

Charge-Induced Changes in the Electrical Properties of Ultra-Thin Films

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Abstract

In an attempt to create trilayer structures that can be used to field gate low-carrier density thin films, the researchers have shown that using an ionic fluid ($\text{BMI}^+\text{BF}_4^-$) as the dielectric produces significant changes in the resistance. A thin layer of indium oxide ($\sim 200 \text{ \AA}$) is grown on glass substrates followed by coating the thin film with an ionic fluid. The films are characterized through resistance measurements as a set voltage is applied to the gate electrode. Although results from AC to DC varied in resistance measurements, both displayed a significant change from 30% to 50%. Even though the results have not always been consistent throughout, they always significantly change the resistance. Previous research using oxides, such as AlO_x , as gate dielectrics sparked our study with an ionic fluid as the dielectric.

I. Introduction

Trilayer structures consist of a thin film and a thin dielectric film that are separated from a gate electrode. By applying an electric field between the electrodes, a charge can be created on the thin film that will affect the electrical properties. This is characteristic of a field-effect transistor (FET), which is a type of switch where a semiconducting channel bridges two electrodes. Application of a voltage to a third

electrode known as the gate controls the current flow between these electrodes by applying voltage to the gate which changes the semiconductor from insulating to conducting. We intended to use reactive ion beam sputter deposition (RIBSD) to create indium oxide (InO_x) films with gate electrodes that will utilize the sample as a FET and a p - n junction. To investigate the InO_x thin film as a FET the InO_x is coated with an ionic fluid ($\text{BMI}^+\text{BF}_4^-$) acting as the dielectric. In addition, study the absorption and reflectivity in the visible and infrared wavelengths of a trilayer structure comprised of $\text{Al}/\text{AlO}_x/\text{InO}_x$.

The InO_x is being used for this study with ionic fluids, as InO_x is known for its low carrier density of approximately 10^{20} e/cm^3 . Conductivity is represented by the equation

$$\sigma = ne^2\tau/m \quad (1)$$

that includes the carrier density as a variable. The carrier density (n) of the InO_x is modulated by the use of field gating across the film. A trilayer structure of $\text{Al}/\text{AlO}_x/\text{InO}_x$ significantly showed a field effect in thin film superconductors. Thus, the superconductor had a small but immediate effect ($\sim 10\%$) when three volts were applied to the gate voltage [1]. The trilayer configuration used a 100 \AA layer of AlO_x as the dielectric to create a change [1]. To consider this type of superconductor for device applications a more significant change is needed. Now, for a larger change a trilayer structure where the dielectric is an ionic fluid will be designed to look for larger field-induced changes.

Investigating the thin films will require learning thin-film deposition techniques including the operation of high vacuum systems that are used to create different films

according to the material needed to design a structure. The thin film techniques that will be required are RIBSD and rf/dc sputtering. Some of the samples will require shadow masks to pattern the films on the substrates, as the films are to be placed at critical positions for the experiments. This project aims to use InO_x to show the properties of a FET and a p - n junction. Also, the creation of a trilayer structure of $\text{Al}/\text{AlO}_x/\text{InO}_x$ is used to study reflectivity as a function of voltage being applied through the gate over multiple wavelengths.

II. Methods

A. Cleaning Substrates

Beginning with the growth process of InO_x films, the substrates on which the film will be deposited have to be prepared. Since the films are so thin, any impurities on a dirty substrate could possibly cause a significant effect on the electrical properties of the films. Thus, microscope slides are cut with a diamond point pen into 1 in x 1 in squares and placed into a plastic substrate holder that protects the slides from being scratched during cleaning. Then, the substrate holder is placed into a glass beaker that is used to hold a series of cleaning agents and placed in a sonicator. The sonicator uses sound waves to stir the cleaning agent, which rinses dirty particles off the substrates. First, alconox detergent is mixed with deionized water to clean the substrates, and the substrates are rinsed with deionized water for 40 minutes each. Next, the beaker is filled with acetone, then isopropanol, and finally methanol where the agents cleanse the substrate for 20 minutes in the sonicator. As each substrate is removed from the methanol with tweezers, it is immediately blown dry with N_2 gas.

B. Vacuum Systems

Once a substrate has been properly cleaned, contacts and the thin film are deposited by the use of vacuum deposition systems. Vacuum systems provide a low-pressure environment that can be used for many applications. Vacuum evaporations of metals are used to make the contacts and thin films. Our vacuum system consists of a diffusion pump, mechanical pump, vacuum chamber, and four valves (Fig. 1). Before loading substrates, we warm up the diffusion pump and vent the vacuum chamber by using the vent valve, as the foreline is open. Now, the substrate is loaded, the vent and foreline valves are closed, and the roughing valve is open, allowing the chamber to be evacuated by the mechanical pump. Finally, the roughing valve is closed, and the foreline and high vacuum valves are opened, using the diffusion pump to pump to a vacuum of about 10^{-7} Torr. The filament is turned on to measure the pressure. Once the chamber has reduced its pressure to about 10^{-7} Torr, the metal will be ready for deposition.

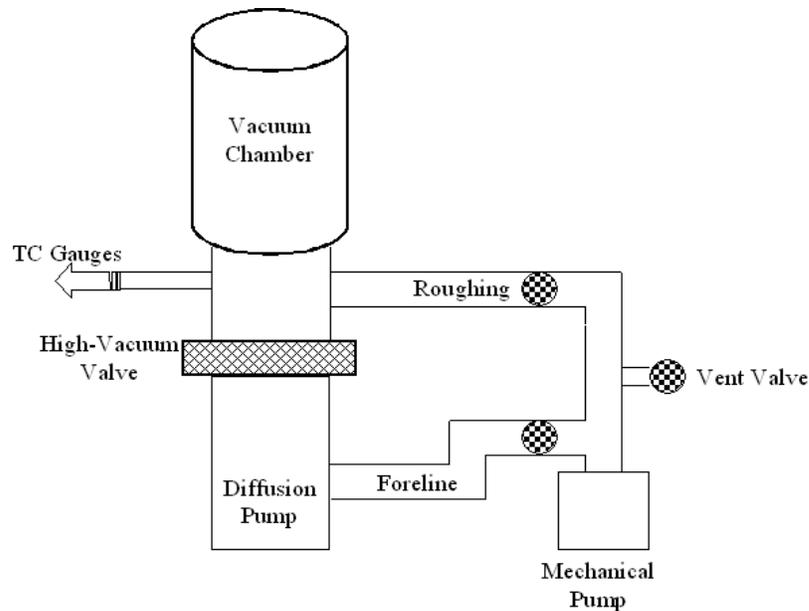


FIGURE 1. Typical Diffusion Pump System

C. Deposition Techniques

After cleaning the substrate, contacts are deposited on the substrate with the help of a shadow mask that is attached with rubber cement. The shadow mask protects the rest of the substrate by keeping it clean from the deposited metal used for contacts. Contacts are created in the Miller system, which can be used for the deposition of thin films for up to six different materials without changing the vacuum. The contacts are made up of a thin layer of chromium that is used as an adhesive for the layer of gold deposited on top.

Once the contacts have been deposited on to the substrate, the shadow mask is removed and the substrate is ready for the deposition of the film. The InO_x thin films are prepared with reactive ion beam sputter deposition (RIBSD). RIBSD is a process involving an argon ion beam that is directed toward an indium target in a high vacuum system that has a reactive oxygen gas released into the system to create the metal oxide film. InO_x films are created as the ion beam sputters indium atoms, which are then oxidized as they travel toward the substrate. A crystal that is located in the vacuum chamber accurately measures the thickness of the thin film. For this experiment, creating a FET, the InO_x films are ≈ 200 angstroms thick. On each substrate, a mask is created with glass where two equally sized films will be created across each side of contacts (Fig. 2). The samples are prepared in a vacuum system called Cyclops because it only has one ion gun; Cyclops is used for RIBSD of InO_x films to study superconductivity.

Finally, a trilayer structure of $\text{Al}/\text{AlO}_x/\text{InO}_x$ is fabricated using rf sputter deposition of an AlO_x film deposited on top of the InO_x film. Using the trilayer structure

we study absorbed wavelengths that produce a reflectivity variable as a function of gate voltage.

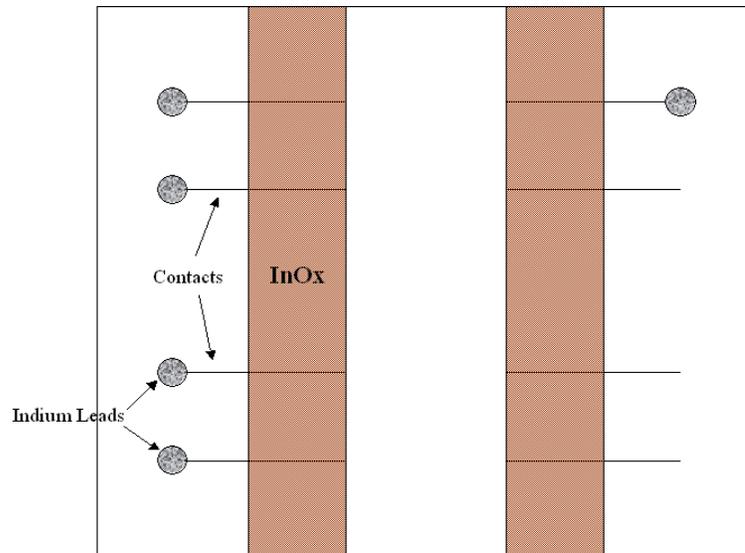


FIGURE 2. Sample substrate

D. Measurements

Once the thin films have been deposited on the substrate, the sample is ready to set up for measuring. For the thin film to be capable to have currents and voltages to run through the film, leads are needed that have gold wire connected to them. Leads are placed on the contacts. The gold wire connects the films into a circuit where currents and voltages are measured (Fig. 3). Resistance of the film is calculated by measuring the voltage divided by the applied current.

The InO_x films are prepared on a glass substrate to be used in the study of resistance of thin films as voltage is applied to the gate electrode on the samples. Next, the resistance is measured in AC and DC to check for variations. The AC and DC measurements are taken using LR700 resistance bridges and a 236 Keithley Source-Measure Unit (SMU), respectively. Investigating the resistance of the InO_x films will go

further as the films will be looked at after ionic fluid coats the InO_x to see how the ionic fluid affects the electrical properties of the InO_x thin films. As the fluid coats the InO_x the resistance is measured at different voltages at each polarity to see if a FET is created consistently.

InO_x films are studied not only in the aspect of a FET but also to see if a $p-n$ junction can be created with the InO_x film and bucky paper (Fig. 4). The InO_x is the n type, which means the conductivity will be controlled by electrons as the negative charge. The p type material is bucky paper, where the conductivity is controlled by holes that are positively charged. Holes are caused when an atom is ionized and an electron is taken away from the valence band and they fill up the space acting just like an electron except they are positively charged. Bucky paper is a type of carbon nanotube that is placed across the InO_x film, therefore allowing measurements at a junction between them to determine if the structure has the behavior of a $p-n$ junction.

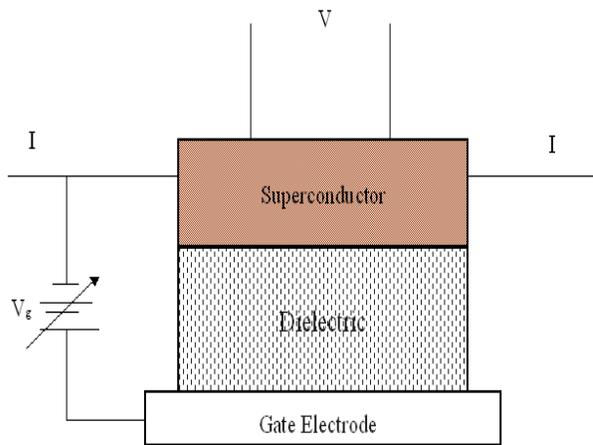


FIGURE 3. Sample circuit to measure the resistance across the thin film through the gate electrode. The InO_x is the superconductor and the ionic fluid is the dielectric.

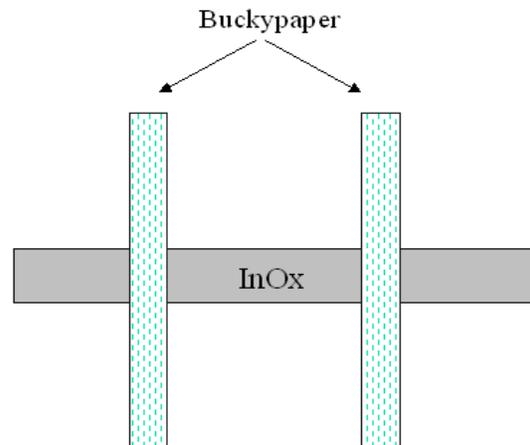


FIGURE 4. Sample used for the $p-n$ junction measurements showing a threshold at a designated current.

III. Results

The variations in the resistance on the electric field as a charge travels through the gate electrode and to the 200 Å thick InO_x film are shown in Fig. 3. The film was a typical sample where the InO_x film had been deposited with the use of a shadow mask on gold gate electrodes. The film was then subjected to $\text{BMI}^+\text{BF}_4^-$ acting as a fluid dielectric. The sample is connected to the LR700 in a 4-terminal measurement where voltage is applied through the gate electrode, therefore allowing the LR700 to measure the resistance in AC while voltages are sent across the film. Fig. 5 shows that as positive voltage is increased, the resistance decreases, and as negative voltage is decreased, the resistance increases. With the increased voltage, electrons are drawn from the InO_x film creating a weakening that results in a lower resistance, whereas a negative voltage has the opposite effect. The resistance showed significant changes from 30 to 50% when voltage was applied up to ± 1 V.

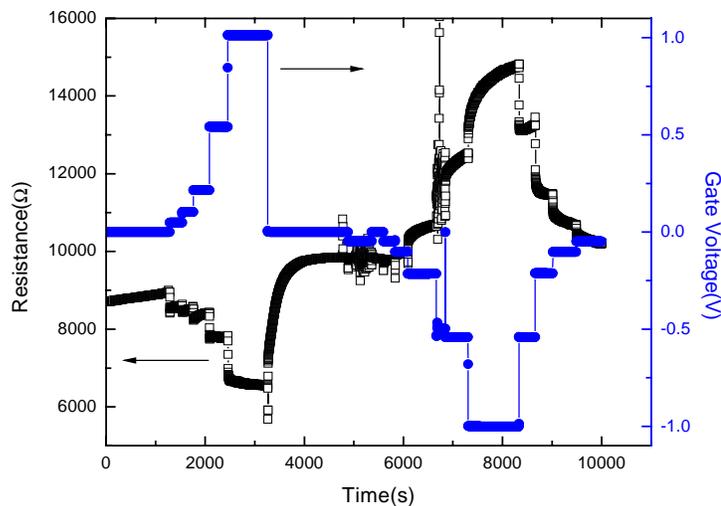


FIGURE 5. Measurements in AC, using the LR700, as an InO_x thin film has been coated with an ionic fluid. The graph shows the time dependence of the resistance (left-hand axis) and the gate voltage (right-hand axis).

Reproducing the sample used above to explore variations in the resistance when applying DC gives results shown in Fig. 6. The resistance was calculated through a 4-terminal measurement where a constant voltage was applied to the gate electrode. However, when we used the 236 SMU for the measurements in DC, a reproducible current traveled across the electrodes. In DC the resistance changes differed from before in AC, where the change is not as extreme and the changes are consistent. The changes were again significant, showing up to a 30% difference in the resistance. In Fig. 6, the DC measurements showed that there is an odd effect for resistance versus voltage.

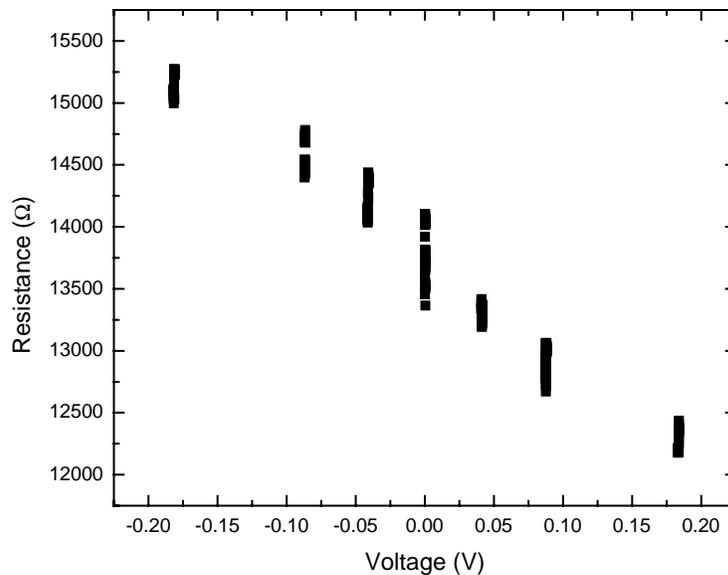


FIGURE 6. This graph represents the data using 236 SMU, DC measurements, where significant changes in the resistance are shown again when the thin film has the ionic fluid as the dielectric.

We also investigated thin film used in a *p-n* junction as bucky paper and the film produced the junction. The 236 SMU measured the current and voltage, current was applied over the junction and produced a result where a threshold occurred at 2.2 mA (Fig. 7) and was consistently reproduced at approximately 2 mA each time.

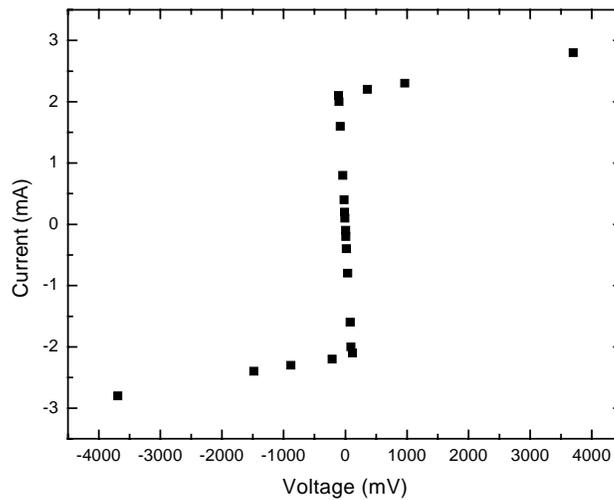


FIGURE 7. The figure above shows the properties of a $p-n$ junction using InO_x film and bucky paper. The junction displays there is a threshold at ± 2.2 mA where the voltage switches polarities.

IV. Conclusion

This project provided preliminary results using ionic fluids as a dielectric, in trilayer structures, in an attempt to enhance resistance modulation. Results in AC and DC both showed a significant change in the resistance as the thin film was subjected to a gate voltage of up to 1 V, in both polarities. The AC measurements are not reproducible due to being out of phase, which caused sporadic results. Although in DC the data provided consistency. We have shown that a fluid dielectric can produce a pronounced FET effect. Using the ionic fluid as the dielectric reveals large resistance changes where only a small change was produced when using a metal oxide in past research [1]. The results are not completely understood and optical properties have not yet been investigated. More research is needed to better understand the changes the ionic fluid causes. In addition, optical research on the trilayer structures with an ionic fluid provides interest for further

research. Since these preliminary results have shown such a significant change with the ionic fluid, future applications, such as voltage controlled displays, are possible.

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References

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