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Integrated Germanium-on-Silicon Waveguides for Mid-Infrared Photonic Sensing Chips

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***Abstract*—Germanium-on-silicon waveguides are designed, fabricated and characterized with a novel near-field infrared spectroscopy technique that allows on-chip investigation of the in-coupling efficiency. On-chip propagation along bends and straight sections up to 0.8 mm is demonstrated around $\lambda = 6$ μm.**

I. INTRODUCTION

WAVEGUIDES represent the key component of integrated silicon photonics. The dominant technology in the near-infrared (λ = 1.55 μm) is the silicon-on-insulator (SOI) platform, where Si waveguides are realized on SiO_2 surfaces grown on Si wafers, exploiting the strong refractive index contrast (n_{Si}=3.4 and n_{SiO2}=1.4-1.7). In the mid-IR range of interest for biosensing ($\lambda > 5$ μm), Si presents non-negligible losses due to impurity states and it cannot be used as the guiding layer, and SiO_2 has huge losses due to optical phonon absorption and it cannot be used at all. Therefore, IR transparent materials have been investigated but their n is typically lower than that of Si so, for use as guiding layers, they have to be physically suspended [1].

Germanium is transparent and has n_{Ge}=4.0 > n_{Si} and therefore it can be used for guiding through simple Ge-on-Si strip waveguides [2]. The main difficulty related to this emerging integrated photonics technology is to couple light from an external mid-IR laser source into the Ge waveguide, and not into the Si substrate. This has been recently attained e.g. by graded Si_xGe_{1-x} virtual substrates [3]. In this work, we have fabricated pure Ge waveguides on Si wafers starting from Ge-on-Si films grown by chemical vapor deposition. We have etched grating couplers and tapers into the Ge layer to engineer the coupling at 70° incidence angle from a wavelength-tunable quantum cascade laser (QCL). Finally, we introduce photothermal expansion spectroscopy as the scanning local sensing tool of the out-coupled power at the waveguide open end.

II. RESULTS

Conventional characterization of on-chip waveguides with dimensions smaller than the wavelngth is typically carried out by moving an optical fiber against the waveguide open-end (butt coupling). Another approach is to tightly focus the free-space radiation onto a taper, i.e. a planar structure initially wider than the actual waveguide, fabricated on the chip edge; the taper width then decreases with increasing distance from the chip edge towards the waveguide width. Both methods are difficult to implement in the mid-IR and with a high-index material such as Ge, due to the unfavorable ratio between waveguide height and free-space wavelength that produces high coupling losses. The coupling losses also intervene when the radiation is out-coupled towards the detector, located in the far-field of the waveguide end. To solve these issues, we propose a method based on near-field mid-IR microscopy, in which the detector is substituted by a near-field sensor made by the combination of a polymer microblock fabricated on-chip by lithography in the same process as the waveguides that one wants to test, and an atomic force microscopy (AFM) probe. When the microblock receives radiation power at a wavelength where it efficiently absorbs mid-IR radiation, it will heat up and result in a photo-induced expansion that can be measured by monitoring the oscillations of the AFM cantilever probe. Also, the in-coupling is obtained by illumination at oblique incidence of a diffraction grating fabricated on the waveguide with a tightly focused mid-IR laser beam, so that different regions of the same chip can be used for in-coupling by simply raster-scanning the laser beam and/or the chip. In this way, each chip with specific epitaxial material properties can contain several hundreds of waveguide circuits. This technique is closely related to the photo-thermal expansion near-field microscopy (AFM-IR) [4, 5], except that the radiation is not directly focused on the tip, but it reaches the tip through the waveguide.

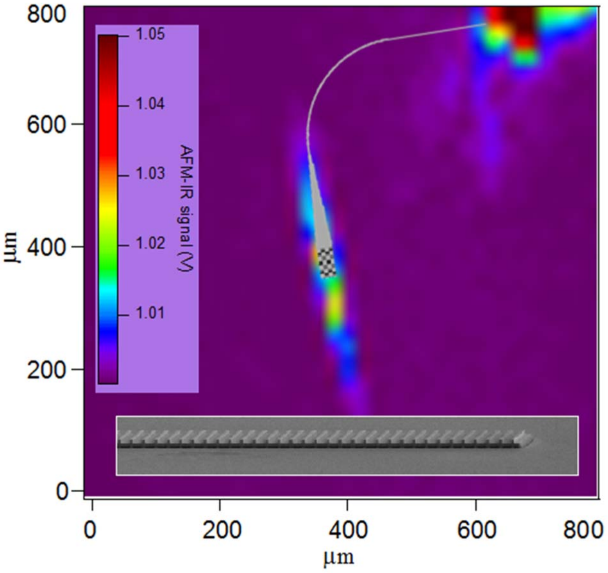

Fig.1 Near-field imaging at λ=5.8 μm of the radiation intensity on a Ge-on-Si photonic chip featuring a waveguide bend (grey line), an incoupling grating with taper (elongated intensity spot, mostly blue) and an open-end waveguide (red spot at the waveguide end, where the near-field probe is positioned). Inset: SEM image of the grating coupler.

In the present work, for analyzing each on-chip Ge-on-Si waveguide circuit, s-polarized radiation from an external-cavity tunable QCL tuned in the 900-1900 cm^{-1} is focused onto the corresponding grating coupler, while the AFM probe was kept on an SU8 microblock (absorbing between 1650 and 1750 cm^{-1}) fabricated by electron-beam lithography at the open end of the specific waveguide, or of a different nearby waveguide to check cross-talking.

Successful in-coupling is demonstrated by scanning the QCL spot on the chip surface (Figure 1). A very bright spot appears when the AFM probe and the SU8 block are directly illuminated by the fee-space radiation, as expected from the AFM-IR principle (top-right spot in Figure 1), but a second elongated spot appears also when the laser is focused onto the grating coupler, with the AFM tip still on the SU8 block.

The spectral efficiency of the grating is measured by tuning the QCL wavelength (Figure 2). A bandwidth of about 30 cm^{-1} to 50 cm^{-1} is obtained for different grating coupler geometries, in good agreement with electromagnetic simulations (not shown). A pattern of Fabry-Perot fringes is also clearly observed, due to back-reflections at the waveguide end and at the coupler-waveguide interface. Propagation losses around 5 dB/cm are estimated from the fringe intensity, indicating that the Ge-on-Si technology is extremely promising for realizing integrated CMOS-compatible molecular sensors.

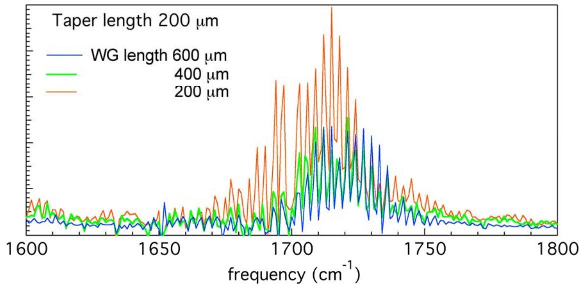

Fig.2 Intensity spectra of the radiation out-coupled at the open end of three straight waveguides of different length. The presence of interference fringes indicates that the radiation travels several times along the waveguides and is reflected by the open end and by the grating coupler. The in-coupling efficiency spectrum of the grating (1670-1750 cm^{-1}) is measured with the photo-thermal near-field probe while the QCL wavelength is tuned across the range shown in the plot.

III. SUMMARY

Germanium waveguides on silicon wafers are characterised by near field imaging and spectroscopy and represent an exciting perspective for mid-infrared integrated silicon photonics sensing chips. A new photo-thermal probe for near-field characterization of on-chip integrated mid-infrared waveguides is introduced, based on an IR-absorbing polymer block of sub-λ size with an atomic force microscopy probe that detects its thermal expansion.

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