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$YBa_2Cu_3O_{7-\delta}$ films on GaAs with high critical current densities

W.Prusseit, B.Utz, S.Corsépius, F.Baudenbacher, K.Hirata, P.Berberich, H.Kinder, O.Eibl†

Physik- Department E10, TU München
James-Franck Str.1
D-8046 Garching,Germany

† Siemens Research Center
Otto Hahn Ring 6
D-8000 München 83, Germany

Abstract

Epitaxial $YBa_2Cu_3O_{7-\delta}$ films were grown on GaAs substrates using an intermediate MgO buffer layer. It turned out that the basic requirements in coping with GaAs related problems such as chemical instability and volatility are lowest possible deposition temperatures and proper encapsulation of bare GaAs faces, respectively. Applying our coevaporation technique we were able to achieve $YBa_2Cu_3O_{7-\delta}$ films on GaAs which can compete with those on standard substrates (T_c = 87 K, $\varrho(100K) = 40\mu\Omega$cm, $j_c = 2 \cdot 10^6$ A/cm^2 at 77 K).

1. Introduction

The low loss tangent and small dielectric constant of semiinsulating GaAs predestinate this material to application as substrate for RF devices. Beyond, semiconductor technology provides cheap large-size wafers with superior surface finish and a lot of know-how in its processing. This offers the chance to build supersemi hybids which may profit from the low resistivity of the superconductor as well as from the high carrier mobility in GaAs heterostructures.

However, all these advantages have to be paid for by a variety of severe problems arising from the high reactivity and chemical and physical instability of GaAs at typical deposition conditions of high temperature superconductors. To some extent these difficulties can be overcome by employing appropriate buffer layers which separate the $YBa_2Cu_3O_{7-\delta}$ film from the GaAs substrate but mediate epitaxy. The best buffer material appears to be MgO, as first reported by Fork et al. [1]. But although their films were essentially epitaxial, their critical current densities were an order of magnitude too low and the normal state resistivities considerably higher than for intrinsic $YBa_2Cu_3O_{7-\delta}$ material – a circumstance which prevents RF applications. In the present paper we will report on ways to solve these remaining problems and to obtain high critical current density films even on this delicate substrate material.

2. Film fabrication

The surfaces of as-received GaAs wafers are covered by amorphous native oxides which prevent epitaxial film growth. To ensure adequate well-defined initial conditions we applied a standard wet etching procedure prior to the buffer layer deposition [2]. The MgO buffer was electron-gun evaporated from a sintered MgO target at an oxygen pressure of 10^{-5} mbar. During this process the substrate was held at a temperature of 460°C just below the threshold where the GaAs surface is damaged by a loss of arsenic in this reactive ambient.

A typically deposited MgO film thickness of 40 nm appears to be sufficient to serve as effective diffusion barrier for the subsequent $YBa_2Cu_3O_{7-\delta}$ growth. The above procedure yields nearly atomically smooth interfaces as revealed by high resolution transmission electron microscopy (HRTEM), applied to a number of samples [3]. Beyond that, the crystallinity and the surface morphology of each film was examined by X-ray diffraction (XRD), reflection high energy electron diffraction (RHEED) and field-emission scanning electron microscopy (FE-SEM). XRD $\Theta-2\Theta$- and φ-scans revealed that the MgO films were single crystalline and epitaxially aligned with the GaAs substrate. The rocking width was 1.5° (FWHM). Consistent with this result, we observed a high dislocation density by TEM. This is not unexpected in view of the lattice misfit of 25.5% which leads to a 4:3 epitaxy of MgO on GaAs.

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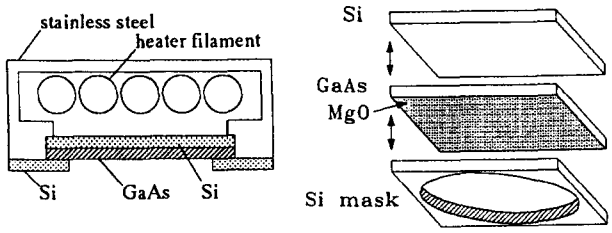

Figure 1. Scetched encapsulation of the GaAs substrate for $YBa_2Cu_3O_{7-\delta}$ deposition. Cross-section of the substrate heater (left) and exploded view (right).

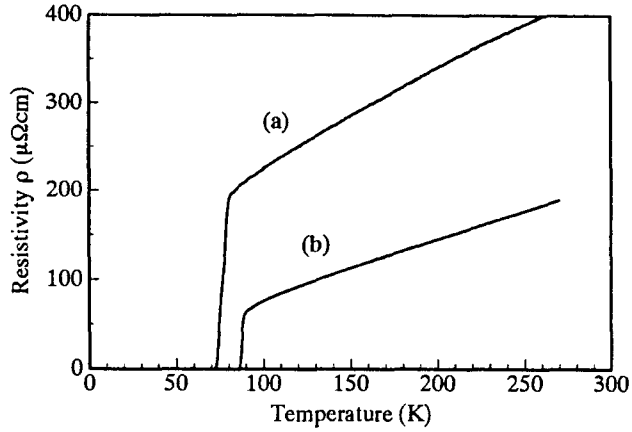

Figure 2. Resistive transitions of $YBa_2Cu_3O_{7-\delta}$ on MgO /GaAs grown without (a) and with (b) encapsulating the GaAs substrate. Zero resistance temperatures are (a) 71.6 K and (b) 86.8 K.

During the characterization and subsequent transfer to the $YBa_2Cu_3O_{7-\delta}$ growth chamber, equipped with a RHEED system, all samples were exposed to room ambient. Although the RHEED pattern was streaky, it had a rather strong diffuse background at room temperature which ceased during heating to 620°C. We believe that this is due to hydroxides which decompose at higher temperatures. Thus, in-situ processing was not necessary.

The $YBa_2Cu_3O_{7-\delta}$ films were deposited by our standard technique of thermal coevaporation of the metals from three boats as descibed elsewhere [4]. The high mobility of the metal species allows a relatively low substrate temperature. In fact, this is a crucial point, because GaAs decomposes above 640°C leading to a visible darkening of the uncovered GaAs surfaces [1]. In addition, with a modified substrate heater the evaporation technique provides the possibility to grow films on large-size substrates (3" and more) as well [5].

The $YBa_2Cu_3O_{7-\delta}$ films on the MgO buffers were epitaxial with the a- and b-axes parallel to the [100] directions of MgO and GaAs The rocking curve of the $YBa_2Cu_3O_{7-\delta}$ was only 0.9°, better than that of the MgO. The surface morphology of the films was similar to our smooth films on MgO single crystals [6].

3. Arsenic contamination

However, in the beginning of this work electrical transport measurements gave similarly unsatisfactory results as in Ref.[1]. We attributed this shortcoming to an arsenic contamination of the $YBa_2Cu_3O_{7-\delta}$ films originating from the sides and the back of the sample which were not covered by the MgO film. A sputter Auger analysis confirmed this. The surface exhibited an arsenic concentration of about 2 at% while there was no arsenic detectable inside the film. This indicates that the arsenic is sublimating from uncovered parts of the substrate and entering the film from the gas phase. In this way it has enough time to accumulate on the surface after the film is completed while the substrate heater is slowly cooling down.

To avoid the arsenic contamination it was necessary to prevent the free surfaces of the sample from outgassing. This was achieved by encapsulating the substrate after the MgO had been deposited: We simply sandwiched the sample between a platelet on top and a frame on bottom, both made of polished silicon wafers. Fig.1 gives an exploded view (left) and the actual realization (right) of this arrangement. The whole stack is fixed in a tightly milled stainless steel block which screens the sides. The frame allows for $YBa_2Cu_3O_{7-\delta}$ deposition on the MgO buffer while covering the edges of the sample.

4. Results and discussions

As a consequence the quality of the superconductor was greatly improved. In Fig.2 the resistive transition of such a film (trace b) is compared to a former result. We determined zero resistance temperatures of 87 K. The slope of the normal state resistance turned out to be a very sensitive indicator for arsenic contamination. With our most recent films we arrived at ratios of R(300K)/R(100K) = 3, i.e. the resistance extrapolates well to zero, and normal state resistivities down to $\varrho(100K) = 40\mu\Omega$cm (not shown).

Critical current densities were determined on 120 x 1000μm^2 Laser-structured bridges applying a 1μV/mm criterion. Its temperature dependence for a 165 nm thick $YBa_2Cu_3O_{7-\delta}$ film is depicted in

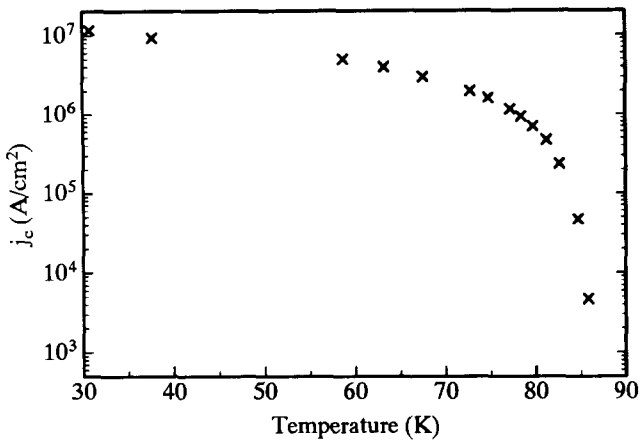

Figure 3. Temperature dependence of the critical current density of a 165 nm thick $YBa_2Cu_3O_{7-\delta}$ film on MgO/GaAs.

Fig.3. In this example the current density reaches $1.2 \cdot 10^6 A/cm^2$ at 77 K. For a variety of samples we used a non-destructive, inductive technique calibrated against the above transport measurements [7]. Herewith, so far we observed optimum values of $j_c(77K) = 2 \cdot 10^6 A/cm^2$. Preliminary measurements of the microwave surface impedance at 87 GHz yielded values similar as for films on MgO substrates (150 mΩ at 77 K, 15 mΩ at 20 K) [9].

Another property which deserves particular attention is the mechanical stability of the films. Large differential thermal expansions between film and substrate can lead to a fracture of the films, a problem especially prominent on silicon substrates [8]. $YBa_2Cu_3O_{7-\delta}$ films on GaAs were grown up to a thickness of 300 nm. In fact, in most films above a critical thickness of 250 nm the magnetic shielding was strongly reduced and cracks could be observed directly by SEM. Fortunately, this thickness limit should not pose severe restrictions to most applications. However, it should be kept in mind because the electrical transport properties of thicker films will be drastically degraded.

In summary, $YBa_2Cu_3O_{7-\delta}$ films with high critical current densities could be deposited on GaAs using MgO buffer layers. Low temperatures and a proper encapsulation of the GaAs substrate during the $YBa_2Cu_3O_{7-\delta}$ deposition guarantee the same excellent electronic properties as on other standard substrates. A 'mechanical encapsulation' as described above may be good enough for laboratory purposes. For technical applications and to improve reproducibility we suggest its substitution by a standard Si_3N_4 or SiO_2 encapsulation of the free GaAs surfaces.

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