Superlattices and Microstructures 69 (2014) 144–148

Contents lists available at ScienceDirect

Superlattices and Microstructures

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

Non-equilibrium normal and critical transport of electrons in strontium-doped bismuthate cuprates

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ARTICLE INFO

Article history:
Received 24 January 2014
Accepted 18 February 2014
Available online 3 March 2014

Keywords:
Defect
Transport
Slip

ABSTRACT

Critical dynamical transitional phases of electronic liquids driven by an initial electric field in a microscopic confined environment at low temperature regime could occur after we investigated by adopting the verified theory of absolute reactions. The critical temperatures related to the nearly frictionless transport of many condensed electrons might be directly relevant to the dynamical transition at low-temperature regime in amorphous materials, say $(Bi_{2-x}Sr_x)_2CuO_6$, after selecting specific activation energies and activation volumes. We also address the normal-state high-temperature transport issue.

1. Introduction

Optimal control of transport processes in scientific (e.g., new novel materials testing and processing) as well engineering applications deserve intensive studies. One essential issue is to obtain much lower resistance (or drag) in confined domains. The best scientific success is to achieve the ability to transport without resistance (e.g., charged superfluidity : Electrons are in the same quantum state and move coherently and result in dissipationless mass flow [1] and perfect conductivity [2]). Meanwhile with quantum corrections to the conductivity analysis there have been a considerable advance in our understanding of electrical transport in two-dimensional disordered conductors. Several theories were developed to calculate the resistivity of amorphous metals at low as well as high temperatures [3,4].

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http://dx.doi.org/10.1016/j.spmi.2014.02.006
0749-6036/

Generally if we consider the electrical resistivity ρ of electronic liquids and amorphous materials their behavior is quite the same. However the slow dynamics of some low-temperature, out-of equilibrium systems can be highly complex. The system is no longer stationary and it will often retain a memory of its previous thermal history [4–6].

In this short paper, with the theory of transition-state or absolute reactions incorporated together with the quantum-mechanic approaches developed by Eyring [6–8], considering the more realistic boundary conditions along the presumed interface of a (circular symmetric) microdomain where electrons flow, however, we shall use the boundary perturbation technique [9] to handle the small-amplitude wavy-roughness along the interface of a cross-section of the microannulus (shell-like, r_2 is the mean outer radius of the cylindrical domain) where electrons pass through. The electric-field-driven transport is already steady and fully-developed within this wavy-rough cross-section. Our primary focus is upon the rather low (electrical) resistance or frictionless transport of many condensed electrons at low temperature regime and the normal state transport at higher temperature regime. This short paper is structured as follows. We will briefly introduce the theoretical approaches in the next section along with the detailed formulas to calculate the resistance of the electronic liquids. Numerical results are presented and discussed in the third section. Conclusions are inferred in the last section.

2. Theoretical formulations

We briefly outline below the transition-state or absolute reaction approach which have included the microscopic treatment [6–8,10,12,13] and the theoretical details could be traced before [6–8,10–13]. Within this approach the motion of composite condensed particles is represented in the configuration space (considering the reaction coordinates, e.g., here: BiSr + CuO $\rightarrow$ Products [7,10]); on the potential surface the stable composite condensed particles are in the valleys, which are connected by a pass that leads through the saddle point. A composite condensed particle at the saddle point is in the transition (activated) state. Under the action of an applied stress the forward velocity of a flow unit is the net number of times it moves forward, multiplied by the distance it jumps [6–8,10–13].

Based on the Eyring's absolute-reaction-rate model of stress-biased thermal activations [6–8,10–13], structural rearrangement is associated with a single energy barrier ΔG that is lowered or raised linearly by a shearing yield stress τ. If the transition rate is proportional to the plastic shearing strain rate with a constant ratio: C_0 (ν_t being the transition rate in the direction aided by stress), we have, from [11,12], the resistance ($\tau \propto \rho$: electrical resistivity [12])

$$\tau = 2\left[\frac{\Delta G}{V_a} + \frac{k_B T}{V_a}\ln\left(\frac{\dot\eta}{C_0 \nu_0}\right)\right] \quad \text{if} \quad \frac{V_a \tau}{k_B T} \gg 1, \tag{1}$$

where V_a is the activation volume, $\dot\eta$ is the shear strain rate, ν_0 is an attempt frequency or transition rate, e.g., for temperatures (T) being of the order of magnitude $O(1)$ K: $\nu_0 \approx k_B/h \sim O(10^{11})$ (1/s) with k_B being the Boltzmann constant and h the **Planck constant**; $C_0\nu_0 \sim \dot\eta_0 \exp(\Delta G/k_B T)$ ($\dot\eta_0$ is a function of temperature with the dimension of the shear rate [12]), or

$$\tau = 2\frac{k_B T}{V_a}\frac{\dot\eta}{C_0 \nu_0}\exp(\Delta G/k_B T) \quad \text{if} \quad \frac{V_a \tau}{k_B T} \ll 1. \tag{2}$$

We need to calculate $\dot\eta$ using the boundary perturbation approach [9,12] before we evaluate τ ($\propto \rho$: electrical resistivity [12]). We remind the readers that, from above equations, the nonlinear character only manifests itself when the magnitude of the stress times the activation volume becomes comparable or greater in magnitude than the thermal vibrational energy. Note that the mathematical details relevant to calculate $\dot\eta$ could be traced in [11,12].

3. Numerical results and discussion

Our main interests are the critical transitional behavior for rather low resistance of the electric-field-driven transport of many condensed electrons at low temperature regime in $(Bi_{2-x}Sr_x)_2CuO_6$