Persistent photoconductivity and magnetoresistance in YBa$_2$Cu$_3$O$_{6.34}$ thin film

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Abstract. We have used persistent photoconductivity to smoothly tune the hole-doping in an underdoped cuprate in the critical doping region and studied its transverse magnetoresistance (MR). A series of YBa$_2$Cu$_3$O$_{6+x}$ (0.02 ≤ x ≤ 1) thin films of thickness ~50 nm were grown by sputtering and the oxygen contents were estimated from the c-axis lattice constant. The film YBa$_2$Cu$_3$O$_{6.34}$, with composition at the critical doping regime for the insulator-metal-superconductor transition ($T_C < 0.13$ K), was chosen for studying persistent photoconductivity and MR. The sample was illuminated at 0.8 K using an ultraviolet stroboscope with wavelength range of 220-700 nm for several hours. Resistivity down to 0.13 K and MR in a field up to 9T were measured in intermittent stages. The sample resistance was found to decrease exponentially with the illumination time. The field dependence of MR changed from quadratic to linear behavior after shining light on the sample for ~ 13 h. This cross-over in the field dependence of transverse MR clearly shows that the topology of the Fermi surface was changed drastically by shining light. Our observations suggest a pseudogap state as a precursor of superconductivity in YBa$_2$Cu$_3$O$_{6+x}$.

1. Introduction
The high temperature superconductivity (SC) in cuprates continues to be an active field of research even after two decades of intensive work. The superconductivity in cuprates is obtained by doping an antiferromagnetic (AF) Mott-insulator. Though the earlier interest was to understand the phenomenon of superconductivity itself, the focus has been currently shifted to the underdoped regime, particularly, into the critical doping region which separates superconductor from the AF insulator. While doping destroys the AF phase, short-range antiferromagnetic spin fluctuations persist well into the superconducting dome [1]. Evidence from various experimental techniques [2] points to a universal phenomenon of a pseudogap state in this regime where parts of the Fermi surface (FS) become gapped while other parts retain their conducting properties. With increased doping the gapped portion diminishes and the material becomes more metallic. In an isotropic metal with a spherical FS, the classical magnetoresistance (MR) is zero [3]. Therefore, studying the MR is particularly appealing because it probes the deviations of the FS from sphericity and provides unique information on the electron scattering processes around the FS. The MR in cuprates is highly anisotropic and strongly depends on the
direction of the current $J$ and the applied magnetic field $B$ [4, 5] owing to the quasi-2D layered structure, the $d$–wave symmetry of the order parameter and the interplay of spin and charge. In YBa$_2$Cu$_3$O$_{6+x}$, the normal-state transverse ($B \parallel c$, with $J \perp c$) MR is positive [6] whereas the longitudinal ($B \parallel J \parallel c$) MR is negative [7], but both display a quadratic dependence to the applied field. On the other hand, a linear field dependence of positive MR has been observed near and below $T_c$ in applied fields high enough to suppress the superconductivity [8]. The origin of this linear MR is not understood.

Here we present transverse MR studies of an underdoped, non-superconducting YBa$_2$Cu$_3$O$_{6+x}$ thin film. In order to dope holes into the CuO$_2$ plane, we use a property called persistent photoconductivity [9], i.e., changing the conductivity of the material at low temperatures in an irreversible way by shining light. The resistivity of the virgin film can be recovered only by heating the sample above 200 K. This method allows us to smoothly tune the hole-doping across the AF-SC boundary in the same sample.

2. Experimental
A series of YBa$_2$Cu$_3$O$_{6+x}$ (0.02 $\leq x \leq$ 1) thin films with thickness $\sim$50 nm were grown on SrTiO$_3$(100) substrates by sputtering. All the films were deposited at 840 $^\circ$C in an oxygen pressure of 300 Pa at a growth rate of about 2.5 nm/min. After the deposition the films were cooled to 600 $^\circ$C at a rate of 100 $^\circ$C/min in oxygen pressure of 300 Pa. In order to control the oxygen content, the films were in situ annealed at 600 $^\circ$C in a reduced oxygen pressure in the range 300 - 0.33 Pa. The films were then cooled to room temperature in the natural cooling rate. The oxygen contents in the films were estimated from the $c$-axis lattice constants [10]. The insulating film YBa$_2$Cu$_3$O$_{6.34}$ (YBCO), with composition at the critical doping regime for the insulator-metal-superconductor transition was chosen for the persistent photoconductivity and MR studies. The resistivity and MR measurements were carried out in a dilution refrigerator (Oxford Instruments). An ultraviolet stroboscope with wavelength range of 220-700 nm was used for illuminating the sample at 0.8 K.

3. Results and discussion
The normalized in-plane resistance $R(T)/R(300)$ of the YBCO film in the range 300 - 10 K is presented in figure 1(a). It shows metal-like behavior down to 120 K. This is close to the Néel
temperature $T_N$ [11]. Below $T_N$, the resistance increases, but the behavior is not consistent with simple band insulator or Anderson model [4]. The influence of the light illumination on the resistivity of YBCO at 0.8 K is displayed in figure 1(b). When the light is turned on, the radiation heats the sample and the resistivity falls sharply. When the light is tuned off, the system cools back to 0.8 K, and the resistivity now has a lower value confirming increased charge carrier density due to the photoexcitation. Mechanisms for this persistent photoconductivity can be found elsewhere [9, 12]. Upon completion of each illumination cycle, the temperature and the field dependence of the resistivity were measured. A series of intermittent resistivity vs. temperature $\rho(T)$ measurements are shown in figure 2(a). After each illumination, $\rho$ decreased and showed an exponential dependence on the illumination time $t$, i.e., $\rho(t) = \rho(0) \exp(-t/t_0)^{-\beta}$, $0 < \beta < 1$, and $t_0$ is a fitting parameter (figure 2(b)). This implies that the further decrease of $\rho$ becomes very slow with increasing $t$. The system could not be driven to superconducting phase even after a total $t$ of 186.7 h. However, after illuminating for $t \sim 13$ h, the sample passed through a regime at which the field dependence of the MR changed from quadratic to linear behavior as can be inferred from figure 3(a). We observe that the transverse MR in $\text{YBa}_2\text{Cu}_3\text{O}_{6.34}$ at 0.8 K (i) is positive and large (increases up to 40% in 9 T) (ii) does not saturate in fields up to 9T (iii) exhibits a crossover from quadratic to linear field dependence when the charge carrier density is enhanced by photoexcitation. The last point is also evident from figure 3(b), where a quadratic and linear fits to the MR data collected after illuminating the sample for $t = 625$ and 88727 s, respectively, are presented. A similar crossover in the field dependence of MR has been observed in electron-doped superconductor $\text{Pt}_2\text{Cu}_x\text{Ce}_x\text{CuO}_4$ in the over doped regime [13]. A linear field dependence of MR has also been found in the normal state of superconducting $\text{Sr}_2\text{RuO}_4$ [14].

Figure 2. (a) The temperature dependence resistivity of YBCO thin film below 2 K after a series of photo illumination for times shown in the figure (b) The resistivity at 0.13 and 0.8 K displaying an exponential dependence on the illumination time.
Figure 3. (a) The field dependence of magnetoresistance of YBCO film at 0.8 K after photo illumination for times shown in the figure. (b) The quadratic and linear dependence of the MR on the applied magnetic field after illuminating the sample for \( t = 625 \) and \( 88727 \) s, respectively.

with field. Whether there exists a QCP in cuprates for a critical doping at the AF-SC boundary is still an open question thereby leaving the exact mechanism of MR unresolved.

In summary, we have studied the magnetic field dependence of transverse MR of \( \text{YBa}_2\text{Cu}_3\text{O}_{6+x} \) thin film as a function of hole-doping. Above a threshold value of doping, a linear field dependence of the MR is observed. This behavior is a manifestation of a pseudogap state as a precursor of superconductivity in \( \text{YBa}_2\text{Cu}_3\text{O}_{6+x} \).

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