Enhanced Mobility in an Insulator Capped 2D Electron Gas at $SrTiO_3$ <100> Surface

Nathan Huber

Physics, Gustavus Adolphus College

NNIN REU Site: Penn State Nanofabrication Laboratory, The Pennsylvania State University, University Park, PA

NNIN REU Principal Investigator: Prof. Qi Li, Physics, The Pennsylvania State University

NNIN REU Mentors: Dr. Ludi Miao and Renzhong Du, Physics, The Pennsylvania State University

Contact: nhuber2@gustavus.edu, qil1@psu.edu, lxm66@psu.edu, rud145@psu.edu

Abstract and Introduction:

Two-dimensional electron gases (2DEGs) at oxide surfaces and interfaces have attracted much attention due to their fascinating exotic properties such as superconductivity, large magneto-resistance, and ferromagnetism. $SrTiO_3$ (STO) based 2DEGs are a typical example. These include 2DEGs at the interface of $LaAlO_3$/STO heterostructures and on STO surfaces [1]. With their high mobility and high dielectric constant at the ground state, these 2DEGs are promising in developing next generation all-oxide devices including field effect transistors and spintronic devices [2].

In this study we have created 2DEGs at STO <100> surfaces by Ar^+ ion irradiation. We found that a SiO_2 capping layer on the 2DEG surfaces significantly decreased surface resistance, while no effect was observed for other oxide capping layer tests (MgO, Al_2O_3, and STO). Specifically the electron mobility of the SiO_2 capped channel had an eight-fold increase relative to uncapped 2DEG at 1.8 K. The bare channel had a resistance ratio ($R_{300\,K}/R_{1.8\,K}$) of 85 compared with the SiO_2 capped channel ratio of 625; this indicates significantly better metallic behavior for capped channels. Our results open a path to create 2DEGs with high mobility in an effective and economic way.

Experimental Procedure:

2DEG measurement units were fabricated at STO surfaces (Figure 1). First, photolithography was used to pattern a Hall bar. The exposed substrate was then subject to Ar^+ ion irradiation (Figure 2). The Ar^+ ion irradiation generates oxygen deficiencies at the surface. Carriers were thus increased in order to neutralize charge at the STO surface. Electrical contacts were fabricated by sputtering titanium and gold. The contact patterns were defined by photolithography. Finally the irradiated surface was capped by sputtered SiO_2.

Experimental variations were made to the 2DEG. The STO substrate was tested at a SiO_2 capped and uncapped state. The dose of ion milling and thickness of capping was also varied. The capping layer effect was tested for several other materials including: MgO, Al_2O_3, and STO.

The Hall bars allowed for five probe and Hall effect measurements. These measurements were made in a physical property measurement system (PPMS). The sample resistance, carrier density, and mobility were measured as function of temperature from 300 K to 1.8 K.

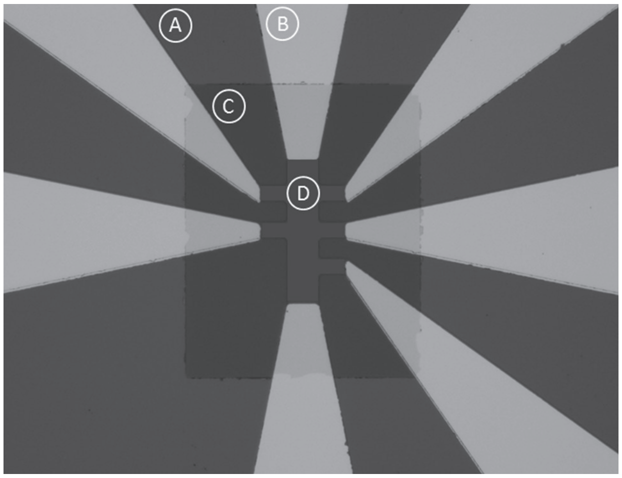


Figure 1: Standard Hall bar layout used for STO 2DEG fabrication and measurements. A. STO substrate B. Titanium and gold contacts C. Capping layer D. Ion milled STO 2DEG channel.

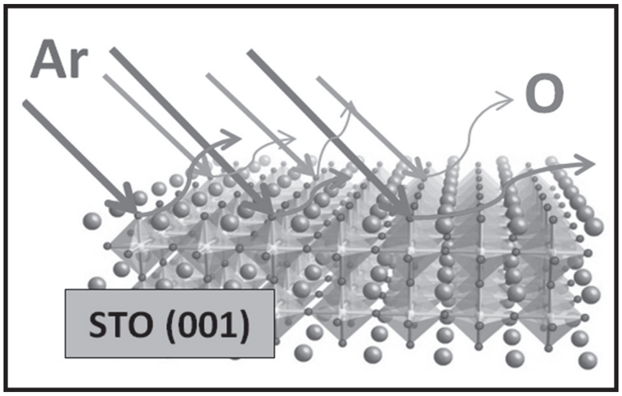
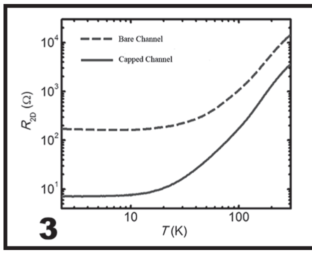


Figure 2: Ar irradiation (ion milling) reduces STO <001> surface to form 2DEG.



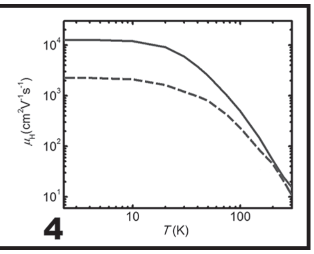


Figure 3, left: 2DEG resistance measure of a bare channel (dashed) compared to a capped channel (solid). The four probe measurement was used to measure channel resistance.

Figure 4, right: Electron mobility in bare 2DEG channel (dashed) compared to a capped channel (solid). The Hall effect was used in coalition with the four probe measurement to solve for mobility. The mobility at 1.8 K was enhanced from its uncapped mobility of 2,100 cm^2/Vs to the capped channel mobility of 13,000 cm^2/Vs.

Results and Conclusions:

From the resistance measurement, it was found that the capped and uncapped STO 2DEG were fully metallic; this is evident from the decrease in resistance as temperature decreases (Figure 3). It was also observed that the SiO_2 capped channel had lower resistance compared to the uncapped channel at all temperatures. The bare channel had a resistance ratio ($R_{300\ K}/R_{1.8\ K}$) of 85 compared with the significantly higher SiO_2 capped channel's ratio of 625. This indicates improved mobility in the capped channel.

Several other oxides were tested as capping layers for the possibility of 2DEG enhancement. Among those capping layers tested (MgO, Al_2O_3, STO, and SiO_2), SiO_2 was the only material to exhibit enhancement. This observation may be explained with a possible mechanism of band bending at the ion milled STO and SiO_2 interface. The shallow work function of SiO_2 could potentially bend the conduction band of the STO below the Fermi level. Further theoretical work must be completed to verify this explanation.

It was also observed that terminated STO substrate increased the conductivity in the 2DEG channel. This increase was expected because the terminated substrate has fewer imperfections to hinder electron flow. Observing this increase motivates future research in depositing more uniform coats of SiO_2. This could lead to increases in channel conductivity.

Finally it was observed that decreasing the ion milling duration and capping layer thickness led to decreases in carrier density of the 2DEG. This is important information because control of conductive channels with low carrier density would be applicable for future field effect transistors.

These results introduce SiO_2 capping of STO 2DEG as a promising method for fabrication of oxide conductors. The enhancement of mobility obtained by this capping has significant implications for oxide electronics.

Future Work:

In the future, the Li research group will continue the characterization of SiO_2 capped STO 2DEG. To attain increased mobility, the group plans to explore SiO_2 capping thickness and uniformity. Basic control of carrier density has been observed by way of gating techniques. Further increasing the mobility and control of the carrier density in this 2DEG would be important for future applications.

Acknowledgments:

I would like to especially thank principal investigator Dr. Qi Li, mentor Dr. Ludi Miao, mentor Renzhong Du, and all of the Li research group. I would also like to thank The Pennsylvania State University and Materials Research Institute staff. Finally, the funding from the National Science Foundation (NSF; Grant No. ECCS-0335765) and the National Nanotechnology Infrastructure Network Research Experience for Undergraduates (NNIN REU) Program support staff are greatly appreciated.

References:

[1] A. Ohtomo, H.Y. Hwang. A high-mobility electron gas at the $LaAlO_3/SrTiO_3$ heterointerface. Nature 427, 423-426. (2003).

[2] A. F. Santander-Syro, et al. Giant spin splitting of the two-dimensional electron gas at the surface of $SrTiO_3$. Nature Materials. 13, 1085-1090. (2014).