Components for Integrated Ge on Si for Mid-Infrared Photonic Sensors

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***Abstract*—Components for mid-infrared chip-scale sensors are reviewed including loss measurements of Ge-on-Si waveguides between 8 and 10.5 μm wavelength. Third-harmonic generation is demonstrated using Ge nano-antennas. Such components are essential for a Ge-on-Si mid-infrared platform technology for healthcare, security and environmental sensing applications.**

I. Introduction

The mid-infrared (MIR) part of the electromagnetic spectrum is used for the identification of many molecules [1]. Whilst 3 to 5 μm has a transparent atmospheric window which allows many simple gas molecules to be identified (e.g. CO_2) many larger molecules have unique signatures in the 6 to 20 μm fingerprint region. For stand-off detection the atmospheric window at 8 to 12 μm wavelengths is extremely important.

Fourier Transform InfraRed (FTIR) spectrometers have been the gold standard for MIR identification but such systems are expensive and require expert users. Recently a range of integrated photonic platforms are being developed which have the potential to provide chip scale sensors that are far cheaper and do not require expert users [2]. Si photonics platforms have low Si losses out to 10 μm but the losses in SiO_2 and Si_3N_4 become significant at 4 and 6.7 μm respectively [2]. Ge on Si has the potential for low losses out to 14.5 μm but to date very few measurements of losses or components for integrated MIR sensing platforms have been demonstrated [2].

We are developing a chip scale platform technology using Ge on Si with a range of waveguides, intersubband detectors [3], bolometers, plasmonic antennas [4], ultrafast photonic components [5] and non-linear elements for MIR sensing for healthcare, security and environmental monitoring applications. Here we measure the losses in Ge on Si waveguides between 8 and 11.5 μm wavelength before using a range of Ge plasmonic nano-antennas to undertake third harmonic generation (THG) in the MIR region.

2 μm thick Ge material with threading dislocation density of 10^7 cm^{-2} was grown using an ASM Epsilon tool. Ge waveguides were patterned by electron-beam lithography and fluorine based dry etching as shown in Fig. 1. Initial modelling indicated a 6 μm width for a rib waveguide of 1 μm etch depth

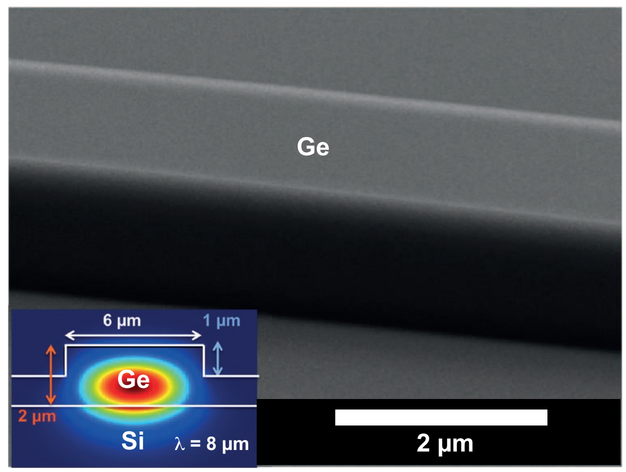

Fig. 1. A SEM image of a 1 μm deep etched Ge rib-waveguide. The insert demonstrates the simulated TM mode profile for a Ge on Si rib-waveguide at 8 μm wavelength.

would be sufficient for the cut-off to be above 12 μm (Fig. 1 insert). Waveguide losses were measured using the cut-back technique with a Daylight Solutions MIRcat laser operating between 8 and 11.5 μm and a liquid nitrogen cooled mercury cadmium tellurium (CMT) detector. An optical chopper with lockin detection was used to remove the background blackbody heating and to improve the signal to noise ratio.

Fig. 2 presents the losses as determined for TE and TM polarisation. The 4.3 dB/cm at 8.5 μm is significantly lower than previous measurements of >10 dB/cm from Ge on Si waveguides [6]. The peak at 9 μm is related to interstitial oxygen in the Cz Si substrate and demonstrates the loss from the strong modal overlap with the Si substrate which is calculated to be ~58% at 10.5 μm (Fig. 1 insert). The TE mode has less coupling (33%) to the Si substrate and demonstrates lower losses suggesting that the contribution from the Si substrate must be considered in this system. If thicker Ge of 4 μm was used then the coupling reduces to ~9% for TM and 8% for TE suggesting that there is significant

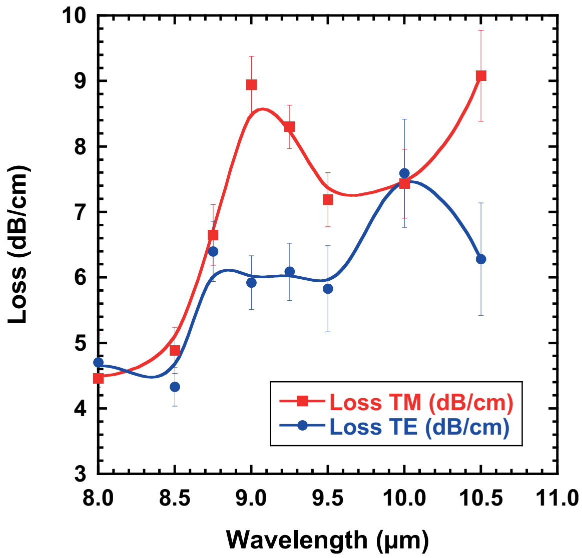

Fig. 2. The measured loss from 6 μm wide Ge waveguides on Si at 300 K.

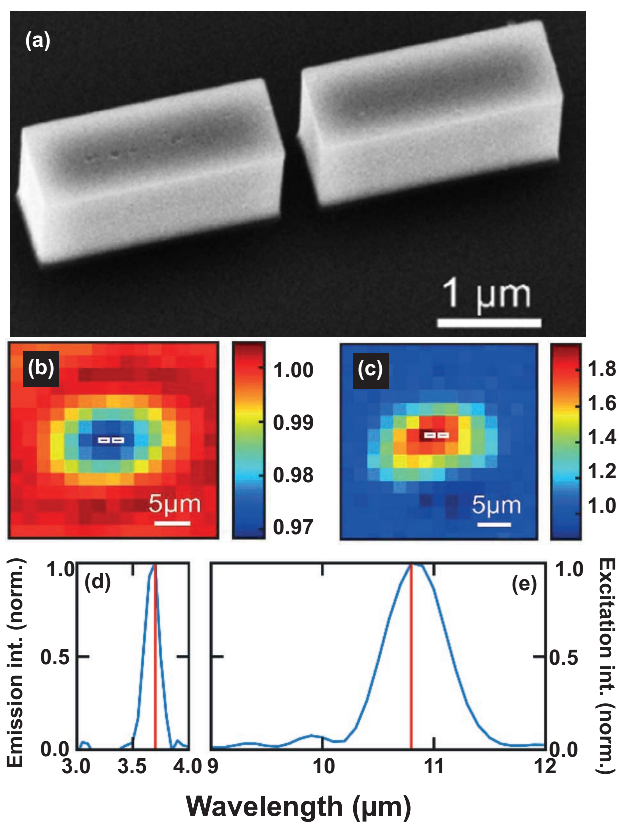

Fig. 3. (a) A SEM image of a Ge nano-antenna of 2.75 μm length with a 300 nm gap on Si. (b) The linear transmission map of a resonant gap antenna illuminated with 10.8 μm. (c) The THG emission map normalized to the Si substrate background emission. (d) The normalized THG spectra and (e) the excitation intensity spectra.

opportunities to improve these results.

Next we demonstrate that Ge on Si nano-antennas are suitable for non-linear processes and THG. Low-energy plasma enhanced chemical vapour deposition [7] was used to grow the n-Ge epilayers on high resistivity Si (001) substrates and were used to fabricate resonant nano-gap antennas (Fig. 3(a)) [4][5]. A Yb:KGW fs laser equipped with optical parametric amplifiers was used to generate MIR pulses through difference frequency generation in GaSe crystals with excitation fields up to 20 MV/cm in the focus of a Cassegrain-Schwarzchild reflective objective. A second objective was used to form a transmission image of the antenna using a CMT detector to allow both linear and non-linear responses to be mapped.

Fig. 3(b) presents the linear transmission at the excitation wavelength of 10.8 μm (the excitation spectrum is in Fig. 3(e)) demonstrating absorption by the antenna of the radiation. Figure 3(c) demonstrates the THG emission from the antenna at 3.6 μm (the emission spectrum is in Fig. 3(d)). By varying the antenna length we have confirmed the role of localized plasmon resonances in producing the THG with efficiencies up to 10^{-6} for single antenna illuminated with 25 nJ pulses.

II. Conclusions

We have presented measurements of Ge waveguide losses between 4.3 and 9 dB/cm over the 8 to 10.5 μm range. Nano-antennas of Ge on Si demonstrated THG with efficiencies up to 10^{-6}. This is the first demonstration of third-harmonic conversion from sub-wavelength plasmonic structures resonant in the MIR.

Acknowledgment

The research was funded by the European Union's 7^{th} Framework Programme (no. 613055), from U.K. EPSRC (EP/N003225/1) and from the Deutsche Forshungsgemeinshaft (Emmy Noether Program BR 5030/1-1).

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