Mid-infrared $GeTe_4$ waveguides on silicon with a ZnSe isolation layer

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ABSTRACT

$GeTe_4$ waveguides were designed and fabricated on silicon substrates with a ZnSe isolation layer. $GeTe_4$ has a refractive index of 3.25 at a wavelength of 9 µm and a lower refractive index isolation layer is needed to realise waveguides on silicon. Numerical modelling was carried out to calculate the thickness of the isolation layer (ZnSe, refractive index ~2.4) required to achieve low loss waveguides. For a loss between 0.1 and 1.0 dB/cm it was found that a ~ 4 µm thick ZnSe film is required at a wavelength of 9 µm. ZnSe thin films were deposited on silicon, $GeTe_4$ waveguides were fabricated by lift-off technique and were characterised for mid-infrared waveguiding.

Keywords: mid-infrared, waveguides, quantum cascade laser

1. INTRODUCTION

Integrated photonic devices for mid-infrared biosensing need highly sensitive planar optical waveguides for efficient and reproducible interaction of analytes with photons. Chalcogenides are the most promising materials for waveguides in the mid-infrared region, corresponding to wavelengths from 2 – 20 µm, due to their broad transparency in this region [1-4]. Chalcogenide materials can be easily deposited as thin films by most common deposition techniques such as evaporation and sputtering [5-8]. It is important to have a suitable substrate, transparent in the mid-infrared region, on which to deposit chalcogenide thin films in order to realise low loss waveguides. Chalcogenide based substrates (e.g. ZnSe) are generally soft and brittle materials and are prone to scratches and are difficult to end-facet polish as compared to conventional substrates such as silica and silicon. Chalcogenide materials are expensive and their cleaning procedures are also not very well established. Moreover, it is important that these materials should be compatible with existing semiconductor fabrication technology to enable integration of electronics and photonics together on a single chip. In our previous work, we have demonstrated the fabrication and characterization of chalcogenide $GeTe_4$ waveguides on bulk ZnSe substrates, where the end facets of the waveguides were prepared using ductile dicing that left the sample end-facet with a staircase - like pattern [9, 10]. Cut end facets are also inconvenient due to practical difficulties encountered in characterizing the waveguides optically; for example, it is difficult to collect light from the output of the waveguide using a fibre or by free space optics, as the contribution of scattered light from the rough cut cannot be avoided.

Silicon is a convenient and cheap flat substrate on which to deposit chalcogenide thin films as compared to bulk chalcogenide substrates. Silicon is well known for its cleavage planes and its smooth surface finish that makes it appropriate to overcome the above problems. Piranha cleaning is also a well-established and straightforward procedure for silicon surface cleaning. $GeTe_4$/ZnSe waveguides were designed and fabricated on silicon substrates for the 2-14 µm band of the mid-infrared spectrum. $GeTe_4$ has a refractive index of 3.25 at λ = 9.0 µm and needs a lower refractive index isolation layer between the silicon substrate and the $GeTe_4$ core to realise low loss optical waveguides.

Numerical modelling was carried out to calculate the thickness of the isolation layer (ZnSe, refractive index ~2.4 at λ = 9.0 μm) required on a higher refractive index silicon substrate (n = 3.42 at λ = 9.0 μm) to achieve low loss waveguides. For a monomode slab waveguide of $GeTe_4$, it was found that ~ 4 μm thick ZnSe film is required at a wavelength of 9 μm to achieve a loss between 0.1 and 1.0 dB/cm due to leakage into the underlying silicon. ZnSe films were deposited on silicon and were characterised for their structure and morphology by XRD and SEM. Photolithography was used to fabricate channel patterns on ZnSe films using a lift-off resist and $GeTe_4$ was deposited on the patterned sample and photoresist removed to form channel waveguides of various widths. Finally, waveguiding was demonstrated at a wavelength of 9 μm.

2. NUMERICAL MODELING FOR OPTIMIZATION OF ISOLATION LAYER

The present design of the waveguide including the refractive indices of the $GeTe_4$ core, ZnSe isolation layer and Si substrate at a wavelength of 9 μm is shown in Figure 1. Since the refractive index of silicon is higher than that of the core and isolation layer of the waveguide, numerical modelling is used to calculate the isolation layer thickness on silicon substrate to avoid light propagation in silicon due to its high refractive index.

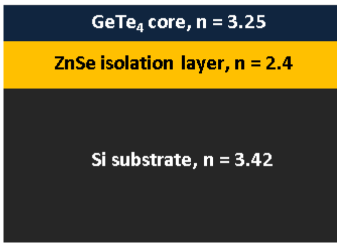

Figure 1. Schematic of the modelled slab waveguide structure

COMSOL Multiphysics was used to find the fundamental modal solutions for the slab waveguide structure shown in Figure 1, resulting in a modal field distribution such as that shown in Figure 2 (a) and a modal loss, which is shown vs isolation layer thickness in Figure 2 (b). All the calculations were carried out for a wavelength of 9 μm and $GeTe_4$ core thickness of 2 μm.

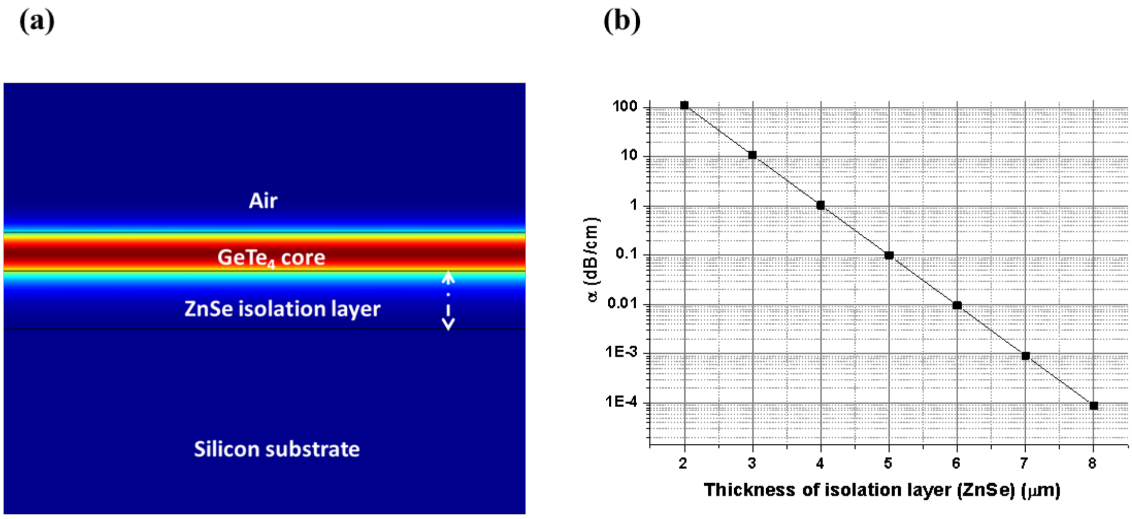

Figure 2. (a) COMSOL simulation showing the modal field for the fundamental mode of a slab waveguide, (b) Waveguide loss due to Si vs. thickness of isolation layer

An acceptable contribution to loss due to the silicon substrate in a practical device is below ~ 1 dB/cm. The corresponding thickness of isolation layer required to achieve a loss below this level can be seen from Figure 2 (b) to be 4 µm.

3. EXPERIMENTAL PROCEDURES

The zinc selenide isolation layer was deposited on a Si (100) substrate by RF magnetron sputtering (Kurt J. Lesker) in an argon atmosphere. A commercial polycrystalline target of zinc selenide (50 mm diameter x 3 mm thick) made by CVD was used (Crystran). The distance between the substrate and the target was fixed at 13.5 cm. The substrates were rotated at a speed of 20 rpm and the deposition was carried out with the substrate maintained at room temperature. The base pressure of the system was 5 x 10^{-5} Torr before deposition. The thickness of the resulting films was measured using a KLA Tencor stylus profilometer. The crystalline phase of the deposited films was determined using a Rigaku X-ray Diffraction system and a Zeiss Scanning electron microscope (SEM) was used to observe the film surface morphology. An Agilent Technologies Fourier transform infrared (FTIR) spectrometer was used to measure the transmission spectrum of the films. Standard photolithography followed by lift off technique was used to fabricate the channel waveguides. The waveguides were characterized using a quantum cascade laser (QCL) (Pranalytica) tunable between 6.4 - 12 µm and a microbolometer based mid-infrared camera (FLIR SC660).

4. RESULTS AND DISCUSSION

A Si (100) substrate and a glass slide were cleaned with Piranha solution (H2SO4: H2O2) and then rinsed with acetone and Isopropyl Alcohol (IPA) and baked overnight at 120° C before deposition. A CaF2 substrate was rinsed with acetone and IPA for cleaning. A sputtering pressure of 20 mTorr, RF power of 45 W and argon flow rate of 40 sccm was used to deposit ZnSe films on Si, CaF2 and normal glass slides substrates, with a deposition rate of 0.05 nm/s, resulting in a ZnSe film of ~ 4.2 µm thickness. The amorphous nature of the films was confirmed using grazing incidence XRD (GIXRD) as shown in Figure 3, where the absence of any sharp peaks is characteristic of an amorphous material. Amorphous films are essential to polycrystalline films for optical waveguides to avoid scattering of light at grain boundaries.

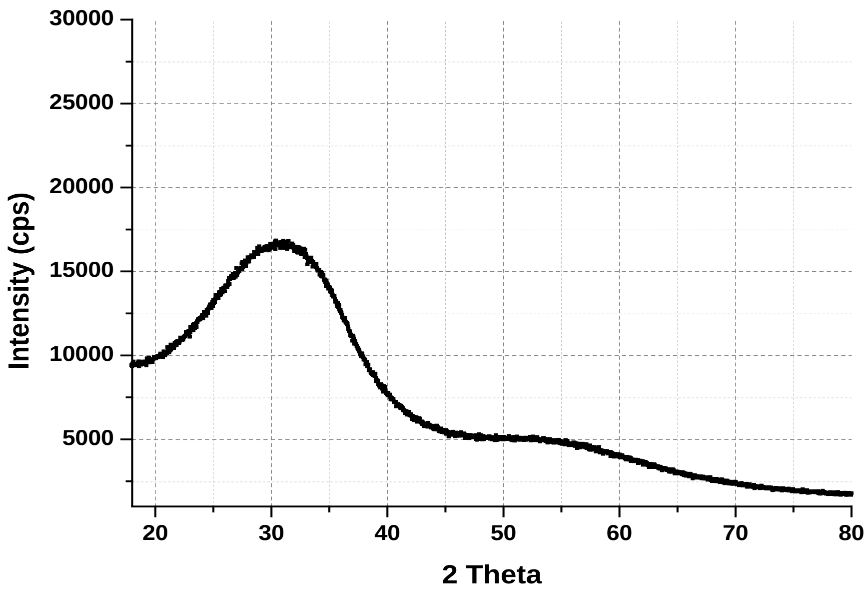

Figure 3. XRD pattern of ZnSe film deposited on a silicon substrate confirming its amorphous nature

The film deposited on the CaF_2 substrate was used to measure the transmission of the deposited ZnSe film in the infrared region using a normal incidence FTIR. First, the transmission spectrum of a 1 mm thick bare CaF_2 substrate was taken with air as background, which is shown in the black curve in Figure 4. Then the transmission spectrum for the ZnSe film deposited on an identical CaF_2 sample was recorded, and the two spectra were ratioed to get the transmission spectrum of the ZnSe film deposited on CaF_2, which is shown in the green curve in Figure 4. A total of 32 scans were averaged with the resolution of 4 cm^{-1}. It can be seen that the deposited film transmits from 2 – 10 µm with a small absorption at around 3 µm, which is due to O-H stretching in liquid water [11]. The interference fringes in the transmission spectrum of ZnSe film are due to the multiple reflections from air/film and film/substrate interface. It is to be noted that ZnSe is transparent for wavelengths from 0.5 µm to 18 µm [4]; the cut-off at 10 µm in Figure 4 is due to the CaF_2 substrate that transmits up to 10 µm.

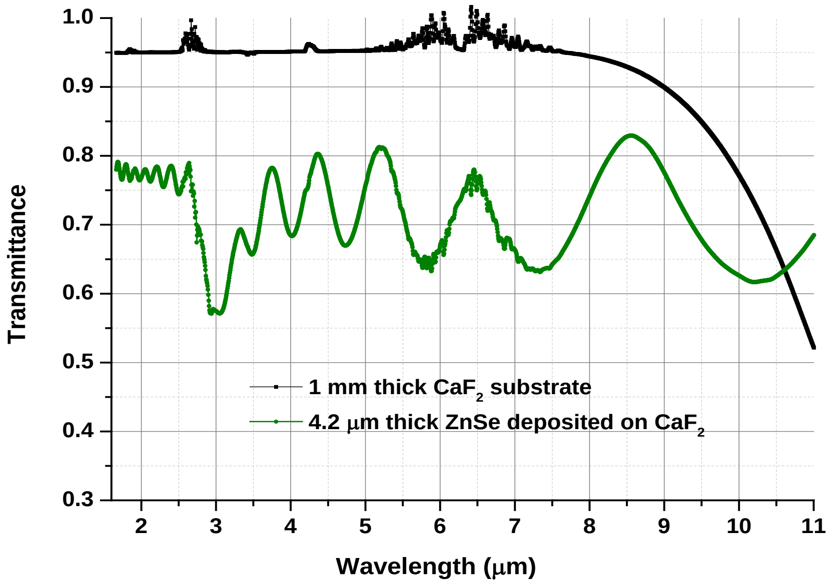

Figure 4. FTIR spectrum of a bare CaF_2 substrate and a ~4.2 µm thick ZnSe film deposited on a CaF_2 substrate

The lift-off technique was used to fabricate rib waveguides. First, ~ 4 µm AZ2070 negative photoresist (Microchemicals) was spun onto the ZnSe/Si samples. After soft baking, the samples were exposed to UV light for 4.5 s using a 350 W Hg light source of intensity 16 mW/cm^2 and then post exposure baked (PEB) to crosslink the exposed resist. Finally, they were developed in AZ726 MIF developer for 40 sec to create the desired undercut photoresist profile. An SEM image of the cross-section of the undercut photoresist is shown in Figure 5 (a). A ~ 2.4 µm amorphous $GeTe_4$ was then deposited on these patterned samples by RF-magnetron sputtering, using the procedure given in Reference 4. An SEM image of the cross-section of the $GeTe_4$ film deposited on the photoresist is shown in Figure 5 (b). Finally, the resist was stripped off by immersing the samples in a resist stripper solution (*N*-Methyl-2-pyrrolidone, commonly known as NMP). The final channel waveguide realised after removing the photoresist is shown in the SEM image in Figure 5 (c). The sample was then cleaved along the Si (100) plane to allow coupling of light into and out of the waveguide end facets and a cross-section of the cleaved sample is shown in the SEM image in Figure 5 (d).

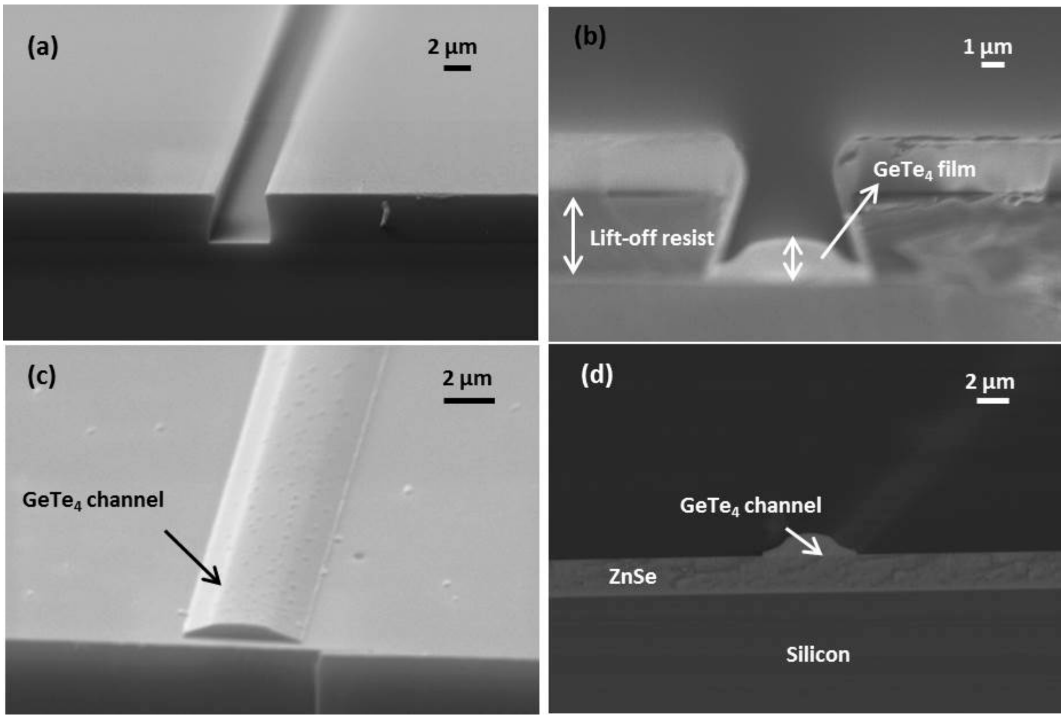

Figure 5. SEM images of (a) the undercut cross-section created in lift-off resist, (b) the cross-section of the $GeTe_4$ film deposited on the photoresist, (c) and (d) Top view and cleaved cross-section of a $GeTe_4$ channel waveguide after lift-off.

To characterize the waveguides, light from a QCL at a wavelength of 9.0 µm was coupled into the waveguide end facet using a single mode As_2Se_3 fiber with a core diameter of about 30 µm and the waveguide output was imaged onto a mid-infrared camera from the top. Figure 6 shows the infrared image of the input and output ends of the ~0.8 cm long sample tested at λ= 9 µm. The straight channels can be clearly seen despite the weak contrast of the image. The bright spot at the end of a channel 2.4 µm thick and 3 µm wide confirms the confinement of light.

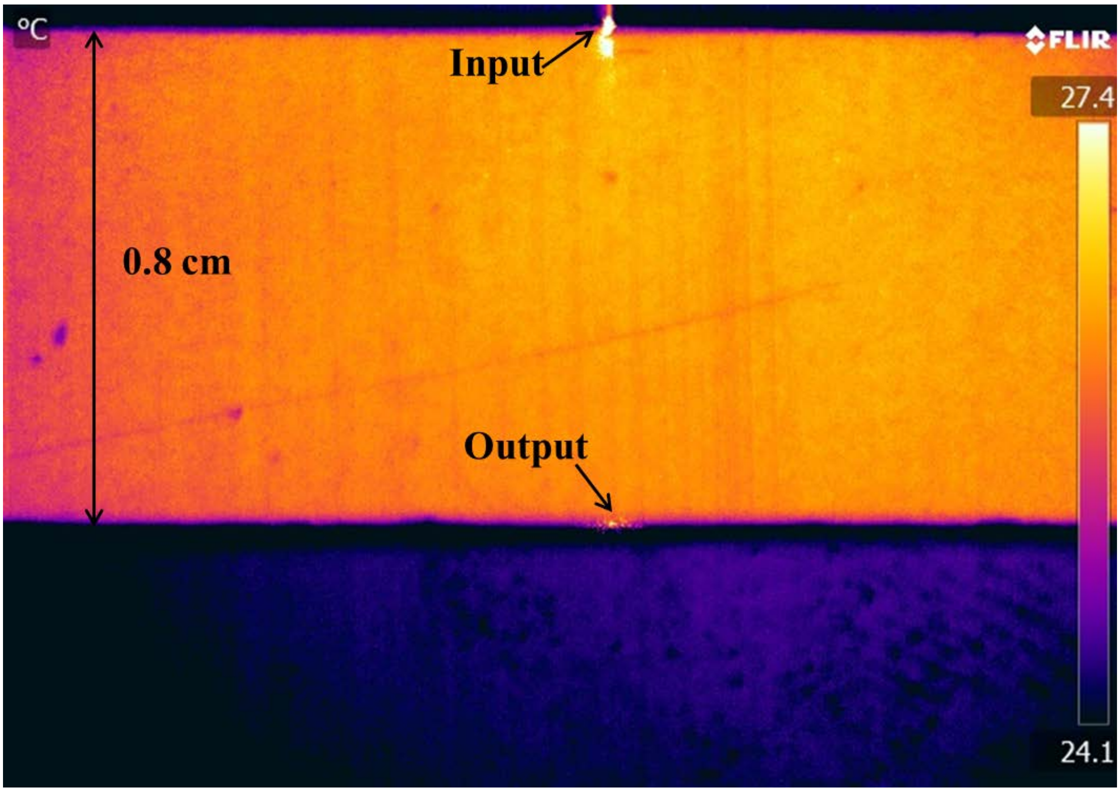

Figure 6. Top-view infra-red image of a waveguide sample showing input and output of a channel waveguide coupled to a QCL at 9.0 µm wavelength using an optical fibre.

5. CONCLUSION

Germanium telluride channel waveguides were designed and fabricated on silicon substrates with a ZnSe isolation layer. The waveguide loss due to light tunneling in to silicon substrate at various ZnSe isolation layer thickness at a wavelength of 9 µm was calculated by numerical modelling. A ZnSe film was deposited on silicon substrate by RF sputtering and was found to be transparent in the mid-infrared region of interest. $GeTe_4$/ZnSe channel waveguides were fabricated on Si substrate by lift-off. The end facets of the waveguides were cleaved and the waveguides were tested at a wavelength of 9 µm and waveguiding was demonstrated. Further characterization such as propagation loss and spectroscopy of bio-chemical analytes on these waveguides are underway.

ACKNOLEDGEMENT

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