Towards the Photonic Integration of Titanium Dioxide-on-Silicon for Datacom and Telecom Application

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Photonics have been identified as a solution to meet the growing demand of huge data traffic due to its high bandwidth and fast signal processing ability. Most current photonic materials including Silicon, Silica, Silicon Nitride, III-V semiconductors etc. suffer from a variety of limiting factors. Nearly all of these material platforms address 1.5 µm telecom band exclusively, and neglect wavelengths around 1300 nm as well as interconnect band around 800 to 900 nm. Therefore, we present Titanium Dioxide - TiO_2 as a novel photonic material for broadband operation for low cost and low power consumption optical data center and telecom networks. Design of photonic integrated circuit building blocks, such as single mode polarization independent waveguide and grating coupler based on TiO_2 material, is presented. The novel photonic integrated circuits enable novel disaggregate and scalable optical data center architectures as well as dynamic metro access switching nodes with edge computing functionalities; and TiO_2 can be the promising candidate in this field.

Introduction

Advancement in nanofabrication techniques have resulted in demonstrations of a variety of photonic integrated devices for applications spanning from optical communications to biosensors. Significant attention has been paid to silicon photonics due to the high refractive index of silicon and well-established manufacturing technology. The use of a nanoscale waveguide made in a material with a high index contrast is essential when compact devices with tight mode confinement are needed. This is important, for example, in devices exploiting the third order optical nonlinearity and in biosensors based on slot-waveguides.

Silicon is the most common material for nanoscale waveguides with low propagation losses of about 2.5 dB/cm [1]. However, silicon is not transparent below 1.1 µm due to its low bandgap. This eliminates the possibility of silicon's use at datacom and visible wavelengths. In addition, two-photon absorption (TPA) in silicon at telecommunication wavelengths limits its applicability in non-linear devices. These facts have led to the search of high-index photonic materials that will be ultra-broadband transparent from visible to infrared wavelengths, and possess large enough nonlinearity, while not suffering from TPA. For instance, significant amount of research has been carried out on Silicon nitride (Si_3N_4) as a broadband material and the propagation losses around 1-2 dB/cm have been reported at the expense of lateral and/or vertical confinement [2].

However, Titanium Dioxide (TiO_2) has recently attracted increasing attention and is emerging as an alternative material for photonic integrated circuits. Several reasons are attributed to this, such as TiO_2 is a cost efficient material due to its abundance in nature, it has a high refractive index varying from 2.12 - 2.76 at 1.55 µm depending on deposition techniques [3], it is transparent from visible to mid-infrared wavelengths due to its large bandgap (Eg ≥ 3.1 eV) [3]. As mentioned, materials with a high refractive index used in integrated optical applications allow a greater index contrast at the core/cladding interface, which naturally leads to better light confinement and guiding properties. In addition, the negligible TPA and large enough third order nonlinearity combined with the tight mode confinement makes TiO_2 a promising material for nonlinear integrated optical devices [4]. TiO_2 is also regarded as a CMOS compatible material [3].

TiO_2 has some important advantages that makes it compete with silicon, silica and silicon nitride for certain applications. Compared to silicon, TiO_2 is a broadband material. Hence, it is more suitable for sensing & novel solid-state lighting applications at visible wavelength and datacom applications at 850 μm. Although the refractive index contrast in TiO_2 is not as high as with silicon. This results in notable reduction of scattering losses. Moreover, the lower index contrast makes the resulting devices more tolerant to fabrication imperfections. Compared to Si_3N_4, TiO_2 also presents several advantages. Such as, it is possible to deposit at lower temperature and it exhibits lower stress constraints for films with thickness over wavelengths of 250 nm. Furthermore, it is important to note that TiO_2 possess a higher linear refractive index than both Si_3N_4 - 2.05 and silica (SiO_2) - 1.45 resulting strong light confinement which allows high density of integration.

Low-loss amorphous titanium dioxide strip waveguides have already been introduced by some researchers [4]. The waveguides were fabricated by the combination of atomic layer deposition (ALD), electron beam lithography (EBL), and reactive ion etching (RIE). Propagation losses of the strip waveguides were found as low as 5.0 dB/cm at 1.55 μm wavelength. According to the researchers, those propagation losses are mostly due to the sidewall roughness of the waveguides that is caused by lithography process. Then the losses were further reduced to 2.4 dB/cm by deposition of an additional layer of TiO2 using ALD [4]. Studies on resonators based on TiO_2 have been reported in visible spectrum and C band to characterize its negative thermo optic coefficient and non-linear property respectively [5–6].

In this paper, we present a polarization independent single mode waveguide which allows a high level of integration, and a grating coupler for fiber-to-chip vertical coupling.

Fiber-to-chip coupling is a critical aspect of any photonic integrated circuit and despite offering a comparatively lower coupling and bandwidth, surface gratings are generally preferred to facilitate fiber to waveguide coupling, owing to ease of fabrication, compact size, wafer-level testing capability, relaxed alignment tolerances and no requirements for polishing facets.

Single Mode Polarization Independent Waveguide

The geometry of the single mode polarization independent waveguide is shown in Fig. 1(a). The thickness and width of the guiding section of the rib waveguide are 0.6 μm and 0.8 μm respectively. The slab thickness of the rib is 50 nm.

The mode profiles for both fundamental TE and TM mode are shown in Fig. 1(b) at wavelength of 1.55 μm. The Fig. 1(c)-(d) show the simulations based on etch depth and waveguide width variation to find out the modes excited after fabrication. Figure 1(c) shows that minimum 500 nm need to be etched to obtain a single mode polarization independent waveguide. The waveguide remains single mode and polarization independent beyond 500 nm etch depth. Figure 1(d) shows that the waveguide remains

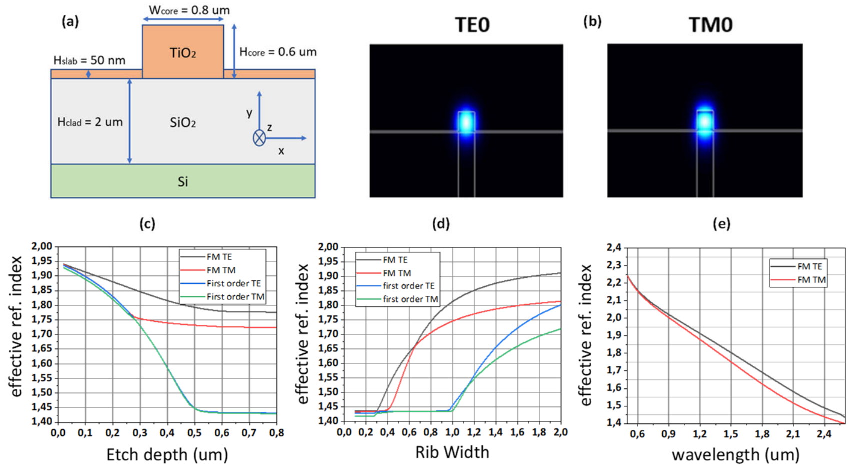

Fig. 1: (a) schematic representation of the waveguide cross section; (b) mode profile of Fundamental TE and TM mode; effective refractive index as a function of (c) etch depth, (d) rib width and (e) wavelength

single mode when the width of the rib is between 0.35 µm and 1 µm. The waveguide becomes multimode beyond 1 µm of rib width. The rib width of the waveguide needs to be between 0.7 µm till 0.975 µm to maintain the single mode polarization independent condition.

The effective refractive indices of the fundamental TE and TM mode are plotted as function of wavelength in Fig. 1(e). The cut off wavelengths for both TE and TM modes are 2.5 µm and 2.3 µm respectively meaning they are no longer guided after these wavelengths. Therefore, both the TE and TM modes are guided from 0.5 to 2.3 µm wavelength range highlighting TiO_2's broadband characteristic.

Grating Coupler

The design parameters of the grating coupler were initially estimated using the basic Bragg condition, and later for modeling and optimization of the device, we used two-dimensional (2D) finite difference time domain method (FDTD) using the commercial software Lumerical [7]. Main parameters to be considered here for optimization of grating couplers are grating period, fill factor, grating etch and inclination angle of source or fiber.

$$\Lambda = \frac{\lambda}{n_{eff} - n_c sin\theta} \quad ; \quad n_{eff} = ff \,.\, n_{eff1} + (1 - ff)\, n_{eff2}$$

where, Λ is grating period, n_{eff} is the effective grating index, n_c is the cladding index, and θ is the fiber inclination angle, ff is the fill factor defined as the ratio of the grating teeth

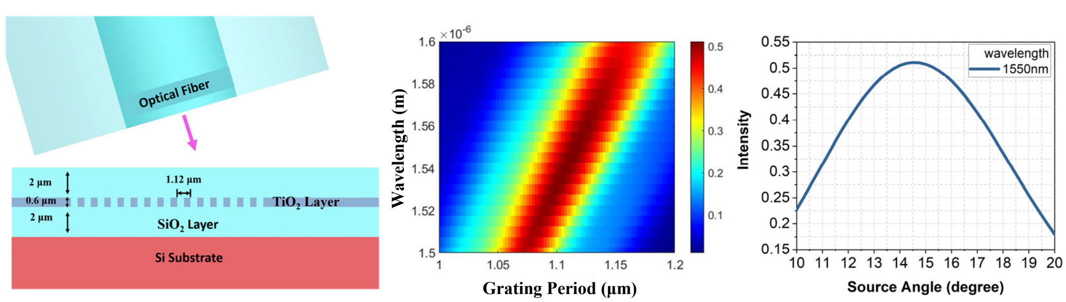

Fig. 2: (a) schematic lateral view of TiO_2 grating coupler; (b) coupling efficiency in terms of grating period and wavelength; (c) coupling efficiency as a function of source angle

to the period, n_{eff1} and n_{eff2} are the effective refractive indices of the fundamental mode for the TiO_2 slab and etched regions respectively.

The grating coupler is designed for single mode coupling of 1.55 μm wavelength, where the thickness of 0.6 μm TiO_2 gratings are buried in 2 μm top and 2 μm bottom SiO_2 layer grown on Si substrate. The slots of gratings were completely etched. The optimized grating period is 1.12 μm with the fill factor of 0.51. The number of grating was taken 14 for the targeted grating region of approximately 15 μm. For the desired light wavelength of 1.55 μm, 50% coupling efficiency can be achieved with this design keeping the angle of fiber inclination 14.5°.

Fig. 1b shows a significant conclusive message about the device. By varying and optimizing the grating period keeping all other parameters same, around 50% coupling efficiency can be achieved with any wavelength ranging from 1500 to 1600 nm with almost the same fabrication tolerances, which indicates the possibility of wide range of applications for TiO_2 based PICs.

Conclusion

Titanium Dioxide is very promising as a broadband photonic material for linear and nonlinear applications due to its unique material properties. The design of single mode, polarization independent and broadband TiO_2 waveguide have been discussed. A TiO_2 based grating coupler with 50% coupling efficiency has been presented and analyzed. This grating coupler facilitates coupling of light to TiO_2 waveguides including wafer level testing, hence widens the research field of integrated PIC based on TiO_2. Currently, fabrication work is going on to realize broadband PICs with TiO_2.

Acknowledgements

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References

[1] H. Cai and A. W. Poon, "Optical trapping of microparticles using silicon nitride waveguide junctions and taperedwaveguide junctions on an optofluidic chip," Lab Chip 12(19), 3803–3809 (2012).

[2] L. Soldano and E. Pennings, "Optical multi-mode interference devices based on self-imaging: principles and applications," J. Lightwave Technol. 13, 615–627 (1995).

[3] Jan Kischkat, Sven Peters, Bernd Gruska, Mykhaylo Semtsiv, Mikaela Chashnikova, Matthias Klinkmüller, Oliana Fedosenko, Stephan Machulik, Anna Aleksandrova, Gregorii Monastyrskyi, Yuri Flores, and W. Ted Masselink, "Mid-infrared optical properties of thin films of aluminum oxide, titanium dioxide, silicon dioxide, aluminum nitride, and silicon nitride," Appl. Opt. 51, 6789-6798 (2012).

[4] M. Häyrinen et al., "Low-Loss Titanium Dioxide Strip Waveguides Fabricated by Atomic Layer Deposition," in Journal of Lightwave Technology, vol. 32, no. 2, pp. 208-212, Jan.15, 2014.

[5] Jonathan D. B. Bradley, Christopher C. Evans, Jennifer T. Choy, Orad Reshef, Parag B. Deotare, François Parsy, Katherine C. Phillips, Marko Lončar, and Eric Mazur, "Submicrometer-wide amorphous and polycrystalline anatase TiO_2 waveguides for microphotonic devices," Opt. Express 20, 23821-23831 (2012)

[6] Orad Reshef, Katia Shtyrkova, Michael G. Moebius, Sarah Griesse-Nascimento, Steven Spector, Christopher C. Evans, Erich Ippen, and Eric Mazur, "Polycrystalline anatase titanium dioxide microring resonators with negative thermo-optic coefficient," J. Opt. Soc. Am. B 32, 2288-2293 (2015)

[7] Lumerical Inc. https://www.lumerical.com/products.