Al_2O_3 and Y_2O_3 Thin Films for Active Integrated Optical Waveguide Devices

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Al_2O_3 and Y_2O_3 are both very promising host materials for active integrated optics applications such as rare-earth ion doped waveguide lasers. In this paper, a reactive co-sputtering process for stable, target condition-independent deposition of Al_2O_3 layers with high optical quality is discussed. The loss of as-deposited Al_2O_3 waveguides in the near infrared wavelength range was 0.3 dB/cm. Reactive ion etching of both Al_2O_3 and Y_2O_3 thin films for defining channel waveguide structures was investigated and compared using CF_4/O_2, BCl_3, HBr and Cl_2 inductively coupled plasmas.

Introduction

Thin films of amorphous aluminum oxide (Al_2O_3) and yttrium oxide (Y_2O_3) offer very promising platforms for active integrated optics applications [1]. In particular, rare-earth-ion doped Al_2O_3 waveguides for integrated optical amplifiers and tunable light sources have been demonstrated [2]. For large scale realization of such active devices, the development of stable, reproducible and straightforward methods resulting in as-deposited low-loss Al_2O_3 layers are required. Sputtering is known to result in fast, well-controlled, uniform deposition over a large substrate area. Er:Al_2O_3 slab waveguides fabricated by DC-driven reactive co-sputtering [3], for example, were optimized to an estimated loss value of about 0.25 dB/cm. The main drawback of the DC-driven method is however a poor process stability and reproducibility due to a strong dependence on the exact condition of the sputtering target.

Low-loss planar optical waveguides of Y_2O_3 deposited by various techniques have also been demonstrated recently [4]. In contrary to the successful channel definition in Al_2O_3 [5] by reactive ion etching (RIE), the utilization of Y_2O_3 channel waveguides is still hampered by the absence of a reliable patterning process. Due to its high chemical stability, structuring of Y_2O_3 has been primarily limited to entirely physical etching techniques [6], [7]. The physical methods often result in high waveguide losses due to poor sidewall quality and severely limit the profile of waveguide structures. RIE, which combines physical and chemical etching, generally allows for low-cost, high resolution structuring of channel waveguides with smooth sidewalls.

In this paper, results on DC- and rf-based reactive co-sputtering of Al_2O_3 films and the reactive ion etching behaviour of Y_2O_3 in various plasma chemistries are presented.

Experimental Set-up

For the Al_2O_3 layer deposition, an AJA ATC 1500 sputtering system has been applied. The substrates are fixed on a rotating substrate holder and heated up to a maximum temperature of 800 ºC. The system is equipped with three Ar sputtering guns for 2-inch sputtering targets, which can be driven by either rf- or DC power supplies, both having a maximum range of 500 W. An oxygen flow is connected to a gas inlet at the chamber, allowing for reactive co-sputtering of metallic targets. For sputtering of Al_2O_3 layers, a high-purity 2-inch Al target was mounted to one of the sputtering guns and deposition was carried out on 100-mm Si wafers, either bare or thermally oxidized to a thickness of 8 µm. The film properties, including refractive index, layer thickness and uniformity, and loss values, were measured by ellipsometry and prism coupling.

For studying the etching behavior of Y_2O_3, an Oxford Plasmalab 100 inductively-coupled plasma (ICP) reactive ion etch system was used. The ICP source was controlled by a 3 kW, 13.56 MHz generator, while substrate bias was controlled separately by a 600 W, 13.56 MHz RF generator. Various standard process gases and combinations of these gases were used, including BCl_3, BCl_3-HBr (50:50), CF_4/O_2 (90:10), and Cl_2. Y_2O_3 films of approximately 900 nm thickness were reactively sputtered on Si substrates using a separate DC sputtering system for the etch experiments. The etch rate of the Y_2O_3 films was determined by measuring the film thickness before and after the etch process with a spectroscopic ellipsometer.

Results and Discussion

Sputter-deposition of Al_2O_3 thin films

The impact of various processing parameters (temperature, pressure, power, total flow and oxygen percentage in flow) on the layer properties (deposition rate, refractive index, film density, stress, material birefringence and optical loss) has been studied for both, DC and rf-driven sputtering. Based on this study, it was found that the optimum deposition conditions include high substrate temperature, high sputtering power, low pressure and higher total gas flow. The optimized films had high refractive index and high density, and a sufficiently large deposition rate for depositing waveguide layers of typical thickness (5.5 nm/min for the optimized rf-sputtered films). The most striking difference found between rf- and DC-sputtering was in the process stability and the optical loss of the waveguides. In the case of DC sputtering the optical quality is highly dependent on the exact condition of the sputtering target. Oxidation of the target surface results in release of large particles from the target due to arcing. In case of all waveguide samples fabricated by the DC sputtering process no propagation could be observed after coupling of light with a 633-nm wavelength. In contrary, the rf sputtering process was highly stable and reproducible, without the occurrence of arcing. Figure 1 (a) shows the refractive index of the optimized Al_2O_3 as a function of wavelength, with low material birefringence based on TE and TM polarization measurements. The refractive index is reproduced within $\pm\ 10^{-3}$. The thickness uniformity, as shown in Figure 1 (b), is within the 1-2% range over an area 4 cm wide in the centre of the wafer. The uniformity of films in the optimized parameter range was also significantly better for the rf-deposited films.

Figure 2 a) shows the optical loss of rf-deposited Al_2O_3 slab waveguides at 633nm as a function of deposition temperature (a), and the optical loss as a function of wavelength for both optimized and non-optimized layers. The film quality is improved significantly as the temperature is increased towards the higher range. In (b), the optical loss throughout the near IR wavelength range of 1200-1600 nm for optimized 660 nm thick rf-sputtered film is about 0.3 ± 0.15 dB/cm. For the optimized rf-process, the absorption peak at 1400 nm (caused by the presence of O-H bonds in the film) is not observed. For rare-earth doping applications, O-H free deposition is required, because these bonds form one of the major quenching sources and largely diminish the gain efficiency.

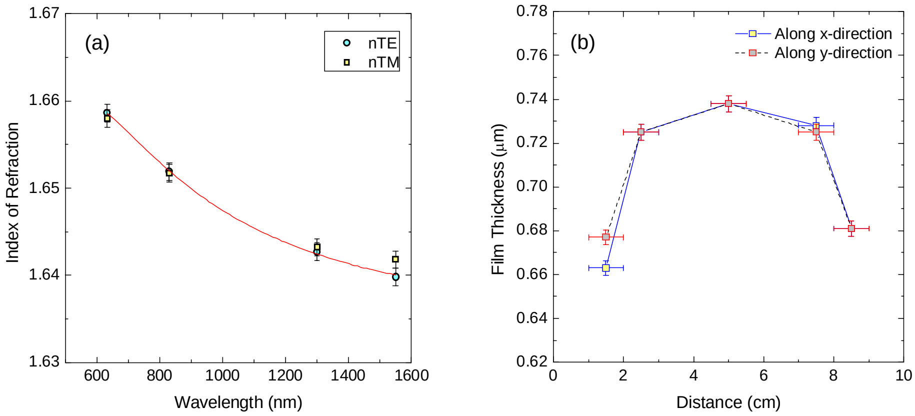


Fig. 1. (a) Variation of the refractive index of optimized Al_2O_3 layer as a function of wavelength. (b) 9-point scan of layer thickness along two perpendicular directions on the 100-mm wafer.

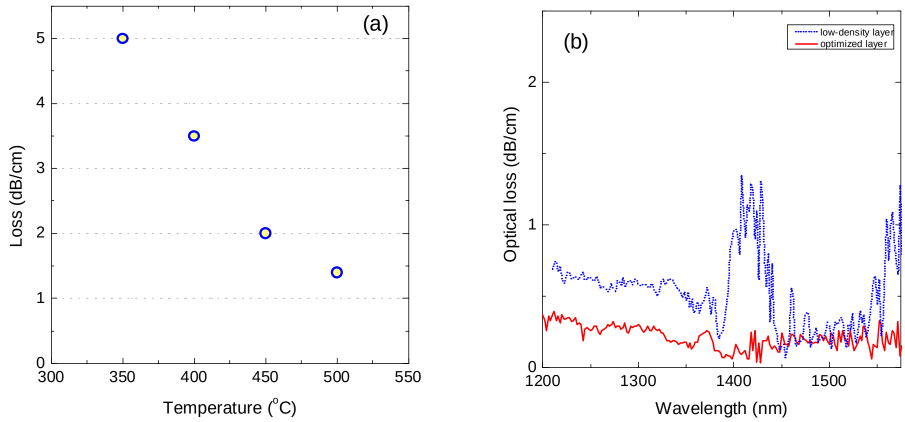
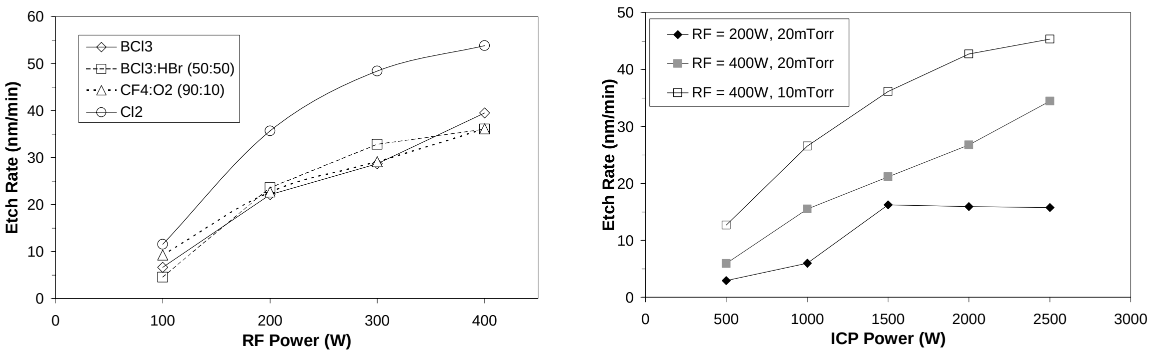


Fig. 2. (a) Change of optical loss of Al_2O_3 slab waveguides at 633 nm as a function of deposition temperature. (b) Optical loss spectrum for both low-density and optimized Al_2O_3 layers in the IR region.

Y_2O_3 thin film etching

The etch rate of the Y_2O_3 films was investigated as a function of applied RF power for various plasma compositions. Figure 3 (a) shows the resulting etch rate as a function of RF power for CF_4/O_2 (90:10%), BCl_3 (100%), BCl_3/HBr (50:50%) and Cl_2 (100%) gases. From these results, it can be seen that with the exception of Cl_2, the various etch chemistries do not significantly impact the etch rate. This indicates that a primarily physical etch process is involved for these process gases. All values were almost an order of magnitude lower than those obtained for the optimized sapphire-etching process in BCl_3-based plasmas [5]. The possible etch products of Y_2O_3 (such as YCl_3, YBr_3, with the exception of YF_3) are generally known to be much less volatile than those of Al_2O_3, indicated by much higher melting points. We therefore expect lower etch rates for Y_2O_3, with primarily physical mechanisms dominating. Of all the process gases used to etch Y_2O_3, Cl_2 clearly exhibits the highest etch rates, with a maximum value of 53 nm/min observed at 400 W RF power. This indicates that perhaps a stronger chemical component is involved in the purely Cl-based etch process.

In the initial studies, it was found that the surface quality of the etched films, as measured by the quality of the ellipsometric measurement fitting parameters, varied significantly for the different chemistries. Specifically, films etched in CF_4/O_2, were found to have significantly higher surface quality. Therefore a study was undertaken to optimize the etch rate in CF_4/O_2 plasma. As shown in figure 3 (b), it was found that the lowest obtainable chamber pressure (~10 mTorr), highest ICP power and highest RF power resulted in the highest etch rate, all trends indicative of strong physical etching. The highest etch rate for this chemistry was still lower than that obtained for the un-optimized etch rate in Cl_2. The poor surface quality in the case of Cl_2 could in fact be attributed to formation of non-volatile etch products, such as YCl_3, by chemical reactions on the surface [8]. As some chemical component is required in order to enhance the etch rate, Cl_2 seems to be the best choice as a process gas for optical waveguide fabrication in Y_2O_3.



(a) (b)

Fig. 3. (a) Comparison of etch rate and RF bias as a function of RF power for 100% BCl_3, BCl_3:HBr (50:50), $CF_4:O_2$ (90:10) and Cl_2 at a total flow rate of 50 sccm. (b) Etch rate as a function of ICP power in CF_4/O_2 (90:10) plasma at a total flow rate of 50 sccm, for varying RF chuck power and chamber pressure.

Conclusion

An rf-based reactive co-sputtering process, which resulted in stable, target condition-independent deposition of uniform Al_2O_3 layers with high optical quality, has been developed. The optical loss of waveguides based on the optimized material is 0.3 ± 0.15 dB/cm throughout the near IR wavelengths ranging from 1200 to 1600 nm. Reactive ion etching of Y_2O_3 thin films was also studied using various plasma chemistries and parameters. A maximum etch rate of >50 nm/min was measured using Cl_2 plasma, which is sufficiently high for the controlled etching of optical waveguide structures to a depth of several hundred nm. Further work will continue towards the realization of active integrated optical devices in both materials.

References

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