Extended Abstracts of the 1995 International Conference on Solid State Devices and Materials, Osaka, 1995, pp. 410-412



# Electric Field Effect in $LaTiO_3/SrTiO_3$ Heterostructure

Chikako YOSHIDA, Hirotaka TAMURA, Akira YOSHIDA*, Yuji KATAOKA,
Norio FUJIMAKI*, and Naoki YOKOYAMA*
*Fujitsu Laboratories Ltd., *Fujitsu Limited*
*10-1 Morinosato-Wakamiya, Atsugi 243-01, Japan*

We have developed a technique to form conductive $LaTiO_3/SrTiO_3$ interdiffusion layers which have a carrier density in the $10^{13}$ $cm^{-2}$ to $10^{15}$ $cm^{-2}$ range. An $LaTiO_3/SrTiO_3$ heterostructure, which showed a field effect, was successfully used as the conductive channel of a transistor which controls superconducting current induced by proximity effect. We also demonstrated that the heterostructure's field effect can be used to control electronic conduction characteristics in the heterostructure, such as the mobility depth profile.

## 1. Introduction

$SrTiO_3$ could possibly play an important role in future oxide electronics[1], because of its semiconducting properties, high permittivity, and compatibility with perovskite and related oxides. $SrTiO_3$ has been used as a channel for various three-terminal devices, such as high- and low-Tc superconducting transistors[2] [3] and room-temperature oxide transistors.[4] To achieve higher current densities and lower operating voltages in these devices, we need a method of forming a high-mobility doped layer with a controlled amount of donor concentration.

In this paper, we discuss a technique to form conductive $LaTiO_3/SrTiO_3$ interdiffusion layers, in which carriers are created by the substitution of $La^{3+}$ with $Sr^{2+}$, and we then investigate the electric field effect of this heterostructure.

## 2. Carrier density control

$LaTiO_3$ films were deposited on $SrTiO_3$ substrates by KrF excimer laser ablation at a substrate heater temperature of 910°C. After deposition, the deposition chamber was evacuated below $1\times10^{-5}$ Torr. Samples were kept at the deposition temperature for 15 minutes before being cooled to room temperature.

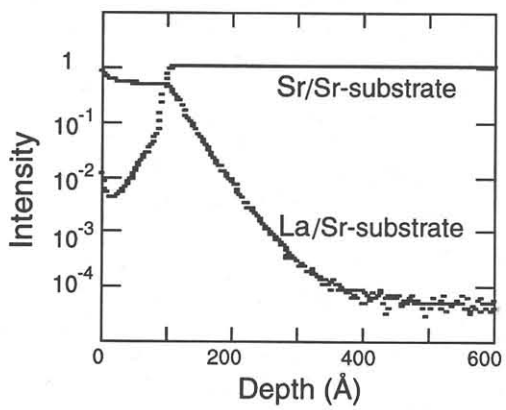


Fig. 1 SIMS depth profile of the heterostructure. Intensity is normalized by the Sr ion count from the substrate.

A secondary ion mass spectroscopy (SIMS) depth profile of a 100 Å thick $LaTiO_3$ film is shown in Fig. 1. By integrating the intensity profiles, it is estimated that about $10^{15}$ $cm^{-2}$ Sr atoms penetrated into the $LaTiO_3$ film and $10^{16}$ $cm^{-2}$ La atoms penetrated into the substrate.

In the $LaTiO_3/SrTiO_3$ interdiffusion layer, carriers are created by the following mechanism. $LaTiO_3$ is a Mott-Hubbard insulator with localized half spins. By Sr-doping (hole-doping) onto an La site[5], insulating state is broken and transformed to the metallic state at the film surface. On the other hand, inside the substrate, an electron is created by the substitution of $La^{3+}$ with $Sr^{2+}$ as $La_x^{3+}Sr_{1-x}^{2+}Ti_x^{3+}Ti_{1-x}^{4+}O_3$.

Hall measurement was performed on the heterostructure and surface carrier density, $N_S$, was estimated at $1.2\times10^{14}$ $cm^{-2}$ at room temperature and $7.5\times10^{13}$ $cm^{-2}$ at 25 K, which is one order of magnitude less than the value expected based on SIMS data.

This discrepancy can be explained by looking at the effect of oxygen partial pressure on La-doped $SrTiO_3$ at high temperature[6]. In particular, Sr may combine with oxygen to form an Sr site vacancy, which compensates for the extra charge created by the substitution of $La^{3+}$ with $Sr^{2+}$. The defect concentration in the Sr sites increases with increasing oxygen partial pressure as,

$$La_{Sr} + \tfrac{1}{2}Sr_{Sr} + Ti'_{Ti} + \tfrac{1}{4}O_2 \leftrightarrow \tfrac{1}{2}(SrO) + \tfrac{1}{2}V''_{Sr} + Ti_{Ti} + La_{Sr} \quad (1)$$

where $La_{Sr}$, $Sr_{Sr}$, $Ti'_{Ti}$, and $V''_{Sr}$ represents La on Sr site, Sr on Sr site, $Ti^{3+}$ on $Ti^{4+}$ site, and double-ionized vacancy on Sr site, respectively.

In order to investigate the effects of oxygen partial pressures, we deposited $LaTiO_3$ films on $SrTiO_3$ substrates with partial pressures of $10^{-4}$-0.2 Torr oxygen during the deposition. The part of the sample surface covered with $LaTiO_3$ film exhibited conductivity, whereas the part of the surface not covered with $LaTiO_3$ film stayed insulating. Figure 2 shows the sheet resistance, Rs, and carrier density vs. oxygen partial pressure of these $LaTiO_3/SrTiO_3$ heterostructures at 25 K. The lower the oxygen partial pressure is, the lower the sheet resistance. Conversely, a lower oxygen partial pressure produces

larger carrier density. When the oxygen partial pressure was below $10^{-4}$ Torr, the whole substrate became conductive because of oxygen deficiency. Figure 2 shows that carrier density can be controlled from $10^{13}$ $cm^{-2}$ to $10^{15}$ $cm^{-2}$ by changing the $O_2$ partial pressure during the deposition of the $LaTiO_3$ film.

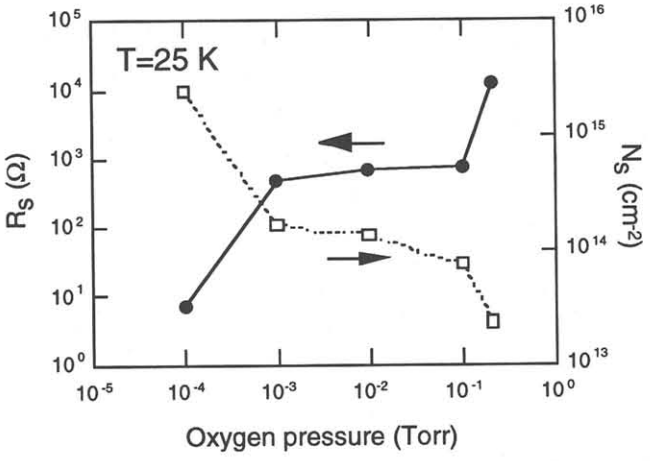


Fig. 2 Sheet resistance and carrier density vs. oxygen partial pressure during the deposition.

### 3. Electric field effect

Next we investigated the electric field effects for a heterostructure formed in 0.12 Torr oxygen. An electrode was attached to the back of the substrate using Ag paste. While applying negative voltage to the electrode, we measured the sheet resistance, $R_S$, and the Hall coefficient, $R_H$, simultaneously at 25 K. As shown in Fig. 3, applying -60 V increased the sheet resistance by 100% and reduced the surface carrier density by 30%.

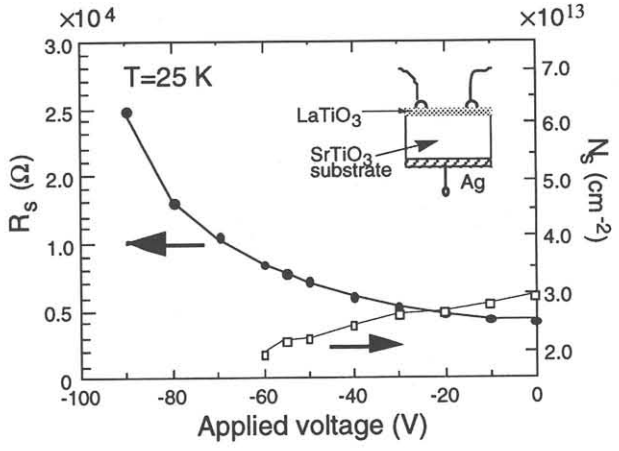


Fig. 3 Sheet resistance and carrier density vs. applied voltage. The inset shows the sample structure.

Since the concentration of La and Sr changes only gradually in this heterostructure, the mobility may be a function of the distance from the surface, x. If the heterostructure behaves as a doped semiconductor, a depletion layer is formed by applying a negative voltage as shown in Fig. 4. Thus, the distance x and mobility can be describedas a function of applied voltage, as x(V) and μ(x(V)). Mobility can then be expressedas,

$$\frac{1}{R_S} = e\int_0^x \mu(x)n(x)\,d$$

$$\frac{R_H}{R_S^2} = e\int_0^x [\mu(x)]^2 n(x)\,dx$$

$$\mu(x) = \frac{\dfrac{d[R_H/R_S^2]}{dV}}{\dfrac{d[1/R_S]}{dV}} \qquad (2)$$

where n(x) denotes the carrier density.

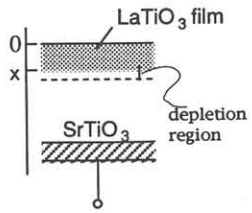


Fig. 4 Schematic illustration of the sample structure. x denotes the distance from the surface.

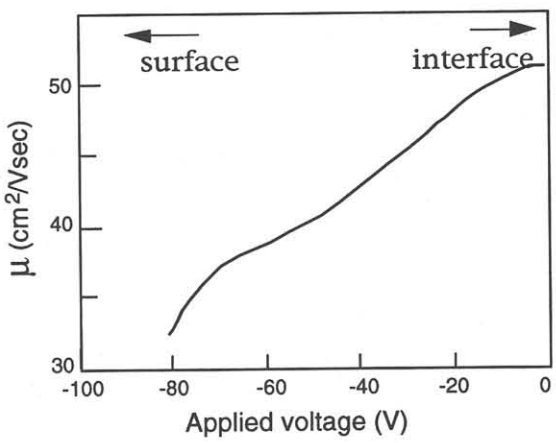


Fig. 5 Applied voltage dependent mobility.

Figure 5 shows the applied voltage dependence of mobility, μ(V) obtained from Eq. 2. Note that μ(V) decreased with increasing negative voltage and thus mobility decreases near the surface.

### 4. Application

The $LaTiO_3/SrTiO_3$ heterostructure can be used as a channel where a supercurrent flows. We fabricated a weak link by coupling Nb electrodes to by the

$LaTiO_3/SrTiO_3$ heterostructure with a 100 nm spacing (Fig. 6). The weak links showed that superconducting current flowed at 4.2 K. We also observed Shappiro steps when microwave power at frequency of using 6.5 GHz was irradiated. The Fraunhofer pattern-like magnetic field response of the critical current shows that a uniform current flows through the weak link. These results show that a Josephson current induced by proximity effect can pass through the $SrTiO_3$ substrate at 4.2 K.

When a voltage of -20 V was applied to a gate which was placed on the back of the substrate, the normal resistance, Rn, (defined as the differential resistance at a voltage of 200 mV in the I-V curve) increased by +5 %, applying 20V decreased Rn by 5 %. The magnitude and direction of the relative change of Rn is reasonable, but we could not observe the change in the critical current when the gate voltage was varied from -20 to 20 V because carrier density was too high. The carrier density in an $LaTiO_3/SrTiO_3$ channel must be controlled at less than $10^{13}$ $cm^{-2}$ for application as superconducting transistors.

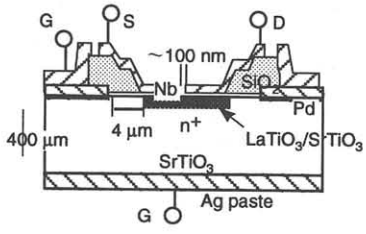


Fig. 6 Schematic crosssection of a Josephson weak link coupled by the $LaTiO_3/SrTiO_3$ heterostructure.

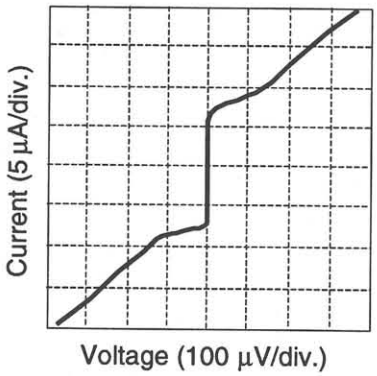


Fig. 7 Current-voltage characteristics of the Josephson weak link.

## 5. Conclusions

We have developed a technique for n-type doping of $SrTiO_3$ which is appropriate for transistor applications. In the $LaTiO_3/SrTiO_3$ heterostructure, an La and Sr interdiffusion layer is formed during the laser ablation deposition process. The electron carriers are created by substitution between La and Sr. At the same time, extra charge is partially compensated for by Sr vacancies which are caused if there is sufficient ambient oxygen at high temperature. Thus, the carrier density can be controlled in the range of $10^{13}$-$10^{15}$ $cm^{-2}$ by changing the oxygen partial pressure at deposition.

This technique can readily be used to fabricate oxide devices with $SrTiO_3$ channels. We found that the resulting conducting layer can be used as a channel where a supercurrent flows.

The $LaTiO_3/SrTiO_3$ heterostructure exhibited an electric field effect, i.e., the sheet resistance increases and the carrier density decreases when increasing the negative applied voltage. Further, in the depth profile for this heterostructure the mobility decreases nearer to the surface. The field effect can also be used to effectively control electronic conduction characteristics in the heterostructure.

## Acknowledgment

This work was performed under the management of FED as a part of the MITI R&D program (High-Temperature Superconducting Electron Devices project) supported by NEDO.

## References

1) H. Koinuma, MRS Bulletin special issue, **19** (1994) 21.
2) A. Yoshida et al., IEEE Trans. on Applied Superconductivity, **4** (1994) 76.
3) A. Yoshida et al., to be published in IEEE Trans. on Applied Superconductivity (1995).
4) K. Gotoh et al. ,Proceedings of the 52nd Annual Device Research Conference, IIIB-4, June (1994).
5) Y. Tokura, et al. Phys. Rev. Lett. **70** (1993) 2126.
6) U. Balachandran and N. G. Eror, J. Electrochem. Soc. **129** (1982) 1021.