# Superconductivity and Electric Field Effects in Ultrathin YBa$_2$Cu$_3$O$_{7-\delta}$ Films

### Yoshichika Bando and Takahito Terashima

Effect of adjacent insulating cap oxide layers on superconductivity of one unit cell thick (1-UCT) YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) layers in PrBa$_2$Cu$_3$O$_{7-\delta}$/YBCO/insulating oxide trilayers has been studied. It is found that the small lattice mismatch between YBCO and the cap oxides, in addition to divalent A ions in atomic AO layers subsequent to the CuO$_{1-\delta}$ terminated surface, is a requirement for superconductivity in 1-UCT YBCO layers. The change in the normal state resistance is well explained by the field-induced change of carrier density.

*Keywords*:    High-$T_c$ superconductivity / YBa$_2$Cu$_3$O$_{7-\delta}$ / Ultrathin film / One-unit-cell / Charge reservoir block / Electric field effect

Ultrathin films and superlattices of high-$T_c$ superconductors have been extensively studied to elucidate the minimum unit for the occurrence of high-$T_c$ superconductivity and interlayer coupling of the CuO$_2$ layers. High-$T_c$ superconductors are characterized by two dimensional CuO$_2$ layers, which are separated by the charge reservoir blocks. An stringent test of the intrinsic nature of the high-$T_c$ superconductors characterized by layered structures can be obtained from transport measurements on one unit cell thick (1-UCT) layer of the superconductor. The smaller carrier density of high-$T_c$ superconductor than that in metal superconductor enables the change of carrier density by applying electric fields. The ultrathin films are expected to exhibit remarkable field effects in $T_c$ and other properties.

In the preparation of such ultrathin layers, we need the deposition technique which enables us to prepare epitaxial films with excellent superconducting properties, precise layer thicknesses and smooth surfaces. We have used a molecular beam epitaxy (MBE) system equipped with reflection high energy electron diffraction (RHEED), which enables real-time, *in situ* layer thickness monitoring by specular beam intensity oscillations [1].

We have found that superconductivity can occur at finite temperatures in the single layer of 1-UCT YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) sandwiched between nonsuperconducting PrBa$_2$Cu$_3$O$_{7-\delta}$ (PrBCO) layers [2] and the minimum unit needed for the occurrence of superconductivity is the CuO$_2$ bilayer sandwiched between the charge reservoir blocks, as shown in Fig. 1(a) [3]. It has been reported that the terminating surface of

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*Scope of research*
*Syntheses of oxide thin films by reactive evaporation and ceramics by solid state reaction and their characterizations are studied. The main subjects are: preparation and characterization of ultrathin films of high-Tc superconductors: investigation of growth mechanism of thin films by in situ reflection high-energy electron diffraction: phase diagram of Bi$_2$O$_3$-SrO-CaO-CuO system: growth and characterization of single crystals of Bi-Sr-Cu-O system: preparation and observation of dielectric properties of ferroelectric thin films: preparation and characterization of metallic and ferromagnetic SrRuO$_3$ thin films: scanning tunneling microscope observation of surface structures and electronic states of metallic oxide thin films*

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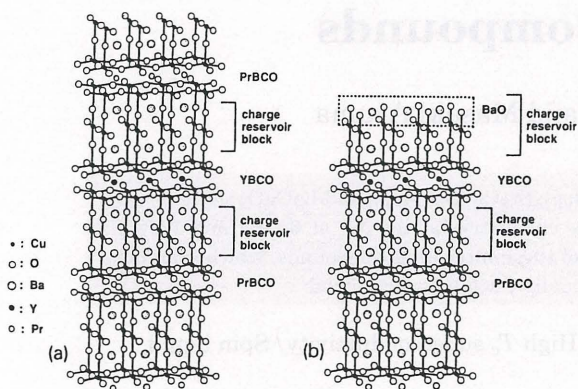IKEDA, Yasunori
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**Figure 1**. Structures of trilayers of (a) PrBCO/1-UCT YBCO/1-UCT PrBCO and (b) PrBCO/1-UCT YBCO/BaO. Note that the $CuO_2$ bilayer interposing an Y layer is sandwiched between the charge reservoir blocks and the terminating layers of growing YBCO and PrBCO are the $CuO_{1-\delta}$ layer.
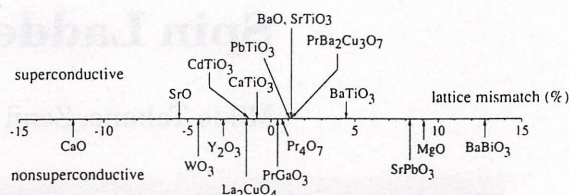


**Figure 2.** Effect of cap oxides on superconductivity in 1-UCT YBCO as a function of value of lattice mismatch to YBCO.

the YBCO layer grown by MBE is the $CuO_{1-\delta}$ layer. As a result, the 1-UCT YBCO layer on the buffer PrBCO layer needs addition of the BaO layer for the completion of the charge reservoir block, as shown in Fig. 1(b). It is found that the capping of the 1-UCT YBCO layer with BaO makes the 1-UCT layer superconducting.

In place of BaO layers, the effects of other alkaline-earth metal oxide "AO" caps on the superconductivity of the samples have been examined. The experimental results are summarized as a function of lattice mismatch value in Fig. 2. We can conclude that divalent metal ions in AO layer adjacent to the $CuO_{1-\delta}$ layer, in systems with mismatch values (<6%) exhibit superconductivity in PrBCO/1-UCT YBCO/cap oxide trilayers.

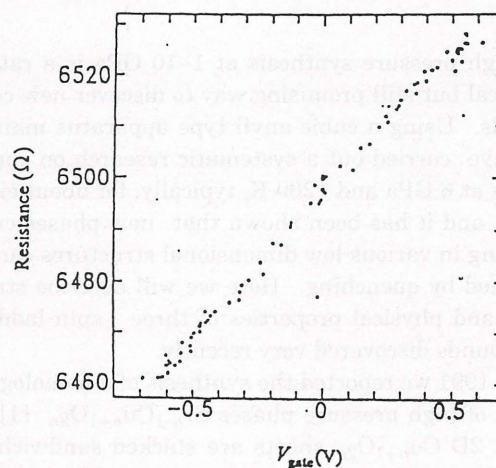We have studied electric field effects in ultrathin YBCO films using heterostructures of $Ag/BaTiO_3(200nm)/$ $SrTiO_3(1.5nm)/$ $YBCO/SrTiO_3$(substrate)[4]. Gate voltage, $V_{gate}$, dependence for 2-UCT YBCO at 72.8K is shown in Fig.3. The application of negative voltage to the Ag electrode, i.e. the YBCO layer is positively charged, lowers the resistance of YBCO layer linearly in $V_{gate}$, while a positive $V_{gate}$ having the opposite effect. The field induced change of the resistance $\Delta R/R$ is 0.5% for the applied field of 0.5V.

Observed $\Delta R/R$ in the normal state can be explained by the field induced carriers ($\Delta N$). In the present experiment, field induced charge $\Delta N$ in the areal density is evaluated as follows.

$$\Delta N = \Delta Q/e, \quad \Delta Q = CV_{gate}/S, \quad N=nd,$$



**Figure 3.** Gate voltage, $V$gate, dependence of resistance for 2-UCT YBCO at 72.8K.

where $S$ is area of electrode, $N$ is total carrier of YBCO layer, $d$ is the thickness of YBCO layer and $n$ is carrier density of bulk YBCO. $\Delta N/N$ is evaluated to be 0.55% by using the values of $n=5\times 10^{21}(cm^{-3})$, C=500(nF) and S=$2.2\times 10^{-1}(cm^2)$. The observed $\Delta R/R$ is in good agreement with the change of the carrier density, $\Delta N/N$.

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