HIGH-INDEX CONTRAST WAVEGUIDES FOR MICROPARTICLE GUIDANCE

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Abstract: Design, fabrication and optimization of high refractive-index contrast Tantalum Pentoxide (Ta_2O_5) nanoscale waveguides are reported. The strong evanescent field in such nanoscale (150nm-250nm thick) and high-refractive index contrast (Δn ~0.65) waveguides provide an ideal integrated platform for cell/micro-particle guiding, sorting and diagnosis applications. Optical guiding velocity of 50 µm/sec was obtained for 8 µm micro-particle with guided power of only 20mW.

1. INTRODUCTION

The capability of optical fields to exert a mechanical force on mass was demonstrated experimentally by Beth [1] even before the discovery of the laser. The drive to non-invasively and microscopically guide and sort micro-particles and cells en-masse led to the investigation of optical waveguides as an integrated platform [2-5] contrasting with optical tweezers [5]. In this paper we report the fabrication of high-refractive index contrast Ta_2O_5 waveguides (Δn ~0.65) of nanoscale thickness (150nm-250 nm) for applications in optical guiding. The high index contrast of Ta_2O_5 waveguides together with their optimum nanoscale thickness (~200nm without any cladding) provides considerable power in the evanescent wave for efficient and fast propulsion of large micro-particles and biological cells (10-20 µm).

2. FABRICATION AND OPTIMIZATION

Ta_2O_5 is compatible with conventional silicon technology enabling its efficient and simple processing. To investigate particle guiding using tantala, different designs of Ta_2O_5 waveguides (rib and strip) were fabricated to compare their potential for optical guiding of particles. A strip waveguide provides the maximum evanescent surface intensity and a rib structure maintains the single mode nature for larger dimensions [6]. This is more crucial for thinner Ta_2O_5 waveguides (~200nm thickness) with high-refractive index contrast (Δn ~0.65), as single mode guidance in such strip waveguides is limited only to waveguides of width 2~2.5 µm. Thus employing a rib structure it is feasible to extend single mode conditions [6]. It has also been reported that with tantala waveguides, the highest surface intensity (evanescent waves) was achieved in the range of 150-250 nm for 633nm wavelength [7]. Consequently, a) fully-etched strip waveguides of thickness (*t*) (150 nm<*t*<250 nm) and width (1 µm< *w*<10 µm) and b) rib waveguides of identical dimensions with etch depth varying from 60 nm to 140 nm were fabricated to allow comparison of the potential of these two designs for particle guidance. For the sake of comparison the total thickness of the two designs reported here are chosen to be 200 nm (H=h +r) and for the ribs the etch depth (r) was chosen to be 60nm as shown in Figure 1.

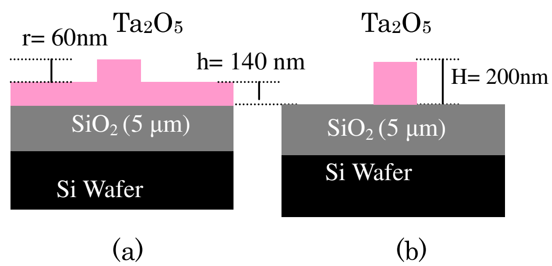

Figure1 Design of Ta_2O_5 a) rib and b) strip waveguides of thickness 200nm.

Ta_2O_5 was deposited using magnetron sputtering on an oxidised silicon substrate (oxide thickness 5 µm) in a vacuum chamber pumped to a base pressure of 10^{-8} Torr. In order to have optically good as-deposited films it is necessary to optimise the sputtering conditions. The parameters optimised for the deposition were the substrate temperature, magnetron power and the oxygen gas flow rate. This optimisation was performed by initially varying the substrate temperature and fixing the other parameters at a reasonable value. The losses were measured after each deposition and the value that gave the lowest loss and a reasonable deposition rate was used to optimise the following parameter. The optimum sputtering conditions to yield low loss thin films were achieved at 200° C substrate temperature, magnetron power of 300 W, Oxygen (O_2) and Argon (Ar) flow rates of 5 sccm and 20 sccm respectively. Under these optimized conditions the slab waveguides exhibited a low loss of 0.4 dB/cm at a wavelength of 633 nm, without annealing [8]. The refractive index of the deposited Ta_2O_5 slab waveguides was found to be 2.092 at a wavelength of 1064 nm, using ellipsometry.

Conventional photolithography followed by ion-beam milling was employed to realise the rib and strip waveguides. For the photolithography, S1813 photoresist was spin coated at 3500 rpm and soft baked at 90 ˚C for 30 minutes. This was followed by a 5 seconds exposure to the UV lamp in the mask aligner. Then the sample was developed in MF319 developer for 40 seconds and finally hard baked at 120 ˚C for 30 minutes. This defined the channels and the mask for ion-beam milling. Ion-beam milling was performed with the following parameters: Ar gas flow 6 sscm, beam current 100 mA, beam voltage 500V and RF power 500 W. It was found that ion-beam milling done at an angle of 45 degrees (sample with respect to the incident ion beam) in contrast to the conventional zero degree angle and uniformly rotated at a speed of 5 rpm reduced the side-wall roughness of channel waveguides considerably. Fig 2 shows scanning electron microscope images highlighting the difference in the sidewalls of waveguides etched at 0 and 45 degrees respectively. Finally, the samples were treated with plasma-ashing (treatment with oxygen in plasma) for 10 minutes to remove any remaining photoresist to yield smooth rib/strip waveguides.

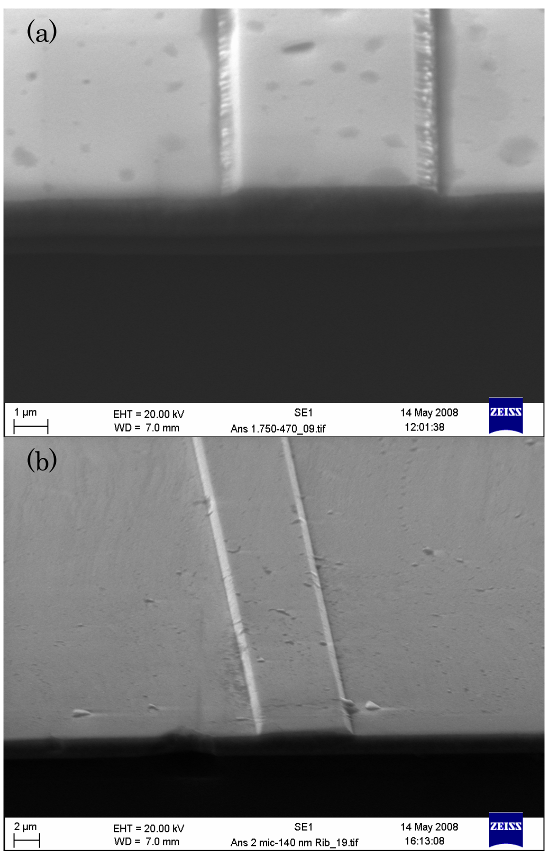

Figure 2 SEM images of waveguides fabricated after Ion Beam Milling at (a) 0 degree with significant sidewall roughness and (b) 45 degrees.

Loss measurements on these waveguides yielded an insertion loss (sum of propagation and coupling losses) in the range of 25-35 dB for unannealed samples, as shown in Fig. 3. The large losses observed were mainly due to the propagation losses of the unannealed samples. In order to reduce the losses, samples (rib and strip waveguides) were annealed at 600 °C in oxygen in a tube furnace for 2-5 hours. Annealing helps in removing the stress built up in the waveguides due to various processes like deposition, etching etc. and in filling oxygen deficiencies to reduce losses. For waveguides of thickness ~200 nm it is crucial to employ higher N.A. objective lens to decrease the coupling loss thus IR coated objective lens of 0.9 N.A. (80 X) was employed to tightly focus the light into the waveguides. Post-annealing significantly reduced the insertion loss to 7-15 dB (propagation loss <1 dB/cm) for both the rib and strip waveguides, as shown in Figure 3. It is also clear from Fig 3 that the annealing time plays an important role in bringing down the propagation losses and can significantly influence the optical guided power and optical guiding of micro-particles. The sample annealed for 5 hours exhibits a slight improvement on insertion loss as compared to the sample annealed for 2 hours. It can also be seen that for wider waveguides (width 8-10 µm) the insertion loss is in range of 6-12 dB (for annealed samples) and for smaller width (1-3 µm) the losses are in range of 15-20 dB which is mainly due to higher coupling loss for narrower waveguides. Figure 4 compares the insertion loss of rib and strip waveguides. It is evident from Figure 4 that both rib and strip waveguides (of identical dimensions) are similar as far as guiding power and optical losses are concerned.

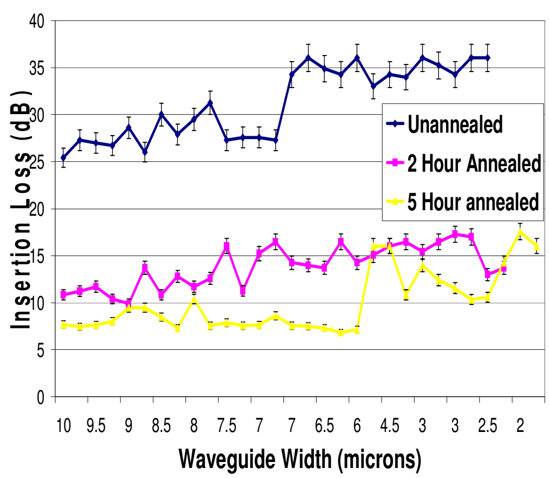

Figure 3 Insertion loss vs width for strip waveguides annealed for different times.

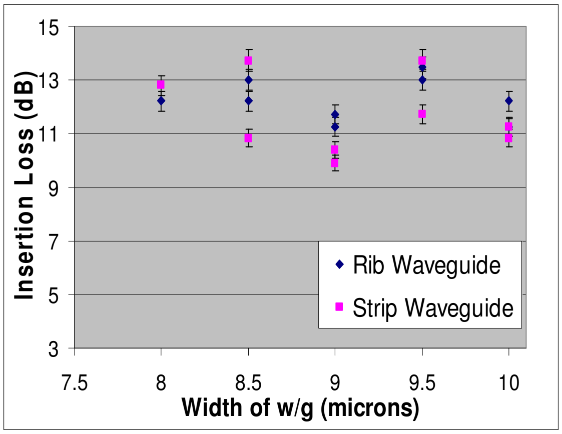

Figure 4 Insertion losses of rib and strip waveguides

3. OPTICAL GUIDING

Optimized low-loss Ta_2O_5 waveguides annealed for 2-5 hours a) rib waveguide and b) strip waveguides were employed for optical guiding experiments (parameters as shown in Figure 1). The experimental apparatus for optical guidance consists of 5 W Single Mode CW Ytterbium fiber laser @1070 nm and light was coupled into nanoscale-waveguides employing an objective lens coated for IR wavelengths (Nachet 0.9 N.A 80X). The output light from waveguide was collected with 10X objective lens. Another 10X objective lens and cooled CCD camera (QImaging) attached to a microscope were employed to capture image. Polystyrene particles (refractive index 1.59, Polyscience Europe) of diameter 8 µm were used.

Rib and strip waveguides of identical dimensions, annealed for similar times, and with similar losses were compared for their capability of guiding micro-particles. Preliminary results showed that the rib waveguides were less efficient in propelling micro-particles as compared with strip waveguides even with equal guided power, suggesting that the surface intensity on rib waveguides is not as strong as on strip waveguides for the chosen parameters. Optical guiding velocities on rib waveguides were found to be lower by a factor of 8-10 than those on strip waveguides for identical guided power. Thus strip waveguides were employed for the remaining experiments.

As described earlier, coupling loss is a significant contributor to insertion loss for narrower waveguides (1-3 µm wide) compared with wider waveguides (6-10 µm) thus for a given input power the guided power and the optical guiding forces on micro-particle over waveguides of varying width is different. It is thus imperative to study in detail the optical guiding velocity of a micro-particle (of same diameter) over waveguide of different widths in terms of both input and output power. Such knowledge of difference in optical guiding velocity for micro-particles (or difference on force exerted on particles) over varying widths of waveguide for different power (input and guided) is useful in sorting micro-particles based on optical fractionalization [9] techniques in presence of an additional force such as that associated with flow [10].

Figures 5 and 6 show the results for optical guiding of 8 µm particles on 200nm thick Ta_2O_5 waveguides annealed for 2 hours. The maximum velocity for the 8 µm microparticle was found to be 50 µm/sec for a guided power of only 20mW on a waveguide of ~ 8 µm width. The optical guidance velocity also increased with increased input or guided power (output power) as shown in Figures 5 and 6. Investigation on the propulsion of micro-particles of different diameters on different widths of waveguide is presently being studied. It is believed that the maximum guidance velocity of the particle will be achieved when its diameter is comparable to the spot size of the guided light. The study and comparison of guided mode with the guiding velocity over different width of waveguide will be carried out in future.

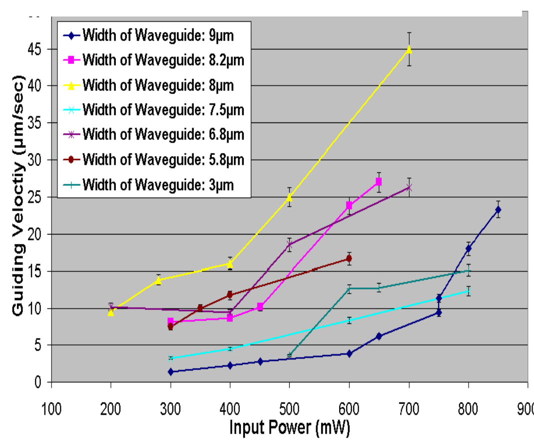

Figure 5 Variation of guidance velocity with input power for 8 µm particles on Ta_2O_5 waveguides of different widths.

The result reported above is the highest optical guiding velocity reported so far for micro-particles, to the best of our knowledge. Table 1 compares various optical guiding results in the literature [3, 4, 10]. The authors in Ref. 3 employed Cs^+ ion-exchange waveguide (Δn=0.03) with waveguide insertion losses of 8 dB. The authors in Ref. 4 employed silicon nitride waveguides of (Δn=0.52) with waveguide coupling loss of 10 dB and propagation loss of 2 dB/cm. The authors in Ref. 10 employed SU-8 polymer waveguides (Δn=0.101) with waveguide coupling loss of 5 dB and propagation loss of 1.3 dB/cm. It should be noted that direct comparison is difficult as the work reported in Ref. 3 and 4 were on particles of different dimensions. However the efficiency of Ta_2O_5 waveguides for guiding micro-particles in terms of both the input and guided (output) power can still be easily observed. The optimization of Ta_2O_5 waveguides plays a crucial role in enabling such high velocity propulsion of microparticles.

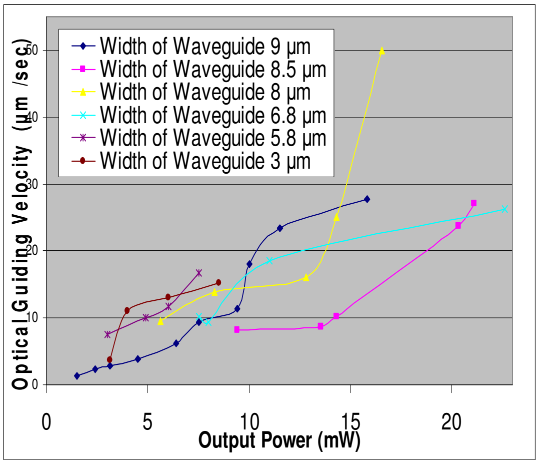

Figure 6 Variation of guidance velocity with output power for 8 µm particles on Ta_2O_5 waveguides of different widths.

Table 1 Comparison of optical guiding of micro-particles as reported by the authors

Ref.	Max. Velocity	I/P Power	O/P Power	Particle Dia.	Width W/G
3	33 µm/s	870 mW	?	10 µm	2.5 µm
4	15 µm/s	?	20 mW	2 µm	2 µm
10	28 µm/s	?	53.5 mW	3 µm	2.8 µm
Ta_2O_5	**50 µm/s**	**700 mW**	**20 mW**	**8 µm**	**~8 µm**

4. CONCLUSION

The optimization and fabrication of low-loss, nanoscale high-index contrast Ta_2O_5 waveguide has been demonstrated. The optimized Ta_2O_5 waveguide has been employed for efficient guiding of micro-particles and maximum optical guidance velocity of 50 µm/sec was obtained for a 8 µm microparticle with a guided power of only 20mW. Due to the high refractive index contrast and nanoscale dimensions Ta_2O_5 waveguides possess high surface intensity in their evanescent waves and are capable of imparting a large optical force on micro-particles near their surfaces. The greater surface intensity and optical force at the waveguide surface is necessary for propelling, sensing and sorting large diameter cells (for example TERA1 cells with diameter ~20 µm) which have a lower refractive index (~1.35) in a suitable environment, for example in DMEM (Dulbecco's Modified Eagle's Medium) which is more viscous than water. It is believed that Ta_2O_5 waveguides are excellent candidates for investigating propulsion and sorting of biological cells.

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