Why a Mott Insulator Turns into a Conductor?

A deep lying transient doped layer can engineer the conductance of a Mott insulator.

To understand the mechanism of high-temperature superconductors is considered a Holy Grail in condensed matter physics. Especially after the LK-99 incident happened in the summer of 2023, the society suddenly realized that the advances in fundamental physics might have the chance to influence the stock market. In this regard, the condensed matter research community has recently turned its attention to emergent low-dimensional electronic systems, with a particular focus on materials such as graphene, two-dimensional (2D) materials, and complex oxides. These materials have displayed unexpected phenomena such as Mott physics and superconductivity, especially in twisted bilayer forms and at interfaces. For example, Jiunn-Yuan Lin (National Yang Ming Chiao Tung University) and his co-workers found an unexpected metallic state in a bulk cuprate Mott insulator, which defied Landau's Fermi liquid paradigm. By combining several experimental techniques, Lin and his co-workers proposed a scenario that has not been expected before. They concluded that a two-dimensional electron gas formed at the transient layer where the crystalline structure transformed naturally.

The sample system under surveillance was an ultra-thin $SrCuO_2$ (SCO) film grown on a TiO_2-terminated $SrTiO_3$ (STO) substrate. As is well-known, the bulk tetragonal (planar-type) SCO consisting of 2D CuO_2 planes alternating with Sr layers is the simplest structure among high-Tc cuprates. First principal calculations indicated a structural transformation from chain type to planar type with increasing SCO film thickness [> 5 unit cells (u.c.)].[1] Both structures are shown in **Fig. 1**. However, traditionally, the SCO can only be synthesized under high pressure, making it difficult to study the thin-film properties and structural transformation.

In the past decade, high-quality SCO thin films have been successfully fabricated using a pulsed-laser deposition method, which has greatly advanced research on SCO thin films and their structural transformation. Conducting transport measurements on these high-quality SCO thin films with 15 u.c. revealed a distinct metallic behavior, despite bulk SCO being known as a Mott insulator.

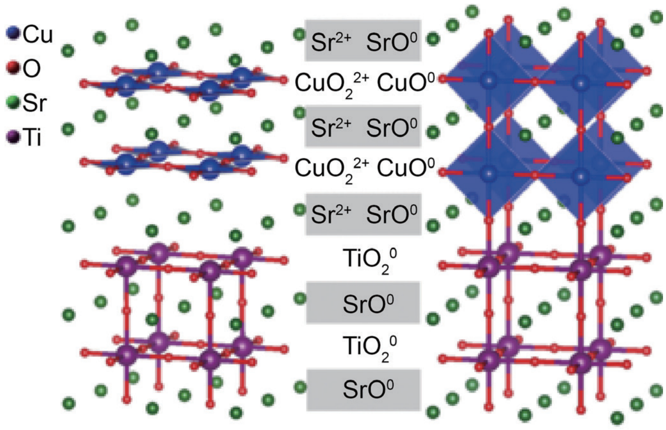

Fig. 1: Schematic plots of the planar-type (left) and the chain-type (right) tetragonal SCO on TiO_2-terminated STO substrates. [Reproduced from Ref. 2]

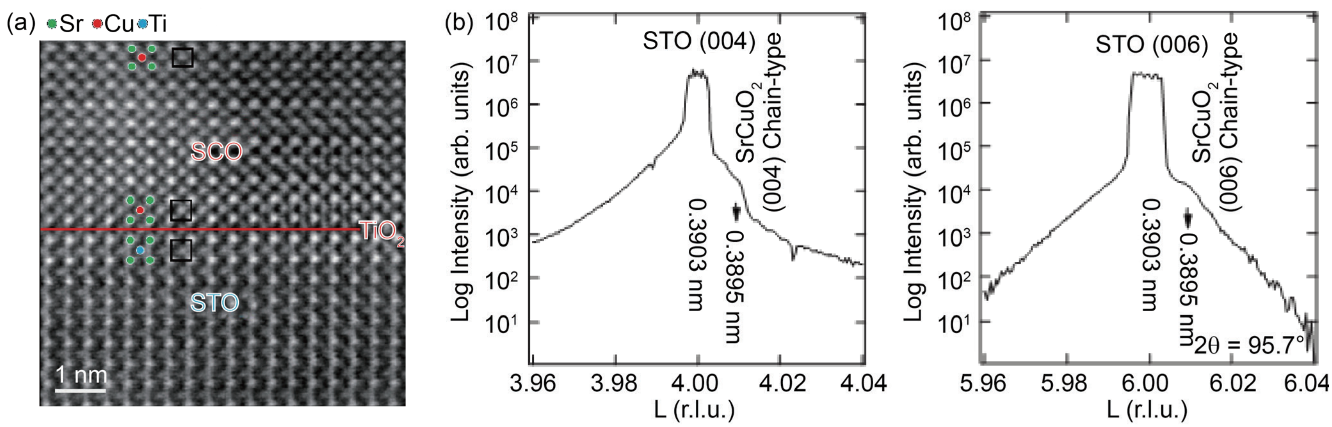

Fig. 2: (a) The STEM image clearly indicates that SCO close to the STO interface forms a chain-type structure similar to STO. The similarity is highlighted by the square black boxes of the same size at the center of this cross-section view. On the other hand, SCO away from the interface forms a planar-type structure with a smaller c-axis than those of SCO and STO. This is marked by a rectangular black box on the top part of image. (b) Energy scan of X-ray Laue diffraction. The existence of the chain-type SCO is evidenced by a shoulder next to the strong STO peak. [Reproduced from Ref. 2]

To tackle the true nature of this unexpected metallic property, Lin and his co-workers employed polarization-dependent X-ray absorption spectroscopy (XAS; **TLS 11A1** and **TLS 20A1**) at both the Cu L-edge and the O K-edge, Laue X-ray nanodiffraction measurements at **TPS 21A**, hard X-ray core-level photoemission measurements (HAXPES) at **SP 12U1**, and scanning transmission electron microscopy (STEM) techniques to study both the atomic structure and electronic structure of the SCO thin film.

By carefully analyzing the lattice constants from STEM images in **Fig. 2(a)** and through the energy scan of X-ray Laue diffraction in **Fig. 2(b)**, Lin and his co-workers concluded that the first few layers of SCO at the interface display a chain-type structure, which is consistent with the theoretical calculation.[1]

Based on the transport, structure, and soft X-ray spectroscopic results, Lin and his co-workers proposed a model for this emergent metallic state, illustrated in **Fig. 3**. For SCO ultrathin films grown on STO, where the epitaxial strain plays an important role, it was predicted that a structural transformation in SCO from chain type to planar type would occur when the SCO thickness exceeds 5 u.c. Near the STO interface, the initial growth of SCO will have a chain-type structure. With increasing SCO thickness, there exist residual layers of chain-type SCO even when the planar-type structure has developed. Within the chain-type SCO, SrO layers alternate with CuO layers, while Sr layers exist with CuO_2 layers in the planar type. Moreover, there exist SrO_x layers in the transient regime (highlighted by the red box at the middle of **Fig. 3**) in which excess oxygen is positioned on top of Cu in the neighboring CuO_2 plane(s), the excess oxygen in the SrO_x layers effectively dopes the holes into the nearby CuO_2 planes. The observed conductivity hence arises from the few doped CuO_2 planes similar to that in cuprate superconductors.

Lin and his co-workers state that the model, although plausible, might not be the ultimate solution for describing the nature of the emergent metallic state, but may be a promising first step to further explore the abundant physics in the SCO cuprate thin films. Whether this metallic state can be tuned into a superconducting state may be further explored. Lin and his co-workers are currently exploring a potential avenue for inducing superconductivity through variation of the doping level. (Reported by Chia-Hao Chen)

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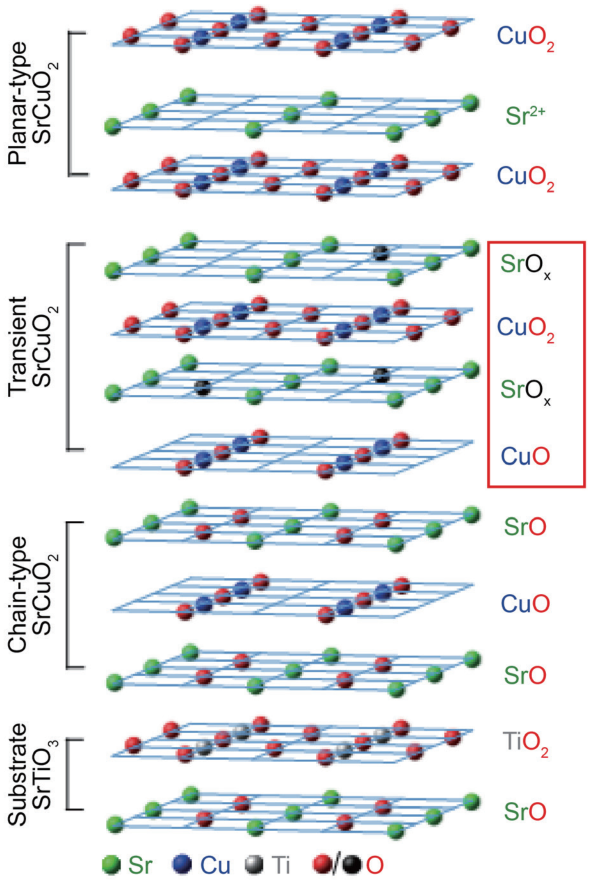

Fig. 3: Schematic of the layered SCO/STO structure displaying the transition region from chain-type to planar-type SCO. The metallic region and doping mechanism are shown in the red box. [Reproduced from Ref. 2]

TPS 21A X-ray Nanodiffraction
TLS 11A1 (Dragon) MCD, XAS
TLS 20A1 XAS
SP 12U1 HAXPES

- XAS, Laue XRD, HAXPES
- Condensed Matter Physics

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