Active tuning of the optical response of field-effect-gated transparent conductive oxides

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Abstract. Transparent Conductive Oxides (TCOs) are a class of materials with high optical transparency and electrical conductivity. This combination makes them extremely appealing for solar cells, optoelectronics and infrared-plasmonics applications. In this work, we report the active tuning of the optical response of aluminium-doped ZnO (AZO) films upon electrical gating within a parallel-plate capacitor configuration. We investigated the electrical-bias-dependent optical response of thin AZO films fabricated by pulsed laser deposition by means of spectroscopic ellipsometry (SE). Calculations based on an exponentially-decaying spatial distribution of injected/depleted charge density in the AZO film are in accordance with experimental observations, allowing the extraction of the Debye length.

1 Introduction

The realisation of active optoelectronic systems has drawn the attention of the scientific community over the last decade due to the possibility of merging optical and electrical control in a single device for next generation optoelectronics and photovoltaics. TCOs (such as ITO, ZnO etc.) are characterised by a combination of high optical transparency (~80%) and low electrical resistivity (~10^{-4} Ω·cm).

Zinc oxide (ZnO) is a n-type semiconductor with direct wide-energy band gap, and is a possible cheaper substitute to the commonly used indium-tin oxide. Aluminium doping increases its conductivity and makes it suitable for applications in optoelectronic devices, as a transparent conductive component and epsilon-near-zero (ENZ) material in the near infrared (NIR).

Actively modifying the optical response of TCOs via field effect is a potentially viable strategy to develop new functional optical materials for optoelectronics, photonics and photovoltaics ([1-2]). Under an applied electric field, the carrier concentration at a dielectric/conducting oxide interface induces charge accumulation/depletion in a thin layer whose width is usually less than 5 nm due to screening effects. Most of the studies about voltage-gated optically-active TCOs have focused on ITO-based systems, and have been limited to reflectance/transmission measurements within the visible and -NIR regimes.

In this study, we show the active tuning of the optical response of thin AZO films on $SrTiO_3$(110) substrates (STO) via field effect, in a spectral range encompassing both the visible and near infrared (NIR) photon-energy range (0.735 to 3.22 eV). The TCO film acts as the top electrode in a parallel-plate-capacitor configuration.30 We successfully observed the active tuning of the optical response of AZO, and quantified the charge profile of the accumulation layer at the TCO/insulator interface.

2 Discussion

In order to realise a large charge modulation AZO films were grown on STO(110) substrates by Pulsed Laser Deposition (PLD). Spectroscopic Ellipsometry (SE) was performed by means of a J.A. Woollam V-VASE ellipsometer. For the SE measurements, the sample was mounted inside an optical cryostat (Oxford Instruments Optistat CF-V) and kept at either 4.2 K or 77 K temperature.

In order to investigate the variations of the optical response of the AZO films upon gating, we applied voltages of ±100 V across the STO substrate, and acquired SE spectra under bias (V=±100V) (Figure 1).

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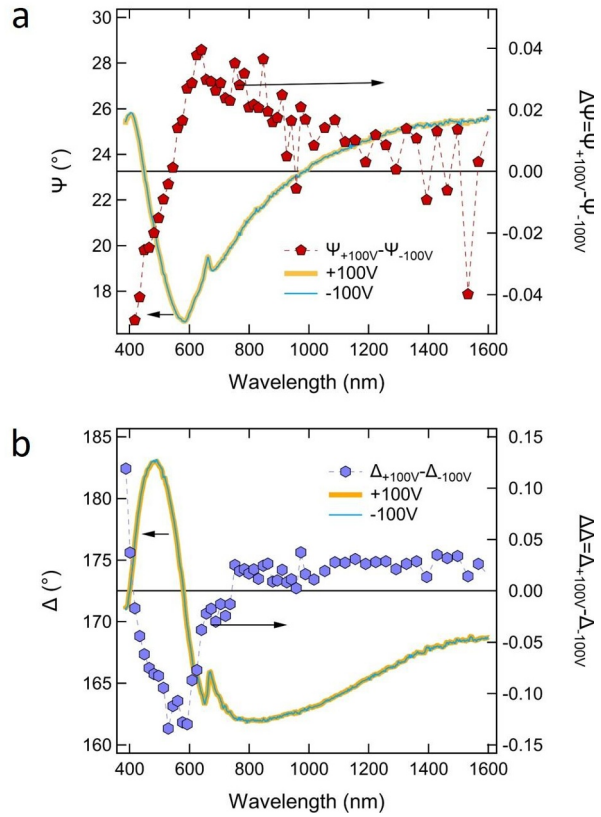

Fig. 1. a (b): Ellipsometry spectra Ψ(λ) (Δ(λ)) of 0.2 at.% AZO on top of STO (110) under bias (orange line: +100V, cyan line: -100V). Red (indigo) squares: Difference spectra δΨ(λ) (Δ(λ)), defined as Ψ(+100V)-Ψ(-100V) (Δ(+100V)-Δ(-100V)). All spectra were acquired at T=4.2 K with an incidence angle of 45°.

An estimate of the gating-induced charge variation in the AZO can be obtained modelling the system as a parallel-plate capacitor, where the STO acts as the dielectric, and the metallic contact at the back of the substrate and the AZO film are the two electrodes. Then , we assume that the injected/depleted charge density exhibit an exponential depth grading, that can be written as:

$$N_e(z) = N_0 \pm \left(\frac{\sigma_e}{\lambda_D}\right) e^{-\frac{z}{\lambda_D}} \qquad (1)$$

where σ_e is the surface charge density on the plates of the capacitor, N_0 is the charge density of unbiased AZO, λ_D is the Debye length, that accounts for the screening length inside the AZO while the ± case corresponds to the injection/depletion case, respectively. Knowing $N_e(z)$, it becomes possible to simulate the optical response of the system, just applying a corresponding variation to the Drude term (Figure 2).

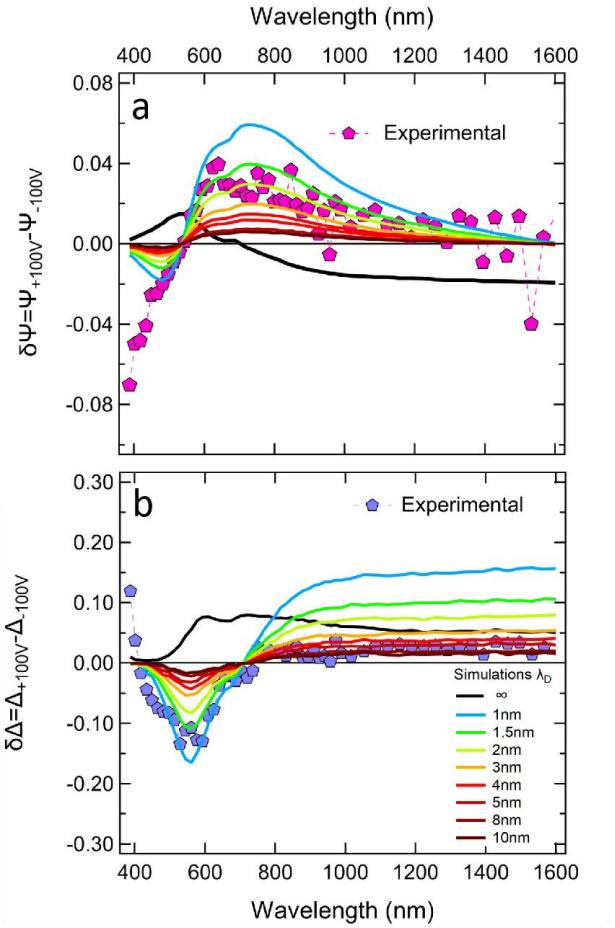

Fig. 2. a (b): Magenta (indigo) symbols: experimental difference spectra δΨ (δΔ)) as a function of wavelength, at T=4.2 K. Solid lines: calculated difference spectra obtained by modelling the charge injection/depletion in the AZO film. Different colours represent different values of the Debye length in the AZO film.

3 Conclusions

We have performed an in-operando optical spectroscopy investigation of the AZO/STO(110) system under field effect. The optical data shown here, and the related modelling, represent a great enrichment with respect to electrical-transport measurements alone, contributing to a deeper understanding of the phenomena.

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References

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