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Growth of $YBa_2Cu_3O_{7-x}$ thin films on Si with a $CoSi_2$ buffer layer

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By using the pulsed laser deposition technique, high-temperature superconducting $YBa_2Cu_3O_{7-x}$ (YBCO) films were grown on Si(001) with a 36 nm single-crystal ⟨001⟩ oriented $CoSi_2$ buffer layer. The films, grown at a substrate temperature of ~700 °C, have a metallic resistive temperature dependence with zero resistance at 85 K. X-ray diffraction, scanning electron microscopy, and ion channeling studies show that the YBCO films are polycrystalline but are strongly *c*-axis oriented normal to the Si substrate. Diffusion at the interface between the YBCO film and silicide buffer layer was minimized. This is essential to the growth of high-temperature superconducting films on Si substrates.

Recent successful growth of high quality epitaxial high-temperature superconducting (HTS) films by several different deposition techniques has attracted research interest directed toward applications in microelectronic devices and the possible integration of semiconductor and superconductor technologies. Silicon is the most widely used semiconductor in the microelectronic industry and it would be desirable to grow high quality, HTS films on it. Unfortunately, due to the relatively high-temperature process necessary in current growth techniques, a film which is deposited directly on the Si substrate reacts strongly with Si, severely degrading the superconducting properties, although some successes have been reported.[1,2] Besides interdiffusion, microcracks in the HTS films are also observed due to the large mismatch of thermal expansion coefficients between YBCO films and Si substrates.[3] Much attention has been paid to the growth of a buffer layer which can prevent the interdiffusion as well as provide a better matching of the thermal expansion coefficients.[3]

Most buffer layers reported between HTS films of $YBa_2Cu_3O_{7-x}$ (YBCO) and Si substrates are dielectric materials; ZrO_2,[4] MgO,[5] SiO_2,[6] $SrTiO_2/MgAl_2O_4$,[7] and $BaTiO_2/MgAl_2O_4$ [3] are examples. The only metallic buffer layer reported to date has been polycrystalline RuO_2.[8] An epitaxially grown metallic buffer layer on Si may provide the additional advantage of a well controlled surface for the fabrication of the superconductor as well as a means of making electrical contact to it. One possible choice is cobalt disilicide ($CoSi_2$), because it is thermally stable at high temperature[9,10] and has excellent electrical properties. $CoSi_2$ is a metal with low resistivity (14 $\mu\Omega$ cm at room temperature[11]). Structurally, $CoSi_2$ has small lattice mismatch with Si (~1.2% smaller at room temperature) and it can be grown epitaxially on Si(111)[12] and Si(001)[13] substrates with an atomically abrupt and a highly planar interface. These features have led to $CoSi_2$ becoming one candidate for the next generation of metals to be used as contacts, gates, and interconnections in very large-scale integration and vertical integration technologies.[14] In addition, $CoSi_2$ has an intermediate thermal expansion coefficient (9.4×10^{-6}/K°) between YBCO (12.9×10^{-6}/K°) and Si (3×10^{-6}/K°), thereby reducing the lattice strain in the interface. In this letter we report the growth of YBCO films on Si with a 36 nm $CoSi_2$ buffer layer. The results show the formation of a *c*-axis preferentially oriented YBCO film with a zero resistance transition temperature at ~85 K.

Epitaxial buffer layers of $CoSi_2$ were grown on Si(001) wafers in a molecular beam epitaxy system with a base pressure of 3×10^{-11} Torr. By direct codeposition of Co and Si at 500 °C at 1:1.8 Co-rich stoichiometry, a 36 nm $CoSi_2$ film with single-crystal ⟨001⟩ orientation, low resistivity (16 $\mu\Omega$ cm), and low ion channeling minimum yield ($\chi_{min} = 5\%$) was obtained.[13]

The present *in situ* pulsed laser deposition (PLD) setup has been described in detail elsewhere.[15] Typically, a 308 nm XeCl excimer laser was operated at repetition rates ranging from 2 to 20 Hz and produced 20 ns pulses with energy of 200 mJ. A bulk, stoichiometric YBCO target was used for the deposition. No special cleaning treatment was done to the sample surface prior to loading it into the chamber which has a base pressure of 1×10^{-6} Torr. The depositions were made at a sample surface temperature of ~700 °C under a vacuum of less than 2.5×10^{-5} Torr. To minimize the oxidation on the silicide surface, the normal deposition process was modified by introducing an oxygen pressure of 0.15 Torr a few seconds after the deposition was started. The deposition rate was 1.8 nm/s. Immediately after deposition, the sample was cooled to room temperature within 30 min at an oxygen pressure of 250 Torr. After removal from the deposition chamber, the sample surface looked uniformly dark, and reflective.

Figure 1 shows a linear plot of resistivity versus temperature for a YBCO film deposited on Si with $CoSi_2$ buffer layer using a standard dc four-point probe method. Zero resistance is observed at a temperature of 85 K with onset temperature at 92 K. The temperature dependence of this film shows a metallic behavior above the onset temperature

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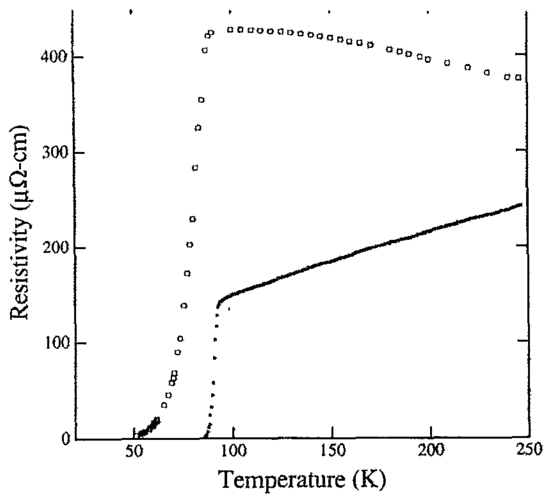

FIG. 1. Temperature dependence of the dc resistivity of a YBCO film deposited directly on Si(001) substrate (open squares); and on Si(001) with a 36 nm, single-crystal ⟨001⟩ oriented $CoSi_2$ buffer layer (filled squares).

with the slope of $\rho(300\ \mathrm{K})/\rho(100\ \mathrm{K}) = 1.88$. The film has a strong *c*-axis orientation normal to the substrate from the x-ray diffraction pattern as shown in Fig. 2. Only (00*l*) diffraction peaks ($l = 1$–10) from the YBCO thin film and the diffraction peaks from the substrate are observed. This result indicates dramatic improvements over the films directly deposited on Si whose typical resistivity versus temperature curve is also plotted in Fig. 1. The zero resistance temperature for the YBCO film directly on Si is 52 K and the temperature dependence of this film shows a semiconducting behavior above the onset temperature. It is worth mentioning here that, to our knowledge, the observed high transition temperature for YBCO films deposited on $CoSi_2$/Si represents the first successful result using such a thin buffer layer. Other reported buffer layer thicknesses used are usually more than 150 nm thick.

Backscattering and channeling measurements were carried out to determine composition and structural properties. An 8.8 MeV He^{++} beam was used in order to separate each composite metal element and thus determine

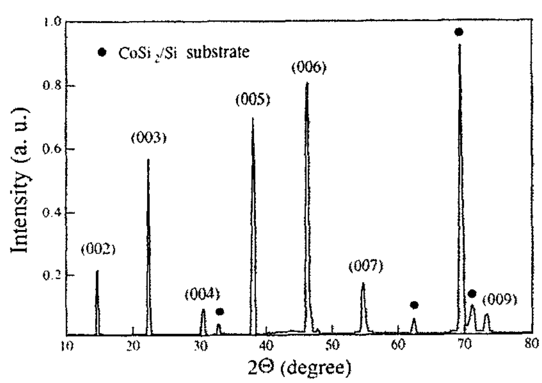

FIG. 2. X-ray diffraction pattern of an as-grown YBCO film deposited on epitaxial $CoSi_2$/Si substrate. The indexed lines are the (00*l*) diffraction peaks from YBCO.

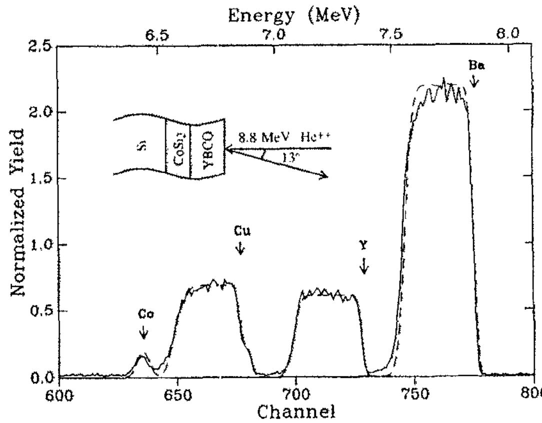

FIG. 3. Backscattering spectrum of a 725-nm-thick, as-grown YBCO film on $CoSi_2$/Si (solid line). RUMP simulation is also presented (broken line).

metal stoichiometry. Figure 3 shows the backscattering yield and RUMP[16] simulation. The metal stoichiometry of the YBCO film was calculated to be Y:Ba:Cu = 1.1:2.0:3.0 normalized to Ba and including the high-energy cross-section correction for the low Z element Cu.[7]

Using this measured stoichometry and assuming that the molecular oxygen composition is 7, the RUMP simulation shows a good match to the data with a film thickness of 725 nm as shown in Fig. 3. At the low-energy side of the Ba peak, a deviation from the simulation can be observed indicating some interdiffusion of the Ba. The range of the Ba diffusion into $CoSi_2$ buffer layer was estimated to be no more than 10 nm from the simulation.

Ion channeling and Rutherford backscattering measurements on the YBCO film reveal basically a polycrystalline structure. A $\chi_{min} = 95\%$ was obtained from the measurement at a He^{+} incident energy of 2 MeV. This is confirmed by scanning electron microscopy (SEM) micrograph of the film shown in Fig. 4. The submicron grains are randomly oriented in the *ab* plane. No microcracks are observed in the SEM micrograph throughout the film with

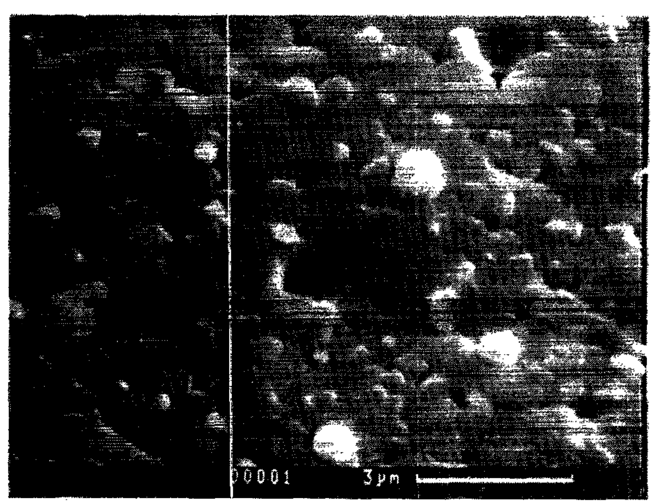

FIG. 4. Scanning electron micrograph of the surface structure of the YBCO/$CoSi_2$/Si sample.

lower magnification indicating the thermal stress between YBCO and Si has been reduced using the buffer layer. Some particulates are seen, which is common in PLD HTS films. It should also be pointed out that it may be possible to grow YBCO film epitaxially on the $CoSi_2$/Si substrate although the orthorhombic crystal structure of YBCO has different lattice constants from that of the cubic $CoSi_2$. By rotating azimuthally the *a* axis of the YBCO film 45° relative to the *a* axis of the substrate, the two different crystal structures can be matched with only $\sim 1.5\%$ average mismatch similar to the yttrium-stabilized zirconia system.[18] The observed polycrystalline nature of the YBCO film might be caused by the Ba diffusion at the interface between YBCO and $CoSi_2$ or by the oxidized $CoSi_2$ surface. Ion channeling measurements on a control $CoSi_2$ sample which went through the same temperature process before deposition show an increased surface peak indicating an amorphous SiO_2 layer was formed on the $CoSi_2$ surface. This insulating layer may explain the relatively high resistivity value of the YBCO film. A perfect contact of the YBCO film with the metallic buffer layer would result in smaller resistivity. A YBCO film with epitaxial quality may be obtained by appropriate cleaning of the sample surface prior to deposition.

In summary, with a 36 nm $CoSi_2$ buffer layer on Si, zero resistance transition temperature at 85 K was obtained for a 725-nm-thick, *c*-axis oriented, polycrystalline YBCO film. The thickness of $CoSi_2$ film represents the thinnest buffer layer reported indicating its good thermal and chemical stability. The advantage of using metallic, epitaxially grown $CoSi_2$ is twofold. First, it serves as a good buffer layer to minimize the interdiffusion between YBCO film and Si substrate. Second, it enables the possibility of practical applications involving three-dimensional device fabrications using superconductor/metal/semiconductor materials. Further study in terms of optimization and characterization of this superconducting film is currently under way and will be reported later.

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Note added in proof: After submission of this letter, a paper appeared in Applied Physics Letters [D. K. Fork *et al.*, Appl. Phys. Lett. **57**, 1161 (1990)] on the growth of YBCO on Si with a 50 nm buffer layer of YSZ.

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