Transport in granular conductors

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The electronic transport in granular conductors is governed by the nontrivial interplay between the diffusive intra-grain electron motion and grain-to-grain tunneling which is accompanied by sequential charging of the grains involved in the particular electron transfer process. Transport properties are controlled by competition between the inter-grain coupling and electron-electron Coulomb interactions. The basic parameter that characterizes transport properties is the dimensionless tunneling conductance, $g_{\rm T}$. Depending on the bare tunneling conductance $g_{\rm T}(0)$, the conductivity can demonstrate either (i) exponential (insulating)-, at $g_{\rm T}(0) \ll g_{\rm T}^{\rm C} = (1/2\pi d)\ln(E_{\rm C}/\delta)$, where $E_{\rm C}$ and δ are the charging energy and the mean energy level spacing in a single grain respectively, or (ii) logarithmic (metallic), at $g_{\rm T}(0) \gg g_{\rm T}^{\rm C}$, temperature dependencies, experiencing metal-insulator transition at $g_{\rm T}(0) = g_{\rm T}^{\rm C}$.

We investigate transport in a granular metallic system at both limiting cases. We show that in the metallic region, $g_{\rm T} \gg 1$, and low temperatures, $T \leq g_{\rm T}\delta$, where δ is the single mean energy level spacing in a grain, the coherent electron motion at large distances dominates the physics, contrary to the high temperature ($T > g_{\rm T}\delta$) behavior where conductivity is controlled by the scales of the order of the grain size. The conductivity of one and two dimensional granular metals, in the low temperature regime, decays with decreasing temperature in the same manner as that in homogeneous disordered metals, indicating thus an insulating behavior. However, even in this temperature regime the granular structure remains important and there is an additional contribution to conductivity coming from short distances. Due to this contribution the metal-insulator transition in three dimensions occurs at the value of tunnel conductance $g_{\rm T}^{\rm C} = (1/6\pi)\ln(E_{\rm C}/\delta)$, where $E_{\rm C}$ is the charging energy of an isolated grain, and not at the generally expected $g_{\rm T}^{\rm C} \propto 1$. Corrections to the density of states of granular metals due to the electron-electron interaction are calculated. Our results compare favorably with the logarithmic dependence of resistivity in the high-$T_{\rm c}$ cuprate superconductors indicating that these materials may have a granular structure.

We investigate the effect of Coulomb interactions on the tunneling density of states (DOS) of granular metallic systems at the onset of Coulomb blockade regime in two and three dimensions. Using the renormalization group technique we derive the analytical expressions for the DOS as a function of temperature T and energy ϵ. We show that samples with the bare intergranular tunneling conductance $g_{\rm T}^{0}$ less than the critical value $g_{\rm T}^{\rm C} = (1/2\pi d)\ln(E_{\rm C}/\delta)$, where $E_{\rm C}$ and δ are the charging energy and the mean energy level spacing in a single grain respectively, are insulators with a *hard gap* in the DOS at temperatures $T \to 0$.

In 3d systems the critical conductance $g_{\rm T}^{\rm C}$ separates insulating and metallic phases at zero temperature, whereas in the granular films $g_{\rm T}^{\rm C}$ separates insulating states with the hard (at $g_{\rm T}^{0} < g_{\rm T}^{\rm C}$) and soft (at $g_{\rm T}^{0} > g_{\rm T}^{\rm C}$) gaps. The gap in the DOS begins to develop at temperatures $T^{*} \sim E_{\rm C} g_{\rm T}^{0} \exp(-2\pi d g_{\rm T}^{0})$ and reaches the value $\Delta \sim T^{*}$ at $T \to 0$.

We further study the electron thermal transport in granular metals at large tunnel conductance between the grains, $g_{\rm T} \gg 1$ and not too low a temperature $T > g_{\rm T}\delta$, where δ is the mean energy level spacing for a single grain. Taking into account the electron-electron interaction effects we calculate the thermal conductivity and show that the Wiedemann–Franz law is violated for granular metals. We find that interaction effects suppress the thermal conductivity less than the electrical conductivity.

We present a unified description of the low temperature phase of granular metals that reveals a striking generality of the low temperature behaviors. Our model explains the universality of the low-temperature conductivity that coincides exactly with that of the homogeneously disordered systems and enables a straightforward derivation of low temperature characteristics of disordered conductors.

We investigate the suppression of superconducting transition temperature in granular metallic systems due to (i) fluctuations of the order parameter (bosonic mechanism) and (ii) Coulomb repulsion (fermionic mechanism) assuming large tunneling conductance between the grains $g_{\rm T} \gg 1$. We find the correction to the superconducting transition temperature for $3d$ granular samples and films. We demonstrate that if the critical temperature $T_{\rm c} > g_{\rm T}\delta$, where δ is the mean level spacing in a single grain the bosonic mechanism is the dominant mechanism of the superconductivity suppression, while for critical temperatures $T_{\rm c} < g_{\rm T}\delta$ the suppression of superconductivity is due to the fermionic mechanism.

Turning to insulating regime, we develop a theory of a variable range hopping transport in granular conductors based on the sequential electron tunnelling through many grains in the presence of the strong Coulomb interaction. The processes of quantum tunnelling of real electrons are represented as trajectories (world lines) of charged classical particles in $d+1$ dimensions. We apply the developed technique to investigate the hopping conductivity of granular systems in the regime of small tunneling conductances between the grains $g_{\rm T} \ll 1$ and derive the Efros–Shklovskii law of Coulomb-interaction controlled transport $\sigma \propto \exp[-(T_{\circ}/T)^{1/2}]$.