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OPTICAL SPECTROSCOPY OF NEODYMIUM-DOPED TANTALUM PENTOXIDE SLAB WAVEGUIDES

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Abstract – *Neodymium doped tantalum pentoxide (Nd:Ta_2O_5) waveguides were fabricated by RF sputtering from a Nd doped Ta_2O_5 target. Waveguide losses, absorption spectra, fluorescence spectra and excited-state lifetime were measured, and show promise for realisation of waveguide lasers.*

INTRODUCTION

Integrated optical waveguides are finding increasing application in telecommunications, sensing and miniature lasers. The production of passive devices such as waveguide splitters and multiplexers is now well-developed [1] and commercialised, and active devices for amplification [2] and lasing [3] are under intense investigation. Devices realised in conventional integrated optics technologies tend to be large, due to large bend radii, and photonic crystal waveguides have the potential for much denser integration [4]. Tantalum pentoxide (Ta_2O_5) is known to be a high-quality optical material that is compatible with silicon technology, may be doped with rare-earth ions [5], has low phonon energy for efficient fluorescence emission [6] and produces low-loss waveguides [7]. It also has a high refractive index (n>2) allowing photonic crystal waveguides to be readily formed. The absorption and fluorescence spectra of crystalline $NdTa_7O_{19}$ have been studied with a view to realising an optically pumped laser [8]. The aim of the present study is to optimise the fabrication of amorphous Nd-doped Ta_2O_5 waveguides and measure their absorption and fluorescence characteristics, to determine their suitability for active integrated optical devices.

EXPERIMENTAL PROCEDURES

Nd doped Ta_2O_5 slab waveguides were deposited onto a thermally-oxidised silicon wafer by radio frequency (RF) magnetron sputtering in a mixed argon/oxygen atmosphere. First, 2.2 μm SiO_2 cladding layers were grown on 4″-diameter p-type Si <100> wafers by thermal oxidisation at a temperature of 1100°C in an O_2 atmosphere. Sputtering conditions were optimized to achieve low losses (<1dB/cm), control of film thickness to ±5% and good uniformity (±5% over the wafer) by adjusting the RF magnetron power density, partial deposition pressure, substrate temperature, Ar/O_2 ratio and gas flow rate. Waveguide losses were optimized using prism coupling and measurement of the decay of the scattered light on a CCD camera. The film index was measured using an ellipsometry and found to be 2.10±0.05 at λ=633nm and film thickness was measured using a reflectance spectroscopy (Nanospecs). The optimised sputter deposition parameters used were: RF magnetron power density of 5 W/cm^2, Ar and O_2 flow rates of 16 and 8 sccm, respectively, chamber pressure of 35mTorr and substrate temperature of 120°C. The Nd:Ta_2O_5 slab waveguides studied here were sputtered from a doped Ta_2O_5 target with a Nd^{3+} concentration of ~2.94×10^{20} ions/cm^3. The final structure consisted of a Nd:Ta_2O_5 core of 1.3μm thickness, on a SiO_2 buffer layer of 2.2μm thickness on a 0.4mm thick silicon wafer. The wafer was then cleaved into several pieces to produce chips with high quality end facets through which light could be end-fire coupled for room temperature absorption and fluorescence measurements. One piece was then

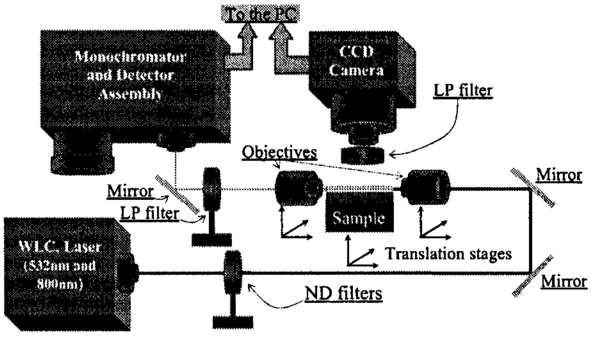

Figure 1: A schematic diagram of basic absorption and FL measurement setup using WLC for absorption, 532nm and 800nm lasers for FL spectra.

annealed at 500°C in oxygen for 48 hours by setting a heating and cooling rate at 2°C/mins to avoid thermal shocking effects.

A schematic representation of the apparatus for spectral measurements is shown in Figure 1. For absorption measurements in the visible and near IR, a TE/TM polarized white-light continuum (WLC), generated using a 800nm femtosecond laser, was launched into an end-facet of a 13.5mm long slab waveguide. The waveguide output was focussed into a monochromator using microscope objective lenses. Fluorescence spectra were measured by optically pumping the sample with lasers at 532nm and 800nm. The same apparatus was also used to measure waveguide loss, using a CCD camera. The excited-state lifetime was measured by modulating the pump and detecting fluorescence on a fast InGaAs photodiode (response time:5ns).

RESULTS AND DISCUSSION

Waveguide loss The waveguide loss was determined at wavelength of 633nm and found to be 2.5±0.5 dB/cm before annealing and 0.9±0.2dB/cm after annealing. It is expected that the loss after annealing is limited by surface roughness, and effect which is increased by the large index contrast in this waveguide and which may be reduced in the future by depositing an appropriate cladding. These loss measurements were again found to be consistent with transmission measurements made using a Ti:sapphire laser tuned off the Nd absorption.

Absorption spectroscopy Figure 2 shows the absorption spectra of an as-deposited Nd:Ta_2O_5 waveguide (TE and TM polarized incident WLC), with examples of Nd:glass and Nd:YVO_4 absorption spectra from the NASA laser database [9] for comparison. At room temperature the absorption spectra of the as-sputtered Nd:Ta_2O_5 slab waveguide shows six broad bands between 400nm and 900nm, mainly centered at 480nm, 523nm, 580nm, 742nm 800nm and 875nm. The absorption spectra did not change significantly after annealing, except for a reduction in the broadband attenuation. Absorption features of Nd:Ta_2O_5 were assigned to transitions from the $^4I_{9/2}$ ground state to the excited states of Nd^{3+} ions. Comparison of the absorption spectrum of the Nd:Ta_2O_5 slab waveguide with that of a Nd:YLF laser crystal and the laser glass shows that the absorption bands are of a similar breadth to the glass, as expected for an amorphous material. The six absorption bands in this wavelength region can be summarized as follows: (a) $^4\mathbf{F}_{3/2}$ (=875.4nm), (b) $^4\mathbf{F}_{5/2}$ (=800nm) + $^2\mathbf{H}_{9/2}$ (=795.3nm) (c)$^4\mathbf{F}_{7/2}$ (=745nm) + $^4\mathbf{S}_{3/2}$ (=738nm) (d) $^2\mathbf{G}_{7/2}$ (=568nm) + $^4\mathbf{G}_{5/2}$ (=588nm) (e) $^4\mathbf{G}_{7/2}$ + $^2\mathbf{K}_{13/2}$(=525nm) (f) $^2\mathbf{G}_{9/2}$ + $^2\mathbf{D}_{3/2}$+ $^4\mathbf{G}_{11/2}$ + $^2\mathbf{K}_{15/2}$(=470-480nm). Some of these bands encompass more than one energy state together with the combination of multiplet energy manifolds and possible energy state splitting due to the influence of the host, and a possible contribution from crystal-field splitting of trivalent Nd clustering in Ta_2O_5 nanocrystallites. Broad absorption bands convey the advantage of relaxing the wavelength tolerance on laser diode pump sources for waveguide lasers. The peak absorption near 800nm is 4.1cm^{-1}, corresponding to an absorption length of approximately 2.5mm and an absorption cross-section of 1.4x$10^{-20}$$cm^2$, assuming that the neodymium concentration in the sputtered film is the same as that in the target. This absorption length was independently confirmed by transmission measurements using a Ti:sapphire laser tuned on and off the Nd absorption bands.

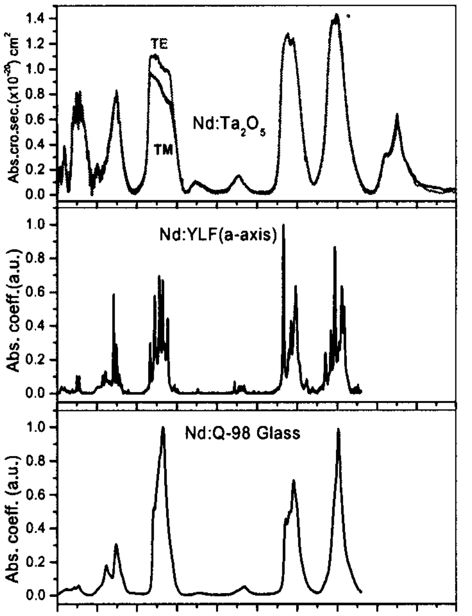

Figure 2: Absorption spectra of Nd:Ta_2O_5 waveguide comparison with those of Nd:YLF and Nd:Glass.

Fluorescence spectroscopy The fluorescence spectrum of an as-deposited Nd:Ta_2O_5 waveguide was measured at room temperature by pumping with laser lines at wavelengths of both 532nm and 800nm, by end-fire-coupling the laser beam into the waveguide using cylindrical and objective lenses. The normalised fluorescence spectra are given in Figure 3, showing transitions from the meta-stable $^4\mathbf{F}_{3/2}$ state to the states $^4\mathbf{I}_J$ (J=9/2, 11/2 and 13/2), centred at 910nm, 1064nm and 1340nm respectively. The main figure shows each peak normalised separately, while the inset shows the spectra normalised to the maximum peak at 1064nm. The fluorescence spectra were observed to be similar for both pump wavelengths and for several launched powers of up to 670mW for 532nm pumping and up to 100mW for 800nm pumping.

Excited-state lifetime The excited-state fluorescence lifetime was determined for pumping at 532nm and was found to be $\tau=(33\pm7)\mu s$ with a dispersion factor of 1.23 before annealing and $\tau=(67\pm7)\mu s$ with a dispersion factor of 0.90 after annealing, where the fluorescence decays have been fitted to a stretched exponential of $\exp[-(t/\tau)^{\beta}]$. Longer annealing may further improve the lifetime. A lifetime of 67μs at 1064nm for annealed waveguide is much shorter than in silicate glasses of similar Nd concentration, but similar to some Nd-doped chalcogenide glasses which have substantially higher refractive indices [10]. At this concentration, the Nd:Ta_2O_5 films may possibly be exhibiting significant concentration quenching, so that the concentration may benefit from further optimization.

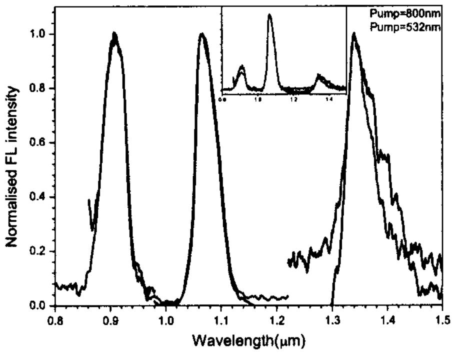

Figure 3: Normalized fluorescence intensities from Nd^{3+} ions in Ta_2O_5 under 532nm and 800nm pumping. Inset shows spectra normalized to the emission peak at 1064nm.

CONCLUSIONS

Neodymium-doped tantalum pentoxide waveguides have been fabricated by a reactively RF magnetron sputtering onto an oxidized silicon wafer from a Nd-doped Ta_2O_5 target in a mixed Ar/O_2 atmosphere. Annealing the waveguides in oxygen at 500°C reduced the broadband losses to below 1dB/cm. The waveguide absorption spectra have been measured and show the normal spectral features of any Nd-doped host, with the broadbands expected in an amorphous material. The peak absorption cross-section has been determined and found to be 1.4×10^{-20} cm^2 at 800nm, which is comparable with other amorphous materials. The fluorescence spectra and lifetimes have also been measured between 800nm and 1500nm and show three emission bands, at 910nm, 1064nm and 1340nm. The lifetime of the excited state was found to be around 33μs before annealing and approximately 67μs after annealing, the latter being similar to that of many Nd-doped chalcogenide glasses, for example. It is expected that further optimization of the Nd concentration and the annealing conditions will further improve the lifetime. This waveguide material shows considerable promise for realization of compact waveguide lasers and hold promise for integration with photonic crystal structures.

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