

The sensitivity limits of spectroscopic ellipsometry to oxygen content in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin films

B.J. Gibbons* S. Trolier-McKinstry

The Pennsylvania State University, University Park, PA 16802, USA

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Abstract

The limits for the sensitivity of spectroscopic ellipsometry (SE) to the presence of near-surface gradations of the oxygen content in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) thin films have been investigated. Using an ellipsometric data modelling program, SE spectra were generated for films with fixed geometries and varying concentration gradients of oxygen. By comparing these spectra, the sensitivity limits of SE to small changes in the diffused depth and/or the surface concentration of oxygen (c_s) were determined. For c -axis oriented films, it was found that the oxygen content can, in principle, be determined to within one unit cell of YBCO, even when the profile is graded. Also, the minimum detectable change in the surface oxygen concentration (c_s) was calculated to be 2–3%, depending on the starting c_s . Similar calculations for YBCO layers buried under a 4 nm layer of metallic SrRuO_3 (i.e. in a superconductor-normal metal junction) showed small changes in these sensitivities. Calculations for a -axis oriented films showed that changes as small as 10 Å in the diffused depth were detectable for both buried and surface layers. The minimum detectable change in c_s for a -axis films was found to be 2–8%. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Spectroscopic ellipsometry; $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$; Oxygen content

1. Introduction

The sensitivity of spectroscopic ellipsometry (SE) to the oxygen content in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) thin films, where $0 \leq \delta \leq 1$, has been exhibited by many researchers [1–6]. This sensitivity is a result of the strong dependence of the dielectric function ($\epsilon_1 + i\epsilon_2$) of YBCO on the oxygen content (δ). Fig. 1 shows the imaginary component of the dielectric function along the a -axis as determined by Kircher et al. [3] for single crystal YBCO. As δ increases from 0 to 1, strong features which are characteristic of the non-superconducting tetragonal phase develop in the dielectric spectra (for both the a/b - and c -axes), particularly near 4.1 eV (302 nm). The sensitivity of SE to any surface layer of oxygen-deficient YBCO on top of fully-oxygenated YBCO is directly related to the refractive index contrast between that surface layer and the rest of the film. The limits of this sensitivity in the case of small changes to graded oxygen contents have not been reported previously. Consequently, this paper focuses on determining the resolution of SE to slight differences of graded oxygen profiles in YBCO films, with particular

emphasis on structures relevant to superconducting junction devices.

Since the discovery of high-temperature superconductivity, research on using YBCO in devices based on Josephson junction technology (i.e. SQUIDS and ultra-fast digital logic circuits) has been widespread [7–12]. Much of this research has focused on superconductor-normal metal-superconductor (SNS) type junctions. In SNS junctions, the critical current decays exponentially with increasing separation of the superconducting layers. For junctions in which the N layer is a metallic oxide, such as SrRuO_3 or $\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta}$, the thickness of the interlayer can only be 3–4 nm for the device to be useful at 77 K [13]. Given this, it is obvious that clean, smooth interfaces between the N and S layers are critical for proper device operation. In addition, the superconductor must be **fully oxygenated all the way to the interface** with the normal layer. Even a very thin oxygen deficient layer at the S/N interface increases the effective thickness of the N layer, thus dramatically reducing the Josephson current. In a recent review by Delin and Kleinsasser [13], it was concluded that the critical current versus temperature response for a majority of the high- T_c SNS devices reported in the literature was related to the presence of pinholes through the N layer, as well as possible interfacial layer effects. Thus, it is clear that improved

* Corresponding author. Now located at Los Alamos National Laboratory.

E-mail address: gibbons@lanl.gov (B.J. Gibbons)

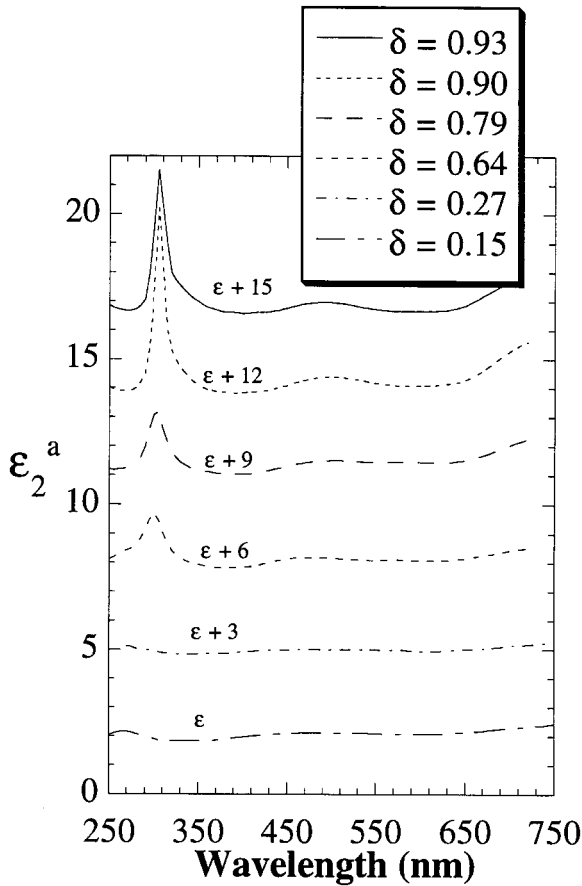


Fig. 1. The imaginary part of the dielectric function along the a -axis of YBCO. Data are taken from Kircher et al. [3]. The data are offset for clarity.

processing and characterization of the junction region is essential to further progress in this area.

The ability to detect interfacial oxygen deficiencies (on the length scale of the YBCO unit cell) for a buried YBCO film should significantly facilitate device processing, and thus improve resulting device performance and reliability.

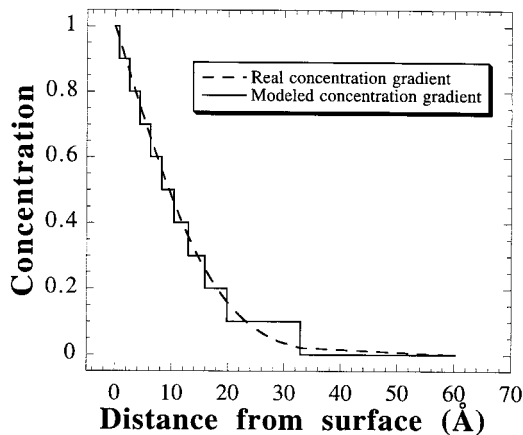


Fig. 2. Schematic of the staircase model used to approximate the concentration gradient in YBCO films. 50 layers were used for the calculation in this work.

Unfortunately, this exceeds the resolution limits for characterization tools such as secondary ion mass spectrometry (SIMS) [14], Rutherford backscattering spectrometry (RBS) [15] and Auger electron spectrometry (AES) [16]. There is recent work, however, that suggests SE is capable of non-destructively depth profiling interfaces with graded compositions while maintaining a resolution far superior to SIMS, providing the dielectric function contrast is sufficiently high [17]. For example, SE was used to measure the graded concentration profile of C in amorphous- $\text{Si}_{1-x}\text{C}_x\text{:H}$ thin films. The SE-determined full-width-at-half-maximum of the diffusion profile was 36 Å, as compared to the knock-in broadened 103 Å measured by SIMS. Spectroscopic ellipsometry has also been shown to be useful for characterization and control of composition in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ quantum well structures [18,19]. In that case, it was shown that the composition could be controlled to within 0.02 in x by comparing SE determined profiles to SIMS data. In this work, it is desired to determine whether SE shows a similar superiority in the detection of small changes to graded oxygen profiles in YBCO thin films.

2. Simulation procedure

Spectroscopic ellipsometry is a technique where light of a known polarization state is reflected from a surface and the changes in the relative phase and amplitude of the parallel (p) and perpendicular (s) components of the light are measured. These changes in the polarization state are characteristic of the depth profile of the dielectric function of the film. The measured ellipsometric parameters, Δ and Ψ , are given by

$$\rho \equiv \frac{r_p}{r_s} = \tan\Psi \exp(i\Delta) \quad (1)$$

where ρ is the complex reflectivity coefficient and r_p and r_s are the complex Fresnel reflection coefficients for the parallel and perpendicular components of the light, respectively. This type of measurement is widely used to extract thickness, surface roughness and optical properties of thin films and heterostructures [20–23]. In order to determine these values, the ellipsometric parameters (Δ and Ψ) are collected for several wavelengths, typically from the near infrared to the near ultraviolet, and then modeled to determine a best fit for the experimental data.

For this work, a modeling program which calculates the reflection coefficients for optically anisotropic multilayer stacks [24] was modified to include a concentration gradient in the sample. The gradient was treated using a complementary error function to describe a diffusion profile. That is,

$$c(x) = c_s \left[1 - \operatorname{erf}\left(\frac{x}{2\sqrt{Dt}}\right) \right] \quad (2)$$

where c is the concentration at a given distance x from the surface of the film, c_s is the concentration of oxygen at the

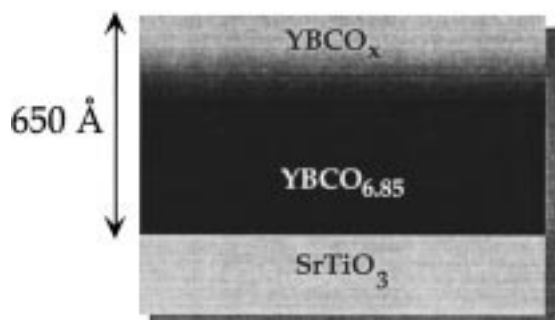


Fig. 3. Geometry used to calculate ellipsometric spectra of YBCO films with varying diffusion depths and/or surface concentrations of oxygen.

surface, D is the average diffusion coefficient and t is the time. The adjustable parameters for the model were taken to be c_s and Dt . A staircase function was used to approximate the concentration profile, as shown in Fig. 2. That is, the continuously varying concentration gradient was treated as a set of discrete layers, each of uniform composition. To eliminate artifacts associated with spurious interference fringes, the graded region was subdivided into 50 layers for this work. In the region where the concentration is changing rapidly, there are more, thinner layers. Where the concentration is changing slowly, the layers are thicker.

$\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ optical reference data for the modelling were obtained from Kircher et al. [3] at values of $\delta = 0.15, 0.27, 0.64, 0.79, 0.90$ and 0.93 . Values were given for the c - and the a/b -axes (the a - and b -axes were taken as optically equivalent). Bruggeman effective medium averaging was used to calculate dielectric functions for δ values between those given by Kircher. SrTiO_3 substrate reference data were obtained from the literature [25], and normal-metal SrRuO_3 optical data were determined by SE from measurements on smooth pulsed laser deposited films [26].

In this work, the modeling program was used to generate Δ and Ψ spectra for YBCO films with varying oxygen concentration profiles at an angle of incidence of 70° . This allowed for the direct comparison of films with slightly different diffusion depths of oxygen and/or slightly different surface concentrations of oxygen. Thus, the sensitivity of SE with respect to these changes could be determined by calculating the differences between spectra and comparing them to the experimental accuracy with which Δ and Ψ can be measured on an ellipsometer. It has been shown that accuracies of SE measurements can be as good as 0.03° in Δ and 0.01° in Ψ , as long as the proper calibration procedures are followed [27–29]. Even higher accuracies have been reported [29] in some cases, but the limits given here are reasonable for a research grade instrument. In this work, two different scenarios were considered: a -axis and c -axis oriented films on SrTiO_3 . For each case, the sensitivities to small changes in the diffusion depth or the surface oxygen concentration were calculated. Also, similar calculations were made for YBCO films buried under a 4 nm layer of

metallic SrRuO_3 to model an S–N junction. Fig. 3 shows the geometry which was used to generate the spectra in this work. Either c_s or the diffused depth (Dt) was changed, with the overall film thickness remaining the same. Calculations for a buried YBCO layer had the same geometry as in the figure, only with the layer of SrRuO_3 on top.

It should be noted that these calculations were completed for ideal films with no surface roughness. With roughness present, these sensitivities would be degraded somewhat. This is likely because the large refractive index contrast between YBCO and air may overwhelm comparatively subtle changes in the YBCO surface oxygen concentration (i.e. the sensitivity would be decreased especially for lightly reduced surfaces). However, there are two factors which suggest that the results presented here are still relevant: First, the effects of roughness on the YBCO ellipsometric spectra have a different spectral dependence than the effects due to changes in the oxidation state. Thus, the two effects should be separable. Secondly, as discussed previously, for Josephson junction applications a uniform, pinhole-free interlayer on the order of 4 nm thick is desired. In this case, the underlying YBCO surface must be very smooth ($x \ll 4$ nm); thus, these calculated sensitivities are relevant for potential Josephson junction device applications.

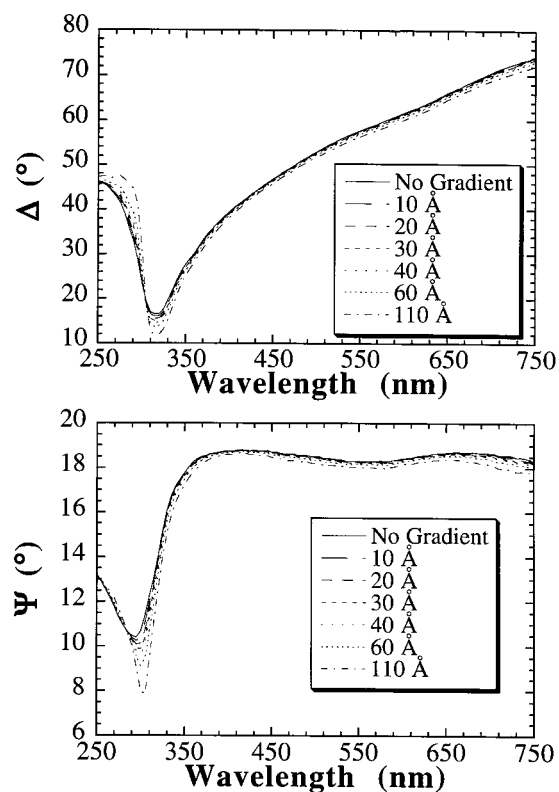


Fig. 4. Calculated Δ and Ψ spectra for a 650 \AA thick, c -axis oriented $\text{YBCO}_{6.85}$ film with a c_s of $\text{YBCO}_{6.07}$. The diffusion depth was varied from 0 to 110 \AA . The solid line corresponds to spectra for a fully oxidized film (no gradient).

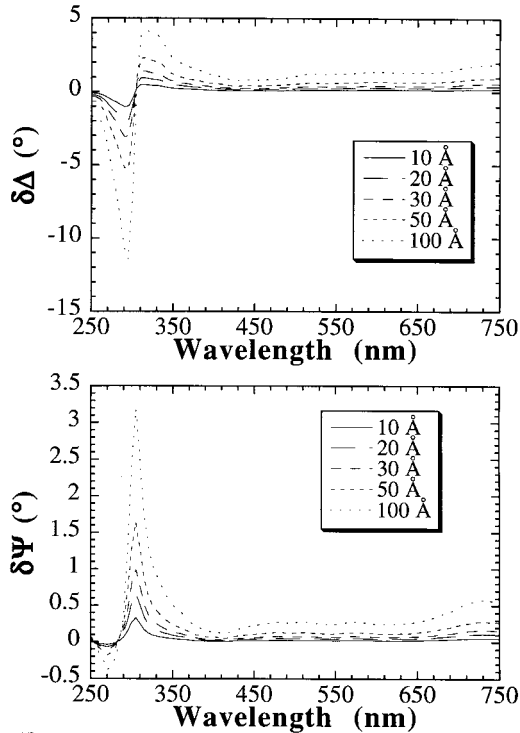


Fig. 5. Changes in Δ and Ψ resulting from changes in the diffused depth from 10 Å for a *c*-axis oriented YBCO film. c_s was fixed at YBCO_{6.07}. The legend describes the amount by which the diffused depth was increased.

3. Results and discussion

3.1. *c*-axis oriented films

3.1.1. Sensitivity to changes in the diffusion depth

The first set of calculations were used to determine the sensitivity of SE to changes in the diffused depth. For these generated spectra, the films are fixed at 650 Å thick with no surface roughness. The diffusion depth was defined as the point where the refractive index of the graded layer was within 0.001 of the non-diffused layer value (YBCO_{6.85}). The surface concentration (c_s) was fixed at YBCO_{6.07} and the diffused depth was varied from 0 to 110 Å or 350 to 450 Å.

Fig. 4 shows the generated Δ spectra for different diffused depths, as well as a pure YBCO_{6.85} film of the same thickness. The effects of the reduced surface layer are clear, even for the thinnest depths. To clarify the effect of small changes to the depth of the graded layer, Fig. 5 shows plots of how Δ and Ψ change ($\delta\Delta$ and $\delta\Psi$) when the reduced surface layer thickness starts at 10 Å and is subsequently increased by 10, 20, 30, 50 and 100 Å (with the surface oxygen concentration fixed to YBCO_{6.07}). Considering the previously mentioned accuracies of ellipsometric measurements, it is clear that for a change in the diffused depth of only 10 Å the changes in the ellipsometric parameters are large enough to detect across the entire wavelength range, with particularly good sensitivity near 300 nm (≈ 4.1 eV). That is, SE is sensitive to

the oxygen content within one unit cell of *c*-axis oriented YBCO, even when the oxygen profile is graded. To the authors' knowledge, there is no other technique which can distinguish small changes to the oxygen content in YBCO thin films on that length scale. In order to determine if this sensitivity is maintained for the same changes to thicker reduced surface layers, similar calculations were done for films with an initial graded layer thickness of 350 Å. For this case, unit cell sensitivity to small changes of the graded oxygen content is still exhibited, only the sensitivity is more pronounced in Ψ rather than Δ .

3.1.2. Sensitivity to changes in the surface oxygen concentration

The next set of generated spectra were used to determine the sensitivity of SE to slight variations of the surface oxygen concentrations (c_s) for graded layers on top of YBCO_{6.85}. For these calculations, the film thickness was again fixed at 650 Å with no surface roughness and the diffused depth was fixed to 40 or 450 Å. Fig. 6 shows the changes in Δ and Ψ for films with different surface concentrations with respect to a YBCO_{6.85} film of the same thickness. For these plots, it can be seen that even a 40 Å thick diffused layer that has a surface oxygen concentration of YBCO_{6.69} can significantly affect the ellipsometric data, specifically at lower wavelengths.

The minimum detectable change in surface oxygen concentration (c_s) is also of significant interest. Since the

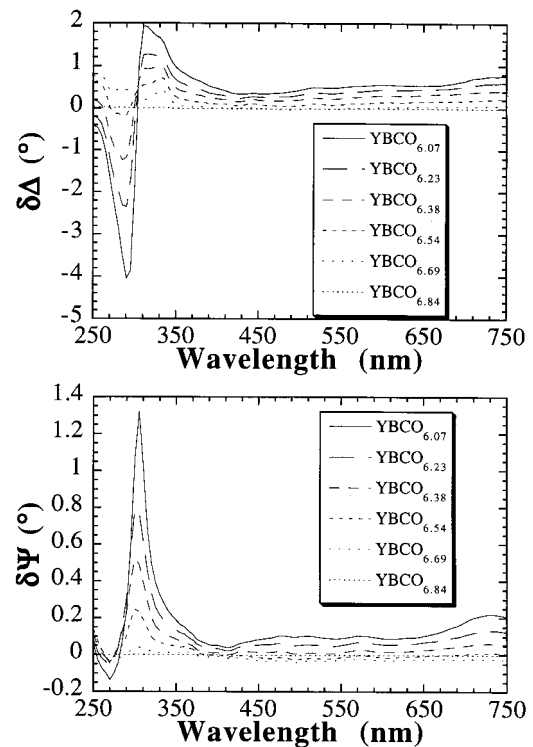


Fig. 6. Changes in Δ and Ψ for varying levels of surface oxygen concentration (c_s). The changes are with respect to a pure *c*-axis oriented YBCO_{6.85} film of the same thickness and the diffused depth was fixed at 40 Å.

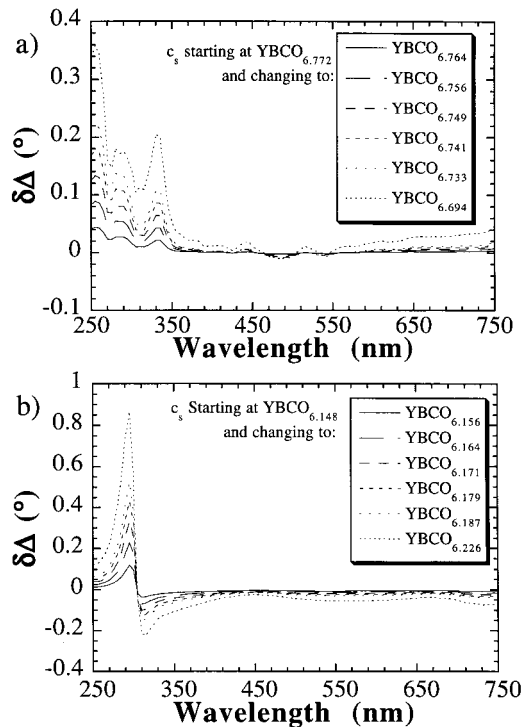


Fig. 7. Changes in Δ for (a) starting c_s of $\text{YBCO}_{6.772}$ and (b) starting c_s of $\text{YBCO}_{6.148}$ when c_s is changed by 0.008, 0.016, 0.023, 0.031, 0.039 and 0.078 for a c -axis oriented YBCO film.

majority of the film is $\text{YBCO}_{6.85}$, it is reasonable to expect that the sensitivity to small changes in c_s will be greater if c_s is further from $\text{YBCO}_{6.85}$ (i.e. for a heavily reduced surface). That is, the sensitivity to a change in c_s will be higher when there is a larger dielectric function contrast between the surface and the rest of the film. Fig. 7a shows the change in Δ when c_s starts at $\text{YBCO}_{6.772}$ ($\delta = 0.228$) and is subsequently changed to $\text{YBCO}_{6.764}$, $\text{YBCO}_{6.756}$, $\text{YBCO}_{6.749}$, $\text{YBCO}_{6.741}$, $\text{YBCO}_{6.733}$ and $\text{YBCO}_{6.694}$. Fig. 7b shows similar calculations for when c_s starts at $\text{YBCO}_{6.148}$ ($\delta = 0.852$) and is changed to $\text{YBCO}_{6.156}$, $\text{YBCO}_{6.164}$, $\text{YBCO}_{6.171}$, $\text{YBCO}_{6.179}$, $\text{YBCO}_{6.187}$ and $\text{YBCO}_{6.226}$. From these plots, it is clear that for surface oxygen concentrations closer to $\text{YBCO}_{6.85}$ the sensitivity is lower, while for surface concentrations further from $\text{YBCO}_{6.85}$, the sensitivity is greater (a smaller change can be detected). Thus, for the lightly reduced surface, a change in δ of 0.023 (to $\text{YBCO}_{6.749}$) can be detected for wavelengths between 250 and 350 nm, while for a heavily reduced surface, a change in δ of 0.016 (to $\text{YBCO}_{6.164}$) can be detected over the same range. Again, to the authors' knowledge there is no other technique which has the ability to detect such small changes in the surface oxygen content of YBCO thin films. When the graded layer is set to 450 Å thick and the same calculations for changes in c_s are made, the sensitivities for both cases are increased. A 0.016 change in δ is, in principle, detectable over the entire wavelength range for heavily reduced surface layers, and for wavelengths from 250 to 350 nm and greater than 450 nm for graded layers with compositions closer to that of the rest of

the film. Again, the sensitivities are more pronounced in Ψ for these calculations.

3.1.3. Sensitivity limits when the YBCO layer is buried under a 4 nm normal metal layer

In the above discussion, it was demonstrated that SE is clearly very sensitive to variations in the oxygen content in YBCO thin films when the graded layer is at the surface. However, in devices based on Josephson junction technology there is always some type of an interlayer (normal metal or insulator) adjacent to the superconducting film. As described previously, for SNS junctions it is critical that the underlying YBCO film be smooth and fully oxygenated all the way to the interface with the normal metal. Even a small oxygen deficiency at the interface will result in a region of poor superconducting properties (depressed critical temperature, critical current, etc.) and thus effectively increase the N layer thickness. As a result, the device operation is significantly degraded and, at some point, it ceases to act as a true proximity-effect junction [13].

In order to understand how the presence of an N layer affects the sensitivity of SE to oxygen content gradations in YBCO, ellipsometric data were generated for the same conditions as described in the previous sections, with the exception that a 4 nm thick layer of metallic SrRuO_3 was added as an overlayer on the surface. SrRuO_3 was chosen due to the availability of accurate optical reference data

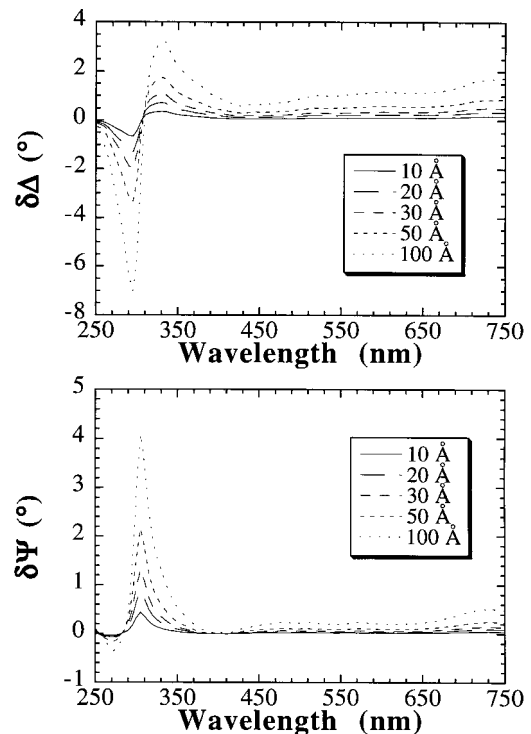


Fig. 8. Changes in Δ and Ψ resulting from changes in the diffused depth from 10 Å when the c -axis oriented diffused layer is buried beneath a 4 nm layer of metallic SrRuO_3 . The legend describes the amount by which the diffused depth was increased.

Table 1

Summary of the sensitivity limits of SE to changes in the diffused depth. For thin layers, the sensitivities are with respect to a starting graded layer thickness of 10 Å. For thick layers, the sensitivities are with respect to a starting graded layer thickness of 350 Å

| | | Detectable change (Å) | Wavelength range (nm) |
|------------------------------------|---------|-----------------------|-----------------------|
| Thin <i>c</i> -axis graded layers | Exposed | 10 | 250–750 |
| | Buried | 10 | 250–750 |
| Thick <i>c</i> -axis graded layers | Exposed | 10 | 250–750 |
| | Buried | 10 | 250–750 |
| Thin <i>a</i> -axis graded layers | Exposed | 10 | 310–750 |
| | Buried | 10 | 310–750 |
| Thick <i>a</i> -axis graded layers | Exposed | 10 | 350–750 |
| | Buried | 10 | 350–750 |

[26]. Fig. 8 shows $\delta\Delta$ and $\delta\Psi$ for changes in the YBCO graded oxygen content layer depth (with respect to a starting graded layer thickness of 10 Å). Again, this diffusion depth is defined as the distance from the S/N interface at which the refractive index of the graded layer was within 0.001 of the non-diffused layer value (YBCO_{6.85}). In Δ , the changes are somewhat damped compared to the generated spectra without the SrRuO₃ layer, while in Ψ the changes are slightly enhanced. However, changes on the order of one unit cell of YBCO are still readily detectable throughout the entire wavelength range. That is, small changes to the oxygen content at the interface in an SN junction can be seen using SE. When the thickness of the graded layer is set to 350 Å and the same changes are introduced, sensitivity on the order of one unit cell is still shown over the entire

Table 2

Summary of the sensitivity limits of SE to changes in the surface oxygen concentration. For thin layers, the diffused depth was fixed to 40 Å. For thick layers, the diffused depth was fixed to 450 Å. Sensitivities are given for both heavily and lightly reduced surface layers. The detectable change given is the minimum change in δ that can be detected

| | | Heavily reduced surface | | Lightly reduced surface | |
|------------------------------------|---------|-------------------------|-----------------------|-------------------------|-----------------------|
| | | Detectable change (%) | Wavelength range (nm) | Detectable change (%) | Wavelength range (nm) |
| Thin <i>c</i> -axis graded layers | Exposed | 2 | 250–350 | 3 | 250–350 |
| | Buried | 3 | 250–350 | 4 | 250–340 |
| Thick <i>c</i> -axis graded layers | Exposed | 2 | 250–750 | 2 | 250–350, 450–750 |
| | Buried | 2 | 430–750 | 2 | 430–750 |
| Thin <i>a</i> -axis graded layers | Exposed | 2 | 275–450 | 8 | 250–310, 500–750 |
| | Buried | 3 | 275–450 | 8 | 250–310, 500–750 |
| Thick <i>a</i> -axis graded layers | Exposed | 1 | 290–750 | 2 | 390–750 |
| | Buried | 1 | 300–750 | 2 | 400–750 |

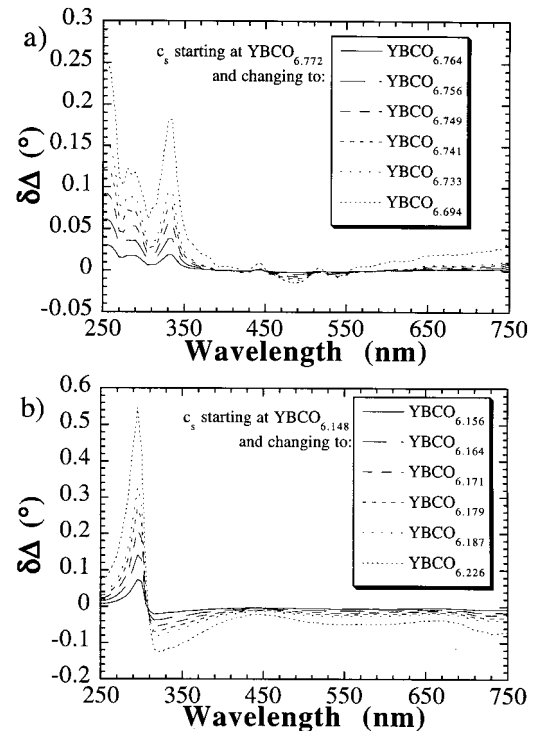


Fig. 9. Changes in Δ for (a) starting c_s of YBCO_{6.772} and (b) starting c_s of YBCO_{6.148} when c_s is changed by 0.008, 0.016, 0.023, 0.031, 0.039 and 0.078 for a *c*-axis oriented YBCO film with a graded surface oxygen content buried under a 4 nm layer of metallic SrRuO₃.

wavelength range, however the sensitivity is exhibited in Ψ rather than Δ .

Next, the interfacial oxygen concentration (c_s) was varied for a YBCO film underneath a 4 nm layer of SrRuO₃. Fig. 9 shows $\delta\Delta$ for when c_s starts at YBCO_{6.772} and YBCO_{6.148} and is changed by 0.008, 0.016, 0.023, 0.031, 0.039 and 0.078 in δ . Here again, the changes in Δ are slightly diminished relative to the case where the YBCO film is not buried. The minimum detection limit of a change in c_s is increased

for samples with a more heavily reduced surface to 0.031 (to YBCO_{6.179}) over the wavelength range 250–350 nm. For calculations with the starting surface oxygen concentration closer to the rest of the film (YBCO_{6.85}), a 0.039 change in δ can be detected between 250 and 340 nm. When the graded layer thickness of the buried YBCO film is 450 Å, the sensitivities for both cases are improved. Minimum changes in c_s on the order of 0.016 can be detected for wavelengths greater than 430 nm.

3.2. *a*-axis oriented films

a-axis oriented YBCO thin films are of significant technological interest for use in sandwich type Josephson junction applications because of the increased critical current density along the *a/b*-direction with respect to the *c*-direction [30]. The necessity for smooth, fully oxygenated YBCO applies to these types of junctions, as well. Thus, as in the above discussion, ellipsometric spectra were generated for *a*-axis oriented films 650 Å thick with and without a 4 nm overlayer of metallic SrRuO₃. For these simulations, the YBCO film was assumed to be twinned in-plane, with equal amounts of *c*- and *b*-axis oriented regions parallel to a given substrate edge for 100 edge-oriented SrTiO₃. Also, the edge of the substrate was set to be parallel to the plane of incidence. For this particular case, the reference in-plane optical data for YBCO is simply an average of the *a/b*- and *c*-axes dielectric functions.

It was found that changes in the diffused depth of as little as 10 Å were detectable with and without the SrRuO₃ overlayer. This was the case for both the 10 Å and 350 Å thick reduced surface layers. When the surface oxygen concentration was changed without the overlayer, the minimum detectable change in c_s was found to be 0.023–0.078 depending on the starting c_s . With the SrRuO₃ in place, the sensitivity drops to 0.031–0.078. For calculations where the diffused depth was fixed to 450 Å, the overall sensitivities to small changes in the surface oxygen content were significantly improved. Detection limits on the order of 0.008–0.016 in c_s were calculated.

Tables 1 and 2 summarize the results for both the *c*- and *a*-axis oriented films on SrTiO₃. The detectable changes and the wavelength ranges where the changes can be seen are listed. The results of this work show that, as expected, the sensitivities of SE are higher when there is a high dielectric function contrast between the surface (or interface for a buried layer) and the rest of the film. As the graded layer becomes thicker, in general the sensitivities are more strongly exhibited in Ψ , rather than Δ . Thus, based on these data, for graded layer thicknesses up to 450 Å the accuracy of measuring changes to the thickness is independent of the total graded layer thickness. This is in contrast to the case of graded composition profiles in all-dielectric systems [31].

4. Conclusions

This work describes the sensitivity of spectroscopic ellipsometry to graded oxygen compositions in YBCO thin films. Specifically, the ability of SE to deduce slight differences in the graded oxygen compositions of films that are otherwise the same was explored. It was shown for *c*-axis oriented films that SE is, in principle, sensitive to changes in the oxygen concentration to within one unit cell, even when the oxygen profile is graded. In addition, the minimum detectable change of surface oxygen concentration was determined to be between 0.016 and 0.023, depending on the starting value of c_s compared to the rest of the film. Subsequently, the sensitivity limits were determined for the case where the YBCO film is buried under a 4 nm thick normal metal layer of SrRuO₃. It was shown that for *c*-axis oriented films the sensitivities of SE were not changed significantly.

Similar calculations were made for *a*-axis oriented YBCO films. In this case, changes in the diffused depth of as little as 10 Å were shown to be detectable with and without the overlayer of SrRuO₃. When the surface oxygen concentration was changed without the overlayer, the minimum detectable change in c_s was found to be 0.023–0.078 depending on the starting c_s . With the SrRuO₃ in place, the sensitivity drops to 0.031–0.078. Finally, it should be restated that these calculations were completed using optical reference data for single crystal YBCO. Any decrease in the dielectric function contrast between oxygen-deficient and oxygen-rich YBCO in thin film form will consequently reduce the calculated sensitivities. However, recent work has demonstrated that the dielectric function contrast in thin films is similar to that of single crystals [6,32].

Acknowledgements

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