

Effect of Photon Exposure on the $\text{LaAlO}_3/\text{SrTiO}_3$ Heterostructures

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Abstract-Two-Dimensional Electron Gas (2DEG) formation between $\text{LaAlO}_3/\text{SrTiO}_3$ (LAO/STO) can be induced by UV light. Here we show the effect of temperature-induced resistance measurements with variation of temperature with incident UV light (250 - 400 nm) on the electrical transport of LAO/STO heterostructures fabricated by pulsed laser deposition at a thickness of 20-unit cells. Our data shows a drop of sheet resistance from 6.90 k Ω m at room temperature to 1.25 k Ω m at 13.33K indicating that this transition occurs with distinctly observed saturation as a function of temperature when measured electrically as a metallic material. Furthermore, under monochromatic UV radiation (250-400nm), the resistance of LAO/STO decreases as a function of time which can be represented as $(R(t) - R_D)/R_D \times 100\%$ over time. The onset of the photoconductivity occurs at approximately 896.66 seconds as the resistivity continues to decrease until it reaches a near-saturation condition. These large increases in conductivity can be attributed to the excitation of electrons from both oxygen vacancy-associated surface states and shallow trap states into conduction band states derived from the Ti 3d states through photon excitation. This will provide support for the concept of optical tunability of the $\text{LaAlO}_3/\text{SrTiO}_3$ interface and establishes a firm basis for understanding how defects in the oxide heterostructure contribute to photoconductivity.

Keywords: Photoconductivity, 2DEG, LAO/STO, thin film.

1. Introduction

Many researchers have investigated the oxide heterostructures of LaAlO_3 (LAO) and SrTiO_3 (STO) interfaces for many years because of the unanticipated fact that a two-dimensional electron gas (2DEG) develops at the interface of LAO and STO (Ohtomo & Hwang 2004). The presence of a 2DEG at the interface of two oxide insulators provides evidence that two oxide insulators have the potential to develop conductivity at their interfaces. Interest has continued to increase in studying the properties of LAO-STO systems as more work is being conducted on them to investigate the possible development of superconducting, magnetic, or tunable electronic properties using an external gate voltage [1-3]. Researchers have produced multiple models that explain how conductivity develops at oxide insulator interfaces, including lattice distortion or physical restructuring of the interface and/or charge carrier defect mediation. LAO/STO Interface: An Extremely Ultraviolet (UV) Sensitive Interface While the transport properties of interfaces are important, using UV

light sources will greatly affect the conductivity of the interface at LAO-STO compound interfaces. The application of UV light results in a significant decrease in resistance principally by generating additional carriers [4-5] via photo-ionization, such as the creation of oxygen vacancy (defects). In fact, the effect of light on a material can remain for a long time since the rate at which electrons recombine with their localized states (i.e., metastable) associated with these defects is much lower after it is illuminated by a photon than when it is not. Consequently, photon conduction can remain a useful tool/model to characterize the defect structure of 0D, 1D, and 2D interfaces of SrTiO_3 -based materials [6]. This work will investigate the relationship of the temperature dependence of resistance and the time dependence of the resistance change caused by UV light exposed to the two-dimensional (20 LaO/SrO) LAO/STO heterostructures. The motive of this work is to understand how UV light influences conductivity at the LAO/STO interface and also to activate the surface defect structure (defects at the surface of the LAO/STO heterostructure).

2. Experimental Details

Using a pulsed laser deposition method, a film composed of 20 unit cells of lanthanum aluminate was created upon TiO_2 terminated (001) Strontium Titanate substrates. Reflection High-Energy Electron Diffraction was used as a way to verify and monitor the unit-cell growth via oscillations. This thin film was then cooled under controlled O_2 gas pressure to minimize the amount of O vacancies created during this process, thus helping to ensure that the lanthanum aluminate film's resistance, as a function of temperature (i.e., using the four-probe method) would show little or no effect from O vacancies being introduced to the lanthanum aluminate crystal from cooling the film under oxygen (O_2) at varying temperatures of 13.33K to 297.04K. To measure the photo-responsive nature of the sample using UV monochromatic light sources at 250nm, 300nm, 325nm, 350nm, 400nm, changes in law and light resistance were made during a 2500-second period. The normalized variation of electric resistance during this period using the relation $(R(t)-R_D)/R_D \times 100\%$, where R_D represents the initial resistance (R , no light).

3. Results and Discussion

3.1 Temperature-Dependent Electrical Transport

As the temperature decreases, the resistance of the heterostructures also decreases. Fig. 1 shows that R decreases from 6.90 k Ω at $T = 297$ K to 1.25 k Ω at $T = 13.33$

K. The decrease in R is consistent with the metallic conduction model, since the scattering of phonons is greater at high temperatures, thus reducing the amount of scattering suppression at low temperatures [2], therefore allowing a steady state with 2DEG conduction over a wide range of temperature (T) changes (i.e., large variation in R with small change in T). The R of the LaAlO₃/SrTiO₃ (LAO/STO) interfaces begins to saturate below ~25 K as can be seen in [7]. The primary origin of the saturation is due to the impurity and interface scattering that establishes a minimum resistance value (minimum R value) due to the decrease in the contribution from phonons to total R. Notably, there is no insulating upturn or any sign of localizing behavior, indicating an unbroken conducting 2DEG exists over the entire T range studied. The continuous R-T dependence indicates that the interface is of good quality and therefore provides an excellent reference for examining further changes caused by illumination.

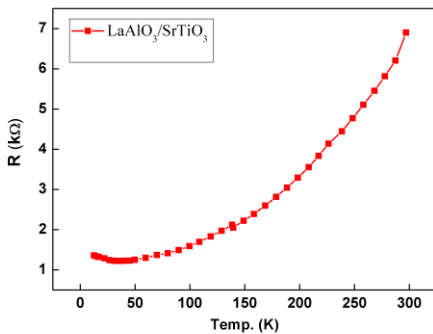


Figure 1: The temperature characteristics and resistance of LaAlO₃/SrTiO₃ heterostructures are investigated with the focus on its photoconductive reaction to optical radiation.

3.2 Photo-Induced Change in Resistance

The ratio $(R(t)-R_D)$ to R_D multiplied by 100% represents an identifiable photo response to a U.V. light because the performance at which this occurs has changed with time since there was an original controlled U.V. light exposure. There is no significant deviation during the initial portion of the response, however, at approximately 896.66 seconds after the initial U.V. light exposure you can observe a deviation from the initial response due to the activation of photocarriers. With the activation of photocarriers, there is generation of new and increased mobility of charge carriers, which leads to a continual decrease in the material resistance through continued illumination. Therefore, the response from U.V. light exposure at shorter wavelengths (250–325 nm) is much higher than from longer wavelengths, as the shorter wavelengths cause excitation of electrons from both deep level defects as well as donor levels from oxygen vacancies [4-5]. On the other hand, there are less dramatic responses to longer wavelengths (350-400 nm), although these are still measurable, and can likely be

attributed to the excitation of deep-level defect states with subband gap energies [6]. The fact that there is a persistent decrease in resistance shows that U.V. Light is influencing the interfacial 2D electron gas potential with respect to the level of defect ionization and photocarrier production.

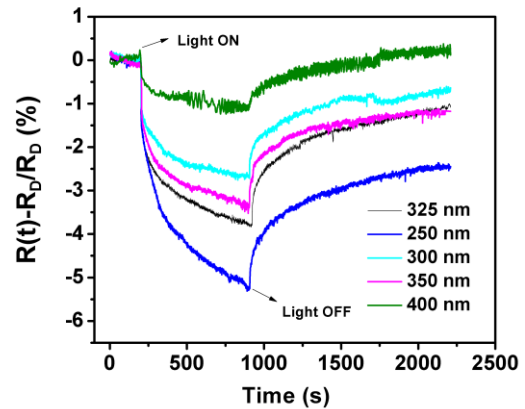


Figure 2: The 20-unit cell LaAlO₃/SrTiO₃ sample shows a time-dependent change in the relative resistance, which is evidence of the photoconductive response of the sample at illumination.

3.3 Photoconductivity Behavior and Possible Mechanism

The LAO/STO heterojunction's electrical characteristics are altered by UV radiation. In particular, the resistance between the two materials is decreased when an electron is promoted to a higher conduction band by a photon during this process. In general, fewer conduction electrons will exist in the localized defect states as compared to the conduction bands [5-6]. The conduction band holds more conduction electrons than localized defect states; therefore, a greater number of conduction electron densities will exist in conduction bands than in localized defects. Consequently, the conductivity of the surface of the heterojunction increases. Additionally, UV radiation, from short-wavelength (250-300nm) light, will facilitate other types of transitions (e.g., band-to-band transitions) which will also contribute to increased carrier densities. When the LAO/STO heterojunction is illuminated by UV radiation, the measured resistance decreases until it reaches a steady-state (saturated) value. This indicates that there is an equilibrium being established between the light produced photo-carrier generation and their redistribution and/or partial trapping within the heterojunction interface region [4]. This describes the nature of photoconductivity found at LAO/STO heterojunction interfaces.

4. Conclusion

Authors conducted an extensive study that examines how temperature affects both the electrical transport characteristics and the photocurrent produced by

ultraviolet (uv) light in a $\text{LaAlO}_3/\text{SrTiO}_3$ heterostructure that consists of twenty unit cells. The presence of two-dimensional electron gas (2DEG) is evidenced by observing metallic behavior and a plateau in conductivity at low temperatures for this heterostructure. During uv irradiation typical of those used for this work, the resistance of this heterostructure exhibited a large decrease in absolute resistance and spectral dependence as compared to what would be expected simply because of thermal heating. This can be explained due to the fact that electrical charge carriers are excited by uv light from defect and oxygen vacancy states into the conduction band and the presence of the two-dimensional character required by 2DEG at $\text{LaAlO}_3/\text{SrTiO}_3$ interfaces. The time at which a photoconductive response was generated (~896.66 seconds after light exposure) and the time for this response to stabilize provides insights into the dynamics of charge generation and stabilization at oxide interfaces. Overall, results of this study demonstrate that when illuminated with light, the electrical properties of LAO/STO heterostructures can be modulated and provide information on defects and enhanced photoconductivity in the heterostructure.

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