Electric Field Effect in LaTiO$_3$/SrTiO$_3$ Heterostructure

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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.$^9$ 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$^+$ 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 $1 \times 10^{-5}$ Torr. Samples were kept at the deposition temperature for 15 minutes before being cooled to room temperature.

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$^+$ with Sr$^{2+}$ as La$_x$Sr$_{1-x}$Ti$_2$O$_5$.

Hall measurement was performed on the heterostructure and surface carrier density, $N_s$, was estimated at $1.2 \times 10^{14}$ cm$^{-2}$ at room temperature and $7.5 \times 10^{13}$ 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$^+$ with Sr$^{2+}$. The defect concentration in the Sr sites increases with increasing oxygen partial pressure as,

$$\text{La}_x + \frac{1}{2}\text{Sr}_{2x} + \text{Ti}^4\text{Ti}^3 + \frac{1}{4}\text{O}_2 \leftrightarrow \frac{1}{2}\text{Sr}_{2x} + \frac{1}{2}\text{V}^+_\text{Sr} + \text{Ti}^4\text{Ti}^3 + \text{La}_x$$

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

$$\frac{1}{R_s} = \int_0^T \mu(x)n(x) \, dx$$

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

where $n(x)$ denotes the carrier density.

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%.

$$\mu(x) = \frac{d[R_H/R_s]}{dV}$$

$$\int_0^T [\mu(x)]^2 n(x) \, dx$$

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, $\mu(V)$ obtained from Eq. 2. Note that $\mu(V)$ 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.

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.

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References