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Chalcogenide Glass Photonic Devices

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Chalcogenide glasses are infrared transmitting glasses containing the chalcogen elements S, Se or Te, compounded with elements such as As and Ge. These glasses are gaining attention for the fabrication of photonic chips because of their unusual combination of physical properties. In particular glasses can be formed over a wide range of compositions allowing fine-tuning of parameters such as the band-edge and index of refraction. The index of refraction is high, 2.4-2.7, making it possible to fabricate high index contrast waveguides with small cross-sectional area incorporating tight bends as well as planar photonic crystals (PCs). Chalcogenide glasses have low absorption losses over a wide range of infrared wavelengths between the electronic band-edge and the *Reststrahlen* bands in the mid IR. An important property is their relatively large third order optical nonlinearity (100-500x silica) that suggests that they can be used for all-optical switching at low powers as well as Raman or parametric amplification. Their moderate Verdet constant (20-100x silica) suggests it is possible to fabricate on-chip magneto-optic devices whilst their low energy phonon bands make them compatible with rare-earth dopants.

To potential of these materials for photonic chips it is necessary to develop techniques for both deposition of high quality chalcogenide films as well as nano-patterning to create complex photonic structures. We are investigating both conventional “top-down” engineering approaches for device fabrication using contact printing and reactive ion etching as well as an alternative method for smaller structure that uses a focused ion beam (FIB) mill. This latter approach provides a versatile, one-step method of patterning chalcogenide films at the nanometer scale to create photonic crystals, waveguide tapers, gratings, micro-ring resonators, etc, whereas conventional pattern transfer and ICP reactive ion etching (RIE) allows larger structures to be fabricated. The FIB is, therefore, suited to creating complex pattern with a spatial resolution in the tens of nm range over a field of view about 0.5x0.5mm, whereas the conventional process allows around 1 μ m resolution over wafer-sized areas.

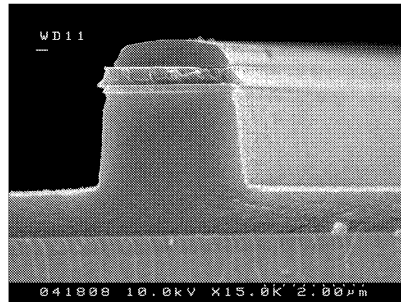


Figure 1: End face of a As_2S_3 glass rib waveguide 2 μ m waveguide produced by contact printing and RIE

To create structures we deposit chalcogenide films onto oxidized silicon wafers using our ultra-fast pulsed laser deposition (UFPLD) method [1,2]. UFPLD has proven to be capable of rapidly depositing (>1 nm/s) uniform, atomically-smooth films over large areas (0.5m²) with losses generally limited only by residual material absorption. Rib or ridge waveguides are created in the films by first transferring the waveguide pattern into a photoresist using a Karl Suss MA6 mask aligner and then etching the glass using an Oxford ICP 100 RIE tool. An example of a 2 μ m rib waveguide produced using this method is shown in figure 1. The waveguides show low side-wall roughness and propagation losses below 0.2dB/cm. Coupling between conventional optical fibres and these small high index contrast waveguide poses significant challenges. UFPLD however offers the opportunity to easily create 2-D up-tapers at the input and output ends of the guides allowing efficient coupling to high NA optical fibres. In addition following the design of Shoji *et al.* [3] it is possible to employ a down-taper embedded in a polymer waveguide. In

the latter case it is necessary to transversely taper the high index waveguide to dimensions below 100nm. Such narrow structures cannot be produced directly using contact printing.

To produce smaller structures we use our Orsay Physics “Canion Plus” FIB combined with a JEOL JSM-6460LV scanning electron microscope. The system as supplied was poorly equipped for high resolution milling of complex patterns since it lacked a pattern generator. We developed our own pattern generation system based on a personal computer and analogue input/output card. The FIB has been used to produce long down tapers in As_2S_3 glass films such as those shown in figure 2. Notice the tapers only thin to around 100nm before also tapering in the vertical direction. Our simulations indicate though that vertical tapering markedly improves the performance of the structure.

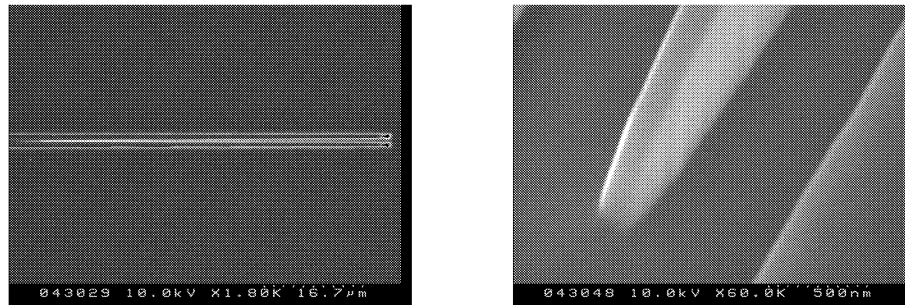


Figure 2: SEM images of a $100\text{nm} \times 1\text{μm}$ taper milled into an As_2S_3 film using the FIB. The close up on the RHS shown the smooth side-walls produced by the FIB and a taper end-width of around 100nm

As another example of the capabilities of the FIB we have produced a triangular lattice of circular holes on a 1.6μm lattice represents a typical planar photonic crystal. The PC structure shown in Figure 2 was directly milled into the As_2S_3 film with a beam energy of 30 keV, current of 102 pA, and exposure of 1.0 s per hole (with 187 holes). High-resolution SEM images taken with a Hitachi 4500 FESEM allowed the surface roughness to be estimated to be below 20nm, whilst the positional accuracy of the structure is believed to be sub-nanometre over the $20 \times 20\text{ μm}^2$ grid.

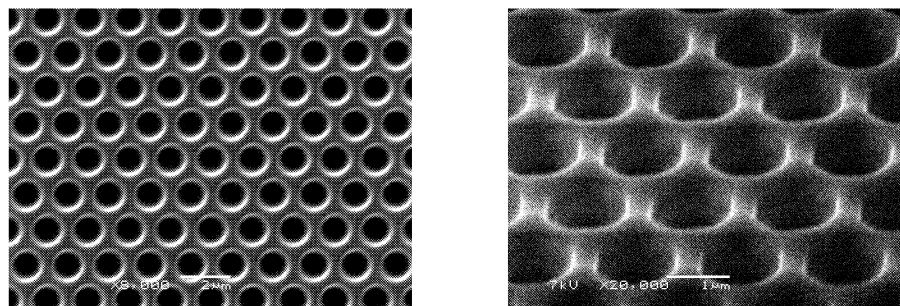


Figure 3: A triangular lattice, lattice constant 1.6 μm , PC structure directly milled into a 2.5 μm thick As_2S_3 film

This talk will review come of the properties of chalcogenides and our progress in developing novel photonic devices in these materials,

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