Mid-infrared Ge-on-Si waveguide propagation loss correlation to measured sidewall roughness

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***Abstract*—Measurements of sidewall roughness by atomic force microscopy has been used to understand the waveguides losses of Ge-on-Si mid-infrared rib waveguides. Simulations indicate the measured roughness is well below values corresponding to the measured losses indicating sidewall roughness scattering is not the dominant loss mechanism.**

***Index Terms*—mid-infrared, photonics**

I. Introduction

The mid-infrared (MIR) spectral region is of significant interest for establishing on-chip spectroscopy for environmental monitoring, healthcare and security applications. In particular wavelengths between 6.7 and 20 μm are important as the unique molecular vibration modes enable a label free sensing platform [1]. Ge-on-Si has been suggested as a platform for sensing in this region, due the Ge transparency up to 15 μm, and its compatibility with Si growth and fabrication processes. The maximum sensitivity of an optical sensing platform depends on the propagation losses in the passive sensing elements (micro-ring resonator, waveguides etc.), as ideally the only source of optical loss would be the analyte. Understanding and minimising these optical losses is therefore crucial to developing highly sensitive sensing systems. There have been a number of demonstrations of MIR waveguides using Ge and Ge rich SiGe waveguides [2], [3]. The source of the losses at MIR wavelengths in such waveguides are unclear, and are often attributed to defects at heterointerfaces, as well as sidewall scattering. Previously, we attributed the residual loss in Ge-on-Si waveguides to the sidewall roughness created by the etching process [4], in part due to the wavelength dependence of the loss. Here, we experimentally investigate the sidewall roughness dependence of the optical loss, by using a novel atomic force microscope (AFM) technique to directly measure the sidewall of Ge-on-Si waveguides with two different levels of root mean squared (rms) roughness resulting from different etch processes. The results indicate there is the potential for unconsidered loss mechanisms in MIR waveguides that could be limiting the ultimate performance of optical sensing systems.

II. Design and Fabrication

Ge epitaxial layers of 2 μm thickness were grown on 150 mm (100) Czochralski (Cz) Si substrates, by reduced pressure plasma enhanced chemical vapor deposition. The two temperature growth technique was used to grow the Ge epi-layers [5], and subsequently cyclically annealed at 800 °C to reduce the threading dislocation density (TDD) to $< 1 \times 10^7$ (cm^{-2}) at the top plane. Ge waveguides were patterned by electron-beam lithography, using hydrogen silsesquioxane (HSQ) resist. Two samples were etched 1 μm in depth by using different gas flow ratios of SF_6/C_4F_8 recipes [6] to form rib waveguide structures with varying sidewall roughness. Waveguide widths of 6 μm were chosen to ensure the cut-off wavelength is beyond that of the longest wavelength in the measurement range. Residual HSQ was removed in dilute hydrofluoric acid, and subsequently the chip was diced and polished to form optical facets. A quantum cascade laser (QCL) system was used to characterize the waveguides in the wavelength range from 7.5 to 11 μm [4]. The waveguide losses were measured using the Fabry-Perot technique [7] in transverse magnetic (TM) polarization. Figure 1 presents the losses for two sets of waveguides with different sidewall roughness. For both sets of measurements a clear peak at around 9 μm can be observed that is caused by the interstitial oxygen, which is commonly observed in Cz grown Si [4]. Clearly, there is a significant dependency of the etch roughness on the propagation losses as the rougher etch was measured to have ∼2 dB/cm higher losses across the wavelengths measured.

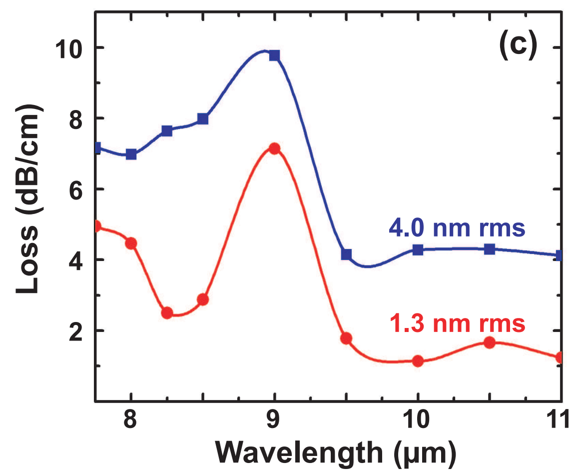

Fig. 1. The waveguide propagation losses measured using the Fabry-Perot technique, in transverse magnetic polarization.

Following the propagation loss measurements a Bruker Dimension Icon atomic force microscope (AFM) was used to characterize the sidewall profiles of the waveguides. To do this, waveguides were diced at a 7.5° angle to the sidewall and subsequently polished to create a smooth edge. This design allowed for a carbon nanotube tip on the AFM system to access the sidewall of the waveguide. The system was operated in tapping mode to achieve high-resolution depth profiles and ensure that the tip was in contact with the sidewall.

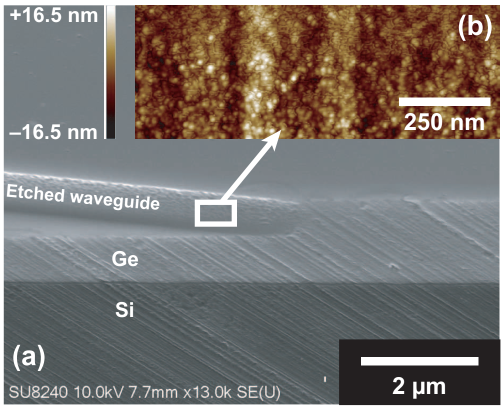

Fig. 2. A scanning electron microscope image of the Ge-on-Si rib waveguide sidewall. Inset: AFM measurement of the sidewall.

III. Results

Figure 2 presents the SEM image of the waveguide and the insert presents the corresponding image that was obtained by the AFM. For the first etch, an roughness amplitude of 4 nm rms was extracted while the second etch, the rms roughness was measured to be 1.3 nm. In comparison, the top surface of the epitaxial Ge was measured to have a rms roughness of ∼0.5 nm.

Scattering losses caused by sidewall roughness using the rms amplitude values were modelled using the Payne and Lacey model [8] as shown in Fig 3. The rms values would have to be orders of magnitude higher than what was measured to produce a 2 dB/cm offset between the etches. The losses caused by the level of roughness measured are below ∼0.25 dB/cm and are negligible in comparison with the optical losses measured. Even taking into account the vertical periodic lines on the sidewalls introduced by the electron beam lithography pattering, the discrepancies between the losses cannot be accounted for using the Payne and Lacey model. Periodicity and amplitude are highly subwavelength and therefore should not have an impact on the losses measured. This was verified using an eigenmode expansion simulation method. It is clear that the observed optical loss is therefore not consistent with sidewall roughness scattering, despite the fact there is a clear sidewall dependent loss mechanism.

IV. Conclusions

Experimental evidence of the sidewall dependent loss mechanism in Ge-on-Si waveguides operating in the MIR was presented. The roughness of Ge waveguides was varied by modifying the etch recipe, and was measured by AFM. The propagation losses were measured for the two levels of rms

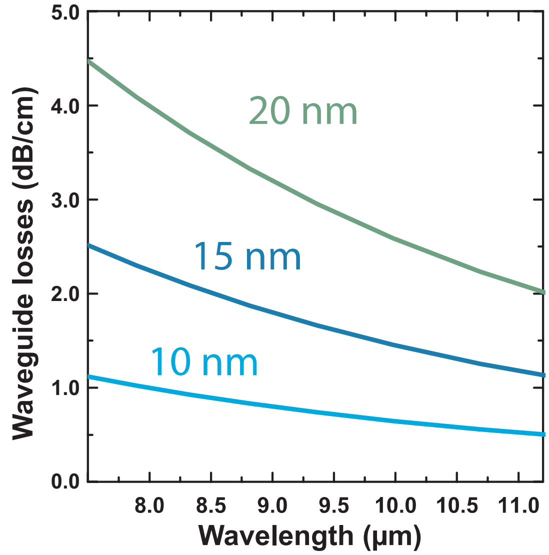

Fig. 3. The calculated scattering losses for measured rms amplitude values of roughness for different etch recipes.

amplitude roughness, and compared to commonly used optical scattering models. It was found that the levels of roughness present (down to ∼1.3 nm rms) cannot account for the optical loss measured. The experimental losses demonstrate, however, that there is a significant dependence of the losses on the etch recipe. This points to the fact that there be sidewall dependent loss mechanisms that have not previously been considered in the MIR for such waveguides. Future work will seek to identify the source of this sidewall dependent loss mechanism.

Acknowledgment

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