



HAL
open science

High-Q silicon-germanium ring resonator for on-chip sensing applications in the mid-infrared

Marko Perestjuk, Rémi Armand, Alberto Della Torre, Milan Sinobad, Arnan Mitchell, Andreas Boes, Jean-Michel Hartmann, Jean-Marc Fedeli, Vincent Reboud, Christelle Monat, et al.

► **To cite this version:**

Marko Perestjuk, Rémi Armand, Alberto Della Torre, Milan Sinobad, Arnan Mitchell, et al.. High-Q silicon-germanium ring resonator for on-chip sensing applications in the mid-infrared. Optical Sensors and Sensing Congress 2022 - Optics and Photonics for Sensing the Environment, Jul 2022, Vancouver, Canada. pp.EM1D.4, 10.1364/ES.2022.EM1D.4 . hal-03800934

HAL Id: hal-03800934

<https://hal.science/hal-03800934v1>

Submitted on 6 Oct 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

High-Q Silicon-Germanium Ring Resonator for On-Chip Sensing Applications in the Mid-Infrared

Marko Perestjuk^{1,2,4}, Rémi Armand¹, Alberto Della Torre¹, Milan Sinobad¹, Arnan Mitchell², Andreas Boes², Jean-Michel Hartmann³, Jean-Marc Fedeli³, Vincent Reboud³, Christelle Monat¹, and Christian Grillet¹

¹Université de Lyon, Institut des Nanotechnologies de Lyon (INL, UMR-CNRS 5270), Ecole Centrale de Lyon, 69130 Ecully, France

²School of Engineering, RMIT University, Melbourne, VIC 3001, Australia

³Université Grenoble Alpes, CEA-Leti, 38054 Grenoble Cedex 9, France

⁴email: marko.perestjuk@ec-lyon.fr

Abstract: We report a high-Q ring resonator in a silicon-germanium on silicon chip-based platform for sensing applications in the mid-infrared. The side-coupled ring exhibits a loaded Q-factor of 90,000 at the operating wavelength around 4.18 μm .

© 2022 The Author(s)

1. Introduction

The mid-infrared (MIR) wavelength range (between 3 and 13 μm) has a large potential for sensing applications, as many molecules have strong fundamental absorption lines in this range [1]. However, the high cost and bulky MIR technology has prevented a real breakthrough so far. The integration of MIR components on-chip can provide a crucial step towards large scale applications.

Ring (and racetrack) resonators are playing a crucial role in a wide variety of different on-chip integrated sensing schemes. First, they can be used to generate frequency combs [2], and could thus provide a broadband MIR light source, which is essential for sensing (Fig. 1a). Second, rings can be used to enhance the interaction between the analyte molecules and the evanescent field of light confined in the ring [3] (Fig. 1b). This can be done using any light source, e.g. a comb again or a supercontinuum directly generated in the waveguide by its nonlinear properties [4]. Third, they can be used for direct sensing of molecules that change detectable properties of the ring as they effectively change the cladding of the ring (Fig. 1c). For example, the molecules can lead to a shift of the resonance wavelength (λ_0 to λ_{sh}) by changing the effective index of the mode propagating in the ring [5]. Or they can lead to change in the quality factor Q due to additional absorption [6]. In all these sensing schemes however, a high Q-factor is necessary.

Several ring resonators have been demonstrated in the MIR [7]. High Q-factors have been achieved predominantly on silicon-on-insulator (SOI, [8]) and silicon-on-sapphire (SOS, [9]) platforms, which, however, have high losses beyond ~ 3.5 μm and ~ 6.5 μm , respectively [1]. High-Q ring resonators in the MIR have been realized also with chalcogenide glass [10], although the material photosensitivity could translate in a low temporal device stability. In addition, group IV materials are preferable for cost-effective large scale fabrication.

Specifically silicon-germanium (SiGe) and germanium (Ge) are promising materials, thanks to their CMOS compatibility and transparency window up to 15 μm [1]. Low-loss SiGe waveguides operating in the MIR have been already demonstrated and their nonlinear properties were exploited for supercontinuum generation [4]. The same applies for Ge [11]. So far, however, only a few SiGe and Ge ring resonator demonstrations have been reported in the MIR, with moderate Q-factors of 1,672 [12], 3,200 [13] and 20,000 [14]. Here, we report a SiGe ring resonator coupled to a bus waveguide, with loaded Q-factor of 90,000 at 4.18 μm .

2. Fabrication and Ring Resonance Measurement

Our platform consists of an air-cladded 3.3 μm thick and 3.25 μm wide $\text{Si}_{0.6}\text{Ge}_{0.4}$ core waveguide on a silicon substrate (Fig. 2a). The resonators were fabricated on a 200 mm CMOS pilot line at CEA-Leti using deep ultraviolet photolithography and deep reactive ion etching. A ring radius of $R = 250$ μm (Fig. 2b) was chosen to target a free spectral range (FSR) of 53 GHz. The coupling gap between ring and bus waveguide is 250 nm.

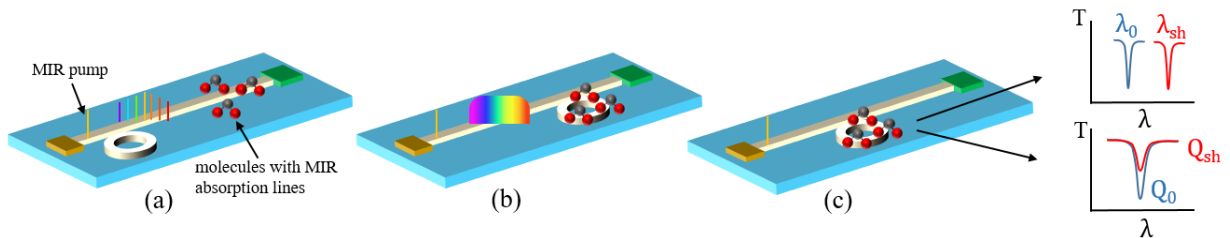


Fig. 1. Different use cases of ring resonator in sensing schemes. (a) Rings for frequency comb generation for sensing light sources. (b) Rings for interaction enhancement with any kind of light source (here: supercontinuum). (c) Rings for direct sensing through the detection of a resonance wavelength shift (top) or Q-factor shift (bottom) caused by the analyte.

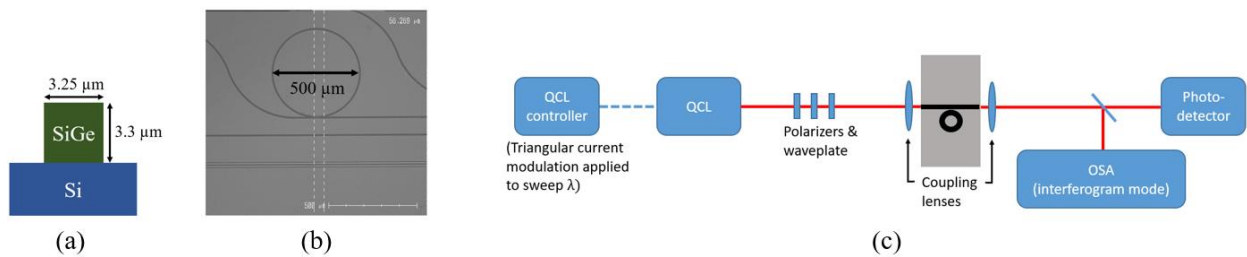


Fig. 2. (a) SiGe platform used for the ring resonator. (b) SEM picture of the ring resonator. (c) Measurement Setup.

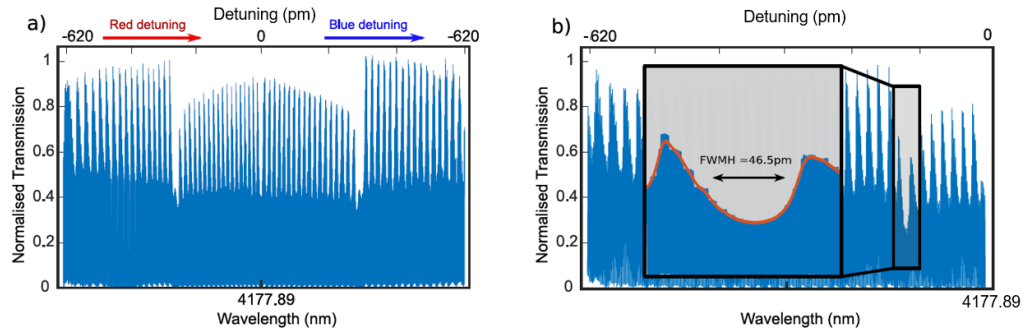


Fig. 3. (a) Wavelength scan (ramp up and ramp down) of the ring resonance with a cw QCL. The ring resonance at one specific wavelength can be clearly distinguished from the Fabry-Perot resonances, which occur due to the waveguide facet at input and output coupling. (b) Zoom-in on the ring resonance.

Fig. 2c shows a scheme of our measurement setup. The ring resonance characterization was done using an Adtech 4.18 μm distributed feedback quantum cascade laser (QCL) providing cw light. The out-coupled light was recorded by a Thorlabs Fourier transform optical spectrum analyzer (OSA). We did not utilize the spectral mode of the OSA but rather used it as a photodetector through the interferometry between the two delay beams to have less noise than with a normal photodetector. The emission wavelength of the QCL was modulated between 4177.27 nm and 4177.89 nm by applying a periodic triangular current modulation. The optical pump power was 20 mW (measured directly before the input coupling lens).

Fig. 3a shows one period of the modulation recorded by the interferogram mode of the OSA. Over the whole wavelength range there are pronounced Fabry-Perot resonances, which result from the cavity formed by the two end-facets of the access bus waveguide. Nonetheless, the ring resonance can be clearly distinguished on this plot: it manifests as an additional dip occurring twice, during the wavelength ramp up and the ramp down, respectively. Fig 3b shows a zoom-in of the ring resonance. From this resonance we could retrieve a total (loaded) quality factor of $Q = 90,000$. We did not determine yet if we are at critical coupling. In any case, for the intrinsic quality factor a value much higher than 10^5 is expected.

4. Conclusion

In conclusion, we have demonstrated a SiGe ring resonator operating around 4.18 μm , with a loaded Q-factor of 90,000. The operation at 4.18 μm was only limited by the availability of the QCL while SiGe allows for much longer wavelengths, so we expect to be able to demonstrate similar Q-factors deeper into the MIR. This results sets the basis for the use of SiGe ring resonators for on-chip MIR sensing applications.

Acknowledgements. We acknowledge the support of the International Associated Laboratory in Photonics between France and Australia (LIA ALPhFA) and the Agence Nationale de la Recherche (MIRSICOMB, ANR-17-CE24-0028). The ECLAUSion project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 801512.

6. References

- [1] R. Soref, "Mid-infrared photonics in silicon and germanium," *Nature Photonics* **4**, 495-497 (2010).
- [2] A. G. Griffith, *et al.*, "Silicon-chip mid-infrared frequency comb generation," *Nat Commun* **6**, 6299 (2015).
- [3] P. Ma, *et al.*, "High Q factor chalcogenide ring resonators for cavity-enhanced MIR spectroscopic sensing," *Opt Express* **23**, 19969-19979 (2015).
- [4] M. Sinobad, *et al.*, "Mid-infrared octave spanning supercontinuum generation to 85 μm in silicon-germanium waveguides," *Optica* **5** (2018).
- [5] Y. Sun, *et al.*, "Optical ring resonators for biochemical and chemical sensing," *Anal Bioanal Chem* **399**, 205-211 (2011).
- [6] C. J. Smith, *et al.*, "Sensing nitrous oxide with QCL-coupled silicon-on-sapphire ring resonators," *Opt Express* **23**, 5491-5499 (2015).
- [7] T. Hu, *et al.*, "Silicon photonic platforms for mid-infrared applications [Invited]," *Photonics Research* **5** (2017).
- [8] S. A. Miller, *et al.*, "Low-loss silicon platform for broadband mid-infrared photonics," *Optica* **4** (2017).
- [9] R. Shankar, *et al.*, "Integrated high-quality factor silicon-on-sapphire ring resonators for the mid-infrared," *Applied Physics Letters* **102** (2013).
- [10] H. Lin, *et al.*, "Demonstration of high-Q mid-infrared chalcogenide glass-on-silicon resonators," *Opt Lett* **38**, 1470-1472 (2013).
- [11] A. Della Torre, *et al.*, "Mid-infrared supercontinuum generation in a low-loss germanium-on-silicon waveguide," *APL Photonics* **6** (2021).
- [12] B. Troia, *et al.*, "Germanium-on-silicon Vernier-effect photonic microcavities for the mid-infrared," *Opt Lett* **41**, 610-613 (2016).
- [13] J. M. Ramirez, *et al.*, "Broadband integrated racetrack ring resonators for long-wave infrared photonics," *Opt Lett* **44**, 407-410 (2019).
- [14] S. Radosavljevic, *et al.*, "Mid-infrared Vernier racetrack resonator tunable filter implemented on a germanium on SOI waveguide platform [Invited]," *Optical Materials Express* **8** (2018).