Grenoble

Infrared GeSn photodetectors: new avenues in monolithic Si photonics

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Polytechnique Montréal, Canada

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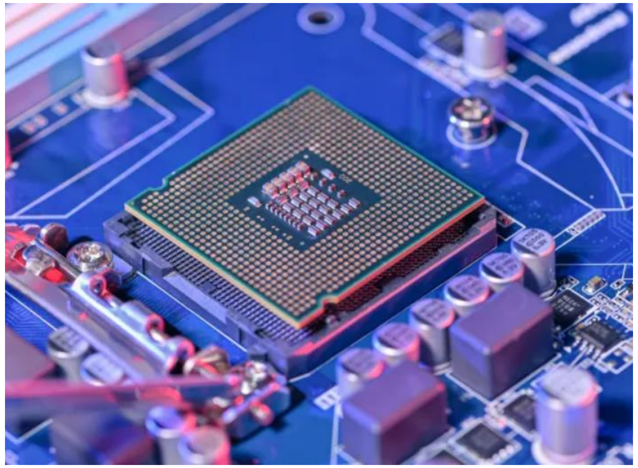
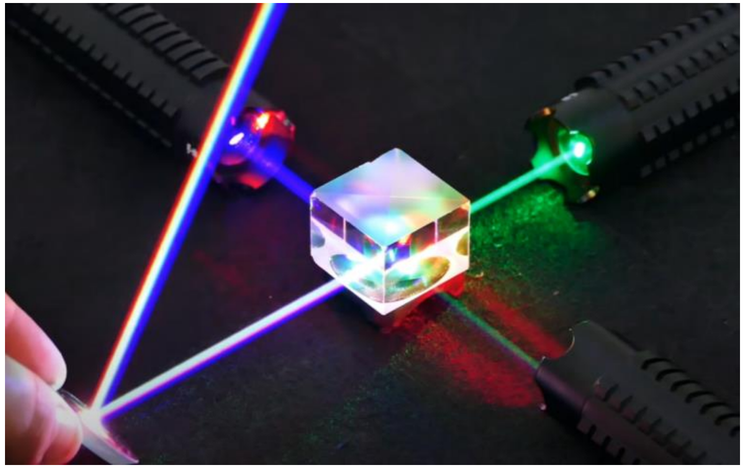
Electronics



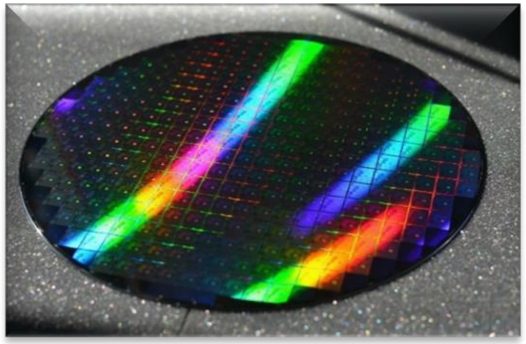
Silicon photonics

Optics



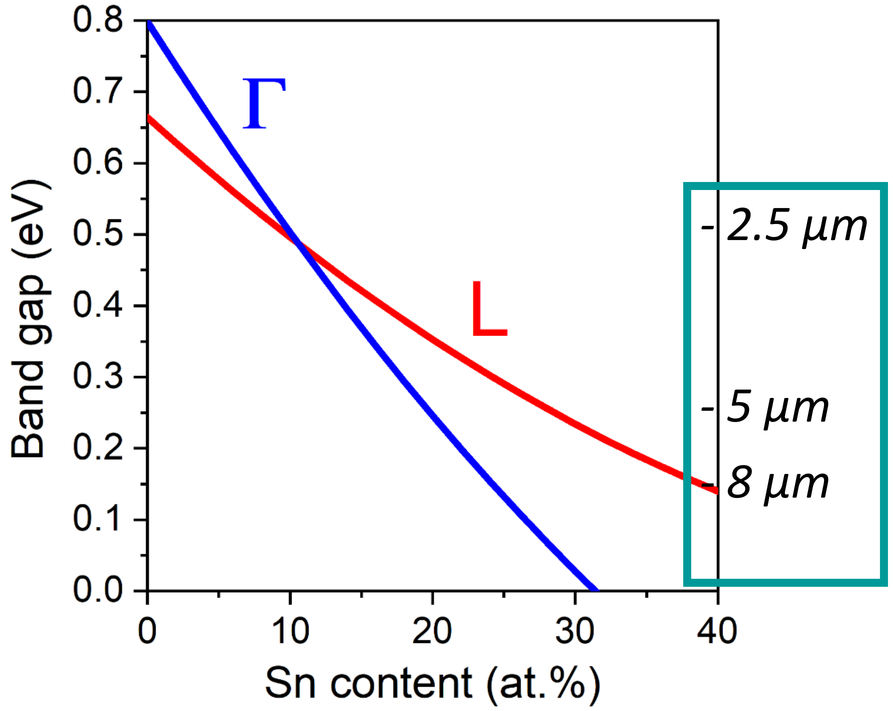
Monolithic integration on a Si wafer:

- Scalable fabrication
- CMOS compatibility
- Cost reduction
- Wide-scale adoption



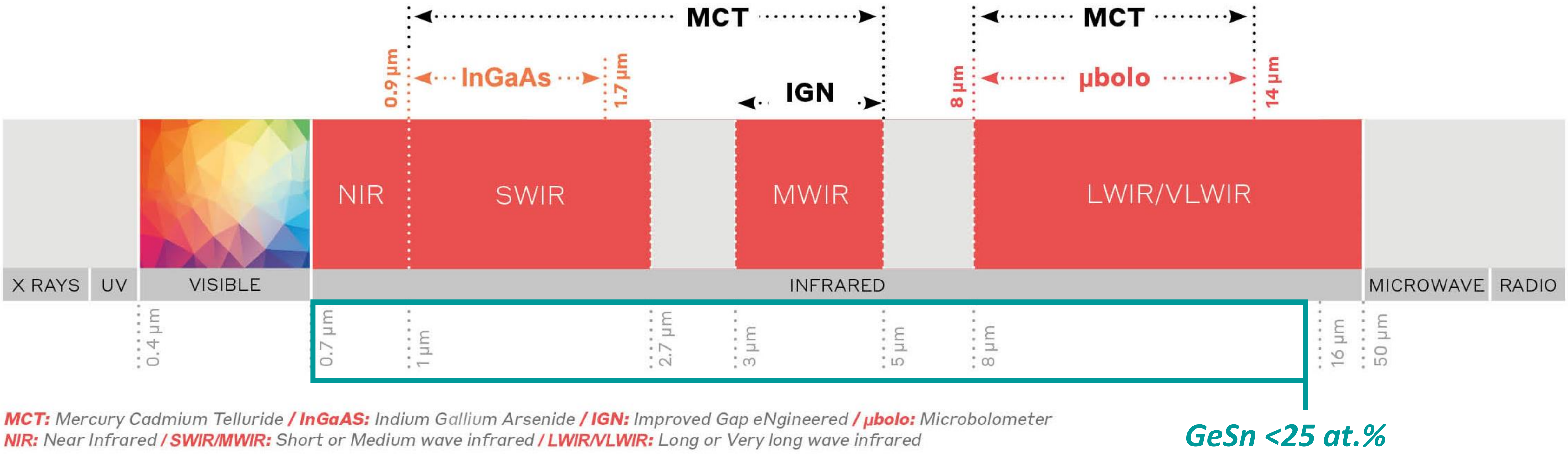
Sn-based group IV semiconductors

- Si, Ge: indirect band gap → Low efficiency light emission, high performance detectors.
- GeSn alloys: indirect to direct band gap transition >9 at.% Sn.
- SiGeSn alloys: incorporate Si to increase the band gap and engineer barrier layers.
- Design high efficiency infrared photonic devices on Si.



A. Attiaoui *et al.*, *J. Appl. Phys.* **116** (2014)

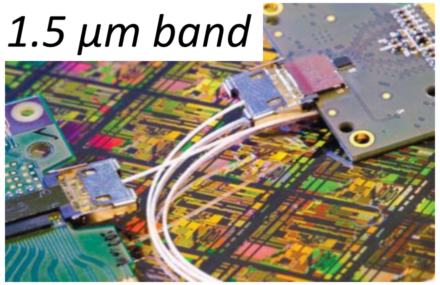
Infrared photonics

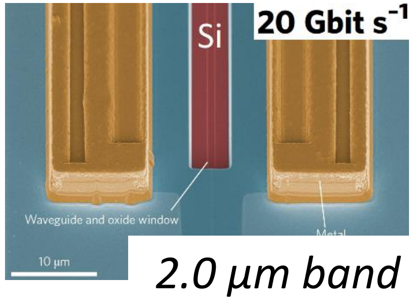


- GeSn in an exceptional infrared photonics platform on Si that can compete with III-V and II-VI technologies.

Infrared photonics

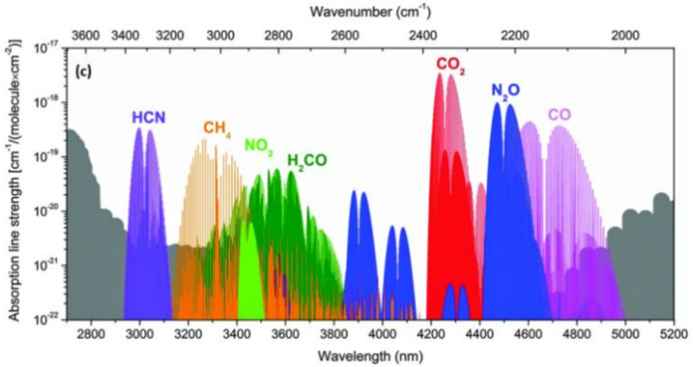
Data communications



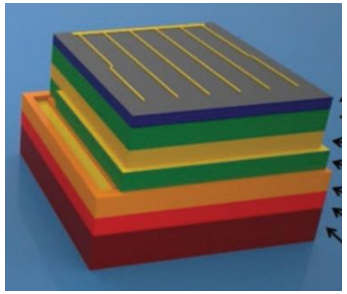


J.J. Ackert, *Nature Phot.* **9** (2015)

Chemical sensing



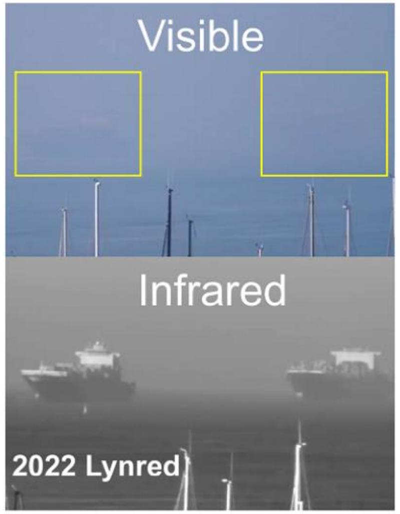
Multi-junction solar cells



M.P. Lumb, *Adv. Ener. Mat.* 1700345 (2017)

Free-space imaging

SWIR



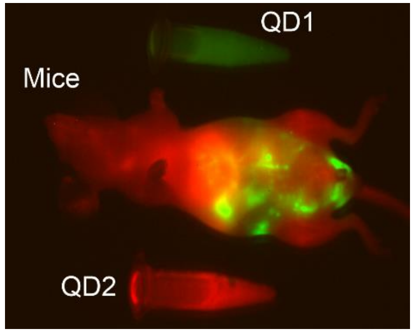
MWIR/LWIR

Food inspection

VIS

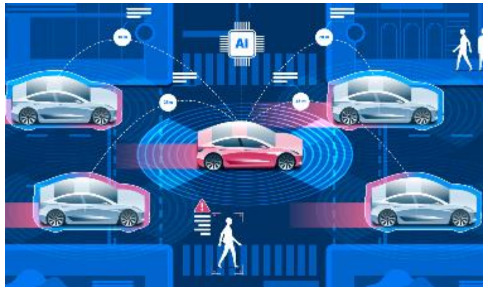
SWIR

In vivo



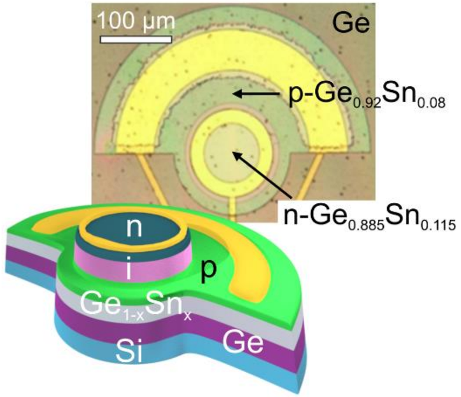
F. Wang, *Nature Nanotech.* **17** (2022)

LIDAR



(Si)GeSn photonic devices

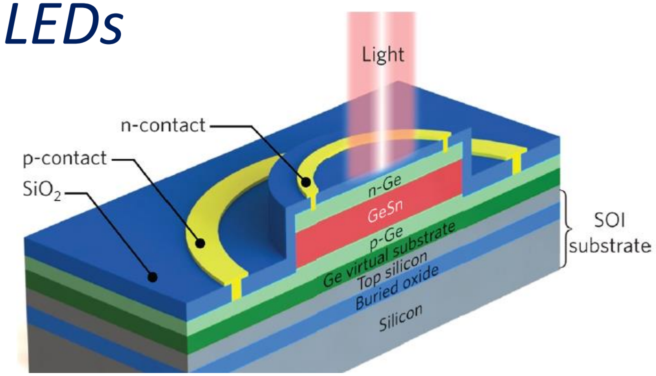
Detectors



H. Tran *et al.*, *ACS Phot.* **6** (2019)
M.R.M. Atalla *et al.*, *ACS Phot.* **9**, 4 (2022)

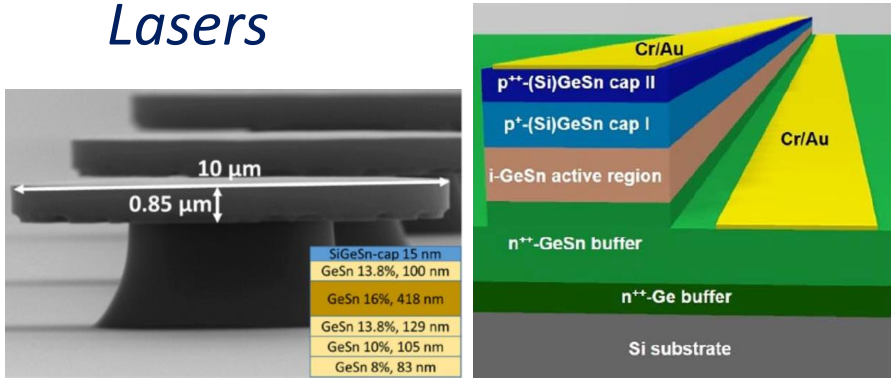
Emitters

LEDs



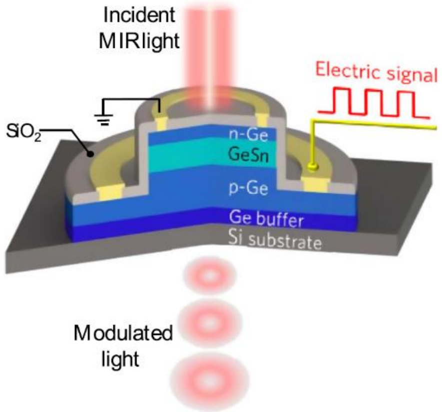
B.-J. Huang *et al.*, *ACS Phot.* **6** (2019)

Lasers



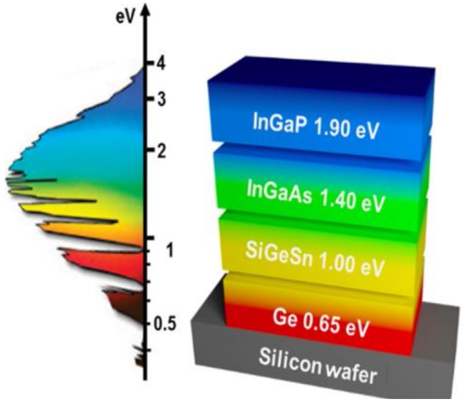
S. Wirths *et al.*, *Nature Phot.* **9** (2015)
A. Elbaz *et al.*, *Nature Phot.* **14** (2020)
Y. Zhou *et al.*, *Optica* **7** (2020), *Phot. Res.* **10** (2022)

Optical modulators



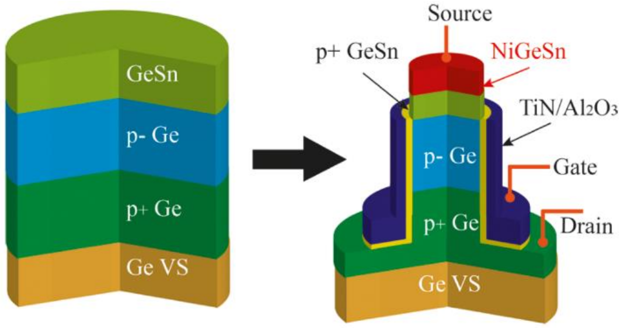
Y.-D. Hsieh *et al.*, *Comm. Mat.* **2** (2021)

Photovoltaics



G. Timó *et al.*, *Sol. Ener. Mat. & Sol. Cells* **224**, 111016 (2021).

Transistors



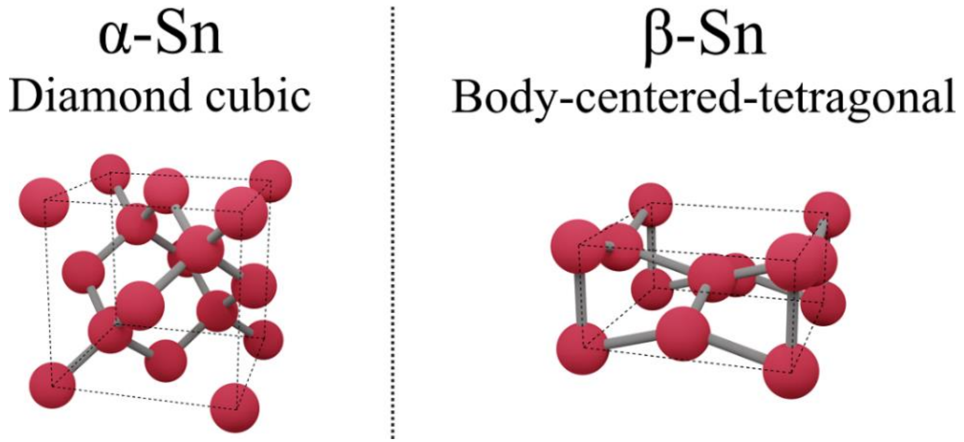
M. Liu *et al.*, *ACS Appl. Nano Mater.* **4** (2021)
M. Liu *et al.*, *Comm. Eng.* **2** (2023)

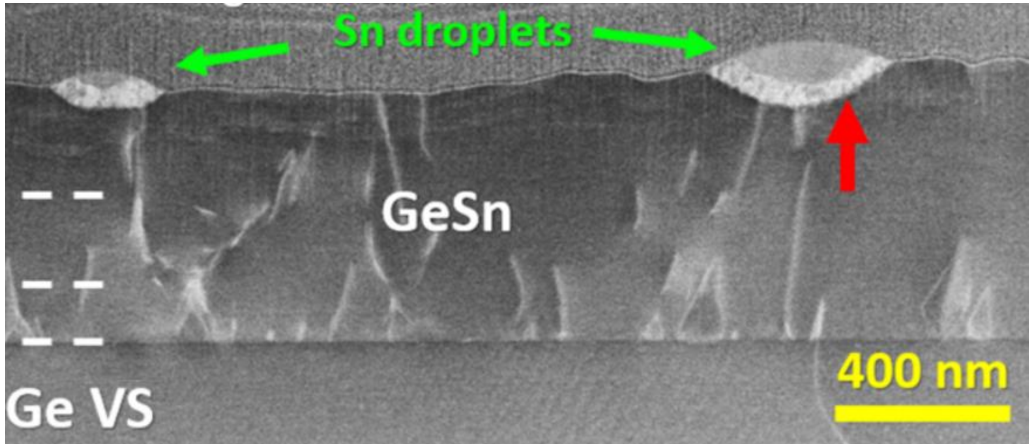
GeSn challenges

1. Low equilibrium solubility of Sn in Ge (~1 at.%).

→ **<u>Metastable</u>** material!

2. Spontaneous phase transition from α-Sn into β-Sn above 13 °C.





J. Nicolas *et al.*, *Cryst. Growth Des.* **20**, 5 (2020)

3. Lattice mismatch Ge and α-Sn up to 14 % → Strain relaxation via dislocations.

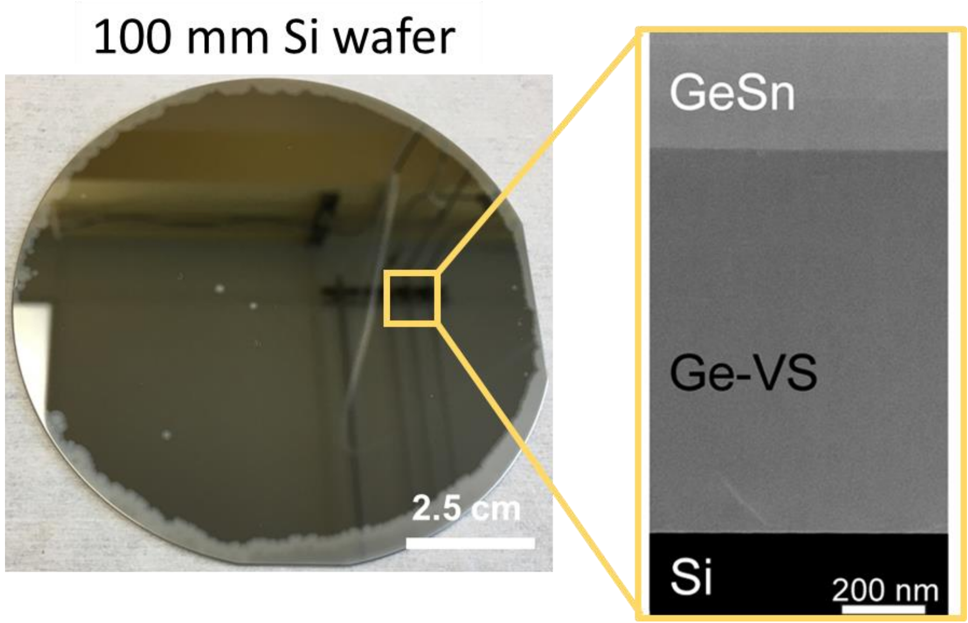
GeSn thin films epitaxy on Si

- Growth in a 100 mm CVD showerhead reactor and H_2 atmosphere.

- Precursors for SiGeSn:
  - Germane (GeH_4)
  - Tin-Tetrachloride ($SnCl_4$)
  - Disilane (Si_2H_6)

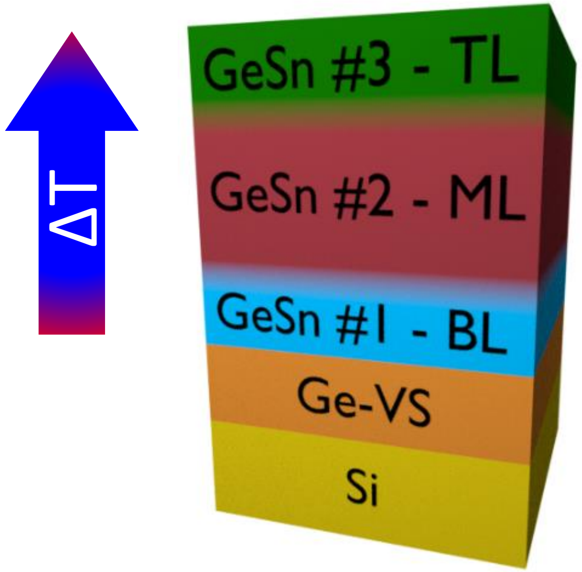
- Doping:
  - Diborane (B_2H_6)
  - Arsine (AsH_4)

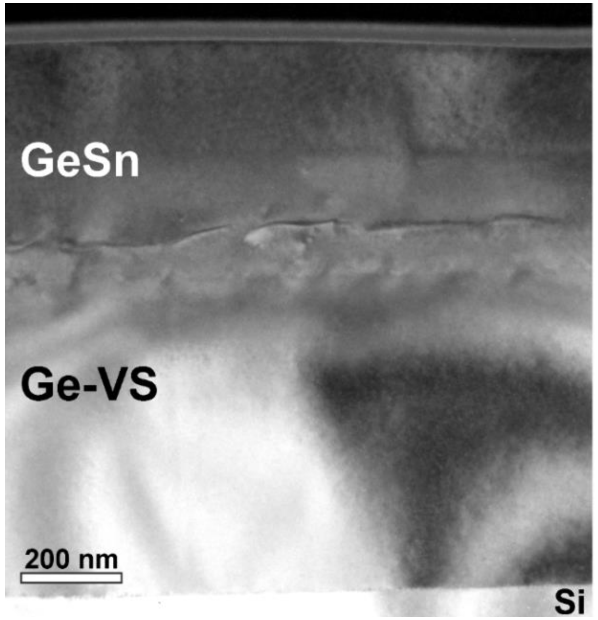
- Isotopically-enriched precursors:
  - $^{28,29,30}SiH_4$, $^{70}GeH_4$

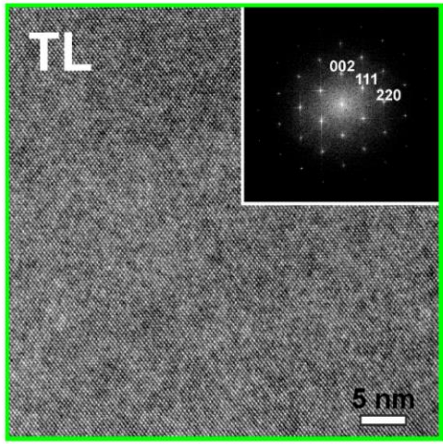


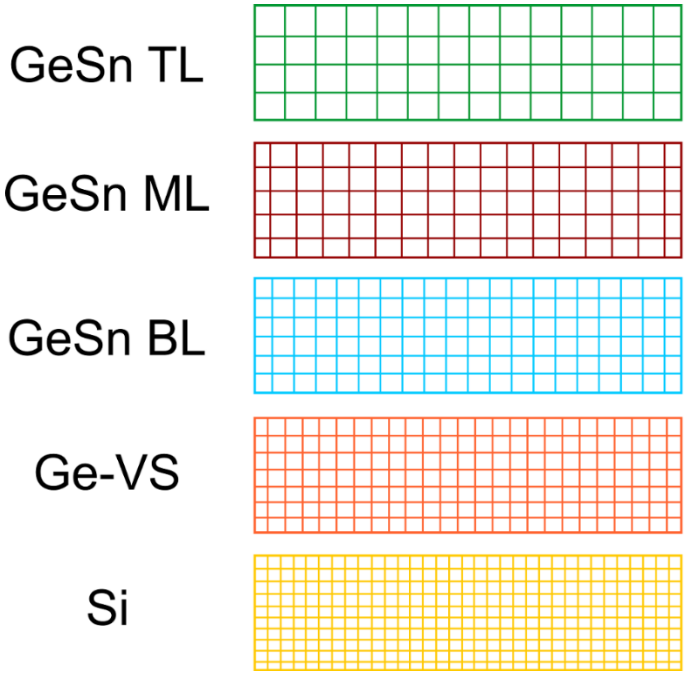
How to boost the Sn incorporation in Ge?

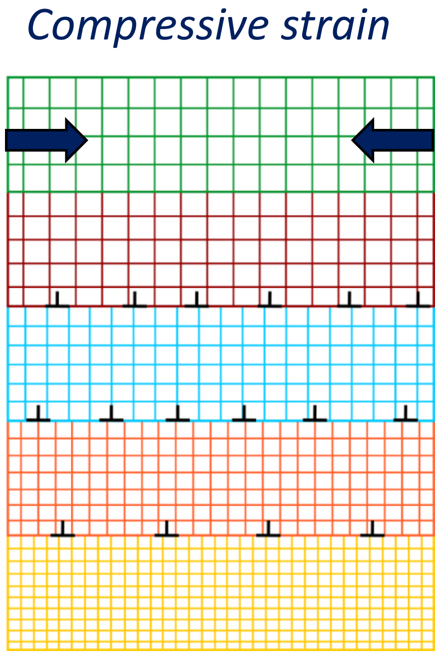
1. Temperature: increase 1-2 at.% Sn every -10 °C.
2. Strain relaxation: multiple buffer layers.
3. Sn/Ge ratio in gas phase.







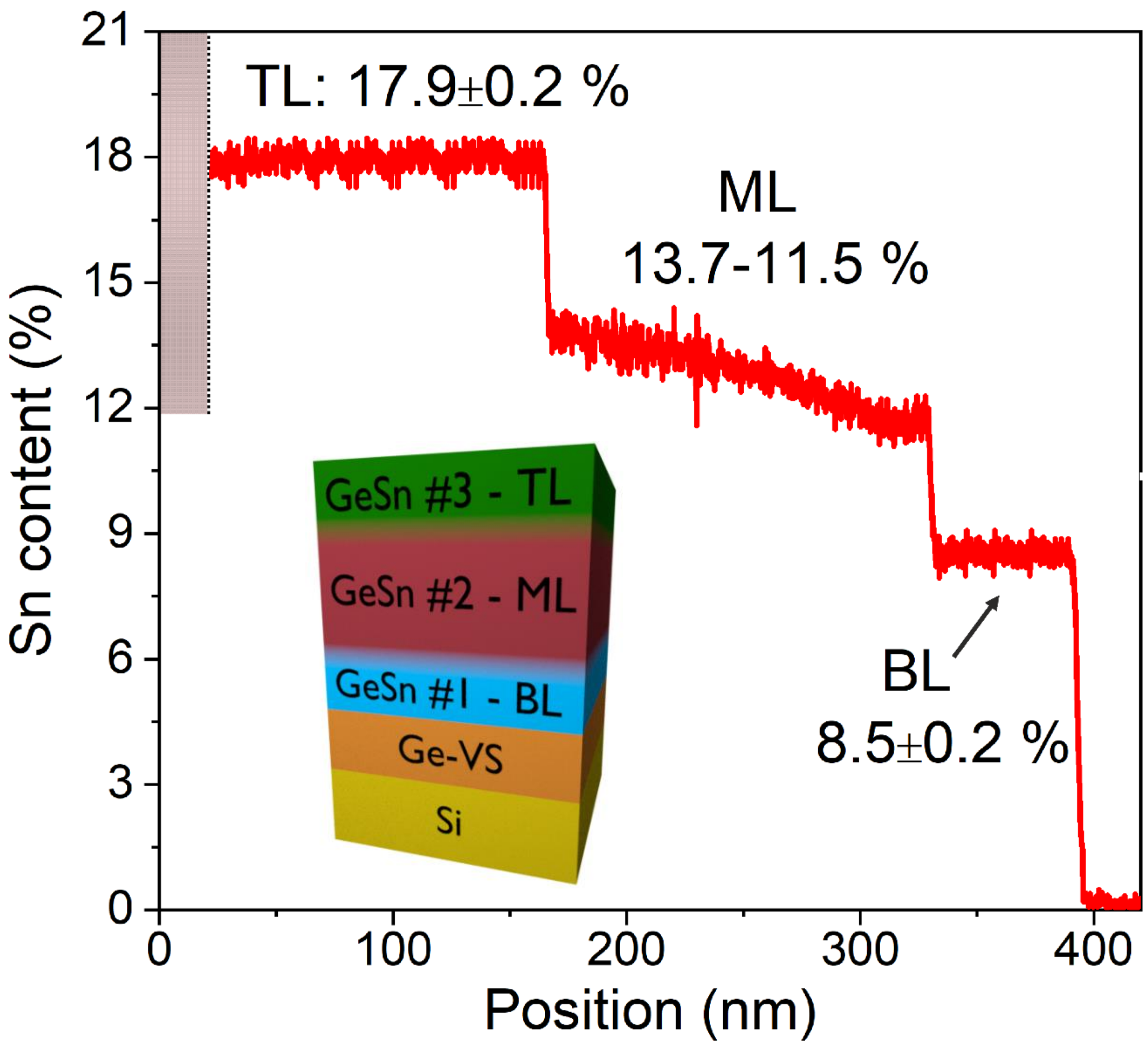


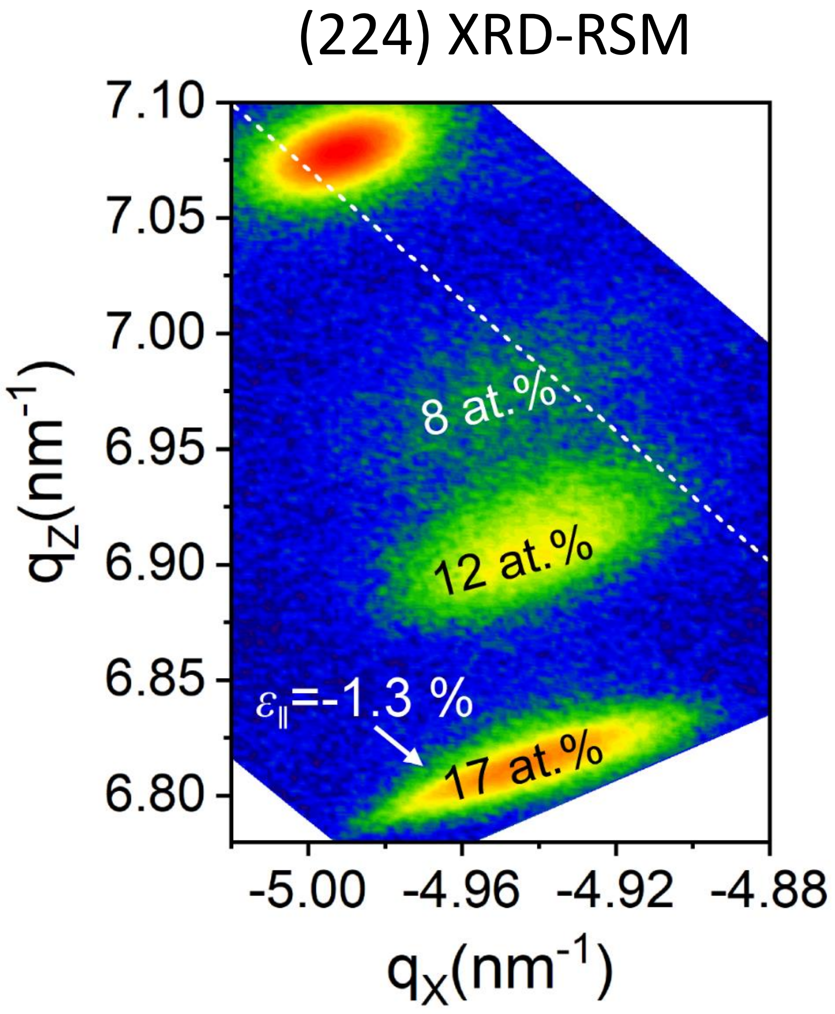


S. Assali *et al.*, *Appl.Phys.Lett.* **112**, 251903 (2018)
S. Assali *et al.*, *J. Appl. Phys.* **125**, 025304 (2019)
E. Bouthillier, S. Assali *et al.*, *Phys. Rev. Appl.* **35**, 095006 (2020)

GeSn thin films epitaxy on Si

- Up to 17 at.% Sn and uniform composition.
- Compressive strain $\varepsilon_{||}$ = -1.3 %.

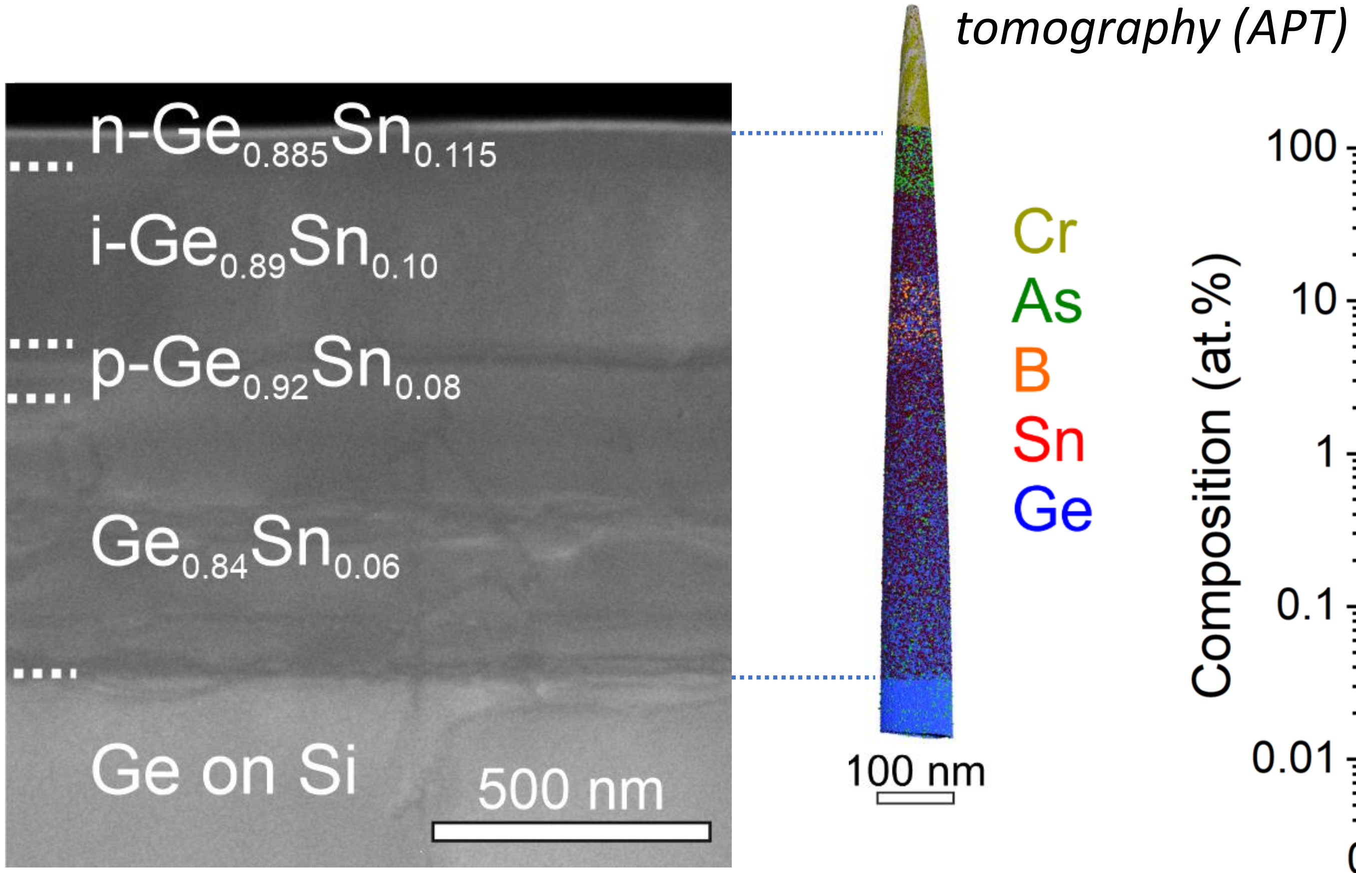


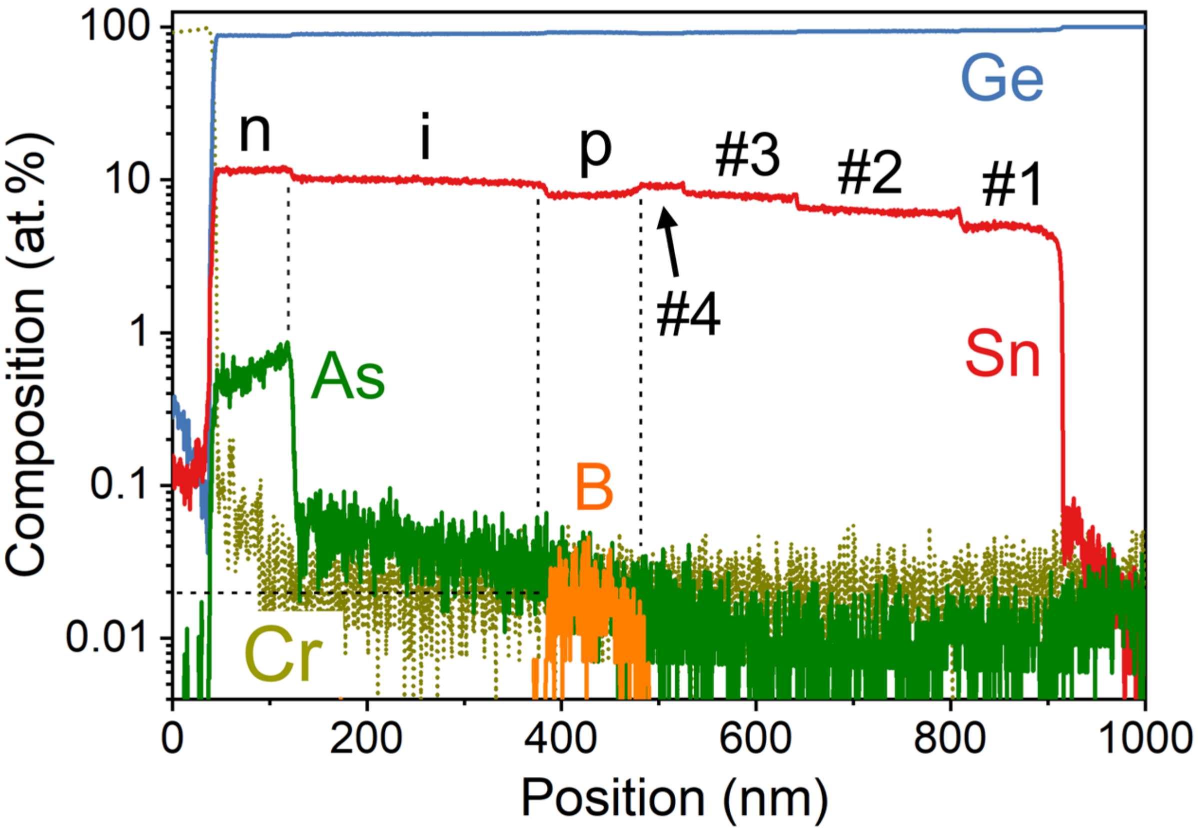


E. Bouthillier, S. Assali *et al.*, Semicond. Sci. Technol., **35** (2020)
S. Assali *et al.*, *J. Appl. Phys.* **125**, 025304 (2019)
S. Assali *et al.*, *Appl. Phys. Lett.* **112**, 251903 (2018)

GeSn thin films photodetectors

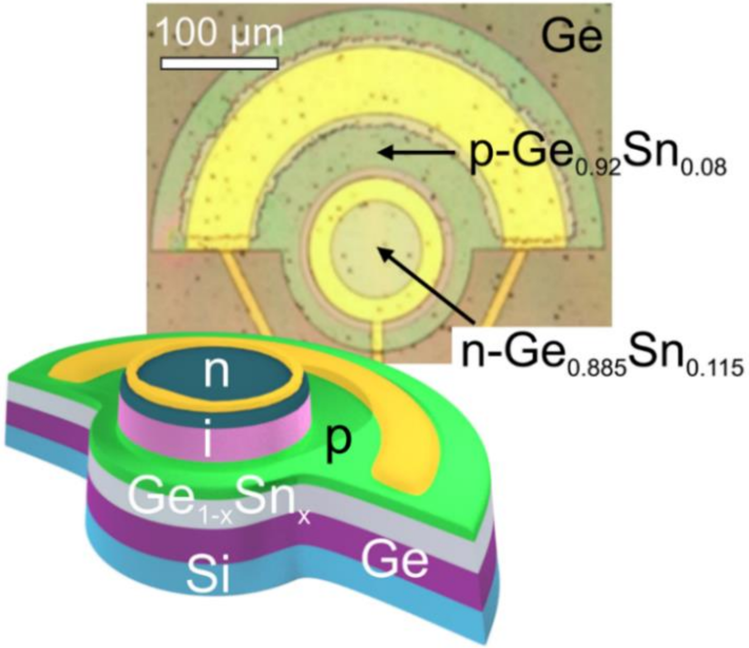
- PIN photodiodes with B (p-type) and As (n-type) dopants.
- i-layer: 10 at.% Sn.



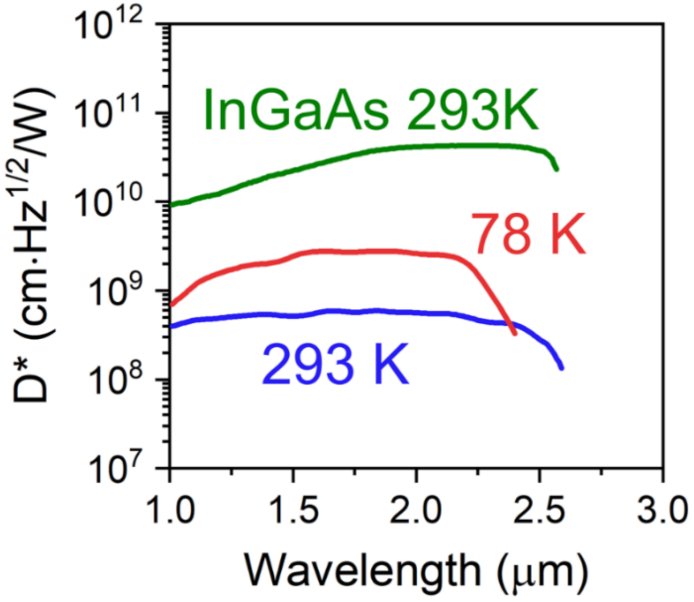


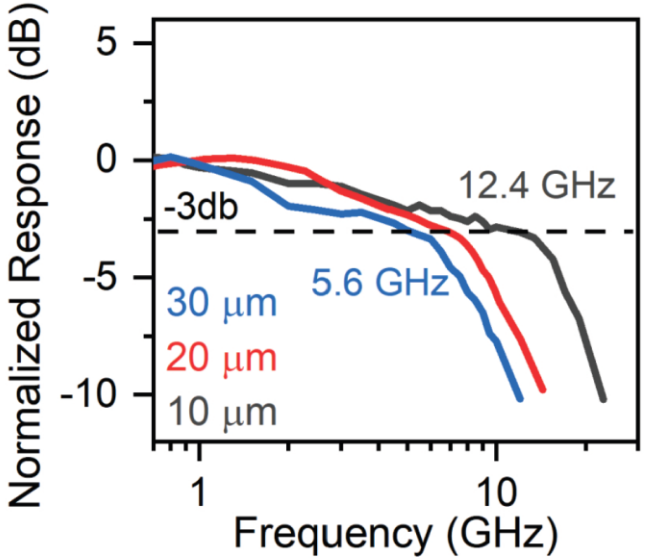
M.R.M. Atalla, S. Assali *et al.*, *ACS Phot.* **9**, 4 (2022)

GeSn thin films photodetectors



Uncooled device @ 2.6 µm, 12.4 GHz



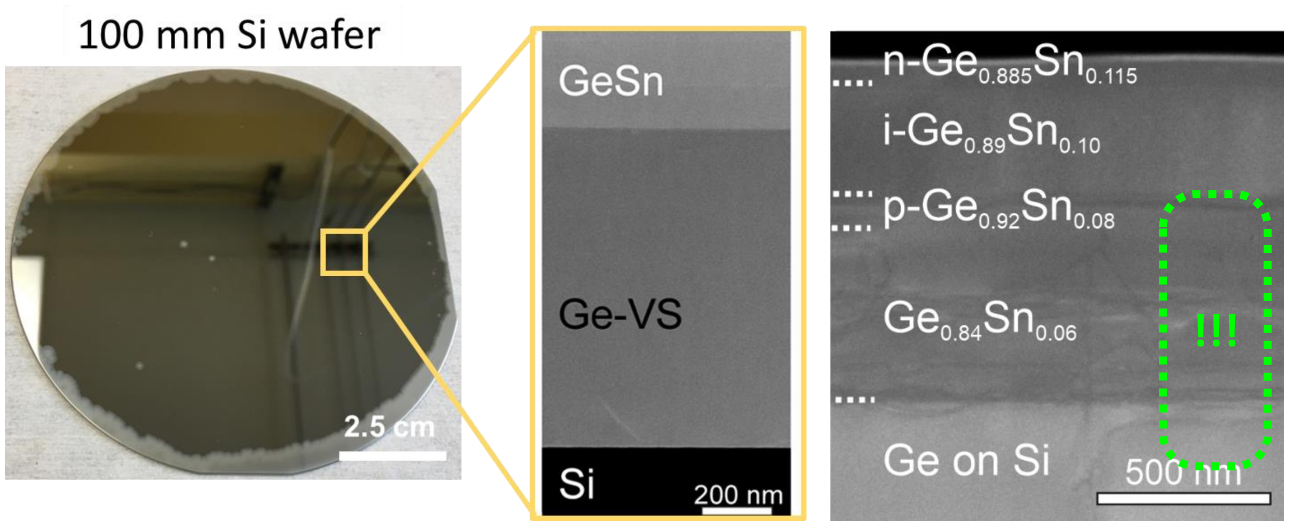


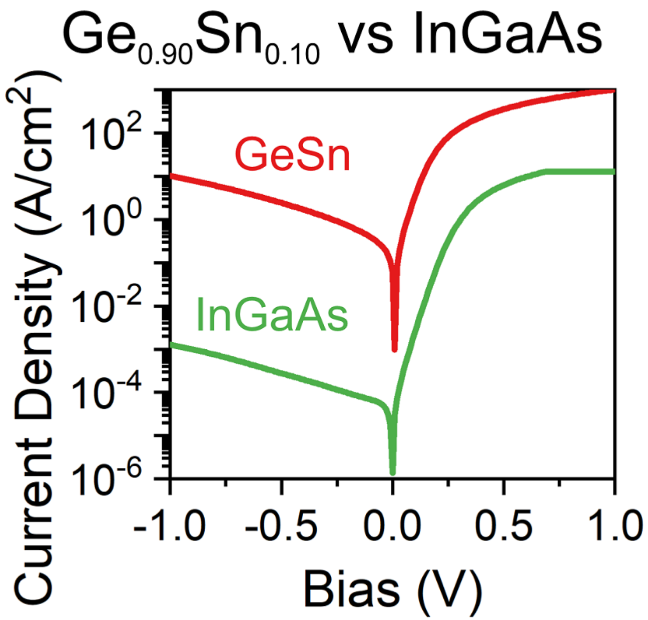
- Excellent performance for a new technology (<10 years old).
- No III-V, II-VI semiconductor technologies can offer similar speed at 2.5 µm at 300 K.

M.R.M. Atalla, …, S. Assali *et al.*, *APL Phot.* **9**, 5 (2024)
M.R.M. Atalla, S. Assali *et al.*, *Appl. Phys. Lett.* **122**, 3 (2023)
M.R.M. Atalla, S. Assali *et al.*, *ACS Phot.* **9**, 4 (2022)
M.R.M. Atalla, S. Assali *et al.*, Adv. Func. Mat. **31**, 2006329 (2021)

GeSn thin films photodetectors

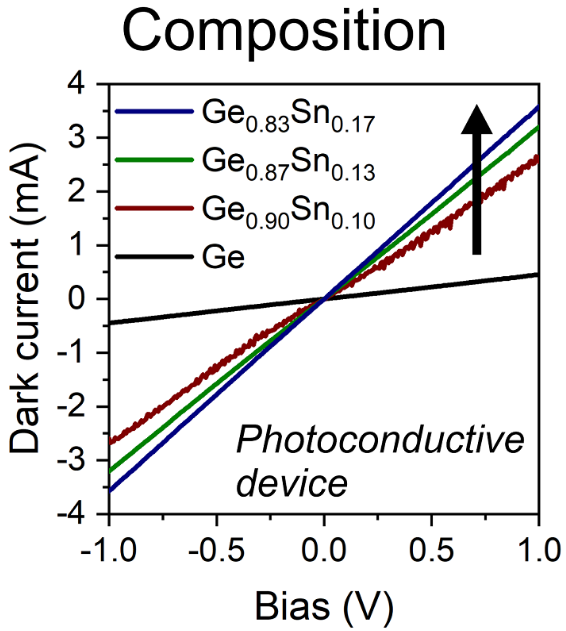
Materials growth p-i-n junction





x <u>Challenge</u>: lattice-mismatch results in defective layers and very high dark current, suppressing efficiency.

- Improving material quality is essential for next generation devices.



M.R.M. Atalla, …, S. Assali *et al.*, *APL Phot.* **9**, 5 (2024)
M.R.M. Atalla, S. Assali *et al.*, *Appl. Phys. Lett.* **122**, 3 (2023)
M.R.M. Atalla, S. Assali *et al.*, *ACS Phot.* **9**, 4 (2022)
M.R.M. Atalla, S. Assali *et al.*, Adv. Func. Mat. **31**, 2006329 (2021)

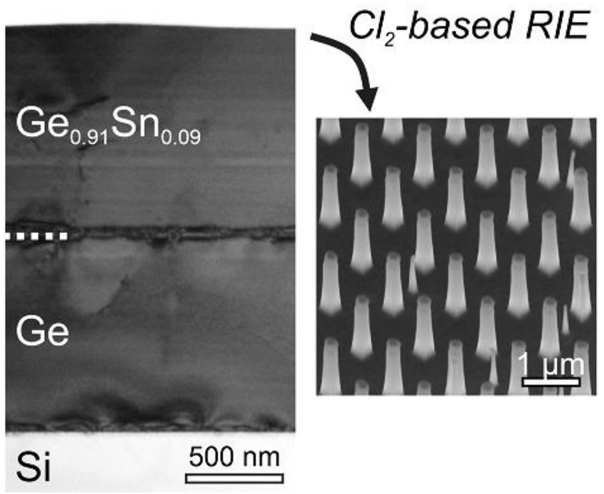
CEA approach: top-down etched NW arrays

- Fabrication: e-beam lithography + reactive ion etching.
- Control the NWs diameters, pitch, and tapering.

Advantages of the NW array devices:

- Enhanced light absorption.
- Tune the resonant peaks with NW parameters.
- Reduced dark current.
- Si-compatible wafer-level fabrication processes.

- **Goal of the PhD thesis of T. Willoquet (PhD)**: exceed thin films device efficiency by 10-100 times and unlock compact, uncooled NW-based photodetectors.



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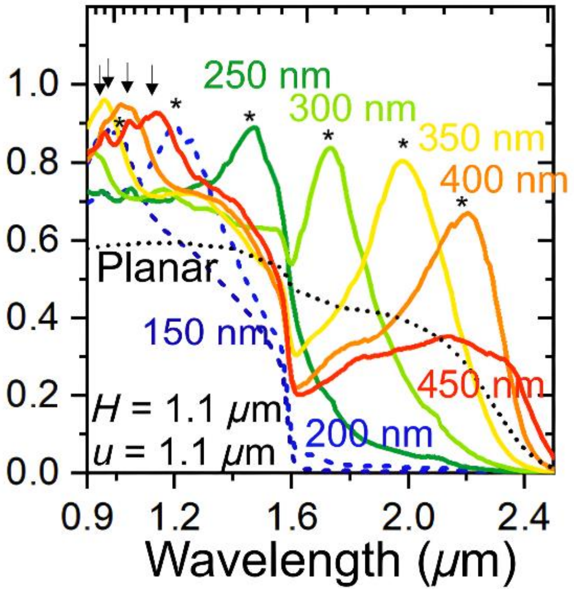
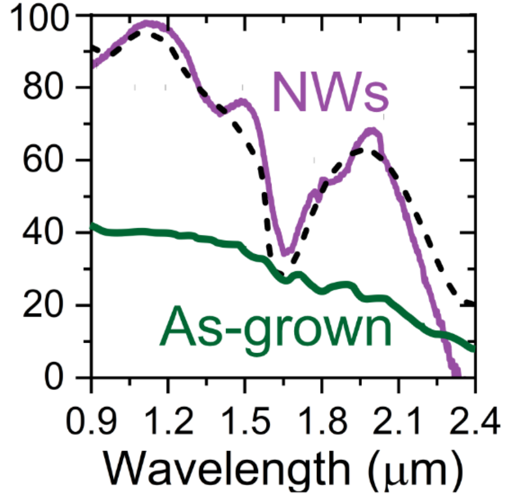
Simulation



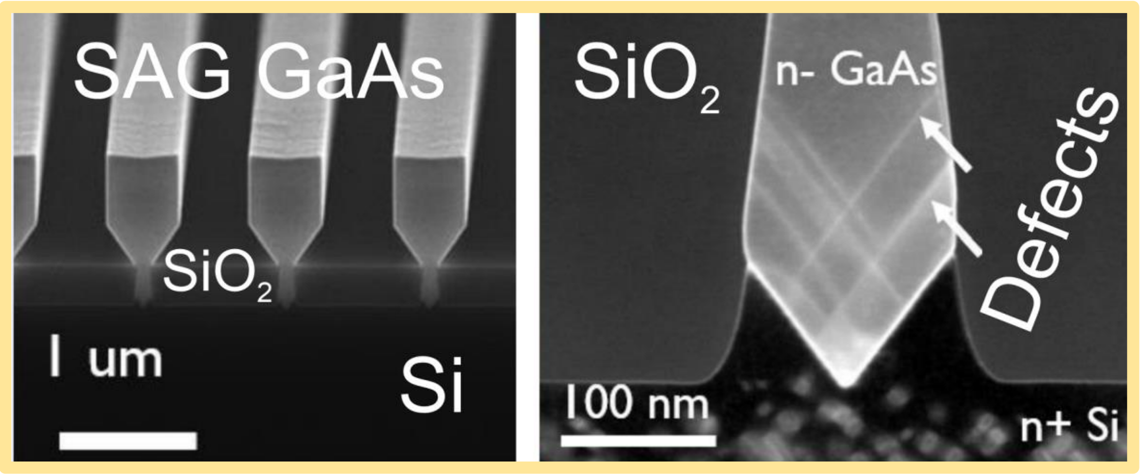
Measurement



A. Attiaoui, S. Assali *et al.*, *Phys. Rev. Appl.* **15**, 014034 (2021)

The future of GeSn: selective area growth (SAG)

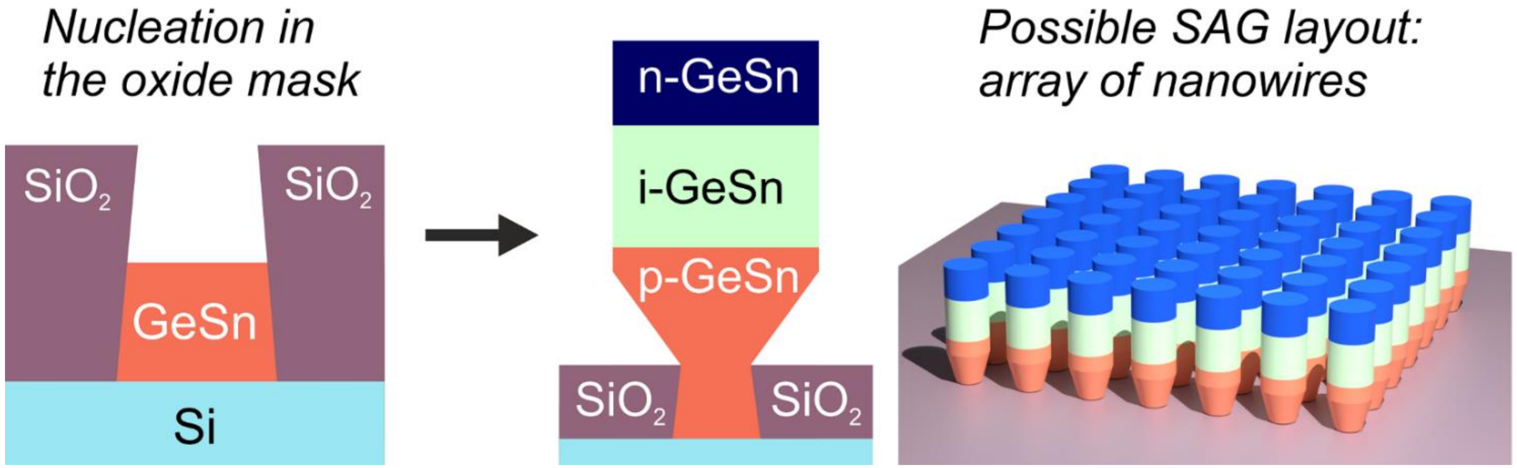
- Filtering dislocations in the oxide mask will result in **defect-free** GeSn devices.



Y. De Koninck *et al.* arXiv:2309.04473 (2024)

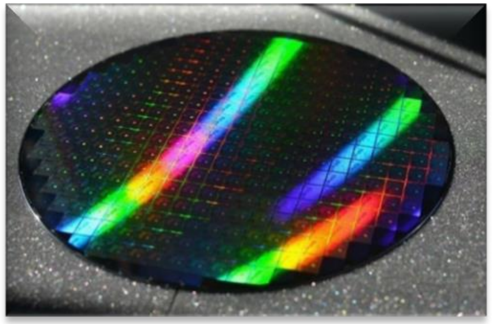
PhD position open! ☺

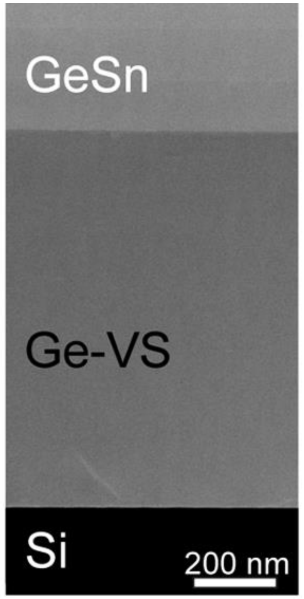
Starting date by Oct 1st.

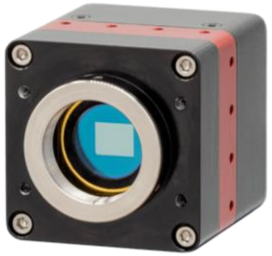


Sn-rich group IV semiconductors

- A rich playground for materials science, photonics, and quantum technologies.
- By controlling composition and dimensionality we can unveil novel material properties.
- Free-space optical technologies are at reach with GeSn semiconductors.
- Yet, fundamental knowledge on material and device properties is missing.







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Thank you for your attention!

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Nicolas Rotaru
Gabriel Fettu

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Anis Attiaoui
Lu Luo

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GeSn detectors
Théophile Willoquet (PhD student)
Nicolas Pauc
Vincent Calvo

MBE+CVD epitaxy
Pascal Gentile

cea leti

CVD epitaxy
Jean-Michel Hartmann