Direct Electrostatic Imaging of Nanoscale Superconducting Channels at LAO/STO Interface Via *In-Situ* Ultra-Low-Temperature AFM

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$SrTiO_3$(STO), the first discovered superconducting semiconductor, offers a unique platform for exploring quantum phenomena. When a thin insulating layer of $LaAlO_3$ (LAO) is grown on top, a two-dimensional electron gas (2DEG) forms at the interface. Over the past decade, it has been demonstrated that precise nanoscale patterning, such as conductive AFM lithography (c-AFM) or ultra-low voltage electron-beam lithography (ULV-EBL) [1,2], can be used to control electronic properties at this interface. These techniques enable the fabrication of nanoscale devices including single electron transistors (SETs), ballistic transport nanowires and complex two-dimensional geometries. These devices led to important discoveries such as electron pairing without superconductivity, one-dimensional nature of superconductivity and so on [3, 4]. However, imaging and understanding these quantum phases and structures locally, at cryogenic temperatures and in a non-invasive manner remains a significant challenge.

In this study, we show that patterned nanostructures at the interface 2DEG can be directly imaged using scanning probe techniques. We combine in-situ low-temperature transport measurements with non-contact atomic force microscopy (AFM) and Kelvin probe force microscopy (KPFM) to investigate patterned LAO/STO devices. Transport measurements confirm the emergence of superconductivity in the written structures. KPFM imaging reveals clear electrostatic contrast at the channel boundaries and smooth potential gradients across the conducting regions. While both samples exhibit contact potential difference (CPD) contrast, topographic contrast is observed in only one of them.

In this presentation, I will highlight the observed similarities and differences in the electrostatic potential landscapes of devices fabricated using c-AFM and UVL-EBL. I will also discuss possible doping mechanisms at the interface, the CPD contrast mechanisms observed in KPFM maps, and the origin of topographic contrast observed in AFM measurements. Together, these results suggest that conducting nanostructures on LAO can host distinct local electrostatic environments shaped by patterning chemistry and LAO thickness. This integrated approach provides a valuable platform for visualizing and tailoring quantum phases in oxide nanostructures.

Reference

[1] D. Yang, et al. Appl. Phys. Lett. **117**, 253103 (2020).

[2] C. Cen, et al. Science **323**, 1026 (2009).

[3] Y.-Y. Pai, et al. Phys. Rev. Lett. **120**, 147001 (2018).

[4] G. Cheng, et al., Nature **521**, 196 (2015).