Optimized Deposition and Structuring of Reactively Co-Sputtered Al_2O_3:Er Waveguide Layers with Net Optical Gain

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Growth of reactively co-sputtered Al_2O_3 layers and micro-structuring using reactive ion etching have been optimized, resulting in channel waveguides in the as-deposited layers with optical propagation losses as low as 0.21 dB/cm. For active functionality, Er-doped Al_2O_3 layers have also been deposited by co-sputtering from a metallic Er target. At relevant dopant levels (~10^{20} cm^{-3}) lifetimes of the $^4I_{13/2}$ level up to 7 ms have been measured and net optical gain of 0.7 dB/cm has been obtained in a 700-nm thick Er-doped Al_2O_3 waveguide. Investigation of active devices, such as lasers and amplifiers, exploiting the developed technology is on-going.

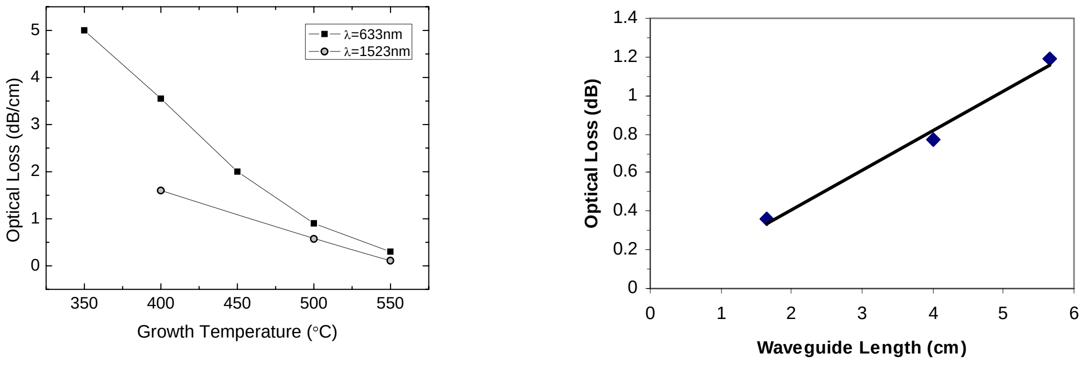
Introduction

Amorphous aluminum oxide (Al_2O_3) is known to be an excellent potential material for active integrated optical devices, owing to the possibility of high erbium concentrations without clustering, low background losses at infrared wavelengths and a wide emission spectrum around 1550 nm [1]. In particular, reactively co-sputtered Al_2O_3:Er offers an advantage compared to other deposition techniques because no further implantation or annealing steps are required, reducing the number and complexity of process steps and resulting in low-loss as-deposited layers. However, in previous studies, the co-sputtering process was unreliable and the channel waveguide fabrication process resulted in higher losses, limiting the net optical gain [2]. In this work, improved deposition and structuring methods resulting in reproducible layers and high-resolution channel waveguide structures with low propagation losses are presented. In addition, the spectroscopic properties and gain characteristics have been measured in rare-earth-ion-doped layers using the same deposition method, demonstrating the high potential for integrated active devices such as amplifiers and lasers using the developed deposition and structuring methods.

Experimental Results and Discussion

Deposition and Structuring of Al_2O_3 Waveguides

Reactive co-sputtering of Al_2O_3 layers has been optimized using an AJA ATC 1500 system [3], resulting in uniform, reproducible, low-loss layers on thermally oxidized Si substrates. The optical loss is shown as a function of deposition temperature in Fig. 1 (a). In order to achieve net gain in rare-earth-ion-doped channel waveguide devices, a structuring method resulting in low additional background losses is required. As such, a dry etching method for fabricating high-resolution, low-propagation-loss channel waveguides in Al_2O_3 layers has also been developed and reported [4]. The optical losses of uncladded 2.5-µm-wide ridge waveguides, etched to a depth of 220 nm in an optimized 700-nm-thick Al_2O_3 layer, were investigated using a fiber butt-coupling setup and broadband erbium-doped fiber amplifier (1520-1580 nm) source. Prior to etching, the background optical propagation loss of the as-grown layer deposited at 550 °C was measured to be 0.11 ± 0.05 dB/cm at 1.5 μm using the prism coupling technique. Applying the cut-back method, with waveguide lengths of 5.65, 4.0, and 1.65 cm, a propagation loss of 0.21 ± 0.05 dB/cm was measured in the ridge wavaeguides, as shown in Fig. 1 (b). This indicates that only very small additional losses on the order of 0.1 dB/cm, are introduced by the dry-etching process.



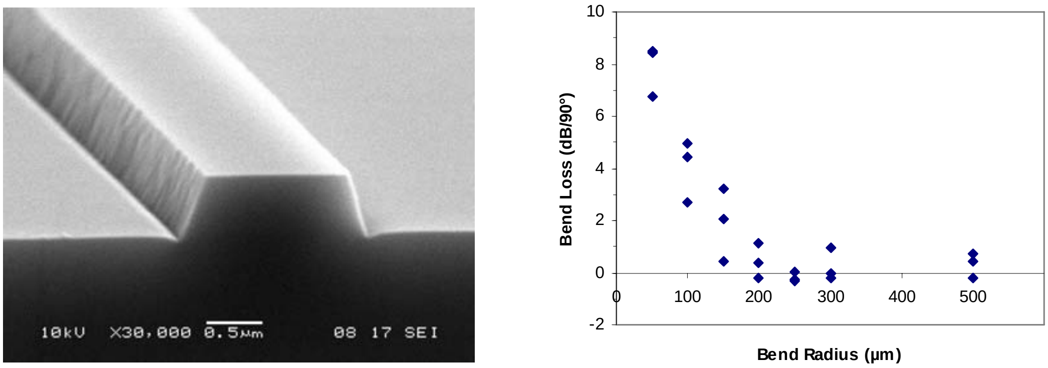
(a) (b)

Fig. 1. (a) Optical loss of as-deposited Al_2O_3 layers as a function of growth temperature and (b) on-chip propagation loss in a 220-nm-deep, 2.5-μm-wide Al_2O_3 channel waveguide measured for varying lengths using the cut-back method.

In order to investigate the feasibility of various potential active and passive functions leading to on-chip resonator devices, high-optical-confinement channel waveguide bends and reflection grating structures have been fabricated and characterized. Channel waveguides with an etch depth of 500 nm and adiabatic bend sections with varying radii from 75 to 500 μm were etched in a 500-nm-thick Al_2O_3 layer and a 3-μm-thick plasma enhanced chemical vapor deposition (PECVD) SiO_2 cladding layer was deposited. A scanning electron microscope (SEM) image of such a waveguide structure without cladding layer is shown in Fig. 2 (a). By comparing the output of waveguides with four 90° bend sections to the output of straight waveguides of equal length, the additional bending loss was determined and is plotted in Fig. 2 (b). Within the measurement limit, negligible additional losses were measured for bend radii as low as 250 μm, which is consistent with simulated bend-loss values of < 0.01 dB/90°. Such low bend losses demonstrate the potential for densely-integrated low-loss resonator structures, as shown in Fig. 3. In addition to microstructuring, nanostructuring of Al_2O_3 has been investigated using Focused Ion Beam (FIB) milling, and on-chip reflection grating structures have been fabricated in optimized Al_2O_3 waveguides [5].

Characterization of Al_2O_3:Er Layers

Al_2O_3:Er layers were deposited using a metallic Er target and the optimized deposition parameters for low-loss un-doped Al_2O_3 layers. The Er concentration, which was measured using Rutherford Back-Scattering (RBS), is plotted in Fig. 4 (a) as a function of sputtering power applied to the Er target. In Fig. 4 (b), the emission and absorption cross-sections, calculated using the measured emission and absorption spectra of four separate samples with concentrations on the order of 10^{20} cm^{-2} are shown. The typical emission peak with a FWHM of 55 nm around 1533 nm can be observed with absorption and emission cross-sections on the order of 4.0 ± 0.6 x10^{-21} cm^{-2}. Lifetimes of the $^4I_{13/2}$ level of up to 7 ms were measured for Er concentrations around 2 x 10^{20} cm^{-3} where optimized gain can be expected [6].



(a) (b)

Fig. 2. (a) SEM image of a 500-nm-deep etched 1.2-µm-wide Al_2O_3 waveguide; (b) bend loss as a function of bend radius for a 500-nm-thick, 2.0-µm-wide Al_2O_3 channel waveguide.

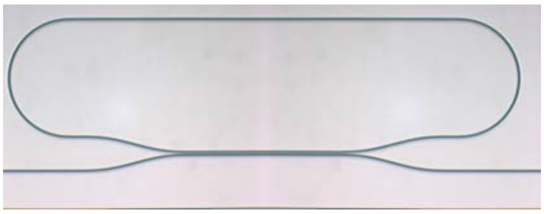
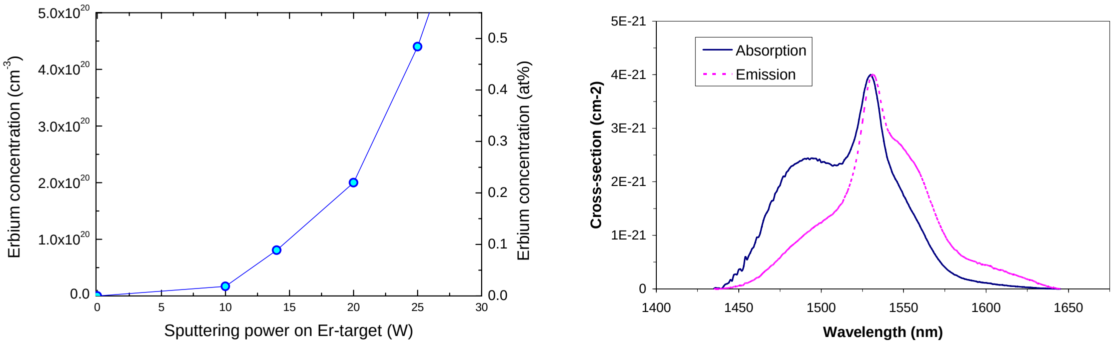


Fig. 3. Resonant structure for on-chip active functions: a micro-fabricated Al_2O_3 racetrack resonator.

In order to characterize the optical gain in the Al_2O_3:Er layers, initially a sample deposited with Er-target sputtering power of 14 W was selected, corresponding to a concentration of 0.09 at% and approximate lifetime of the $^4I_{13/2}$ level of 6.1 ms. Shallow channels of 25 nm, width 8 µm, and length 6.4 cm were etched in the layer to confine both signal and pump light and ensure good overlap of the resulting optical modes. To measure the small signal gain in the layer, 977-nm pump light from a Ti:sapphire source and signal light from a tunable laser source (1480-1600 nm) were coupled in simultaneously via a lens. Pump light and signal light were chopped separately at different frequencies and the signal light was collected and measured using a lock-in amplifier. The gain was determined by measuring the ratio of the amplifier output with pump on and off and the net gain was calculated by subtracting the absorption at the signal wavelength known from the measured absorption spectrum of the sample. The amount of pump power coupled into the waveguide was determined by measuring the output power of the lens at the focal length and calculating the overlap of the minimum beam spot with the simulated optical mode profile in the waveguide. A maximum net gain of 0.7 dB/cm was measured at a pump power of approximately 50 mW, and net gain was measured over a wavelength range of 35 nm. The threshold pump power was determined to be approximately 24 mW. The efficiency and threshold pump power are expected to improve for smaller, higher confinement channel waveguides and a pump wavelength of 1480 nm, and further optimization of the gain by varying the dopant concentration is under investigation.



(a) (b)

Fig. 4. (a) Erbium concentration as a function of Er-target sputtering power and (b) absorption and emission cross-sections of erbium in the resulting Al_2O_3:Er layers.

Conclusions

Reactively co-sputtered Al_2O_3 waveguide layers with optical losses down to 0.11 dB/cm have been reliably grown. Furthermore, microstructuring of high resolution channel waveguides with low propagation and bend losses has been demonstrated in the as-deposited low-loss layers. Active Er ions have been incorporated in the optimized Al_2O_3 layers and a wide emission spectrum (55 nm) and high luminescence lifetime (7 ms) have been realized. A net gain of 0.7 dB/cm was measured at 1533 nm, and net gain was measured over a wavelength range of 35 nm, which, coupled with the low background losses in channel waveguides, demonstrates the feasibility of active devices in the microstructured Al_2O_3:Er layers. Optimization of the net gain and characterization of reflection grating and ring resonator structures useful for tunable microlasers are on-going.

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