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In-plane pressure effect in strained $YBa_2Cu_3O_7/La_{1.85}Sr_{0.15}CuO_4$ superlattices

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Superconducting strained superlattices have been formed by epitaxial stacking along the c axes of two kinds of unit layers, $YBa_2Cu_3O_7$ (YBCO) and $La_{1.85}Sr_{0.15}CuO_4$ (LSCO). In these superlattices, the ab plane of YBCO is compressed and the c axis is elongated due to the LSCO layer, which has smaller lattice constant a than that of the YBCO layer. When the thickness of the YBCO layer is reduced, the superconducting transition temperature ($T_{c_{end}}$) of YBCO gradually decreases. The decrease of T_c is, however, much smaller in this system than that in $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ and $YBa_2Cu_3O_7/(Nd,Ce)_2CuO_4$ superlattices. The $T_{c_{end}}$ for only two units (2.4 nm) of the YBCO layers is as high as 72 K. The correlation between the T_c and the in-plane strain along the a, b axes suggests that the effect of pressure in changing the Cu-O bond length along the CuO_2 plane of the superconducting YBCO layer is one of the important factors in raising the T_c value.

Recently, high-pressure experiments on copper-oxide-based superconductors have been carried out using a variety of materials.[1-3] In most cases, isostatic pressure has been applied to the materials and the changes of superconducting transition temperature have been observed. The application of uniaxial or in-plane pressure has been limited because of the layered structure of the high-T_c materials, although these approaches are definitely important for the elucidation of the intrinsic properties of these materials. Studies of superconducting superlattices and multilayered films, on the other hand, have been carried out as approaches to the artificial construction of materials and to clarify the mechanism of high-T_c superconductivity.[4-8] These superlattices are suitable for purposes such as the evaluation of the dimensionality, proximity effect, and strain effect of the superconductors. Among these effects, we examine the in-plane pressure effect caused by the strain between stacked layers with different lattice constants. It is possible to mimic the effect of high pressure by the strain at the interface of such layers. In the present study, strained superlattices are formed by the stacking of the 90-K superconducting layer of $YBa_2Cu_3O_7$ (YBCO) and the 40-K superconducting layer of $La_{1.85}Sr_{0.15}CuO_4$ (LSCO) along the direction of the c axis. Since the LSCO superconductor has smaller lattice constants a and b ($a=b=0.378$ nm) than those of $YBa_2Cu_3O_7$ ($a=0.388$ nm, $b=0.383$ nm), compression of the ab plane in $YBa_2Cu_3O_7$ is expected in this superlattice. The relation between the lattice constants a,b,c and the changes of T_c of YBCO is investigated. By comparing this relation with that reported for $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattices[4,6,7] having no strain in the YBCO layer, we found that a much smaller decrease of T_c occurs in this strained YBCO/LSCO superlattice even when the layer thickness of YBCO is extremely small (2.4 nm). This strain effect will be compared with the pressure effect in the bulk system.

The superlattices were formed by a laser ablation method using an ArF excimer laser which was described earlier.[9] Briefly, laser pulses were focused on YBCO and LSCO targets successively in a vacuum chamber, and ablated species were alternately accumulated on an MgO(100) substrate to form $YBa_2Cu_3O_7/(La,Sr)CuO_4$ superlattices. The targets for the ablation of YBCO and LSCO layers were sintered disks with the composition of $YBa_2Cu_{3.5}O_y$ and $La_{1.85}Sr_{0.15}CuO_y$, respectively. The thickness of each layer in the superlattice was monitored *in situ* by a quartz oscillating thickness monitor, and was confirmed by measuring the thickness by optical interference spectrometer. A mixture of O_2 and O_3 (8 vol.%) was dosed during film formation with a total gas pressure of 3×10^{-3} Torr at the substrate temperature of 700 °C. The properties of the samples were evaluated by powder x-ray diffraction, four-circle x-ray diffraction (4CXD), scanning electron microscope (SEM), reflection high-energy electron diffraction (RHEED), and resistivity-temperature (R-T) measurements.

Figure 1(a) shows the x-ray diffraction pattern of the YBCO/LSCO film formed by the stacking of 30 nm of YBCO and 30 nm of LSCO. The sharp (001) peaks show that both YBCO and LSCO layers have good crystallinity and have c axes of normal orientations to the substrate. A sharp streak pattern is observed in RHEED measurements, indicating that both YBCO and LSCO layers grow epitaxially on the MgO substrate. SEM observation has confirmed that the surface of this multilayered film is extremely smooth. In order to obtain precise parameters for the a, b, and c axes, we have determined the lattice constants of the YBCO layer in the superlattices by the 4CXD method. These lattice constants have been precisely determined using (303), (033), (116), and (005) peaks as shown in the stereo projection (pole figure) of Fig. 1(b). This figure also shows the epitaxial relations of LSCO and YBCO layers on the MgO single crystal. Figures 2(a) and 2(b) show the changes of the lattice constants a, b, and c of the YBCO layer as a function of the thickness of the YBCO layer, with the thickness of the LSCO layer constant at 30 nm. When the thickness of the YBCO layer is also 30 nm, the lattice constants a, b, and c of the YBCO layer are 0.3878, 0.3830, and 1.172 nm, respectively, which are close to the known values of bulk $YBa_2Cu_3O_7$.[10] With decrease of the YBCO thick-

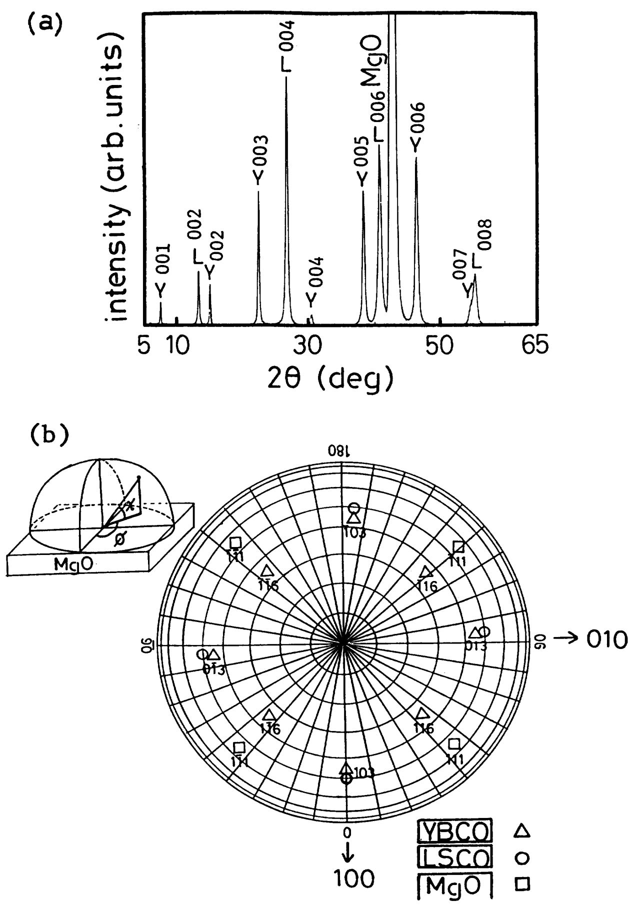

FIG. 1. (a) The x-ray diffraction patterns (θ-2θ) for the YBCO/LSCO (30/30 nm) multilayered film. (Y:$YBa_2Cu_3O_7$, L:$La_{1.85}Sr_{0.15}CuO_4$). (b) The pole figure for the YBCO/LSCO on MgO(100) determined by four-circle x-ray diffraction measurement.

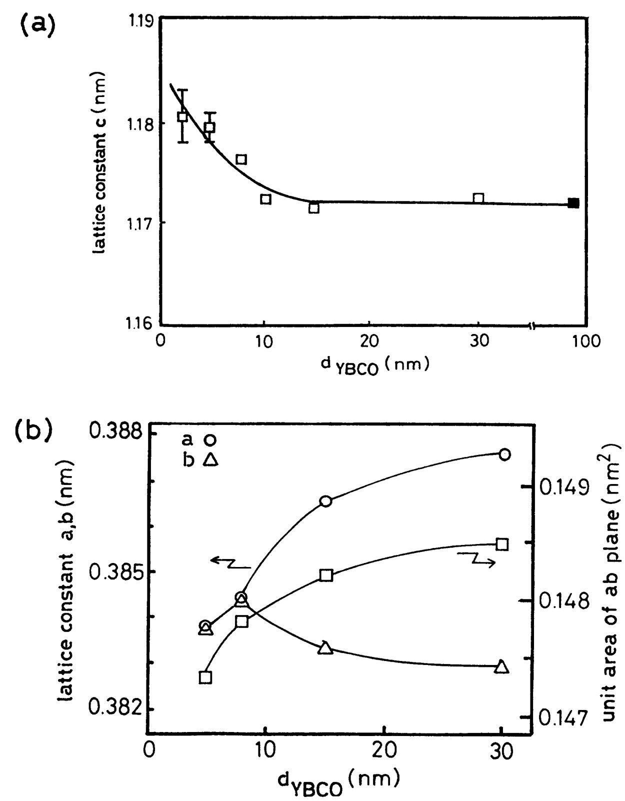

FIG. 2. (a) The lattice constant c vs the thickness of YBCO layer in the YBCO/LSCO superlattice. The filled square shows the value for the normal YBCO thin film with 100 nm thickness. LSCO layer thickness is fixed at 30 nm. (b) The lattice constants a and b vs the thickness of the YBCO layer. The circles are the lattice constant a and the triangles are the lattice constant b. The squares represent the changes of the unit area of ab plane by the compression.

ness, the lattice constants a and b approach an equal value, and the tetragonal structure is achieved when the YBCO thickness becomes ~8 nm [see Fig. 2(b)]. Furthermore, shrinking of both a and b is observed below 8-nm thickness. When the YBCO thickness is 8 and 5 nm, the lattice constants a of YBCO are shrunk to 0.3844 and 0.3838 nm, respectively. These behaviors are assumed to be caused by the neighboring LSCO layer which has smaller lattice constants ($a=b=0.378$ nm) than those of YBCO. The c axes, on the other hand, are expanded to 1.176 and 1.180 nm, respectively. This elongation of the c axis is due to the Poisson's relation corresponding to the compression of the ab plane in the YBCO layer.

Superconducting transition curves for these YBCO/LSCO superlattices are plotted in Fig. 3. The resistivities of all films are around 400$\mu\Omega$ cm at room temperature and independent of the YBCO thickness owing to similar resistivity between YBCO and LSCO films. At 15 nm of the YBCO layer (YBCO/LSCO=15/30 nm), the $T_{c_{end}}$ is 86 K. With the decrease of the YBCO thickness, the $T_{c_{end}}$ gradually decreases. However, even when the YBCO thickness becomes 2.4 (2 unit cells) and 3.6 nm (3 unit cells), the transition temperature ($T_{c_{end}}$) is 72 and 77 K, respectively. These values of T_c are very high for isolated ultrathin YBCO unit layers (Fig. 3 shows comparison among reported multilayers, superlattices, and YBCO ultrathin films of the same YBCO thickness[4,6,11]).

Figures 4 shows the variations of T_c of $YBa_2Cu_3O_7$ with thickness of the YBCO layers in superlattices and ultrathin films. Figure 4(a) shows the result obtained in our YBCO/LSCO superlattices. Figures 4(b)–4(d) show the variations of T_c reported in $YBa_2Cu_3O_7$/$PrBa_2Cu_3O_7$ (YBCO/PBCO),[6] $YBa_2Cu_3O_7$ ultrathin film on MgO(100) substrate[11] and $YBa_2Cu_3O_7$/$Nd_{1.85}Ce_{0.15}$-CuO_4 (YBCO/NCCO).[8] The YBCO layer in the YBCO/PBCO superlattice has almost no strain along the ab plane because of the similar lattice constants a, b of each layer. The T_c of this system is naturally suppressed with the decrease of YBCO thickness because of the suppression of the interlayer coupling[4,6,7] or the changes of the Kosterlitz-Thouless transition temperature. On the other hand, the CuO_2 plane of YBCO in YBCO/NCCO is expanded by the larger lattice constants of NCCO ($a=b=0.394$ nm).[8] The rapid decrease of T_c in this system was explained by the expansion of the ab plane of the YBCO layer by the NCCO layer.[8] Thus, in Fig. 4, a systematic correlation between the T_c and the strain in the

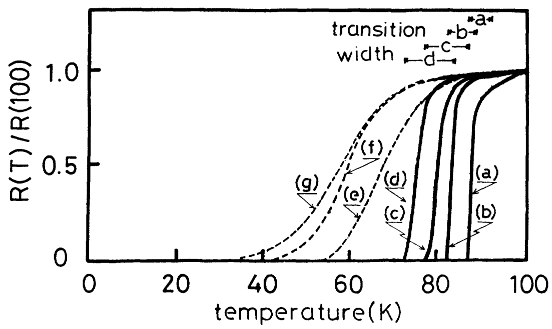

FIG. 3. Resistance-temperature curves of YBCO/LSCO and YBCO/PBCO: (a) YBCO/LSCO (15/30 nm); (b) YBCO/LSCO (8/30 nm); (c) YBCO/LSCO (3.6/30 nm); (d) YBCO/LSCO (2.4/30 nm). The thickness of LSCO is fixed at 30 nm and only those of the YBCO layer are varied. (e) YBCO/PBCO (2.4/10 nm) [Li *et al.* (Ref. 6)]; (f) YBCO/PBCO (2.4/14.4 nm) [Triscone *et al.* (Ref. 4)]; (g) ultrathin film for YBCO (3 nm) [Terashima *et al.* (Ref. 11)].

ab plane of YBCO is observed. The YBCO ultrathin film[11] on MgO shows a similar decrease of T_c to the YBCO/PBCO with no strain. In our YBCO/LSCO superlattice, on the other hand, the T_c shows a much smaller decrease correlating with the compression along the *ab* plane. This correlation is observed clearly in the region of YBCO layers thinner than 100 Å, where the compression of the *ab* plane is readily observed as shown in Figs. 2(a) and 2(b). These results imply that the increase of T_c in the YBCO/LSCO superlattice compared with YBCO/PBCO and YBCO/NCCO is brought about by the

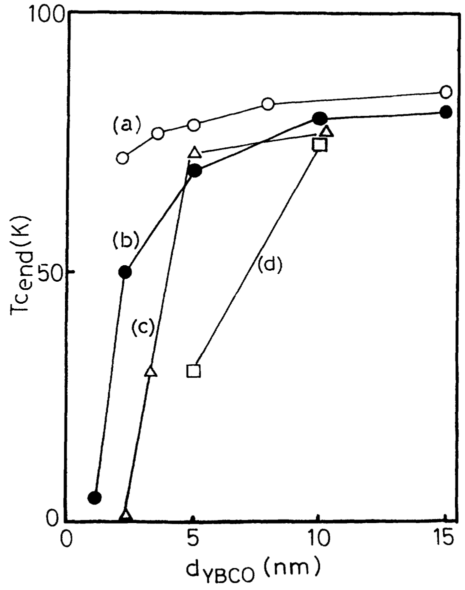

FIG. 4. The $T_{c_{zero}}$ vs the thickness of the YBCO layer in various superlattices or ultrathin Y-Ba-Cu-O films: (a) YBCO/LSCO (open circles); (b) YBCO/PBCO [Li *et al.* (Ref. 6)] (filled circles); (c) YBCO ultrathin films on MgO(100) substrate [Terashima *et al.* (Ref. 11)] (open triangles); (d) YBCO/NCCO [Gupta *et al.* (Ref. 8)] (open squares).

compression of the *ab* plane, presumably the compression of Cu-O bond length in the CuO_2 plane, similar to the pressure effect reported in bulk samples.[3,12,13] We have confirmed that the replacement of the hole-doped LSCO layer by a nondoped La_2CuO_4 layer gives the same T_c in the superlattice. This indicates that the change of carriers in the neighboring $(La,Sr)_2CuO_4$ layers does not have an effect on the T_c of YBCO layer in this superlattice. The proximity effect is neglected here for the following reasons. The T_c's of YBCO/LSCO and YBCO/LCO are the same, although LSCO is a metal and LCO is a semiconductor. If proximity effect is dominant, the T_c of YBCO/LSCO and YBCO/LCO should be different.

Oxygen depletion also does not explain the changes of T_c from the following reasons. The relation among T_c, the *c*-axis length and the oxygen deficiency (y) in $YBa_2Cu_3O_{7-y}$ has been reported. When y increases, the *c* axis expands and T_c decreases remarkably. In the case of YBCO/NCCO superlattices,[8] the lattice constant *c* of YBCO is gradually shrunk with the decrease of the stacking periodicity, but the T_c decreases. On the other hand, in our YBCO/LSCO, the *c*-axis length of YBCO increases, but T_c does not decrease rapidly. These results indicate that the T_c change of both superlattices is not due to oxygen depletion. Furthermore, the T_c of YBCO/PBCO with no strain shows a middle value between YBCO/NCCO and YBCO/LSCO. From these systematic results, the T_c change is considered to be due to the strain.

There is the possibility of partial interdiffusion between the layers, rather than complete interdiffusion.[14] The systematic changes in T_c of superlattices, however, can be largely explained based on the strain effect at the interface between the layers. Now, interdiffusion cannot systematically give an explanation for the change in T_c without some speculation. The superlattices prepared were well defined crystallographically, without evidence of interdiffusion from our cross section TEM images. Interdiffusion seems to have some effect on broadening the temperature ranges of the transitions and causes scatter in our data, because T_c is locally different due to the different degrees of interdiffusion at the interfaces.

As shown in the case of the YBCO/LSCO=5/30 nm superlattice, the lattice constant *a* is compressed to 0.3838 nm from the usual YBCO value of 0.3880 nm. Using a da/dP of 0.00008 nm/kbar (Ref. 12) in YBCO, this strain of *ab* plane corresponds to an isostatic pressure of 50 kbar. A T_c elevation of 4.5 K is expected according to the reported dT/dP of 0.09 K/kbar,[13] on the assumption that the compression of the *ab* plane causes the changes of T_c. In the YBCO/LSCO superlattice, a T_c elevation of about 6 K is observed in comparison with the YBCO/PBCO superlattice of the same YBCO thickness. This roughly agrees with the value of 4.5 K deduced from the isostatic pressure effect. This equivalence of the effects of compression of the *ab* plane and isostatic pressure suggests that strain in the CuO_2 plane is more effective for high-T_c superconductivity than strain of *c* axis. Actually, the *c* axis of YBCO is rather elongated in YBCO/LSCO. Recently, it was reported that in the bulk LSCO single crystal, the uniaxial pressure along the *ab* plane increases

T_c, while the pressure along c axis decreases the T_c.[15] This experiment agrees with our data on a strained superlattice, although the system is different. Also observed is that uniaxial bending of YBCO film to induce compression increases the T_c.[16] We have recently reported the big decrease in T_c when the ab plane of the LSCO layer is expanded by Sm_2CuO_4 in LSCO/SCO superlattices.[17] All these data can be consistently understood with the present data in that the compression of ab plane of CuO_2 sheets has a positive effect on T_c, and expansion has a negative effect. In isostatic high-pressure experiments, the a, b, and c axes are simultaneously compressed, so that the most effective axes to be compressed to raise T_c has not been revealed. The present results may imply that the Cu-O bond length in the conductive CuO_2 plane is one of the important factors for the T_c value. The changes of the electronic properties induced by the strain, such as changes of the effective carrier density in the CuO_2 plane, are now under investigation.

In summary, we have formed strained superconducting superlattices with a combination of $YBa_2Cu_3O_7$ and $La_{1.85}Sr_{0.15}CuO_4$. The compression of the ab plane of the YBCO layer due to the LSCO layer has been confirmed by four-circle x-ray diffraction. The changes of the lattice constant correspond to the pressure more than 50 kbar in the isostatic pressure experiment for the bulk samples. In this superlattice, only a small decrease of T_c is observed when the thickness of the YBCO layer is reduced. The very thin YBCO layer of only 2.4 nm (2 unit cell) shows the $T_{c_{end}}$ of 72 K which is unusually high for the T_c of 2.4-nm YBCO layer. The cause for these behaviors is explained by the in-plane compression of the CuO_2 plane of the YBCO layer brought by the epitaxial stacking with LSCO layers.

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