# Germanium for photonic applications

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## 1. Introduction

Polycrystalline and crystalline germanium have been demonstrated to be excellent materials for the fabrication of integrated microsystems in complementary metal oxide semiconductor (CMOS) micro-electromechanical systems (MEMS) and photonics. Crystalline Germanium or Silicon Germanium on silicon or insulator is also a desirable and preferred system for applications in near infrared and mid infrared photonic devices. For near infrared, Silicon Germanium is crucial for the fabrication of detectors [1, 2], QCSE modulators and detectors [3-5] and Franz Keldysh modulators [6]. When extended to mid infrared wavelengths, Germanium becomes one of the waveguiding media of choice, with optical transmission all the way up to 10 microns. In order to fabricate optical components and enable the confinement of light in the horizontal and vertical direction, the deposition of high quality crystalline Germanium on insulator is of utmost importance.

In this paper we demonstrate a way to obtain crystalline Germanium on insulator and we report a 50 Gb/s aggregate receiver using Germanium grown directly on Silicon.

## 2. Crystalline Germanium on insulator using PECVD deposition and Liquid Phase Epitaxy

Germanium was deposited at a temperature of 250 degrees using PECVD. The deposition process was developed such that a high quality germanium layer was deposited across a 6” wafer without showing any deposition selectivity between the oxide and the silicon.

This recipe was used to deposit 400 nm of Germanium on a silicon wafer covered with 20 nm PECVD $SiO_2$. The oxide was removed using HF in specific areas to uncover the silicon and create a seed for the Germanium Liquid Phase Epitaxy (LPE) to occur. One micron of PECVD silicon dioxide was deposited on top of the Ge etched structure to form a crucible for the germanium melt.

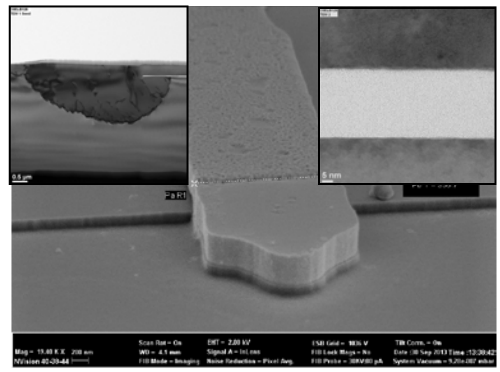

Fig. 1. SEM of the Germanium LPE wire. Top inserts are Cross-section TEM of the seed area and Si/oxide/Ge interface

The wafers were then heated in an RTA in order to melt the encapsulated Ge and initiate recrystallisation upon cooling. The temperature of the RTA was stabilized at 500 °C before ramping to 940 °C, at a rate of approximately 90 °C/s, for 1 second and cooling at 100 °C/s. Finally, the top $SiO_2$ layer was removed using a 20:1 HF wet etch to allow for layer characterization. Figure 1 shows an SEM scan of the germanium wire structure. The SEM picture shows the seed area of the wire and provides an insight into the structural integrity of the wire. Electron Back Scattering Diffraction (EBSD) measurements were also performed which confirm single crystal Ge, with the same orientation as the Si substrate, has been grown. The top inserts show a TEM of the seed area where the defects are located and a High resolution TEM of the Silicon / silicon dioxide/ Germanium interface.

## 3. Germanium near infrared integrated receiver

The demonstration of a single angled multimode interferometer (AMMI) [7] and an interleaved 8-channel AMMI [8] on the silicon-on-insulator (SOI) platform offers a convenient way to build a silicon wavelength division multiplexing (WDM) optical transceiver. The AMMI based transceivers could have the distinct advantages of both low insertion loss (hence, low input power for transmitter and high responsivity for receiver) and ease of fabrication (single lithography and etch step on the WDM part) at the same time. Here, we report a silicon photonics receiver using an AMMI as the WDM structure integrated with lateral germanium photodetectors on the 220 nm SOI platform. Light from a variable wavelength laser was coupled into the receiver device via an optical fibre and a grating coupler.

In order to characterise the high-speed performance of the 4-channel receiver a 10 mW, 12.5 Gb/s modulated optical signal was generated using an electrical pseudo-random binary sequence (PRBS) source, driver amplifier and commercial $LiNbO_3$ modulator. This signal was amplified using an erbium doped fibre amplifier (EDFA) and coupled to the device using an optical fibre and a grating coupler. A -1 V reverse bias was applied to the devices. The electrical signal from each channel was measured using a high-speed ground-signal-ground (GSG) probe and digital communications analyser (DCA). The resulting open eye-diagrams for each channel at its peak wavelength are shown in Figure 2, giving an aggregate data rate of 50 Gb/s.

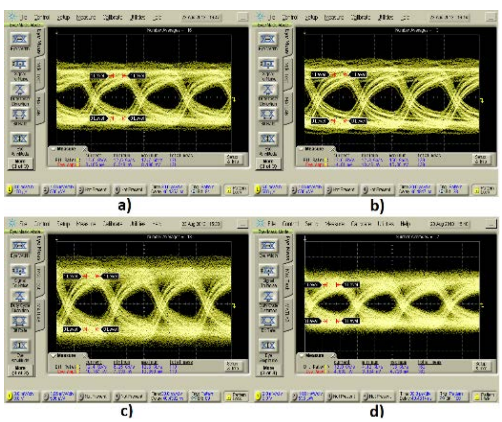


Fig. 2. 12.5 Gb/s eye diagrams of detectors operating a -1 V showing a) channel 1 at 1545 nm, b) channel 2 at 1555 nm, c) channel 3 at 1565 nm and d) channel 4 at 1575 nm[9]

## 4. Mid-IR waveguides

As Ge is transparent from 1.9 to 14 µm it can provide a material platform for mid-IR applications. We have designed and fabricated Ge waveguides using 2 µm Ge on Si grown by CVD. The rib waveguides were 2-2.5 µm wide. We have used a tuneable mid-IR Quantum Cascaded Laser (QCL), mid-IR optical fibres and lenses, liquid nitrogen cooled InSb detector and lock-in amplifier to characterize the fabricated waveguides. In-plane coupling was used as well as the cut-back measurement technique to estimate the loss. A minimum propagation loss of 2.3 dB/cm at the wavelength of 3.8 µm was measured. To the best of our knowledge, this is the lowest propagation loss measured for Ge waveguides in the mid-IR. Future work will include design and fabrication of Ge photonic devices based on this platform, such as splitters, couplers, resonators, modulators and spectrometers.

## 4. Conclusions

Localized GOI wires have been grown using a LPE process resulting in single crystal layers up to 400 µm in length and 5 µm in width. We have reported on the design, fabrication and characterisation of a 4-channel AMMI structure integrated with germanium *p*-i-*n* photodetectors to form a silicon photonics receiver. Light detection at 50 Gb/s has been demonstrated with a low dark current of < 20 nA at -1 V bias. The AMMI structure exhibits a low insertion loss of < -0.5 dB and cross-talk of < -15 dB across the 4 channels.

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