Non-Fermi-liquid Behavior and their Doping Asymmetry in an Organic Mott Electric-double-layer Transistor

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In materials with a half-filled band, strong on-site Coulomb repulsion localizes the conduction electron at each site. This type of insulator is called Mott insulator. Electron or hole doping into the Mott insulator reduces the commensurability between the electron density and the lattice potential, and the electrons are delocalized (band-filling-controlled Mott transition). The Mott transition has been intensively studied in relation to the high-temperature (high-T_C) superconductivity because the high-T_C cuprates have been found to be doped Mott insulators.

In the cuprates, high-T_C superconductivity emerges between the Mott insulating and metallic (Fermi liquid) states as we increase the doping concentration. Indeed, the normal state of the high-T_C superconductors has been found to be a strange metal. The resistivity increases with temperature far above the Mott–Ioffe–Regel limit at sufficiently high temperatures (the bad metal behavior). The Hall coefficient is strongly temperature-dependent despite the metallic-like transport. On the other hand, the cotangent of the Hall angle is proportional to T^2 as in a Fermi liquid. These anomalies have often been viewed as key unresolved signatures of strong correlation, which is probably relevant to the superconductivity. To discuss their origins, it is important to investigate these behaviors in different systems which can be described with similar models, to speculate what behavior is material-dependent and what behavior universally appears in the proximity of the Mott transition.

Recently, we have developed electric-double-layer doping into an organic Mott insulator κ-(BEDT-TTF)$_2$Cu[N(CN)$_2$]Cl (hereafter κ-Cl), resulting in observation of ambipolar superconductivity surrounding the Mott insulating state in one and the same sample. Therefore, our organic Mott electric-double-layer transistor (EDLT) would likely show the non-Fermi-liquid behavior in the normal state. In this study, we investigated the temperature dependence of the transport properties in an organic Mott EDLT, with varying doping across half filling in a single sample.

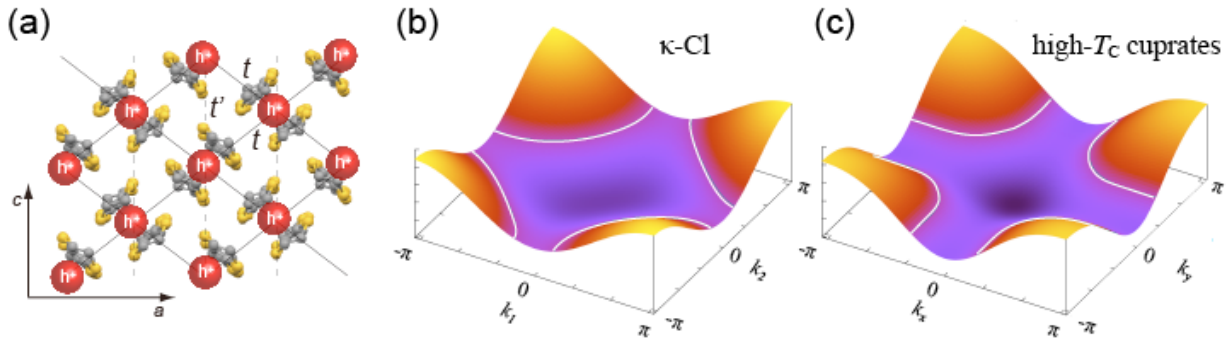

Fig. 1. (a) Top view of the conducting BEDT-TTF layer in κ-Cl. Each BEDT-TTF dimer has one hole carrier. t and t' denote nearest- and next-nearest-neighbor hopping energy. (b), (c) Band structures of single-band models for κ-Cl and the cuprates.

Figure 2 shows the temperature dependence of the surface resistivity under electron doping. Above ca. 100 K, metallic-like conduction above the Mott–Ioffe–Regel limit is observed in a wide range of doping level. This is the bad metal behavior in the sense that the mean-free path of carriers is shorter than the site distance. On the other hand, at low temperatures, the Fermi-liquid behavior (quadratic-in-temperature resistivity) and semiconducting behavior appears under electron and hole doping, respectively.

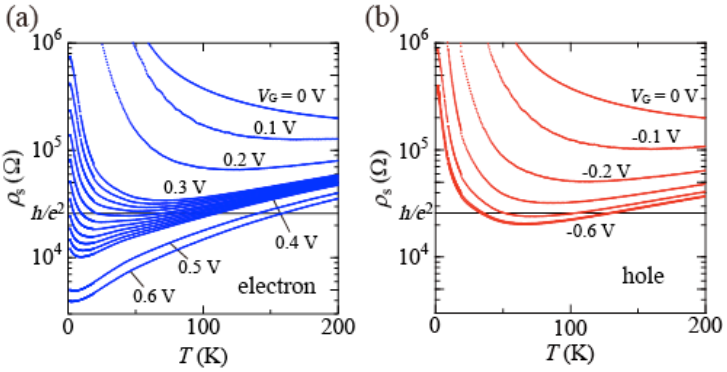

Fig. 2. Temperature dependence of the resistivity in a κ-Cl EDLT under (a) electron and (b) hole doping. Solid black line denotes the Mott–Ioffe–Regel limit in two dimensions. The resistivity under sufficient electron doping ($V_G \geq 0.5$ V) is quadratic in temperature (the Fermi liquid behavior).

Figure 3 shows the temperature dependence of the Hall coefficient and the cotangent of the Hall angle. Under electron doping, the Hall coefficient does not depend significantly on temperature and corresponds to the carrier density in the non-interacting case. On the other hand, under hole doping, it largely increases with cooling despite the metallic-like conduction, indicating a reduction of the carriers down to approximately one-third of the non-interacting carrier density. Nevertheless, the cotangent of the Hall angle is quadratic in temperature in a wide temperature range.

To summarize these results, (1) the bad metal behavior widely appears except at half filling regardless of the doping polarity at high temperatures. (2) At lower temperatures, the pseudo gap behavior is observed only under hole doping, while (3) the Fermi-liquid-like behavior is observed under electron doping, within the doping region studied here (up to ~±20%).

Although we need further studies to conclude, the bad metal behavior seems a universal high-energy scale phenomenon in doped Mott insulators, while the pseudo gap behavior is based on lower energy scale physics that can be influenced by details of the band structure, according to these results and the theoretically predicted effect for a quantum spin liquid [3].

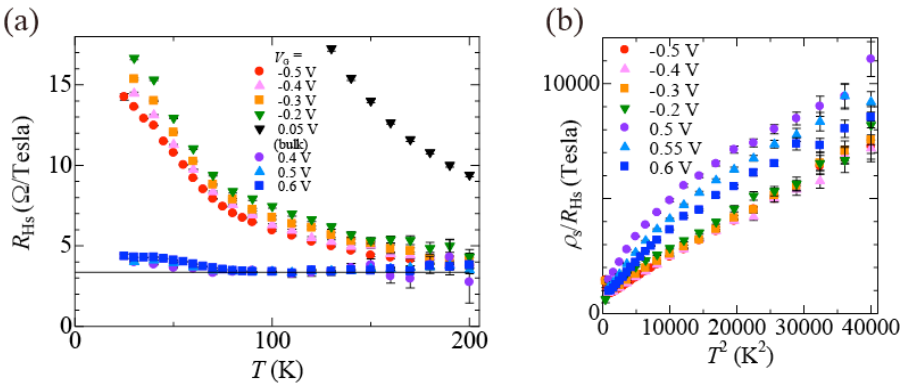

Fig. 3. (a) Temperature dependence of the Hall coefficient in a κ-Cl EDLT. (b) Hall angle vs T^2 plots. They appear more linear under hole doping.

References

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