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Macro- and mesoscopic electrical transport properties of $PrBa_2Cu_3O_{7-\delta}$

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Abstract. In this paper we investigate the resistivity of both macroscopic $PrBa_2Cu_3O_{7-\delta}$ (PBCO) thin films, and mesoscopic YBCO/PBCO/YBCO junctions. The electric transport properties of thin films can be described in the framework of Mott's variable-range hopping theory. In the mesoscopic regime direct and resonant tunnelling are the main transport processes in junctions with a barrier thickness up to 50 nm.

1. Introduction

Directly after the discovery of the exceptional semiconducting behaviour of $PrBa_2Cu_3O_{7-\delta}$ (PBCO) research started on bulk samples of this intriguing material [1]. The bulk transport properties of PBCO single crystals and pellets were studied extensively, and could be well described by the Mott theory for variable-range hopping. For several years now, PBCO has been widely used as a barrier material in high-T_c Josephson junctions. The transport properties of these junctions are described on a mesoscopic scale by assuming a quantum mechanical potential barrier - with or without localized states - between two superconducting electrodes.

2. Theory

In the *macroscopic* Mott model charge carriers hop between localized states, and are trapped on a localized state for a certain time. The classic Mott model can be extended to include both temperature and electric field activation [2]. This yields in the two dimensional case for the PBCO resistivity ρ_{PBCO} as a function of the temperature T and the applied electric field E in the x direction:

$$\rho_{PBCO}(T,E) = \rho_0 \exp\left(\left[\frac{k_B T_0}{k_B T + e\varepsilon_r E r_x(T,E)}\right]^{1/3}\right), \qquad (1)$$

with $r_x(T,E)$ being the average hopping distance in the direction of the applied electric field, e the unit charge, ε_r the relative dielectric constant, T_0 a constant temperature, and k_B Bolzmann's constant.

In the *mesoscopic* regime the Glazman - Matveev (GM) theory [3] describes the inelastic tunnelling across thin amorphous films. Glazman and Matveev derived for the averaged conductivity $<G_n>$ of a channel containing n localized states as a function of the temperature T, the barrier thickness d, and a decay length a:

$$\langle G_n \rangle \propto (k_B T)^{n-\frac{2}{n+1}} \left(\exp\left(-\frac{d}{a} \right) \right)^{2/(n+1)} . \tag{2}$$

In the limit for strong electric field, $eV >> k_BT$, eV is substituted for k_BT. On increasing the activation energy, the channels containing more localized states become dominant in the total barrier conductance. In the literature the GM theory was applied successfully to conduction in Nb junctions with a thin amorphous silicon barrier [4]. Some authors applied the GM theory to high-T_c YBCO/PBCO/YBCO junctions [5,6].

3. Experimental

All films used in this research are deposited by off-axis RF magnetron sputtering, are c-axis oriented and optimally oxygen loaded. In order to pattern the samples for the thin film measurements we employed wet chemical etching, for the ramp-type junctions we used Ar ion-milling to etch the ramp in the YBCO/PBCO bi-layer. A detailed study of the growth of the PBCO barrier on the ramp was carried out, and revealed a complicated non-homogeneous island type growth mechanism [7].

Employing the Transmission Line Model to compensate for the contact resistance of the noble-metal electrodes, we measured the resistivity of PBCO thin films as a function of temperature and applied electric field. The results are plotted in figure 1. Above 120 K thermal activation determines the PBCO resistivity, below 120 K additional activation by the applied electric field can be identified.

From the data presented in figure 1 we calculated the average hopping distance r_x in the direction of the applied field. An increase in the average hopping distance in the x direction implies an increase in the average total hopping distance. On increasing the

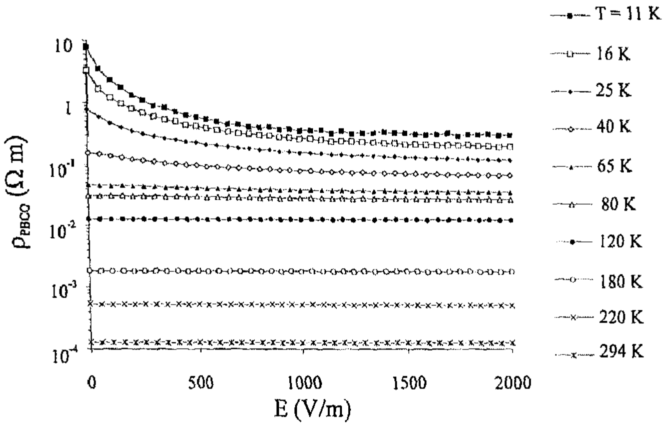

Figure 1: The PBCO resistivity ρ_{PBCO} as a function of temperature T, and applied electric field E.

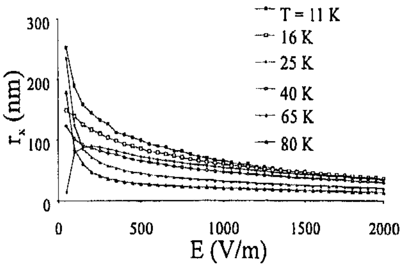

Figure 2: The average hopping distance r_x in the direction of the applied electric field E.

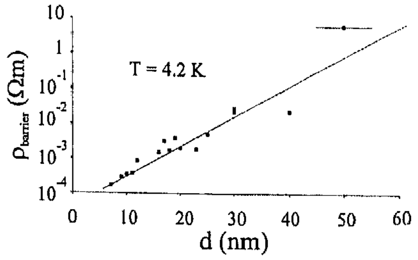

Figure 3: The normal-state resistivity of PBCO barriers as a function of the barrier thickness d.

activation energy by raising the temperature or applying an electric field, more states near the initial state become available to the electron, and the average hopping distance decreases. In large field the average hopping distance in the x direction approaches a constant minimum value of approximately 14 nm. We interpret this minimum hopping distance as nearest-neighbour hopping between localized states. The obtained value of 14 nm is comparable to the estimate in the literature for the nearest-neighbour distance $x_{NN} \approx 10$ nm [8].

We analysed the barrier conductance of YBCO/PBCO/YBCO ramp-type junctions for barrier thicknesses ranging from 5 to 50 nm. The normal-state barrier resistivity depends on the barrier thickness d as $\rho_N \propto \exp d$, characteristic for direct tunnelling or resonant hopping through one localized state. For thicker junctions we would expect a transition from direct or resonant tunnelling, to hopping in channels with two or three localized states in the barrier, resulting in a change of the slope in figure 3. Due to the error in the absolute barrier thicknesses and the approximately 5 nm rms roughness of both YBCO/PBCO interfaces, we can not identify different slopes in figure 3.

In figure 4 the total barrier conductance $<G(T,V)>$ of a junction with a 50 nm PBCO barrier is presented on a double logarithmic scale. We see an increase of the conductance with the applied voltage and the temperature, indicative of an electric field and temperature activated transport process. At high temperatures and relatively weak fields the barrier conductance is independent of the applied electric field as thermal activation is dominant in this regime. For high activation energies, i.e., in strong fields and at high temperatures, the curves converge.

In figure 5 we plotted the temperature dependent part $<G(T,V{=}0)>$ of the barrier conductance of the same junction as a function of the temperature. The drawn line represents the $<G(T,V{=}0)> \propto T^{4/3}$ relation, as predicted by GM for conductance in channels containing

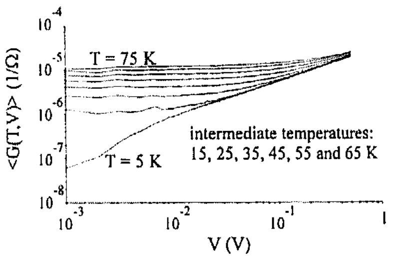

Figure 4: The total barrier conductance $<G(T,V)>$ as a function of voltage V, and temperature T of a 50 nm PBCO barrier.

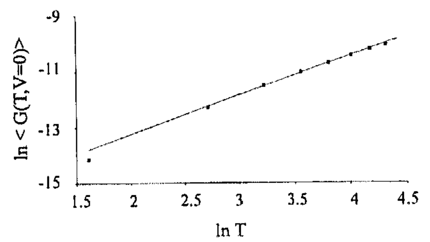

Figure 5: The temperature dependent barrier conductance $<G(T,V{=}0)>$ as a function of temperature T of a 50 nm PBCO barrier.

two localized states. At low temperatures we see a deviation from the drawn line. We did not observe any higher order conduction channels in the temperature activated conductance. Switching between different channels with an increasing number of localized states should, at temperatures $T << eV/k_B$, also be visible in the *IV* characteristics (see equation 2). However, we cannot identify the characteristic GM slopes in a plot of the voltage dependent part of the barrier conductance $<G(T,V)> - <G(T,0)>$ versus the applied voltage.

4. Discussion

The thin film measurements are described in the framework of Mott's macroscopic model for variable-range hopping. The average hopping distance in the direction of the applied electric field decreases for higher activation energies to a minimum value of approximately 14 nm. This minimum hopping distance can be interpreted as nearest-neighbour hopping.

In the barrier of junctions the electric field is extremely strong compared to the electric field as applied in the measurements on the thin films. In this strong-field regime variable-range hopping is replaced by nearest-neighbour hopping, in which case the electrons hop to the nearest available site in real space, and emit a phonon with each hop. As the nearest-neighbour hopping distance in PBCO is in the order of 14 nm, the macroscopic Mott model we would predict that the electrons cross the barrier of a Josephson junction in a few nearest-neighbour hops. If nearest-neighbour hopping would be the transport process across the barrier, we would expect: firstly, a thickness independent barrier resistivity comparable to the macroscopic value, and secondly, the (normal-state) barrier resistivity following $\rho \propto \exp E^{-1/3}$.

The observed resistivity of PBCO barriers depends on the thickness up to 50 nm, and is generally lower than the resistivity of PBCO thin films. Hence, the barrier resistivity can not be described in terms of macroscopic nearest-neighbour hopping. From the $\rho \propto \exp d$ dependence we conclude that a tunnelling mechanism determines the barrier resistivity. We tested the GM theory for resonant tunnelling across a barrier containing localized states on the ramp-type junctions. As the uncertainty in the exact thickness of the barriers is approximately 10 nm, we cannot identify transitions from direct to resonant tunnelling in the thickness dependence of the barrier resistivity.

The thermal activated conductance $<G(T,V=0)>$ can be fitted with the GM theory for hopping through a channel with two localized states. In the voltage dependence of the conductance we can non identify these channels. Possibly the barrier roughness, causing a non-homogeneous electric field profile over the barrier, hinder the observation of the resonant conduction channels.

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