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1. Introduction

Flexible integrated photonics is a new technology which only started to burgeon in the past few years, opening up emerging applications ranging from flexible optical interconnects to conformal sensors on biological tissues. One of the most important factors dictating the performance of these flexible devices is the material choice. Organic polymers are generally considered to be compatible with flexible substrates. However, the low refractive indices of polymers (compared to semiconductors) cannot provide the strong optical confinement necessary for compact photonic integration. Besides polymers, semiconductor NanoMembranes (NMs), thin slices of single crystal semiconductors with sub-micron thickness, are being actively pursued for photonic device integration on flexible substrates. Unlike their rigid bulk counterparts, NMs can be tightly bent

without cracking, since surface strain induced by bending linearly scales with the membrane thickness. To make photonic devices, NMs structures are usually first patterned on a rigid substrate such as silicon. The fabricated structures are then picked up by a PDMS rubber stamp and transferred onto the final flexible substrate. This multi-step hybrid process limits processing yield and throughput. Therefore, we turned to amorphous glasses – the material of choice for optics given their exceptionally low optical attenuation. In flexible photonics, using these non-crystalline materials also enables a monolithic fabrication route as they can be directly deposited onto flexible substrates without resorting to epitaxial growth. Specifically, we focus on chalcogenide glass materials and amorphous TiO_2, as both can be deposited at relatively low temperature (250 °C or less) compatible with flexible substrate integration [1-5].

2. Chalcogenide glasses for 2.5-D photonic integration on flexible substrates

Chalcogenide glasses (ChGs) are amorphous semiconductors containing one or multiple chalcogen elements, namely sulfur (S), selenium (Se), and/or tellurium (Te). Their extraordinary infrared (IR) transparency has made them popular materials for infrared optical components such as IR windows, lenses, optical fibers and coatings. Phase change memories, all-optical signal processing, chem-bio sensing as well as on-chip light switching and modulation are other emerging applications where ChGs are playing an important role [6]. By incorporating a multi-neutral-axis mechanical design, we were able to demonstrate low-loss, robust photonic devices on flexible polymer substrates capable of sustaining repeated bending down to sub-millimeter radius despite the intrinsic fragility of ChG materials [2].

In addition to their exceptional optical properties, ChGs also boast extreme processing versatility, as they can be monolithically deposited on virtually any technically important substrate and can be shaped into functional device forms via traditional lithography or a variety of soft lithographic methods including molding, imprint, and ink jet printing [7]. Therefore, ChGs are uniquely poised for 2.5-D photonic integration, which refers to vertical stacking of photonic devices in multiple layers.

Indeed, prior work have shown that ChGs can be readily form planar multi-layers (e.g. Bragg mirrors) via sequential thin film deposition [8]. We extend the process to stacking of patterned photonic device by introducing a planarization step between film depositions. In the process, a polymer layer spin-coated on top of patterned ChG films is first thermally annealed to allow the polymer to flow and planarize the surface before cross-linking, thereby facilitating subsequent deposition and patterning steps. Using the techniques, we have demonstrated an array of multi-layer photonic components on flexible substrates such as vertically stacked optical resonant filters, an overpass structure for waveguide crossings and a woodpile photonic crystal (Fig. 1a) [2]. Recently we have further shown that the approach is also applicable to integration of active optoelectronic components with passive glass photonics. Fig. 1b shows a top-view SEM image of a ChG waveguide integrated with an adhesive-bonded semiconductor nanomembrane

photodetector, and Fig. 1c plots the measured photocurrent as a function of guided power in the waveguides. Compared to traditional photodetectors which only capture free space illumination, the much smaller optical mode volume enabled by waveguide integration underlies the much larger (and potentially much faster) optical response in these detectors. These results open up exciting applications where ChGs can be seamlessly integrated with other optical materials to enable unconventional functionalities.

3. Foldable and cytocompatible sol-gel TiO$_2$ photonics

Sol-gel TiO$_2$ is the other amorphous material we investigated for flexible photonic integration. Besides sharing the same processing advantages such as low-temperature deposition and ease of integration as ChGs, TiO$_2$ is particularly attractive for biophotonic applications since it is generally considered biocompatible and has been used in dental fillers, cosmetic products, and artificial bone scaffolds.

In our work, amorphous TiO$_2$ films were deposited using an organic-free sol-gel process. SEM image shown in Fig. 2c indicates the uniformity and a smooth surface of the sol-gel coated TiO$_2$ thin film. A critical parameter in determining the TiO$_2$ film quality is the post-deposition annealing temperature. As is shown in Figs. 2a and 2b, increasing annealing temperature contributes to removal of chemical residues and reduction of parasitic optical absorption. However, annealing at above 250 °C results in partial crystallization which leads to optical scattering by crystalline grains. TiO$_2$ films annealed at 250 °C feature a uniform and smooth surface (Fig. 2c) and a relatively low optical loss of 3 dB/cm suitable for photonic integration. Using the sol-gel technique and plasma etching, we fabricated and tested TiO$_2$ optical waveguides and resonators monolithically integrated on flexible polymer substrates (Fig. 2d). In the same vein as ChG flexible photonics, the multi-neutral-axis design renders the TiO$_2$ devices extremely flexible: fabricated TiO$_2$ waveguides can even be repeatedly folded in half without introducing measurable optical degradation (Fig. 2e). We further validated cytocompatibility of these TiO$_2$ devices through *in vitro* cell viability tests (Fig. 2f), which shows that Human mesenchymal stem cells (hMSCs) cultured on the TiO$_2$ devices exhibited the same level of metabolic activity as those grown on a reference cell culturing plate. Building on these results, our ongoing work now focus on integrating TiO$_2$ flexible photonic sensors with biological tissue engineering platforms to enable real-time monitoring of cell growth processes [1].

4. Summary

Compared to epitaxy which is mandated for growing traditional optical crystal materials, processing of amorphous thin films is far more forgiving. Consequently, they can be readily mated with other functional materials to create composite structures possessing unique properties not accessible to glasses alone. Here we have demonstrated that integration of amorphous chalcogenides and TiO$_2$ on polymers can enable photonic devices with exceptional mechanical flexibility. On the other hand, integration of glasses with semiconductor NMs enables full active-

passive integration towards realizing standalone flexible "system-on-a-chip" photonic platforms. These are certainly just two cases exemplifying the universal multi-material photonic integration paradigm, in which we foresee that amorphous thin films will continue to play a pivotal role.
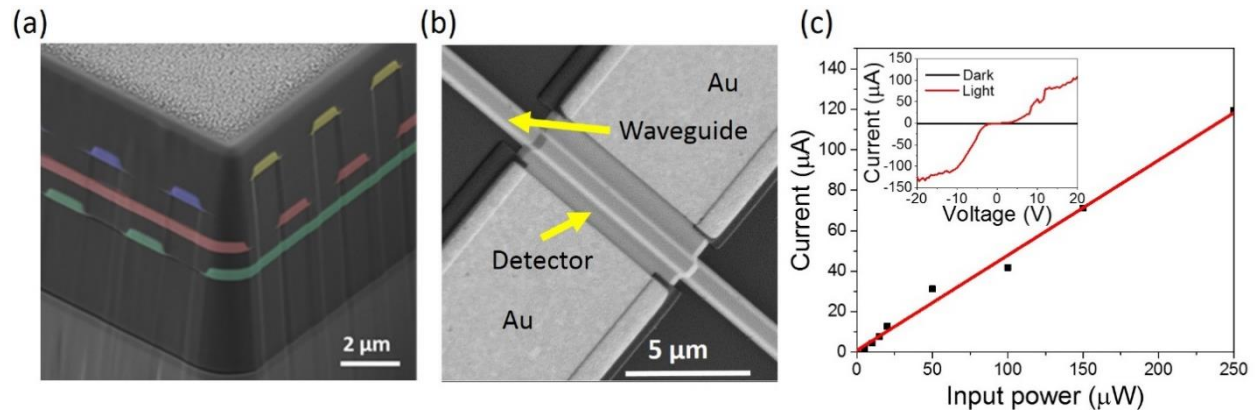

Figure 1. (a) Tilted focused ion beam scanning electron microscopy view of a multi-layer woodpile photonic crystal (before delamination from the silicon handler substrate) where the colors indicate different layers (image courtesy of [2]). (b) SEM image of a chalcogenide glass waveguide integrated photodetector. (c) Measured photocurrent of the photodetector as a function of waveguided optical power at 1550 nm wavelength; inset: I-V characteristics of the detector in dark and at 250 µW input optical power.
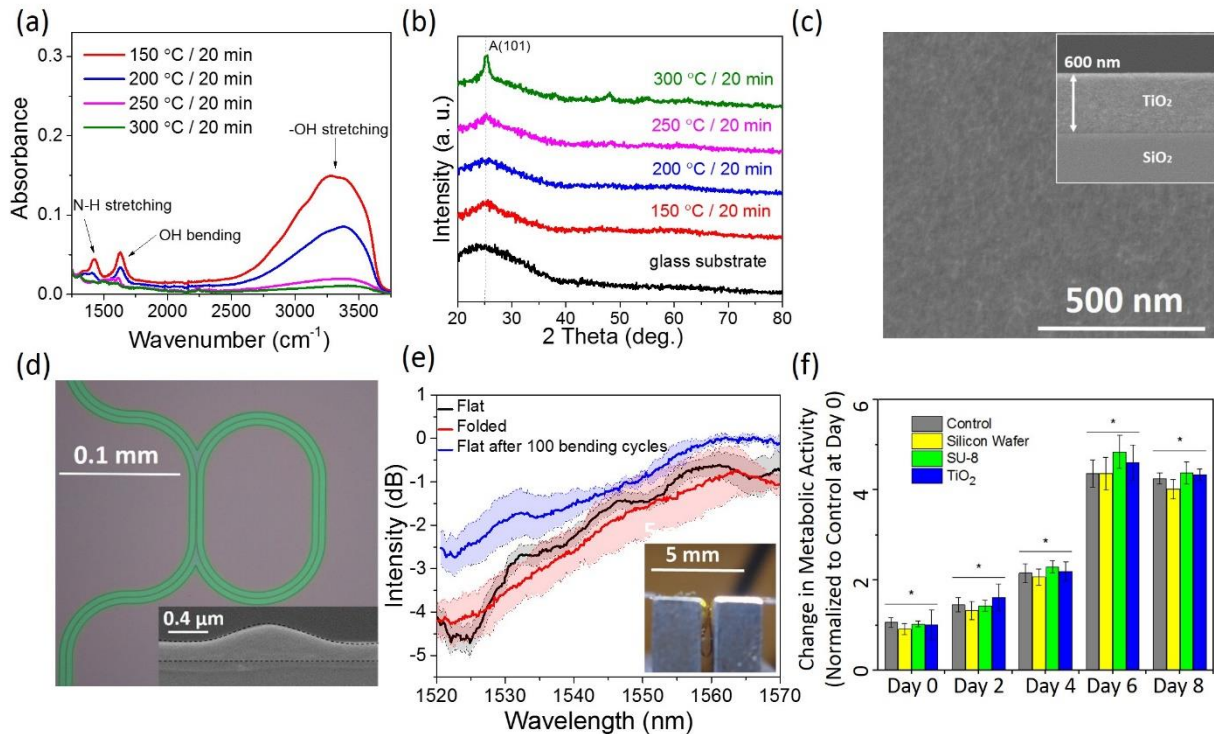
Figure 2. (a) Infrared spectra and (b) X-ray diffraction spectra of sol-gel TiO$_2$ thin films annealed at different temperatures. The arrows indicate (a) characteristic optical absorption bands of chemical residues; and (b) the diffraction peak of the anatase phase. (c) Top-view SEM image of a TiO$_2$ film annealed at 250 °C; inset: film cross-section. (d) Optical microscope top-view image of a TiO$_2$ racetrack micro-resonator. The inset shows the cross-sectional SEM image of the waveguide. (e) Normalized optical transmission spectra of a flexible TiO$_2$ waveguide prior to and after repeated folding; inset: photo of a folded TiO$_2$ waveguide sample under test. (f) Proliferation of hMSCs in indirect contact with the photonic materials (image courtesy of [1]).

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