Enhanced Mobility in an Insulator Capped 2D Electron Gas at SrTiO$_3$ <100> Surface

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**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$_2$O$_3$, 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 ($R_{300K}/R_{1.8K}$) 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$_2$O$_3$, 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.

![Ar irradiation (ion milling) reduces STO <001> surface to form 2DEG.](image-url)
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 SiO₂ capped channel had lower resistance compared to the uncapped channel at all temperatures. The bare channel had a resistance ratio \((R_{300\text{K}}/R_{1.8\text{K}})\) of 85 compared with the significantly higher SiO₂ 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, Al₂O₃, STO, and SiO₂), SiO₂ 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 SiO₂ interface. The shallow work function of SiO₂ 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 SiO₂. 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 SiO₂ 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 SiO₂ capped STO 2DEG. To attain increased mobility, the group plans to explore SiO₂ 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.

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