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Structural characteristics and optical properties of plasma assisted reactive magnetron sputtered dielectric thin films for planar waveguiding applications

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ABSTRACT

Thin films of aluminum oxide (Al_2O_3), tantalum pentoxide (Ta_2O_5), titanium oxide (TiO_2), yttrium oxide (Y_2O_3) and zirconium oxide (ZrO_2) were deposited by plasma assisted reactive dual magnetron sputtering to determine their suitability as a host for a rare earth doped planar waveguide upconversion laser. The effect of deposition parameters such as cathode, plasma power and oxygen gas flows were studied and the operational working points were determined. Both power and lambda control were used to optimize the optical quality of each material. By using lambda control feedback system, the magnetron power fluctuates to sustain a fixed oxygen flow in the target area reducing the compound layer growth on the material and maintaining a healthy deposition rate. The optical properties, structure and crystalline phase of each film were found to be dependent on the process parameters. X-ray diffraction (XRD) analysis revealed that the thin films varied from amorphous to highly crystalline depending on the deposition conditions. X-ray photoelectron spectroscopy (XPS) was utilized for surface compositional analysis revealing that films had varying stoichiometric ratios which are controlled for each material by the deposition parameters chosen. The waveguide loss for the thin film layers was investigated and Ta_2O_5 was shown to have a slab waveguide loss of ~1 dB/cm at both visible and infra-red wavelengths making it ideal for planar waveguide and laser applications. TiO_2, Y_2O_3 and ZrO_2 were found to deposit in a highly crystalline phase. Waveguiding in the TiO_2 layers was not possible at 633 nm or in the infrared region. The Y_2O_3 samples gave low loss (2–4 dB/cm) at the 1.3 and 1.5 μm wavelengths but no waveguiding at 633 nm or 833 nm was possible. Atomic force microscopy showed rough surface topography for TiO_2, Y_2O_3 and ZrO_2 akin to their crystalline growth with the SEM images confirming the regular crystalline columnar structure for the case of Y_2O_3 and ZrO_2.

1. Introduction

There has been considerable interest in optimization of the deposition processes for planar waveguide materials as hosts for solid-state lasers and optical amplifiers. These include aluminum oxide [1], zirconium oxide [2], titanium oxide [3], scandium oxide [4], yttrium oxide [5–7] and tantalum pentoxide [8]. Planar waveguide lasers based on rare earth doped thin films provide a desirable method to achieve high optical gain in a small and compact device [5]. Essential properties of host materials include: low optical loss, low peak phonon energy, ability to be doped and ability to waveguide at the pump and emission wavelengths.

Aluminum oxide (Al_2O_3) when deposited as a thin film has a moderate refractive index (1.6–1.7) [9–12] and has a wide transmittance range from 200 nm up to 7 μm. Al_2O_3 thin films have good adhesion, hardness, durability and anti-wear properties. These characteristics make it an ideal material for many applications such as optical interference coatings, multilayer polarizers and filters and micro-electromechanical systems (MEMS). Another key application for Al_2O_3 thin films is insulating layers in metal–oxide–semiconductor (MOS) transistors. Methods to deposit Al_2O_3 include plasma enhanced chemical vapor deposition [13], dual ion beam sputtering [14], plasma assisted electron beam evaporation [15,16], plasma assisted reactive magnetron sputtering [17], direct current reactive magnetron sputtering [10], pulsed laser deposition (PLD) [18] and cathodic arc deposition [19]. Aluminum oxide has already been proven as a suitable host material for rare earth dopants [20,21]. In particular erbium doped optical waveguide amplifiers operating at 1.53 μm with a net optical gain of 2.3 dB have been reported [22]. Very low optical loss (1 dB/cm) Al_2O_3 ridge waveguides have previously been created by post annealing films at 800 °C [23].

Due to its high dielectric constant, high refractive index in the visible spectral range [24] and high chemical and thermal stability, tantalum pentoxide (Ta_2O_5) thin films have been studied for applications such as high density dynamic random access memories (DRAMs) [25,26],

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decoupling capacitors [27,28], antireflection coatings [29,30] and optical waveguides [31]. Many different techniques to deposit Ta_2O_5 thin films have been utilized allowing its use in compact photonic circuits and as a potential host for rare earth ions to achieve optical gain [32]. Ta_2O_5 has a large energy band gap of 4.2 eV [24] which in principle allows nearly absorption free transmission from 400 nm to 10 μm [33], and is a proven host material for rare earth dopants [32,33], with low phonon energy and capability to produce low loss waveguides [34].

Titanium oxide (TiO_2) is an important material for optical applications such as antireflective coatings [35], microelectronic devices [36,37] and protective layers [38], has a high refractive index and is transparent across the visible wavelength range. The waveguiding

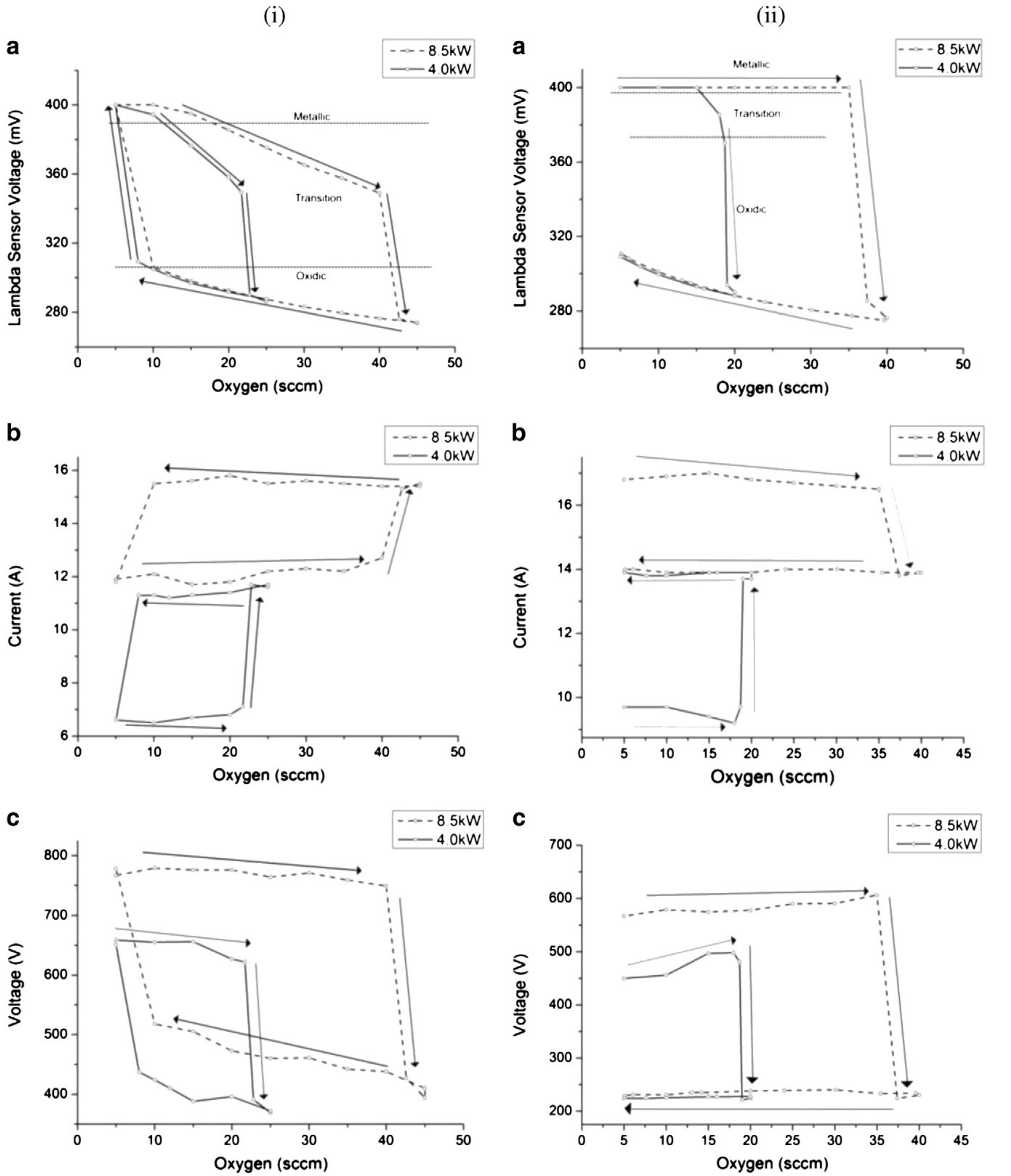

Fig. 1. Comparison of operational curves for (i) Al_2O_3 and (ii) Y_2O_3 measured at two target power levels, 8.5 kW and 4.0 kW. Argon flow in the target area: 35 sccm. The additional plasma source was operated at 1.5 kW with an oxygen flow rate of 15 sccm. The lambda sensor voltage behavior is shown in (a), cathode target current in (b) and cathode target voltage in (c).