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Low-loss $YBa_2Cu_3O_7$ films on flexible, polycrystalline-yttria-stabilized zirconia tapes for cryoelectronic applications

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High-temperature superconducting films on flexible, low-thermal conductivity, low-loss substrates offer a unique base for the development of cryoelectronic digital interconnects. Using an ion-beam-assisted pulsed-laser-deposition technique, we developed biaxially textured $YBa_2Cu_3O_7$ (YBCO) films on flexible polycrystalline-yttria-stabilized zirconia (YSZ) substrates with the following materials properties: (i) in-plane x-ray Φ-scan full width at half maximum of ~7°; (ii) transition temperatures (T_c) in the range of 88–89 K with transition widths (ΔT_c) of ~0.5 K; (iii) critical current densities (J_c) in the range $1.5-2\times10^6$ A/cm^2 at 77 K, zero field; (iv) magnetic penetration depth (λ) of 284 nm at 77 K; and (v) surface resistance (R_s) of 700 $\mu\Omega$ at 77 K, 10 GHz. The low-microwave loss, biaxilly textured YBCO films combined with the low-thermal conductivity YSZ substrate could facilitate a variety of RF cryoelectronic applications. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1358845]

Low-microwave loss, high-temperature superconducting (HTS) thin films on flexible substrates provide an excellent opportunity to transmit large channels of digital data with low-signal attenuation from a low-temperature environment (~4 K) to moderate temperatures (~80 K), if the substrate chosen has the following attributes: a low-thermal conductivity for thermal isolation (between 4 and 80 K), a high-flexural strength and high-fracture toughness for flexibility, a low-RF-loss tangent for obtaining low-signal attenuation, and a relatively low-dielectric constant for low cross talk between the channels. Another important consideration is that the substrate should have a good compatibility with respect to HTS film growth, namely, a close thermal expansion coefficient match with the HTS film and no chemical reaction between the film and the substrate at the growth temperatures. Flexible substrates are desirable since they meet important packaging needs of the superconducting cryoelectronics community.[1]

Polycrystalline-yttria-stabilized zirconia (YSZ) has a low-thermal conductivity of 0.015 $\mathrm{W\,cm^{-1}\,K^{-1}}$, a low-RF loss ($4\times10^{-4}$ at 5 GHz, 77 K),[2] a relatively low-dielectric constant ($\epsilon_r\sim28$), and is compatible with $YBa_2Cu_3O_7$ (YBCO) film growth requirements. Further, this substrate is flexible with a high-flexural strength of 1500 Mpa. With these material attributes, flexible YSZ presents a unique substrate material for developing low-loss HTS transmission lines carrying digital signals over a wide bandwidth for cryoelectronic applications. It may be mentioned here that polycrystalline substrates are more desirable than single-crystalline substrates in applications where flexibility of the substrate is an important consideration.

HTS films deposited on polycrystalline YSZ substrates are polycrystalline and contain high-angle grain boundaries. It is well known that these high-angle grain boundaries (with grain misorientation angles greater than 5°–7° in the film plane) have Josephson weak-link behavior and exhibit degraded dc and RF properties.[3] It is, therefore, very essential to eliminate or minimize these high-angle grain boundaries, to achieve desirable RF and microwave performance. In this letter, we present a summary of our recent results on the development of low-microwave-loss YBCO films on flexible, polycrystalline, low-thermal-conductivity YSZ tape substrates. An ion-beam-assisted pulsed-laser-deposition (PLD) technique was used to create a biaxially textured template over the polycrystalline and randomly oriented substrate. This template facilitated a high degree of structural order and, hence, a low-microwave loss in subsequently deposited YBCO films.

Ion-beam-assisted deposition (IBAD) has recently emerged as an innovative method for depositing in-plane aligned structural templates on polycrystalline substrates.[4,5] This technique has been widely popular among groups developing biaxial YBCO films on metallic tape substrates for high-current applications.[4,5] The present work focuses on RF applications using this approach, and considers a low-thermal conductivity polycrystalline ceramic substrate (YSZ) for cryoelectronic RF applications.

A commercially available ion-beam-assisted PLD system, manufactured by Neocera®, was used to deposit biaxially textured YSZ templates. The experimental geometry used during template deposition is shown in Fig. 1. Briefly, a Kr–F excimer laser operating at 248 nm was used at a pulse repetition rate of 10 Hz. The energy density at the YSZ tar-

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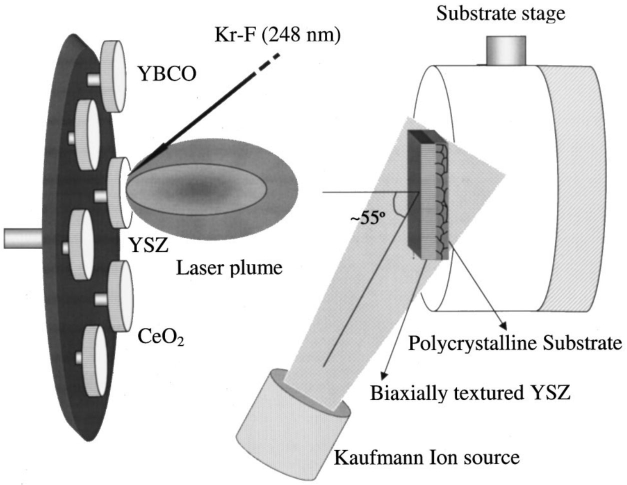

FIG. 1. Experimental arrangement for depositing biaxilly textured YSZ templates by ion-assisted PLD.

get during film deposition was ~2 J/cm^2. A 3 cm Kaufmann ion source from Commonwealth Scientific, operating at 200 eV and 10 mA beam current was directed towards the growing YSZ film at an incidence angle of ~55° with respect to the substrate normal. The background pressure during YSZ film deposition was 7×10^{-4} Torr in a mixture of 100:1 argon and oxygen. The YSZ film thickness was about 1 μm and the deposition rate was 0.1 Å/pulse. The substrates used were polycrystalline, randomly oriented YSZ. It is significant to mention that no substrate heating was employed during YSZ template deposition. (The substrate temperature rose up to about 50–70 °C due to self-heating associated with ion bombardment (Ar+O) from the ion gun during YSZ deposition.) About a 100-Å-thick CeO$_2$ buffer, and 4000-Å-thick YBCO were subsequently deposited at 770 °C and 300 mTorr of oxygen. CeO$_2$ and YBCO were deposited without any ion assistance. CeO$_2$ was chosen as a structural template due to the following. It is generally observed that YBCO films deposited directly on YSZ contain large-angle grain boundaries (45°) due to two coincidence sites of YBCO and YSZ oxygen sublattices.[6] It has been established in a previous study that the CeO$_2$ buffer layer is an ideal structural template and does not promote any high-angle grain boundaries.[7]

Figure 2 shows the four-circle x-ray diffraction Φ-scan data of the multilayer heterostructure. Shown in Fig. 2(a) are the (103) reflections of the YBCO film. The in-plane texture is evident in the Φ-angle scan by the four peaks separated by 90°. The full width at half maximum (FWHM) for these peaks are ~7°, indicating excellent in-plane texture. In this plot, Φ-scan data are also presented for the IBAD YSZ biaxial template [Fig. 2(c)] and the CeO$_2$ structural template [Fig. 2(b)]. The data are obtained from the (202) reflections in both the cases and the FWHMs in this case are 12°–13° and 7°–8°, respectively. It may be mentioned here that texture development during ion-assisted YSZ film growth is evolutionary with thickness,[8,9] with the surface layers having a superior in-plane texture than the film closer to the film–substrate interface. The larger FWHMs seen in the case of the YSZ film are, therefore, a cumulative effect since our x-ray diffractometer cannot distinguish between surface and volume contributions. The FWHMs observed in the case of CeO$_2$($7°-8°$) are supportive of this viewpoint that the YSZ surface has a superior in-plane texture. X-ray diffraction (XRD) scans obtained in the θ–2θ mode (not presented here) indicate that all the films are *c*-axis oriented. The XRD measurements, therefore, establish an excellent biaxial texture (both in the *ab* plane and along the *c* axis) in the YBCO films.

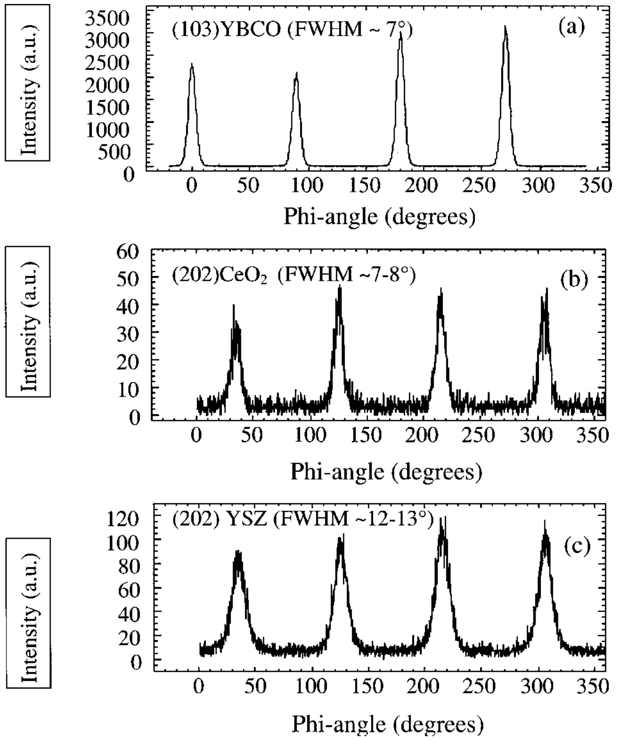

FIG. 2. Four-circle x-ray diffraction data for biaxially textured YBCO (a). Data are also presented for a biaxially textured (b) CeO$_2$ buffer layer and (c) a YSZ template.

The biaxially textured films were evaluated for transition temperature (T_c), transition width (ΔT_c), and critical current density (J_c) by ac susceptibility measurements. The T_c measured for two representative films were in the range 88–89 K with transition widths around 0.5 K. Figure 3 shows data obtained from a representative YBCO sample. Critical current densities measured for these two representative films at 77 K and zero field were $1.5-2\times10^6$ A/cm^2 at 77 K. Figure 4 presents J_c data obtained from one of the

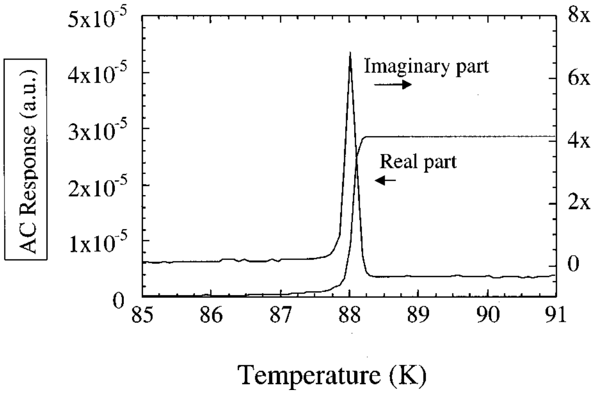

FIG. 3. Ac susceptibility data of biaxially textured YBCO on polycrystalline YSZ substrates.

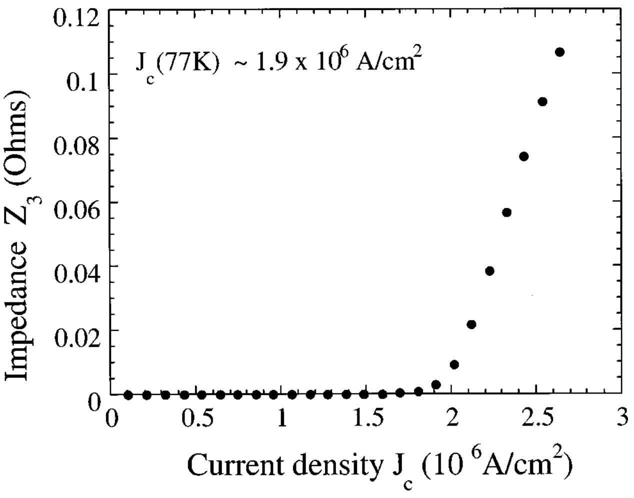

FIG. 4. Critical current density data for biaxially textured YBCO.

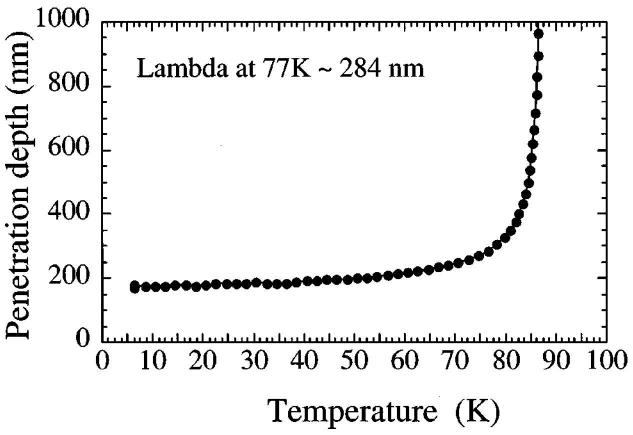

FIG. 5. Magnetic penetration depth data for biaxially textured YBCO.

YBCO films. The T_c and J_c data obtained by electrical transport should be very interesting indicators for applications to interconnects.

The magnetic penetration depth was measured by the mutual inductance technique described in an earlier publication.[10] These measurements were carried out over a wide temperature range (5–87 K) and are presented in Fig. 5. The penetration depth (λ) measured at 77 K is 284 nm, indicating excellent electromagnetic properties in the present biaxially textured YBCO films.

The microwave properties of the films were evaluated by measuring the surface resistance (R_s) of the films. R_s was measured by a parallel-plate resonator (PPR) technique. The details of this technique have been published elsewhere.[11] Briefly, these measurements were carried out using two nominally identical thin films. The films were brought together, face to face, sandwiching a thin Teflon dielectric (typically, 12.5 μm thick). This combination forms a two-conductor parallel-plate transmission line which can carry a quasi-TEM electromagnetic wave. This transmission line can be made resonant under special conditions and from the Q factor of the PPR, the surface resistance can be calculated.

At 10 GHz, 77 K, we obtained surface resistance (R_s) values of 700 $\mu\Omega$ for the biaxially aligned YBCO films. It may be mentioned that epitaxial YBCO films deposited on single-crystalline substrates and measured with the same PPR technique typically exhibit R_s values in the range of 400–500 $\mu\Omega$ at 10 GHz, 77 K. It is, therefore, noteworthy that the R_s values obtained in the present case are among the best reported for YBCO on any polycrystalline substrate so far. The measured microwave properties also validate the possibility of fabricating a variety of low-loss components using this material technology. Our future work will involve design, fabrication, and testing of a multichannel cable employing the current materials base. The results of this effort will be published separately.

In summary, biaxially textured YBCO films were developed on flexible, polycrystalline YSZ substrates using an in-plane aligned YSZ template. The in-plane FWHM of the YBCO films are about 7° as seen by x-ray Φ scans. The films exhibit transition temperatures of the order of 88–89 K with transition widths of 0.5 K. The critical current densities measured at 77 K are in the range of 1.5–2×10^6 A/cm^2. The surface resistance of the films measured at 10 GHz, 77 K, is 700 $\mu\Omega$ indicating an excellent potential of these films in RF applications. The HTS film quality in conjunction with a low-thermal conductivity (0.015 W cm^{-1} K^{-1}), low-loss, and flexible YSZ substrate forms a unique material base for a variety of cryoelectronic applications. Even though similar YBCO film quality has been achieved in other related work,[12,13] our technique is relatively simple and uses pulsed-laser deposition both for buffer layers as well as for YBCO film depositions.

The structural, electrical, and microwave measurements presented also establish the possibility of obtaining a ‘‘single-crystalline-like’’ film quality, even when deposited on amorphous and/or polycrystalline substrates. In device applications where there is a demand for high structural film quality (as required in the case of HTS, ferroelectrics, magnetic oxides, etc.), and at the same time restrictions on available single-crystalline substrates, the feasibility demonstrations presented in this letter have significant ramifications.

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