The Role of Defects in Persistent Photoconductivity in YBa$_2$Cu$_3$O$_{6+x}$

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Received 28 June 2000

In the persistent photoconductivity (PPC) phenomena, illumination of a material with light leads to a long-lived photoconductive state. During illumination of oxygen deficient YBCO near the insulator-metal transition, the illuminated material may even become superconducting. Accompanying the large relative changes in resistance are transport and structural changes as well as changes in the photoluminescence and infrared quenching spectrum. Infrared quenching data show that the magnitude of IR quenching saturates quickly as a function of visible photon dose, long before the PPC effect saturates. Our experimental and theoretical results have suggested that persistent photoconductivity (PPC) in YBCO may be explained by a model that incorporates both electrons trapped at defects (oxygen vacancies) and resulting structural rearrangement in the basal plane. A simple cellular automata model based on the idea that trapped electrons in the basal plane lead to structural rearrangements when illuminated with light predicts the correct time dependence of the photoexcitation process.

KEY WORDS: photoconductivity; superconductivity; quenching; defects.

1. INTRODUCTION

Several years ago the phenomena of Persistent Photoconductivity (PPC) [1] and Photoinduced Superconductivity (PISC) [2] were first reported in oxygen deficient YBCO. Persistent photoconductivity is characterized by a long-lived photodoped state. Accompanying the large relative changes in resistance ($\Delta \rho/\rho \sim 100\%$ or more) in the normal state are transport and structural changes. During illumination, the $c$-axis is observed to contract, with the same functional dependence on time as the resistivity [3]. Additionally, the bond length distribution between the Cu(1) and apical O(4) sites is observed to split into two well-defined peaks during illumination [4]. During illumination, oxygen deficient material near the insulator-metal transition may even become superconducting. Resistance, mobility, optical, and structural experimental studies and theoretical explanations of the PPC and PISC effects have recently been reviewed [5].

Attempts to explain the mechanism have generally fallen into two classes: (1) photoassisted oxygen ordering [6], and (2) a defect mechanism [7–10]. In the defect mechanism, an absorbed photon of light generates an electron–hole pair. The photogenerated electron is trapped at a defect—presumably an oxygen vacancy [11,12]. The trapping of an electron prevents the recombination of the hole with the electron, resulting in the transfer of a hole to the CuO$_2$ planes where it contributes to the conductivity. PPC has also been observed in overdoped compounds such as Tl$_2$Ba$_2$CuO$_{6+x}$ (Tl2201) [13]. In contrast to YBCO, the changes induced by visible illumination are completely reversible by illumination with infrared light. In this material there is no analogous structure to the chain layers in YBCO, so the mechanism for PPC is thought to be defect based [18], with the role of oxygen vacancies being replaced by that of interstitial oxygen.

In the photoassisted oxygen-ordering model, photons enable basal plane oxygen atoms to move...
within the lattice and become part of the CuO\(_x\) chains. As these chains lengthen, they inject holes into the CuO\(_2\) planes by acting as charge reservoirs \[14\]. A study of the enhancement of \(T_c\) by illumination \[15\] shows that, as a function of oxygen content, the net change in \(T_c\) is similar to the room temperature annealing effect studied by Veal et al. \[16\]. Likewise, the time dependence of the resistivity changes and corresponding energy barriers are similar for PPC and oxygen ordering. Because of these parallels, PPC was viewed by some as simply due to basal plane oxygen rearrangement \[5\].

Given our optical, transport, and structural experimental results for YBCO, we have come to believe that any successful model for PPC will include both defects as well as structural rearrangements. In particular, the trapping of photogenerated electrons at defect sites is a precursor to structural rearrangement.

2. EXPERIMENTAL DETAILS

The YBa\(_2\)Cu\(_3\)O\(_{6-x}\) samples used in this study were either fabricated at the Army Research Laboratory (ARL), the Naval Research Laboratory (NRL), or Advanced Technology Materials (ATM). Samples were grown either by pulsed laser deposition (PLD) or by single liquid source metalorganic chemical vapor deposition (MOCVD) with the details of the film growth, annealing, and characterization published elsewhere \[8–10\]. Typical samples studied had an oxygen content in the range of \(x = 6.2–6.4\). Samples are attached to a cold finger and placed in an optical cryostat. The samples are cooled and fully immersed in liquid nitrogen (LN\(_2\)). For each run, before illumination, the sample’s resistivity versus temperature curve is recorded. A current is applied across a bias resistor and a differential voltage across the sample is measured using standard 4-point resistivity techniques.

3. EXPERIMENTAL EVIDENCE FOR DEFECTS

3.1. Luminescence

If defects are important for PPC and PISC, then perhaps the defects luminesce and the luminescent intensity changes during exposure to light as the defects (traps) become filled. Experimental results \[8\] showing a correlation between photoluminescent intensity and the PPC state as well as a correlation between the photoluminescence spectrum and the wavelength dependence of the photoinduced conductivity suggest that defects play a role in PPC in which the defects act as weakly luminescent F-centers under illumination. Theoretical treatments of defects in YBa\(_2\)Cu\(_3\)O\(_{6.6}\) have shown that stable F centers can form in the CuO\(_2\) chains \[17\]. Moreover, it has been shown that changes in the c-axis and local orthorhombic symmetry can be directly attributed to electron trapping in the chain layers or the conversion of an \(\text{O}^2^-\) ion into \(\text{O}^-\) \[18\].

As an example, Fig. 1 shows the time dependence of the resistivity and 1.88-eV luminescence during the 4-W illumination of a YBa\(_2\)Cu\(_3\)O\(_{6.6}\) sample. The correlation between the photoinduced conductivity and

![Fig. 1](image-url)