Characteristics of Y-Ba-Cu-O superconductor films on GaAs with an Al_2O_3 or $AlGaO_3$ buffer layer

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(Received 25 October 1990; accepted for publication 11 March 1991)

By depositing a buffer layer of Al_2O_3 on GaAs, we have been able to laser ablate a superconducting film of $Y_1Ba_2Cu_3O_{7-x}$ overtop. The onset of superconductivity is 92 K and zero resistance is observed at 80 K in a structure with a suitably annealed Al_2O_3 film which is converted to $AlGaO_3$. Both the Al_2O_3-GaAs and the Al_2O_3-$Y_1Ba_2Cu_3O_{7-x}$ interfaces are remarkably well preserved with virtually no interdiffusion or interaction. The Al_2O_3 or homolog $AlGaO_3$ film also prevents decomposition of the GaAs at the deposition temperature of 730 °C.

Among the most promising applications of high T_c superconductors are thin-film structures for microelectronics, particularly at microwave frequencies. The properties generally required for such applications include a high onset temperature (T_c), a sharp transition to zero resistance, low normal state resistance, and low surface resistance at microwave frequencies. Additionally, the films should possess a high critical current density, uniformity of superconductivity over distances comparable to any geometrical structures formed with the films, and compatibility with the requirements of a multistep fabrication process. With respect to Y-Ba-Cu-O superconductors, thin films have been deposited on (001) oriented $SrTiO_3$ single-crystal substrates, or homologs such as $LaAlO_3$ and $LaGaO_3$, resulting in highly *c*-axis-oriented films with onset temperatures close to 93 K, and critical currents[1] as high as 10^7 A/cm^2 at 77 K. The crystallographic lattice matching of the superconductor film with the substrate is an important parameter for producing a film of high quality. The superconducting properties of such films have also been found to depend markedly on materials properties such as stoichiometry, purity, orientation, grain structure, grain boundaries, and strain.

During the past year or so, measurements at microwave frequencies (77 K) on Y-Ba-Cu-O films deposited on dielectric substrates have shown their surface resistance to be approximately an order of magnitude lower than copper or gold films to frequencies of about 35 GHz.[2] This is expected to improve significantly with better performance stretching to hundreds of GHz. As matters presently stand, high T_c films can offer a significant improvement in the performance of passive device components.[3]

While it is now clear that high T_c superconductors will improve existing microwave circuits by replacing normal metals with low-loss superconductors, resulting in lower insertion losses, higher *Q*'s, and much smaller circuits, the real impact will come with the integration of these materials into semiconductor microelectronics. Experiments to date with the deposition of superconductor films on silicon and gallium arsenide have led to the observation that such films react with the semiconductor surfaces forming undesirable interfacial layers which quench the superconductivity. In the case of silicon, buffer layers have been employed to reduce such interactions, but these buffer layers generally are thick, and/or do not produce sharp interfaces.[4] In this letter, we report on the successful deposition of thin films of Y-Ba-Cu-O on GaAs with Al_2O_3, or an alumina homolog such as $AlGaO_3$, as a buffer layer. To our knowledge, this is the first such report where the buffer layer presents sharp interfaces with respect to the GaAs and the Y-Ba-Cu-O, with little or no interdiffusion or chemical interaction across these interfaces.

GaAs is of particular importance because its electronic properties allow fabrication of microelectronic devices which can operate at high frequencies. However, it is a difficult semiconductor to process. It oxidizes and decomposes in the presence of oxygen at temperatures in the vicinity of 600 °C, whereas bulk sintered superconductors of Y-Ba-Cu-O must be formed in oxygen ambient at 930–950 °C. For any successful deposition technique on GaAs, much lower temperatures are required. The laser ablation process is known to produce good superconductor films at temperatures as low as 720 °C, but even at this temperature, the reaction on the GaAs surface is catastrophic, especially since a high oxygen ambient is required during the deposition process. Thus, a buffer layer is required.

The literature reports only two significant attempts to deposit Y-Ba-Cu-O on GaAs, one using CaF_2,[5] and the other an AlGaAs buffer layer.[6] Neither was particularly successful. We have taken the approach of depositing Al_2O_3 on GaAs at room temperature, and found that it acts as an excellent buffer layer, forming a sharp interface with the GaAs, as well as with the subsequent laser-ablated Y-Ba-Cu-O film. Using a homolog such as $AlGaO_3$ increases the performance of the superconducting film. Al_2O_3 is a particularly attractive substrate buffer for the Y-Ba-Cu-O because of its excellent dielectric properties and low-loss tangent at microwave frequencies. It could also form the necessary isolation layer through which there would be access to active devices within the GaAs as part of a more complex integrated circuit.

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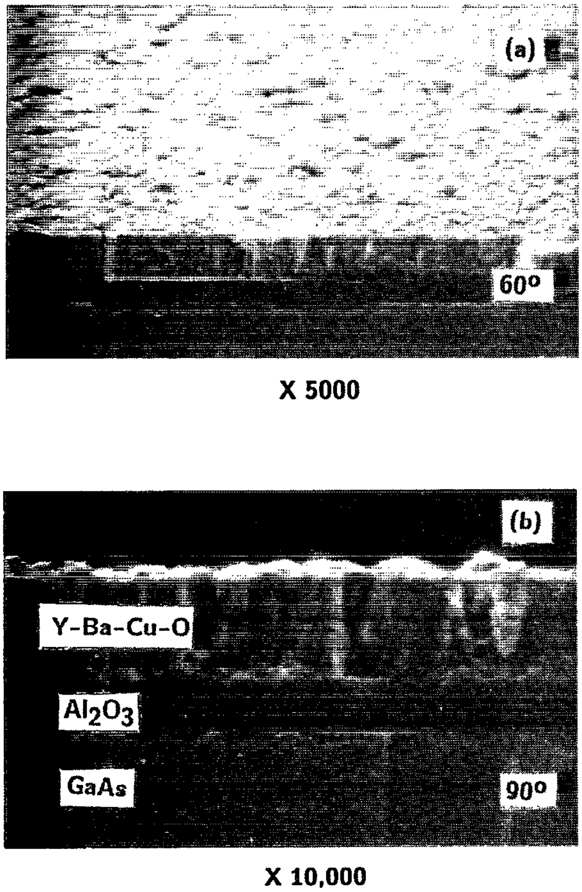

FIG. 1. Scanning electron micrographs of laser-ablated Y-Ba-Cu-O deposit on alumina coated GaAs for view angles of (a) 60° and (b) 90° the pellet face, with the magnifications shown.

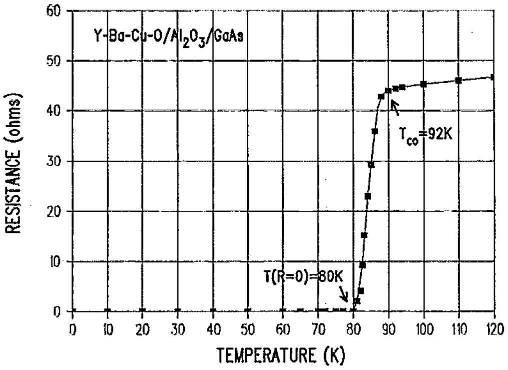

FIG. 2. Resistivity as a function of temperature for a film deposited on high-temperature annealed buffer layer.

A Nd:YAG laser is used[7] to produce a 266 nm beam with a 10 ns pulse width at 10 Hz. Smooth epitaxial films with few morphological defects[8] can be produced by using wavelengths in the ultraviolet (~200–300 nm). The beam is focused onto a rotating, sintered target of Y-Ba-Cu-O situated inside a vacuum chamber, with a spot size of about 1.5 mm diameter. The fluence per pulse is about 1 J/cm^2. As the laser pulse impinges on the target, ablation occurs via a nonequilibrium process, producing a plasma plume which extends from the target to the substrate, through an ambient O_2 pressure of 100 mTorr. Deposition rate was ~0.5 nm/s on the substrate of Al_2O_3-coated, or homolog-coated, GaAs held at 730 °C. After deposition, the substrate is cooled to 450 °C in 760 Torr of O_2, annealed at that temperature for 30 min, and then cooled to room temperature.

The buffer layer of Al_2O_3 on the room temperature held GaAs was produced by an electron beam evaporation of a compacted powder source at 10^{-6} Torr. Scanning electron micrograph (SEM) examination showed the films to consist of tightly packed grains about 100 nm in diameter. Initially, we were unable to detect the alumina film by x-ray diffractometry, most probably because the film was thin and the crystallites small. However, ellipsometry[9] was used to confirm that the film had the correct optical constants for alumina and was of the thickness (about 1 μm) indicated by SEM micrographs. As substrates we used commercial grade, Cr-doped GaAs material of (001) orientation, polished one side and cut into squares of approxiamtely 1.25×1.25 cm. Figure 1 shows a SEM micrograph of a laser-ablated deposit of Y-Ba-Cu-O on top of an Al_2O_3-coated GaAs wafer. The Al_2O_3 layer was about 1 μm in thickness and the Y-Ba-Cu-O film about 2 μm. We deliberately deposited thick layers in order to test the integrity of the two interfacial regions against decomposition and interdiffusion during the processing. A much thinner Al_2O_3 buffer is possible. Indeed, data are presented later for a 1000-nm-thick Y-Ba-Cu-O film deposited overtop a 100 nm alumina buffer layer.

Films show oriented columnar growth with *c*-axis orientation perpendicular to the substrate surface. However, the lattice mismatch of the hexagonal Al_2O_3 (lattice parameters of 0.475 and 1.3 nm) with the perovskite $Y_1Ba_2Cu_3O_{7-x}$ ($a=0.383$ nm, $b=0.388$ nm, $c=1.17$ nm) does not permit good structural morphology, and cracks in the superconducting film can appear. Nonetheless, what is remarkable is that the interface between the $Y_1Ba_2Cu_3O_{7-x}$ film and the Al_2O_3 films is highly preserved and sharp. This was confirmed with high magnification SEM micrographs. The micrograph in Fig. 1(a) taken at an inclination of 60° reveals granules on the surface of the superconductor film. These are believed to be artifacts of the laser ablation process which can be eliminated with tuning of the process.[8] The surface is mirror reflecting.

The interface between the Al_2O_3 and the GaAs is similarly preserved and sharp, and essentially in the same condition as when the Al_2O_3 was initially deposited on the GaAs. In addition to serving as a buffer layer, the Al_2O_3 film acts to prevent the GaAs from decomposing. We note that a previous attempt to deposit Y-Ba-Cu-O films on single-crystal Al_2O_3 (sapphire) using laser ablation,[10] resulted in films with a zero resistance at 75 K and a critical current of 4×10^3 A/cm^2 at 40 K. The films consisted of grains of about 50 nm size and there was no preferred orientation.

Our early films, deposited on room-temperaure alumina buffer layer, indicated the onset of superconductivity

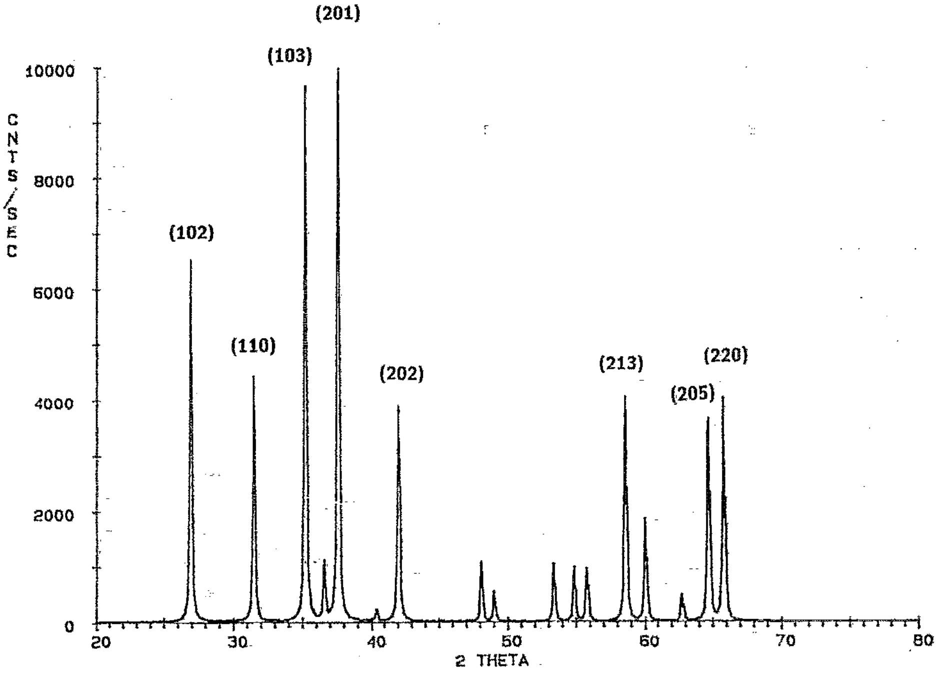

FIG. 3. X-ray diffraction pattern taken for an annealed alumina film on GaAs indicating the major lines for $AlGaO_3$.

at 92 K but zero resistance was not achieved until about 55 K. The critical current density of the film measured at 5 K indicated a value of about 10^5 A/cm^2. This reduced value, in comparison to films on epitaxially matched substrates, is consistent with the strained morphology of the film.

A dramatic improvement in the properties of the superconducting film resulted following a high-temperature anneal of the alumina film prior to the laser ablation deposition of Y-Ba-Cu-O. In this case, the zero resistance of the film was brought up to 80 K as shown in Fig. 2. We believe that an alumina homolog of the type $AlGaO_3$ is formed which aids in the crystallographic matching ($a = 0.570$ nm for $AlGaO_3$ vs 0.565 nm for GaAs). X-ray data using a Rigaku Diffractometer on a suitably thickened film revealed the characteristic lines for $AlGaO_3$ as shown in Fig. 3. Commensurate with the improvement in the resistance-temperature profile, there was a narrowing of the magnetic moment-temperature curve, and the J_c increased to 10^6 A/cm^2 at 5 K. SEM data presented essentially the same morphology as for the alumina films in Fig. 1, except that the columnar grain sizes had increased by an order of magnitude in diameter. Experiments are currently in progress to deposit an alumina homolog directly on the Y-Ba-Cu-O.

In conclusion, we have demonstrated for the first time that Al_2O_3, or an alumina homolog such as $AlGaO_3$, can act as a buffer layer on GaAs to allow the deposition of Y-Ba-Cu-O superconductor films with sharp interfacial layers. We believe that this preservation can be accomplished with aluminate buffer films as thin as 100 nm. With proper lattice matching and good crystallinity of the buffer layer, superconductor films having sharp resistive transitions as high as 92 K should be possible.

This work was partially supported by the U. S. Army Research Office under contract No. DAAL-03-87-K-0007 and DAAL-03-89-K-0071, and the Air Force Office of Scientific Research under the contract No. AFSOR-90-0214. In addition, the Kellogg Foundation has generously provided support for the laser ablation system.

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