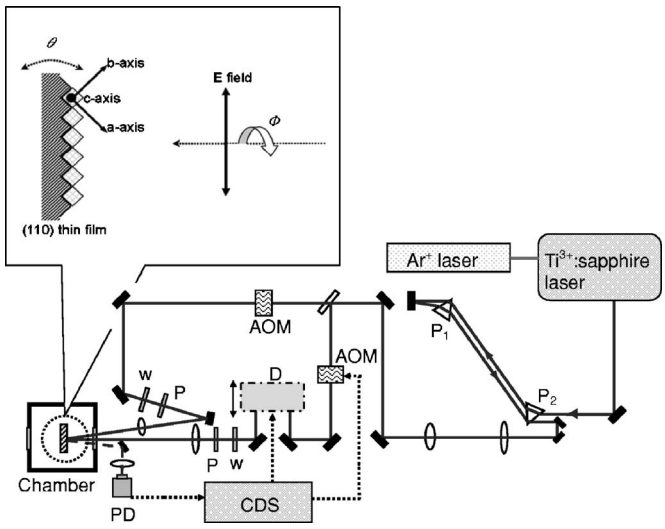

FIG. 1. The experimental setup for pump-probe spectroscopy. Code: AOM: acousto-optic modulator. *P*: polarizer. *w*: λ/2 plate. PD: photodiode. *D*: delay stage. CDS: control and detection system. P_1, P_2: prism pair for pulse compression. Both solid and dashed lines represent the laser beam paths and the dotted lines stand for the electrical signal connection. Inset: ϕ is the angle between the *c*-axis of the samples and the polarization of the pump (or probe) pulses. θ is the angle between the surface of samples and the polarization of the pump (or probe) pulses.

could be simply illustrated by Fig. 2. Here we consider some charges C_a, C_b, and C_{ab} located along the *a* axis, *b* axis, and *ab* diagonal in a cubic lattice structure, respectively. Under a proper driving force (e.g., the electric field of light), each charge could only move along one specific direction noted by its suffix. For the electric field $\mathbf{E}_a$ which is parallel with the *a* axis and incident along the *c* axis [i.e., **k** in Fig. 2(a)], the charge C_a will be driven and the charge C_{ab} will also be driven by the decomposed part of $\mathbf{E}_a$ which is parallel with the *ab* diagonal. The responses from other polarizations in Fig. 2 are summarized in Table I.

According to the results in Table I, there is no way to get the pure response of each type of charge via the simple configuration in Fig. 2(a), i.e., the propagating direction of incident light is perpendicular to the plane to be investigated. For example, the inset of Fig. 3 clearly demonstrates that the

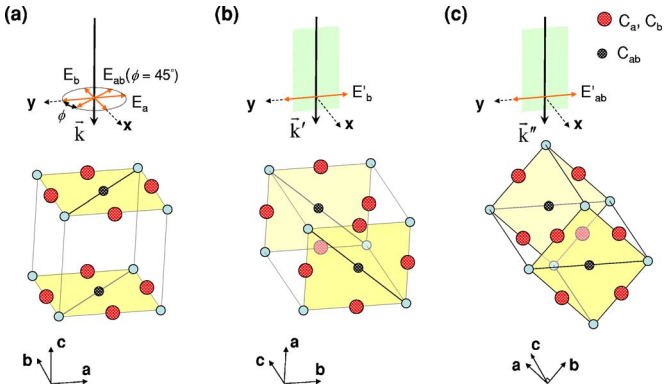

FIG. 2. (Color online) Schematic illustrations of the geometric relation between the polarized light and the two-dimensional (2D) charges in an anisotropic structure. C_a, C_b, and C_{ab} are the charges along the *a* axis, *b* axis, and *ab* diagonal, respectively. **k**, **k**′, and **k**″ are the wave vectors of the polarized light. ϕ is the angle between the *y* axis and **E** field.

TABLE I. The driven charges under various polarization configurations in Fig. 2(a).

Polarization of incident light	Driven charges
$\mathbf{E}_a$	C_a, C_{ab}
$\mathbf{E}_b$	C_b, C_{ab}
$\mathbf{E}_{ab}$	C_a, C_b, C_{ab}
$\mathbf{E}'_b$	C_b
$\mathbf{E}'_{ab}$	C_{ab}

responses on the twin-free (001) YBCO thin films are polarization independent. The $\Delta R/R$ measured at various polarization angles ($\phi=\phi_{\text{pump}}=\phi_{\text{probe}}=20°$, 50°, and 90°) are essentially identical. In this measuring configuration, the **E** field on *ab*-plane can be decomposed into two parts that are along the *a*-axis and *b*-axis, respectively. Therefore, the average responses of *a*-axis, *b*-axis, and ab-diagonal are always observed in (001) YBCO thin films, whether the polarization direction is parallel to the *a*(*b*)-axis or not. Furthermore, the usual (001) YBCO thin films often contain significant twins,

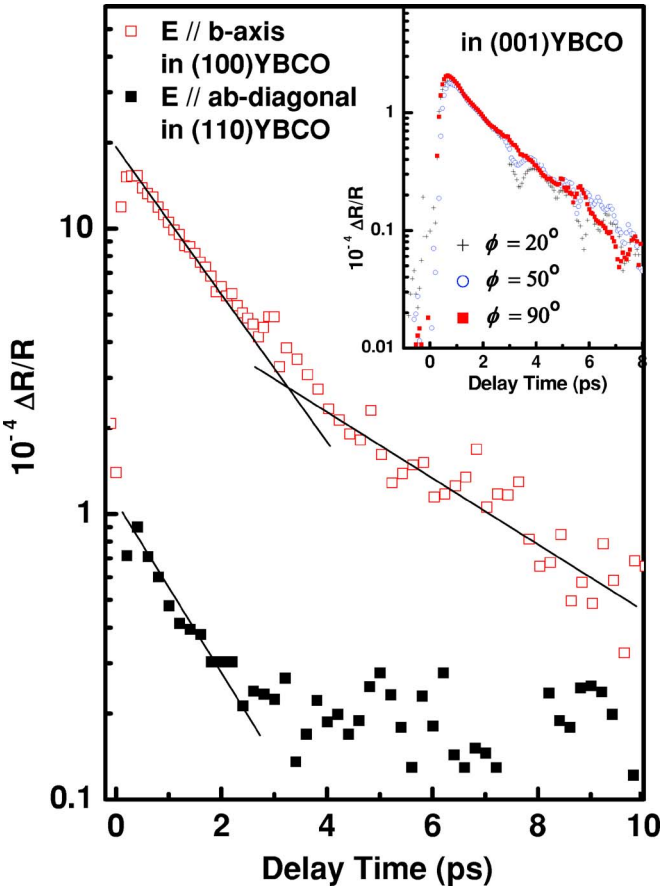

FIG. 3. (Color online) $\Delta R/R$ semilogarithmic plots of vs pump-probe delay time at 60 K on various crystalline orientations. The $\Delta R/R$ signal in the $\mathbf{E}\|b$-axis configuration was measured for (100) YBCO films by the polarized light with the wave vector **k**′ shown in Fig. 2(b). The $\Delta R/R$ signal in the $\mathbf{E}\|ab$-diagonal configuration was measured for (110) YBCO films by the polarized light with the wave vector **k**″ shown in Fig. 2(c). The solid lines are guides to the eye emphasizing the relaxation behavior of the photoinduced carriers along various crystalline orientations. Inset: $\Delta R/R$ signal measured at 70 K for a (001)YBCO thin film in several configurations with different angle ϕ between the *y* axis and **E** field [Fig. 2(a)] presented on a semilogarithmic scale.

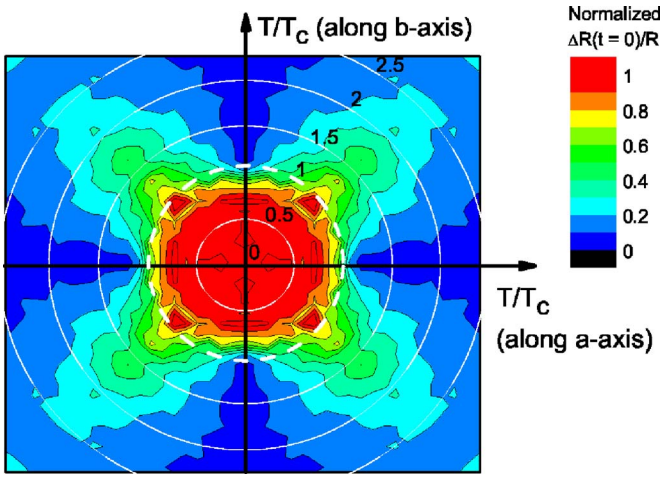

FIG. 4. (Color online) 2D distribution of the amplitude of $\Delta R(t=0)/R$ as a function of the reduced temperature (T/T_c) on the *ab* plane of YBCO. Inside the dashed circle is the superconducting zone where the temperature T is below T_c.

making it difficult to resolve the intrinsic properties along respective crystalline orientation. Thus, there is only one way to obtain the pure responses of charge C_b by the configuration in Fig. 2(b) or charge C_{ab} by the configuration in Fig. 2(c). For the direction of incident light $\mathbf{k}'$ or $\mathbf{k}''$, the propagating direction of the EM fields must lie along either the *a*/*b* axis or the *ab* diagonal so that the **E** field, which is perpendicular to the propagating direction, cannot be decomposed into the components along any directions on the *ab* plane [i.e., **E** field cannot be decomposed on the shaded plane in Figs. 2(b) and 2(c)]. Therefore, the $\mathbf{E}'_b$ field of incident light with propagating direction $\mathbf{k}'$ could only drive the charge C_b. Similarly, the $\mathbf{E}'_{ab}$ field of incident light with propagating direction $\mathbf{k}''$ could only drive the charge C_{ab}.

As shown in Fig. 3, the photoinduced $\Delta R/R$ responses along the *b* axis (or antinodal direction) and *ab* diagonal (or nodal direction) have been directly measured in the (100) and (110) YBCO thin films, respectively. It is extremely difficult to perform the same measurements in (001) thin films or single crystals. The $\Delta R/R$ along the *b* axis is dramatically distinct from the other one along the *ab* diagonal not only in the amplitude, but also in the relaxation dynamics. Two relaxation processes can be definitely observed along the *b* axis. Conversely, the slower relaxation process which could be associated with a generic manifestation of the superconducting gap opening[6] is absent along the *ab* diagonal (i.e., the nodal direction) within our experimental resolution. This disappearance of a QP relaxation bottleneck may be due to the complete shrinking of superconducting gap along the nodal direction. Furthermore, the amplitude difference of $\Delta R/R$ is about 5–10 times larger in the *b* axis than that in the *ab*-diagonal direction. These results evidently demonstrate that the dichotomy of QP relaxation between the *b* axis and *ab* diagonal.

The data displayed in Fig. 4 depict the amplitude evolution of the normalized $\Delta R(t=0)/R$ as a function of the reduced temperature (T/T_c) along various crystalline orientations on the *ab* plane of YBCO. For the *b* and *a* axis, the amplitude of $\Delta R(t=0)/R$ dramatically changes near T_c (dashed circle in Fig. 4), which is suggestive of the opening of the superconducting gap. However, there is no such kind of sharp boundary along the *ab* diagonal. The monotonic temperature evolution of $\Delta R(t=0)/R$ along the nodal direction may be dominated by the dynamics of QP thermalization[7] or recombination.[8] This result strongly suggests the behaviors of photoinduced QPs between nodal and antinodal directions are markedly different and obviously indicate that the symmetry of superconducting gap in the YBCO superconductors is *d*-wave symmetry. Moreover, this dichotomy phenomenon is consistent with the observations by other experimental methods. For example, the angle-resolved photoemission spectroscopy evidences that a nodal-antinodal dichotomous character does not only exist in the cuprate superconductors, e.g., underdoped $(La_{2-x}Sr_x)CuO_4$ (Ref. 9) and lightly doped $Ca_{2-x}Na_xCuO_2Cl_2$,[10] but also in the colossal magnetoresistive bilayer manganite $La_{1.2}Sr_{1.8}Mn_2O_7$.[11]

In summary, we have demonstrated a method which combines both polarized femtosecond spectroscopy and thin film preparation with specific orientations to directly reveal the dichotomy of photoinduced QPs on the CuO_2 planes of YBCO.

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