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## **(Invited) Silicon Photonics Based on Ge/SiGe Quantum Well (QW) Structures and Ge-Rich Materials for Near-IR and Mid-IR**

**Joan Manel Ramirez, Vladyslav Vakarin, Papichaya Chaisakul, Samuel Serna, Qiankun Liu, Jacopo Frigerio, Andrea Ballabio, Xavier Le Roux, Laurent Vivien, Giovanni Isella, Eric Cassan, Nicolas Dubreuil, Delphine Marris-Morini**

### **Abstract**

Silicon photonics is a disruptive technology poised to revolutionize several areas of our society. It has often been considered as the natural step forward to overcome some of the inherent bottlenecks of current microelectronics technology. Importantly, photonic integrated circuits can be implemented using CMOS-like fabrication processes, hence benefiting from a mature technology that provides low-cost mass fabrication using advanced tools. A large pool of Si components has been demonstrated, standing for low-loss waveguides, filters, micro-ring resonators, Mach-Zehnder interferometers, array waveguide gratings or photonic crystals, among others [1]. Similarly, the incorporation of Ge in Si photonic platforms has yielded the demonstration of several active optical devices such as high-speed optical modulators and photodetectors with unprecedented performance [2]. In addition, strong electro-absorption and electro-refraction has been demonstrated in Ge/SiGe quantum wells showing strong Quantum Confined Stark Effects (QCSE), allowing for efficient optoelectronic modulation and detection at telecom wavelengths [3]. Interestingly, tuning the QW design allows fine tuning of the absorption band edge of devices over a wideband range. Moreover, light emission from the direct bandgap transition HH1-CT1 has also been reported in SiGe/Ge quantum wells, opening the route towards the development of light emitting devices fully integrated in a silicon chip [4].

Noticeably, all the above described activities are meant to develop Si-based photonic platforms in the near-infrared wavelength range, where most applications are foreseen. Lately, however, there is an increasing interest in the exploitation of Ge-based photonic platforms at longer wavelengths up to the mid-infrared [5]. Having Ge a transparency window up to 15  $\mu\text{m}$ , there are good prospects for the development of advanced photonic sensing platforms leveraging from the strong mid-IR molecular absorption bands of several chemical and biological substances. Besides, Ge-based platforms have also been proposed as ideal candidates to exploit the nonlinear properties at mid-IR wavelengths, owing to a higher  $\chi^{(3)}$  nonlinearity and the absence of two-photon absorption beyond  $\lambda \approx 3.15 \mu\text{m}$  [6]. Important benefits are also expected in data communications, taking advantage from the two atmospheric transparency windows at  $\lambda \approx 3\text{-}5 \mu\text{m}$  and  $\lambda \approx 8\text{-}13 \mu\text{m}$  and the relaxed wavelength regulations put in place.

Thus, in this presentation we will show our recent work on the development of Ge-based photonic devices for telecom and mid-IR applications. For that, a review of the advanced optoelectronic devices demonstrated so far in our group will be presented, including high-speed SiGe/Ge QWs electro-absorption modulators and detectors exploiting the QCSE. Then, further insight on the room temperature luminescence of QWs will be provided, followed by its integration in light emitting diodes in waveguide configuration for planar emission. In addition, a novel mid-IR photonic platform based on Ge-rich graded-index SiGe alloys will be presented. This platform offers an interesting set of advantages over other existing mid-IR approaches such as low-loss propagation and optimal modal area over an unprecedentedly broadband wavelength range [7]. As a consequence, the first demonstration of ultra-wideband mid-IR Mach-Zehnder interferometers operating from  $\lambda = 5.5 \mu\text{m}$  to  $8.5 \mu\text{m}$  was performed using the graded-index SiGe platform [8]. Finally, the third-order nonlinear properties of this platform will be discussed, supported by experimental data on Ge-rich SiGe waveguides using a bidirectional top hat D-scan method [9]. Promising results were obtained, thus providing a promising scenario to develop broadband optical sources based on the supercontinuum generation.

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Figure 1

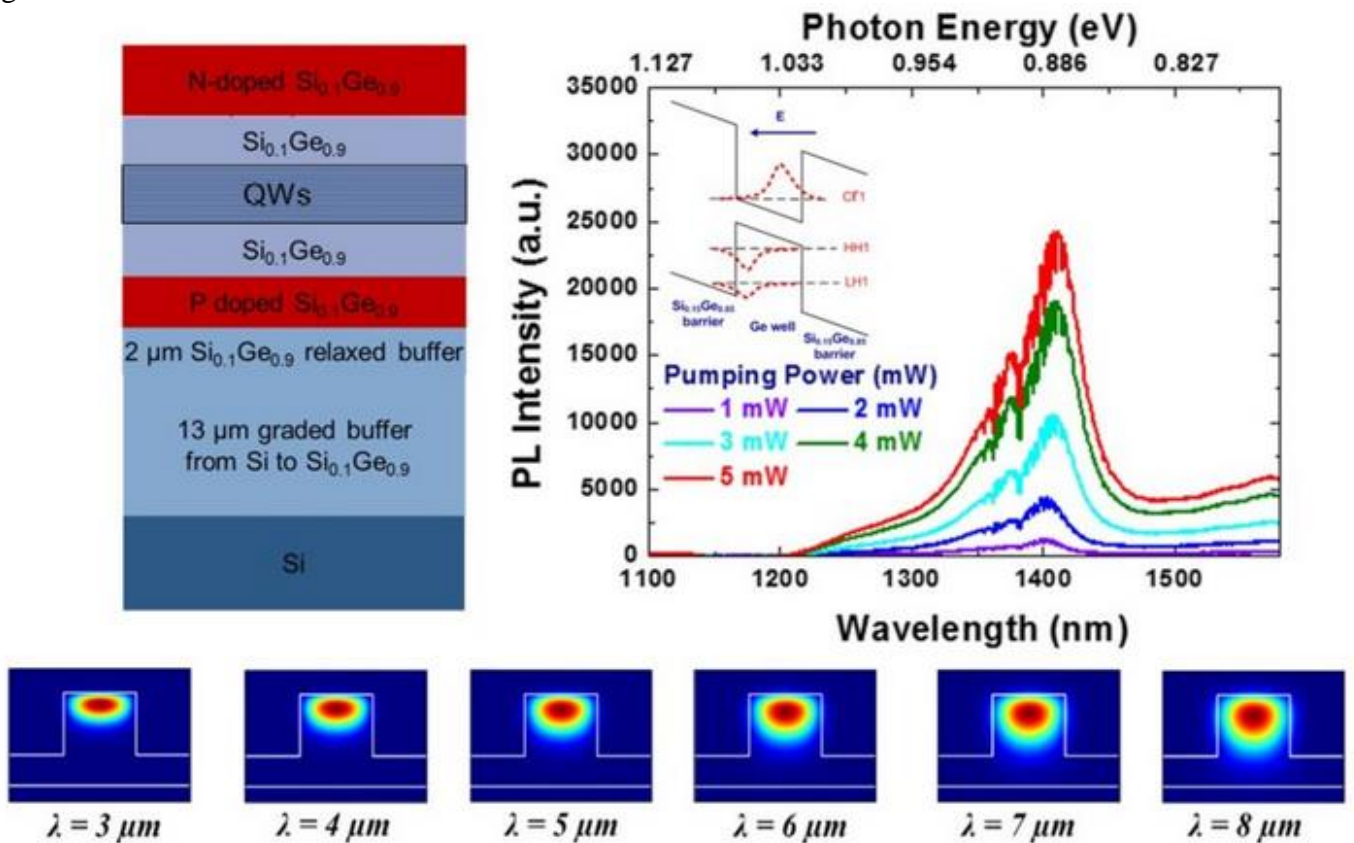


Figure 1. Schematic cross-section of the studied QWs devices (top-left). Top-right figure shows a typical luminescent spectrum of QWs, and bottom panels depict the evolution of the optical mode as a function of wavelength for a Ge-rich graded-index waveguide with flat anomalous dispersion.