Electrical and Magneto-electronic Properties of p-La$_{0.7}$Ca$_{0.3}$MnO$_3$/SrTiO$_3$/n-Si Heterostructure for Spintronics Application

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Abstract. An experimental study of p-La$_{0.7}$Ca$_{0.3}$MnO$_3$/SrTiO$_3$/n-Si heterostructure in which the LCMO and Si are separated by a thin interfacial SrTiO$_3$ (STO) layer with typical thickness of about 15 nm, has been in situ fabricated with the Pulsed laser deposition technique. The La$_{0.7}$Ca$_{0.3}$MnO$_3$ (LCMO) film of about 70 nm has been grown on STO at substrate (n-Si) temperature of 800°C in 0.5 mbar oxygen pressure. The junction exhibits good rectifying behavior over the temperature range of 10 - 300 K. Electrical properties of p-La$_{0.7}$Ca$_{0.3}$MnO$_3$/STO/n-Si MOS like heterostructure exhibits nonlinear I–V characteristics in a wide temperature range. The heterostructure also exhibits MOS-diode like behavior with all type of possible current flow mechanisms (such as thermionic emission, tunneling, recombination, degeneration, etc.) through the heterojunction. The ideality factor, reverse saturation current, series resistances and turn-on voltages of the heterojunction have been estimated at different operating temperatures. The junction magnetoresistance (JMR) properties of p-LCMO/Si heterostructure have been studied over the temperature range of 100-300 K. The current–voltage characteristics at all temperatures conclusively show the high sensitivity junction magnetoresistance (JMR ~ 48% at 150 K and ~ 30% at 300 K) under the external 7 T magnetic field. The JMR is positive and strongly depends on temperature at an applied forward bias voltage (3 V). The relation between JMR and external magnetic field is found to be of ($\Delta\rho/\rho \approx \alpha H^\beta$) type having both $\alpha$ and $\beta$ temperature dependent. We attribute the emergence of positive JMR to the quantum mechanical tunneling transport mechanism along with the modification of barrier height across the heterojunction.

1. Introduction

The field of spintronics which employs the electron spin along with the electron charge to design devices with novel functionalities is the focus of much current research interest. Utilization of the spin degree of freedom provides opportunities to create devices with superior performance compared with those that use only electron charge [1, 2]. One class of materials that is promising for use in spintronic devices is the 3$d$ transition-metal complex oxides, which owing to their highly correlated $d$ electrons, exhibit a wide variety of electronic and magnetic properties [3, 4]. The research on manganite materials (R$_{1-x}$A$_x$MnO$_3$, where R is a trivalent rare earth and A is a divalent alkaline ion) for their integration into spintronics devices has recently received much attention. The half-metallicity of these materials makes them proper electrodes in magnetic tunnel junctions (MTJ’s). Generation of spin polarization usually means creating a non-equilibrium spin population which can be achieved in several ways. Recently, a lot of research studies have been focused on perovskite based oxide semiconductors and semimetals heterojunctions with
different semiconductors [5-7]. It is still an open question to model the interface between different perovskite-type oxides. Previous studies reveal that the transport process in manganite heterostructures can be approximated by p-n junctions or Schottky type junctions [8, 9]. P. L. Lang et al. also demonstrated that La$_{0.67}$Ca$_{0.33}$MnO$_3$/SiO$_2$/Si type p-n heterojunctions show Space Charge Limit (SCL) diode characteristics with the presence of the SiO$_2$ layer [10]. The most of the studies focused on the transport process based on current voltage characteristics. Generally the current-voltage characteristic is guided by tunneling of conduction electrons between the junctions though the presence of edge leakage which makes the transport mechanism complicated. As a result there is difficulty in the extraction of actual barrier height.

In present work we have fabricated p-LCMO/STO/n-Si heterojunction by pulsed laser deposition technique. We have explicitly studied the junction current–voltage ($I$–$V$) characteristics of p-LCMO/STO/n-Si junction without and with 7 T external magnetic field. The JMR properties of the same heterojunction also studied under the external magnetic field up to 7 T. The origin of JMR has been explained using standard spin injection theory.

2. Experimental procedures

At first we have prepared the LCMO target using the “prypophoric reaction” route. Final sintering of the LCMO target was carried out at 1200 °C for 24 h. La$_{0.67}$Ca$_{0.33}$MnO$_3$ film on n-Si (100) substrate was grown by Pulsed Laser Deposition process. The substrate was thoroughly cleaned in ultrasonic bath using acetone and alcohol followed by chemical cleaning with mixture of H$_2$O$_2$ and H$_2$SO$_4$ (1:1). The oxide layer was etched by 10 % HF. The film was deposited on <100> Si substrate using following steps. (1) The substrate was first heated at 800 °C and STO film was deposited at 0.5 mbar O$_2$ pressure. (2) Then LCMO film was deposited at the same physical condition. The laser pulse of energy 300 mJ was applied on the STO and LCMO targets for 20 min at a frequency of 10 Hz and the target - substrate distance was kept at 4 cm. (3) finally, the film was then sintered at 800 °C and 0.5 mbar O$_2$ pressure for 1 h. A cryogen free superconducting magnet (8 T) fitted with a closed cycle helium refrigerator system was used to measure the electrical transport properties of the LCMO/STO/n-Si heterojunction. The junction magnetoresistance properties of p-LCMO/STO/n-Si heterostructure were measured at different temperatures in the range of 100 K-300 K. The ohmic contact on the back side of n-Si semiconductor was made by high purity indium and other side contact on LCMO film was made by silver paste.

3. Results and discussion

The I-V characteristics of p-LCMO/STO/n-Si heterojunction have been shown in Fig. 1(a) at different temperatures (150 K, 200 K, 250 K and 300 K) in absence of external magnetic field. The heterojunction shows very good rectifying diode like behavior in all temperatures.

![Figure 1.](image_url)
The junction current is found to increase with increasing temperature which is generally expected in p-n junction characteristics. Figure 1(b) shows the I-V characteristics of same heterojunction at same temperatures with external magnetic field 7 T. At low forward voltage the current increased exponentially which has been usually observed in diodes and attributed to recombination, degeneration or tunneling mechanism. The detailed comparative study of I-V without and with applied 7 T magnetic field measured at different temperatures (150 K and 300 K) for LCMO/STO/n-Si heterojunction have been shown in Fig. 2. The current across the junction decreases with increasing the magnetic field at a 3 V forward bias voltage. The junction I-V characteristics of this heterojunction can be described using modified diode equation [11]

\[ I = I_0 \exp \left( \frac{e(V - V_0 - I R_s)}{\eta kT} \right) \]

(1)

where \( I_0 \) is the reverse saturation current, \( V_0, \eta \) and \( R_s \) are turn on voltage, ideality factor and junction series resistance, respectively. The best fit parameters (\( \eta, I_0, R_s \) and \( V_0 \)) for LCMO/STO/n-Si heterojunction have been evaluated using equation (1) at different temperatures.

Figure 2. (a) and (b) The detailed comparative I-V study for LCMO/STO/n-Si heterojunction at 150 K and 300 K without and with external magnetic field 7 T, respectively.

The JMR (JMR=\((R_{H=6T} - R_{H=0T})/R_{H=0T}\)\)*100) properties (up to 6 T magnetic field) of the same heterojunction have been studied at different temperatures (150 K and 300 K) under the bias voltage of 3 V, which has been shown in Fig. 3. The junction resistance is increases with increasing of magnetic field which leads to positive JMR. It shows that the JMR behavior follows a simple empirical relation with magnetic field as [12],

\[ JMR = \alpha H^\beta \]

(2)

where, \( \alpha, \beta \) and are coefficients. The best fit parameters (\( \alpha =16.08, 4.2 \) and \( \beta =0.56, 0.97 \) at 150 K and 300 K, respectively) for LCMO/STO/n-Si heterojunction have been evaluated using equation (2). The coefficient \( \beta \) is lower than one at both temperatures, showing non-linear magnetic field dependence of positive JMR of the junction. It shows the positive JMR properties for all the temperatures and the magnitude of positive JMR is also temperature dependent. The % JMR at a fixed bias voltage of 3V has been found to decrease sharply with the increase in temperature. The origin of positive JMR in this heterojunction can be best explained by the spin injection theory of magnetic p-n junction where p-Si is nonmagnetic semiconductor. Spin injection generally occurs in n-side and spin extraction generally occurs in p-side. Both spin injection and spin extraction becomes large with applied magnetic field. The current through the magnetic p-n junction depends on magnetic field because of the spin orbit splitting of magnetic materials. The magnetically active electrons in LCMO cause non-equilibrium polarized conduction electrons by the application of external magnetic field. This non-equilibrium population at magnetic n-side enhances the spin injection through the space-charge region [13]. It causes a high
magnetoresistance (positive junction MR) according to standard spin injection theory [14]. Highest positive JMR for LCMO/STO/n-Si heterojunction has been found to be 48 % at 150K (30 % at 300K) at a fixed applied bias voltage of 3 V. Ferromagnetic metal (F) – non magnetic semiconductor (N) tunneling is the process, where the electrons tunnel through a barrier in the presence of a high electric field.

![Figure 3](image_url)

**Figure 3.** The JMR properties for LCMO/STO/n-Si heterojunction at different temperatures (150 K and 300 K) at a fixed bias voltage of 3 V (up to 7 T magnetic field).

This quantum-mechanical tunneling process is an important mechanism for thin barriers as those in metal– semiconductor junctions on highly doped semiconductors [15-18]. The dominating current transport mechanism is tunneling. Hence, it can be concluded that the appearance of positive JMR is due to tunneling of electron through the heterojunction.

4. Conclusions

In conclusion, the I-V properties of LCMO/STO/n-Si heterojunction have been studied at several temperatures. The heterojunction shows good rectifying behavior at all temperatures. The JMR behavior of the same heterojunction has been studied which shows that the high value positive JMR (48 %) observed at 150 K. The % JMR at a fixed bias voltage of 3V has been found to decrease sharply with the increase in temperature. The junction magnetoresistive property has been explained using standard spin injection mechanism in magnetic p-n junction. The properties of these heterojunction are very useful in the area of spintronics devices.

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