Superlattices and Microstructures 68 (2014) 6–15

Contents lists available at ScienceDirect

Superlattices and Microstructures

journal homepage: www.elsevier.com/locate/superlattices

Temperature-independent pseudogap and thermally activated *c*-axis hopping conductivity in layered cuprate superconductors

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ARTICLE INFO

Article history:
Received 30 October 2013
Received in revised form 31 December 2013
Accepted 8 January 2014
Available online 15 January 2014

Keywords:
Cuprate superconductors
Nanoscale phase separation
Electron–phonon interactions
Localized (bi)polarons
Pseudogap formation
c-Axis charge transport

ABSTRACT

The carrier localization (confinement) and *c*-axis charge transport in high-T_c layered cuprates have been investigated in the temperature-independent pseudogap state over a wide doping range from the underdoped to the overdoped regime, focusing on the nanoscale phase separation into two different domains (i.e. carrier-rich CuO_2 layers and carrier-poor regions between the CuO_2 layers) caused by inherent nanoscale electronic inhomogeneities and on the real-space pairing of polaronic carriers caused by strong electron–phonon interactions in carrier-poor regions. A simple microscopic model for layered cuprate superconductors is proposed to describe the carrier confinement and formation of localized bipolarons in the low-doping regions between the CuO_2 layers and to simulate the *c*-axis hopping transport at the thermal dissociation of such bipolarons. This model is found to describe properly the *c*-axis charge transport, which is governed by thermally activated hopping of polarons residing in the localized state between the CuO_2 layers due to the existence of the temperature-independent bipolaronic pseudogap, and the insulating behavior of the *c*-axis resistivity $\rho_c(T)$ observed above T_c in various cuprate superconductors, from the underdoped to the overdoped regime. It is found that the insulating behavior of $\rho_c(T)$ is changed to metallic behavior with disappearing of bipolaronic pseudogap.

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http://dx.doi.org/10.1016/j.spmi.2014.01.004
0749-6036/

1. Introduction

Since the discovery of the high-T_c cuprate superconductors [1,2], their peculiar normal state properties have been extensively studied over the past decades. It has increasingly clear that the mechanism of high-T_c superconductivity in the cuprates is related to the unusual normal state properties of these complex materials not encountered before in conventional superconductors. The most attractive normal state properties of underdoped to overdoped cuprates are their charge transport properties, which are significantly different from those of conventional superconductors [3–13]. In these materials, the electronic inhomogeneity and charge ordering play an important role in nanoscale phase separation in real space with the formation of alternating metallic and insulating stripes [14–17]. It has also been suggested that the so-called pseudogap (PG) phase could be resulted from inhomogeneous charge distributions containing carrier-poor and carrier-rich regions [17,18]. The transport coefficients in cuprates show interesting non-Fermi liquid behaviors, many of which have not been settled yet theoretically. Numerous experimental studies (see, e.g. Refs. [4–13,19,20]) have shown that the in-plane and c-axis charge transport properties of underdoped to overdoped cuprates deviate from the standard Fermi-liquid behavior. Such deviations become even stronger in the PG phase, as testified by the monotonic increase of the out-of-plane (c-axis) resistivity ρ_c down to T_c [4–9,12] and a change of slope in the temperature dependence of the in-plane resistivity ρ_{ab} in high-T_c cuprates in the lightly to moderately overdoped range [5,10,13,19,21,22]. For the normal state of underdoped to overdoped cuprates, ρ_{ab} shows unusual metallic behavior above T_c, while the normal-state charge transport along the c-axis is incoherent and ρ_c in most of cases shows insulating behavior. Such a contrasting behavior between $\rho_{ab}(T)$ and $\rho_c(T)$ is not expected in the conventional Fermi-liquid metal. Here, one of the key questions is that why the c-axis resistivity differs so much from the in-plane resistivity in the normal state of high-T_c cuprates.The c-axis conductivity in high-T_c layered cuprates is interesting due to possible link with the nature of a PG observed in these materials. The c-axis resistivity quickly increases with decreasing doping and temperature, indicating that there is some kind of carrier localization in the c-direction. It is likely that the carrier localization becomes possible in the PG state and is responsible for the carrier confinement in the low-doping regions between the CuO_2 layers of the cuprates. It is believed that the non-Fermi-liquid state called "carrier confinement" manifests itself in the nonmetallic transport and in the suppression of c-axis conductivity at relatively low temperatures especially for the underdoped cuprates, which are in strong contrast to a Fermi-liquid metal. There have been many different views regarding the carrier confinement and incoherent c-axis conduction in the cuprates [7,20,23,24], but it is fair to say that the carrier confinement, the PG formation and c-axis charge transport mechanisms are not well understood yet. A simple microscopic model capable of a unified description of these interrelated phenomena in high-T_c layered cuprates is therefore desirable.

In this work, we study the specific mechanisms of carrier localization (confinement) and c-axis charge transport within a simple microscopic model for layered cuprate superconductors, based on the nanophase segregation into two different domains (i.e. carrier-rich CuO_2 layers and carrier-poor regions between the CuO_2 layers), the existence of localized bipolarons in carrier-poor regions and the existence of the energy barrier with the height equal to the binding energy of bipolarons, over which the charge transport is determined by two complementary processes, namely thermal dissociation of localized bipolarons lying between the CuO_2 layers into separate polarons and subsequent thermally activated hopping of polarons over the barrier along the c-axis. We argue that in doped cuprates the inhomogeneous spatial distribution of polaronic carriers leads to their segregation into carrier-rich and carrier-poor regions in the form of alternating nanoscale metallic and insulating domains with mobile and immobile (i.e. localized) carriers, respectively. We show that the temperature-independent bipolaronic PG and carrier-confinement effects are responsible for the insulating behavior of ρ_c observed in the cuprates. Using the proposed model, we have been able to fit a large set of ρ_c data taken in various high-T_c cuprates following the change of the temperature dependence of the c-axis resistivity with increasing of the doping level.

The paper is organized as follows. In the next section we analyze the role of the electronic inhomogeneity and real-space pairing of interlayer polaronic carriers in the nanoscale phase separation,