Substrate Orientation Mediated Epitaxial GeSn Optoelectronic Materials

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6th Tri-Service Workshop on GeSn and GeSiSn, Oct 25-26, 2023, Colorado Springs

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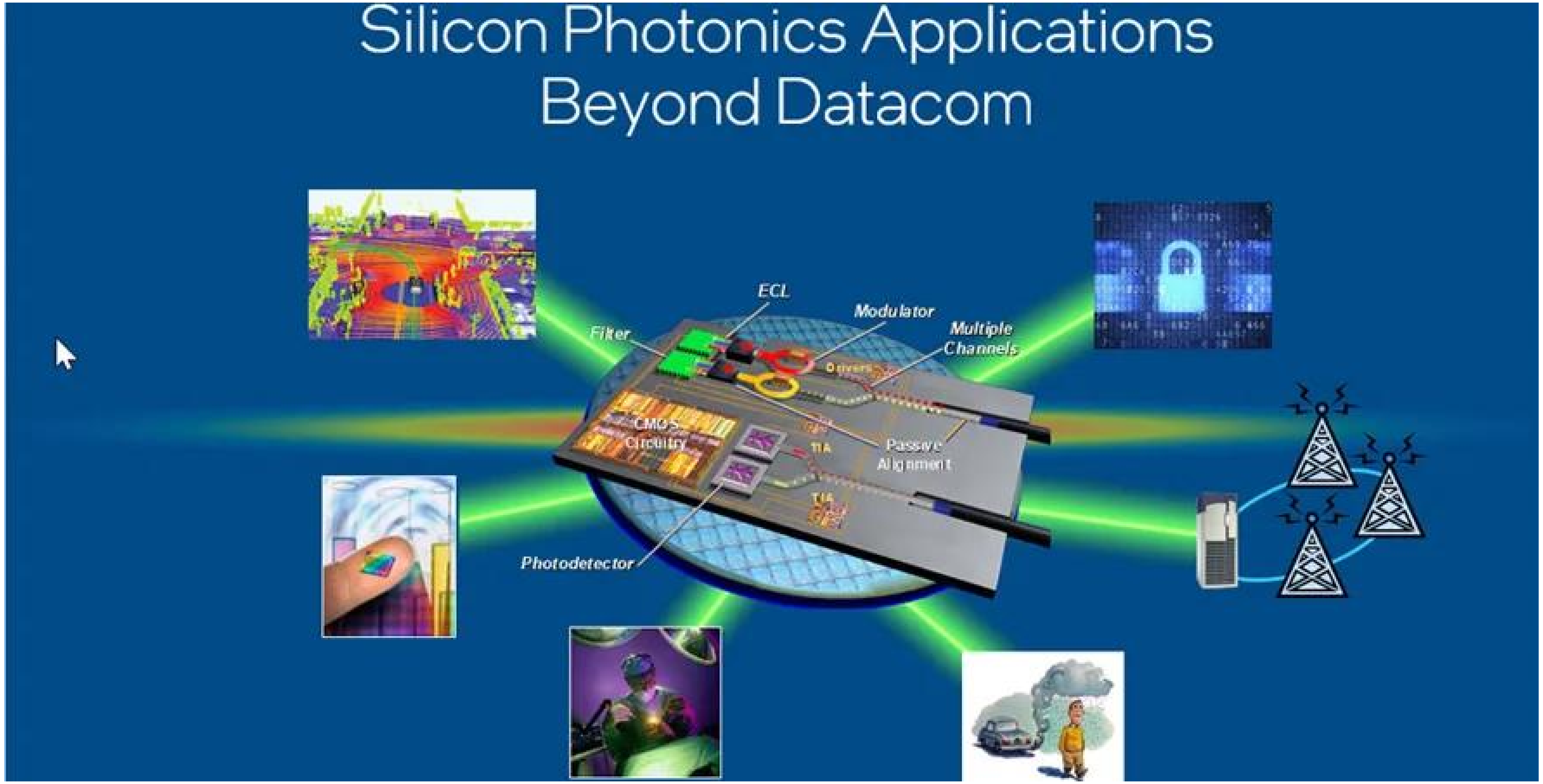
Ack: NSF ECCS- 2042079

Outline

- Update from 5th Tri-Service GeSn and SiGeSn workshop
- Substrate orientation mediated GeSn materials
  - GeSn materials synthesis
  - X-ray, TEM, and Raman analysis
  - Carrier lifetime *via* microwave photoconductive decay (μ-PCD)
  - Interface modeling by QuantumATK
- Summary

TSMC teams with Nvidia, Broadcom on Silicon Photonics

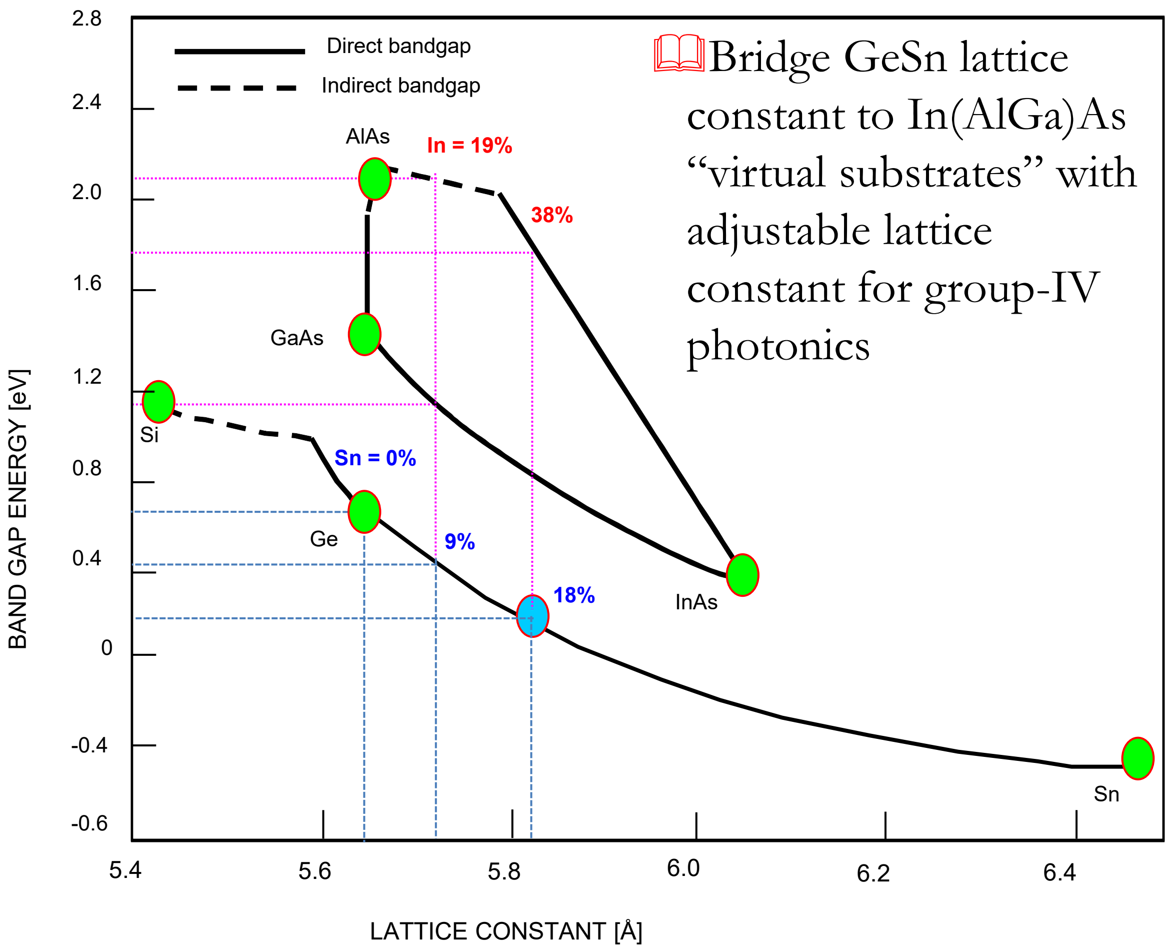


TSMC has formed a silicon photonics R&D team of 200 engineers to work with Nvidia Corp. and Broadcom to target AI in the data centre

September 12, 2023

https://semiwiki.com/forum/index.php?threads/tsmc-attacks-silicon-photonics.18758/

Epitaxial ε-Ge and GeSn : Lattice Mismatch



Challenges:

❶ ~15% lattice mismatch between Ge and Sn

❷ Defects and misfit dislocations

❸ Reduced carrier lifetime

Defects mitigation approaches:

❶ Lattice matched structure

❷ Pseudomorphic growth

❸ Epitaxial lift-off the device layer

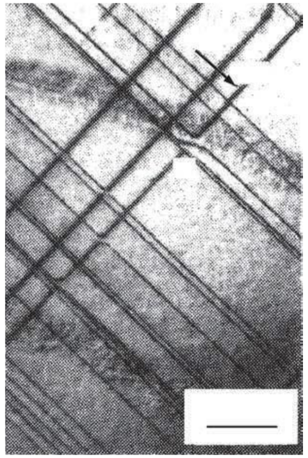
InAlAs, InGaAs, In(AlGa)As are lattice matched layer options

Defect Microstructures: Epitaxial InGaAs, SiGe, ε-Ge

$In_xGa_{1-x}As/GaAs$

[ref: 1]

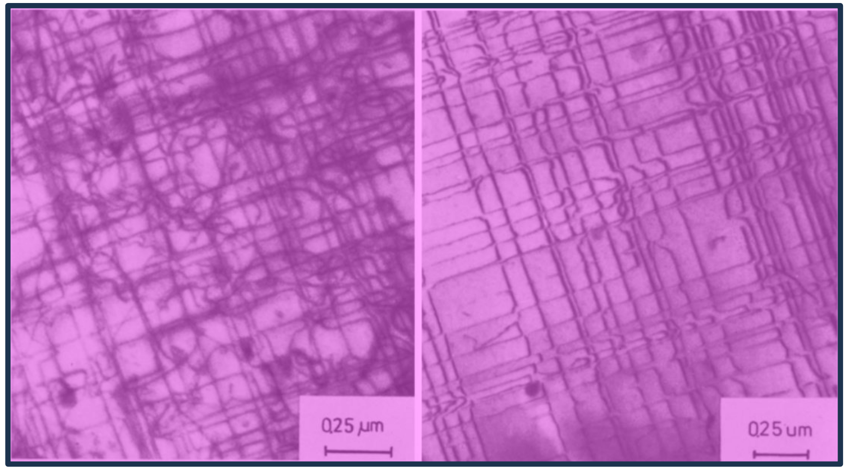
(a): 1 μm $In_{0.1}Ga_{0.9}As/GaAs$ (MDs only)



(b): 20 nm $In_{0.2}Ga_{0.8}As/GaAs$ (MDs only)

[ref: 2]

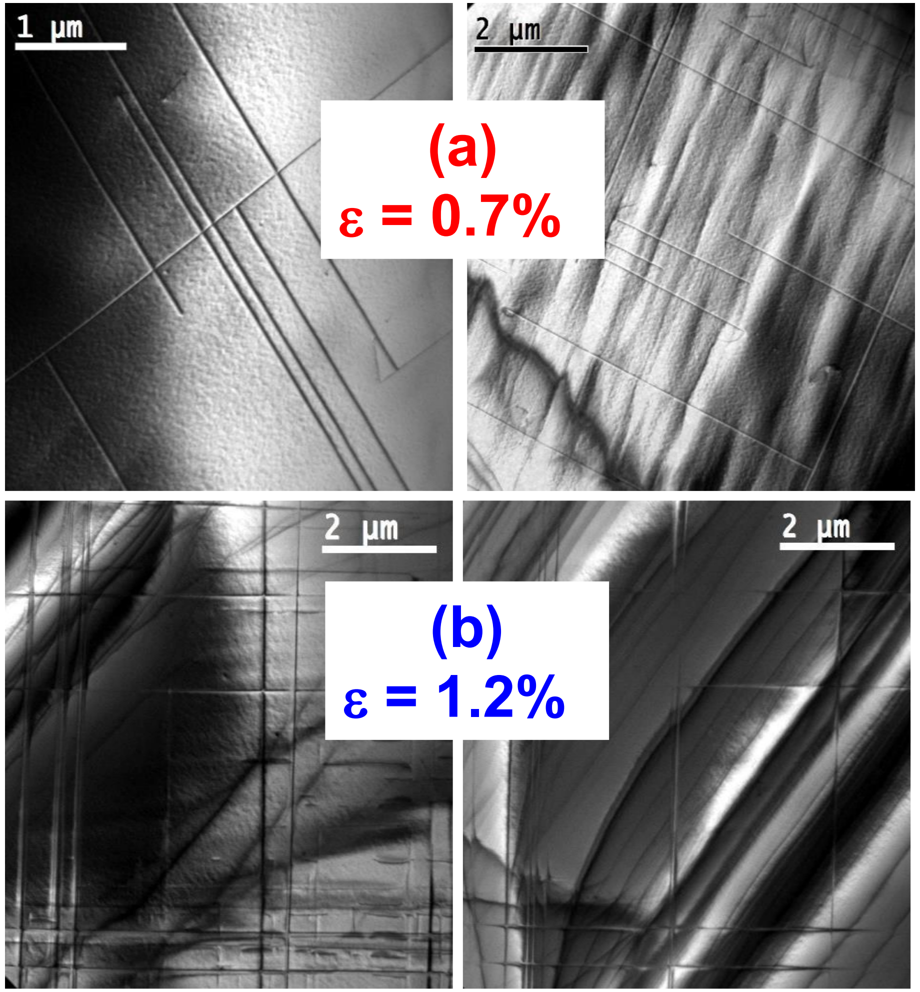
$Si_{0.85}Ge_{0.15}/Si$



(c): 1 μm $Si_{0.85}Ge_{0.15}/Si$ (MDs + TDDs @700°C)

(d): 1 μm $Si_{0.85}Ge_{0.15}/Si$ (MDs only @ 750°C)

[ref: 3]

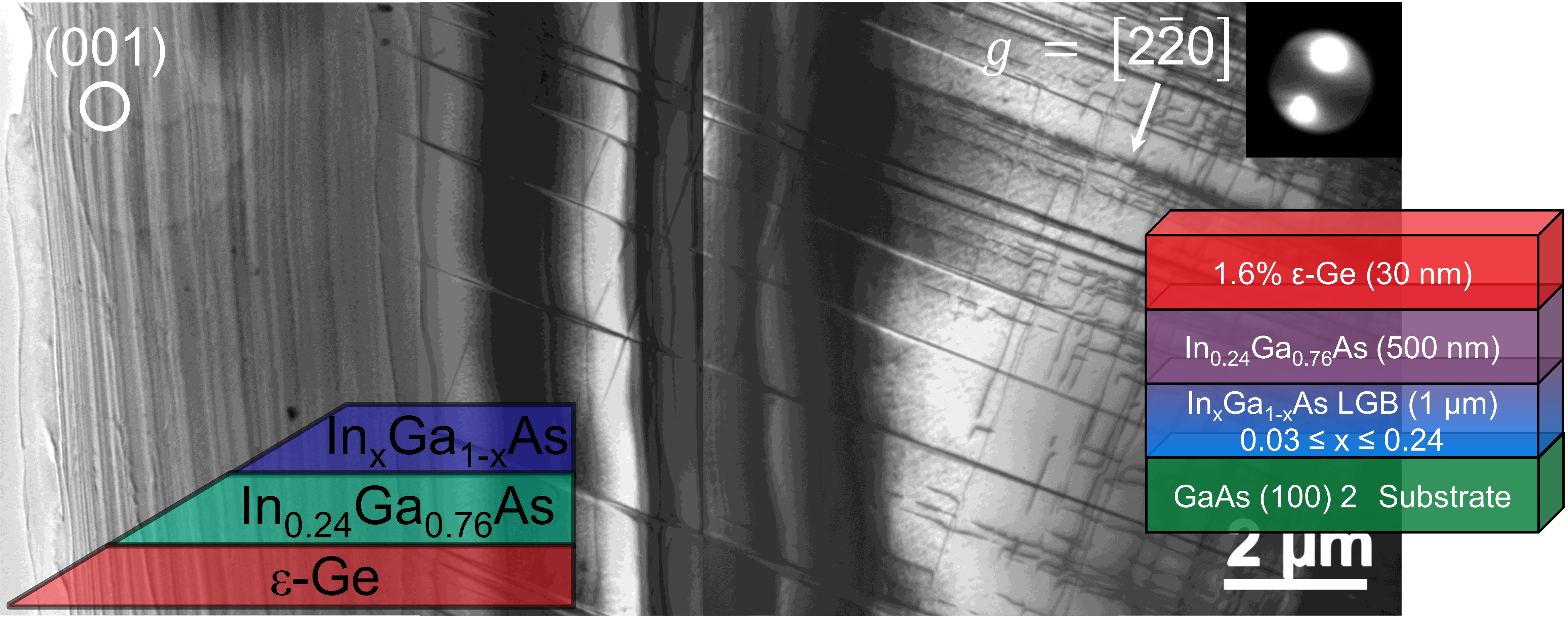


[ref: 4]

5th Tri-Service GeSn and SiGeSn workshop

[1] P. Goodhew, K. Giannakopoulos, "Strain relaxation in III–V semiconductor heterostructures", Micron 30, 59–64 (1999).; [2] R. Dixon and P. Goodhew, "On the origin of misfit dislocations in InGaAs/GaAs strained layers", *JAP* 68, 3163–3168 (1990); [3] E. Kasper, et al., "A one-dimensional SiGe superlattice grown by UHV epitaxy", *Appl. Phys.* **8**, 199–205 (1975).; [4] M. Clavel, et al, Multi-Valley Electron Conduction at the Indirect-Direct Crossover Point in Highly-Strained Germanium. *Phys. Rev. Appl.*, **2022**, *18*, 064083-1-12.

Defect Microstructures and Interface: Epitaxial ε-Ge



☑ Defects are confined within the graded $In_xGa_{1-x}As$ buffer

☑ PV-TEM confirms the "virtually defect-free" ε-Ge layer

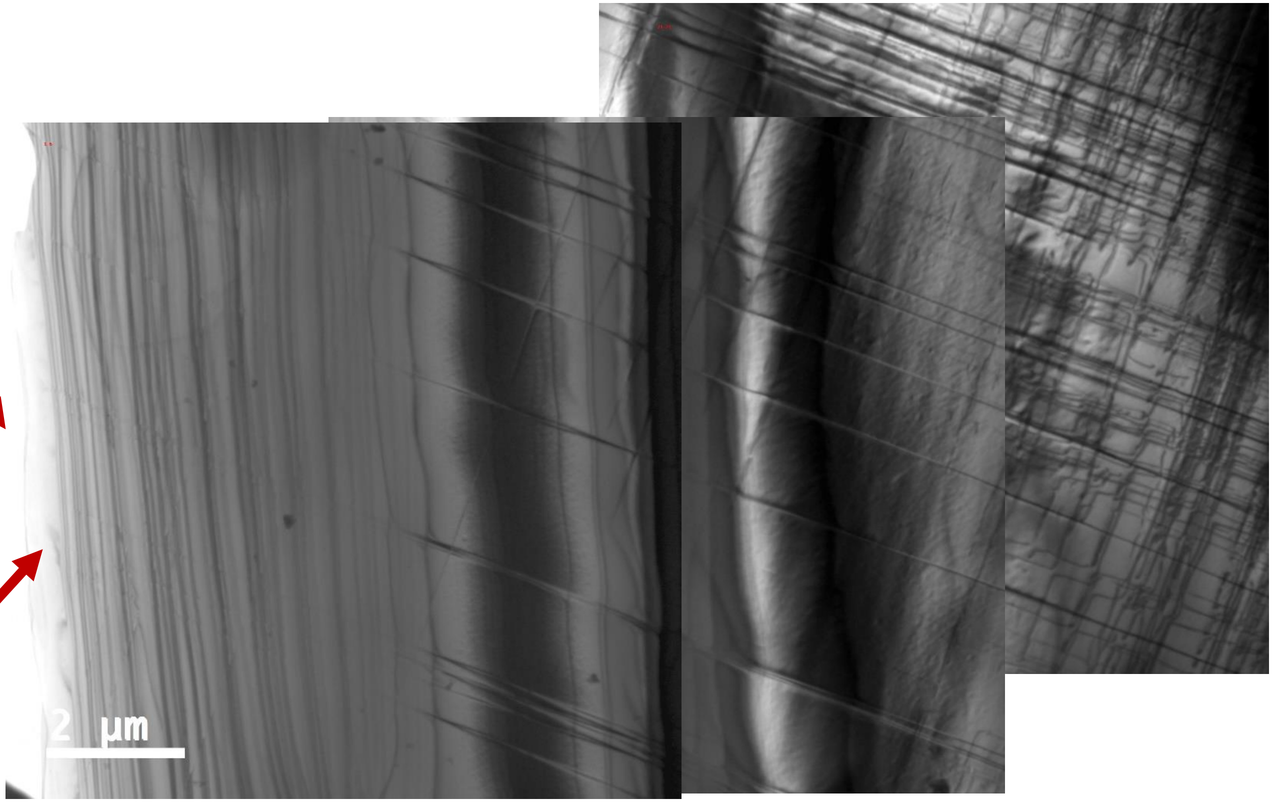
[Ack: Patrick Goley]

M. Clavel, et al, Multi-Valley Electron Conduction at the Indirect-Direct Crossover Point in Highly-Strained Germanium. *Phys. Rev. Appl.*, **2022**, *18*, 064083-1-12

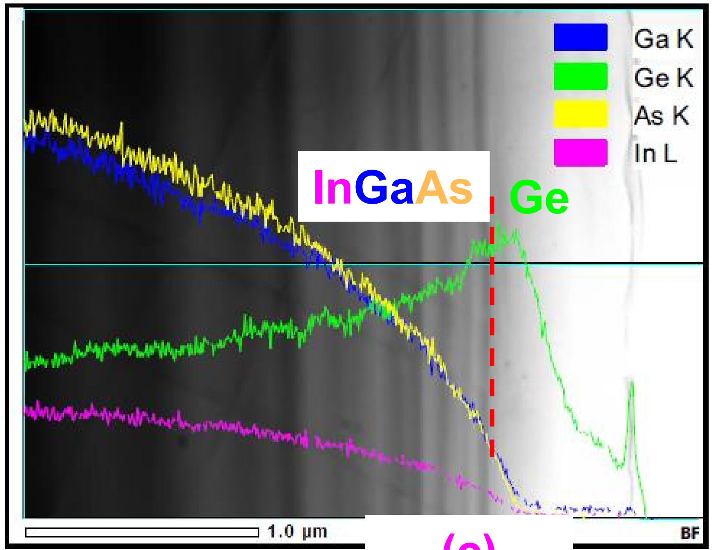
Defect Microstructures and Interface: Epitaxial ε-Ge

Thinner ⟷ Thicker

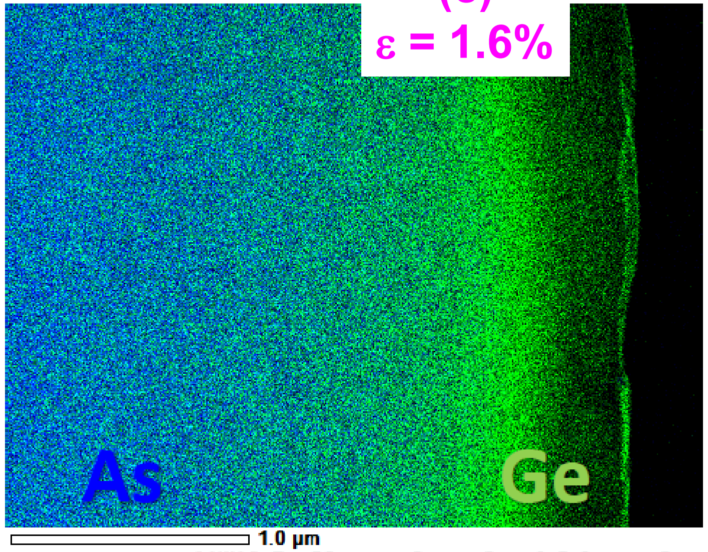
Vacuum



Pure Ge at the tip of the foil wedge

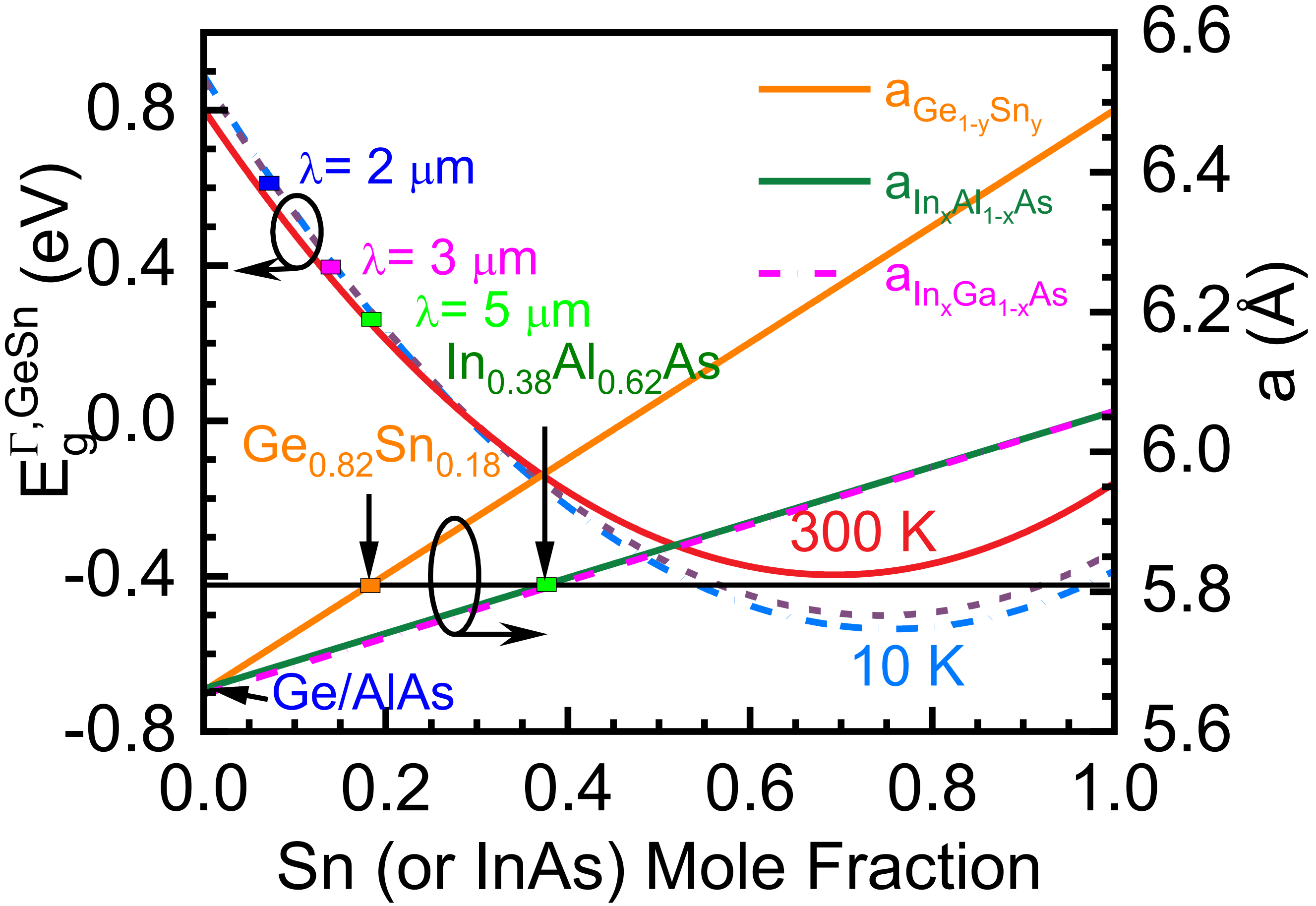


(c)
ε = 1.6%



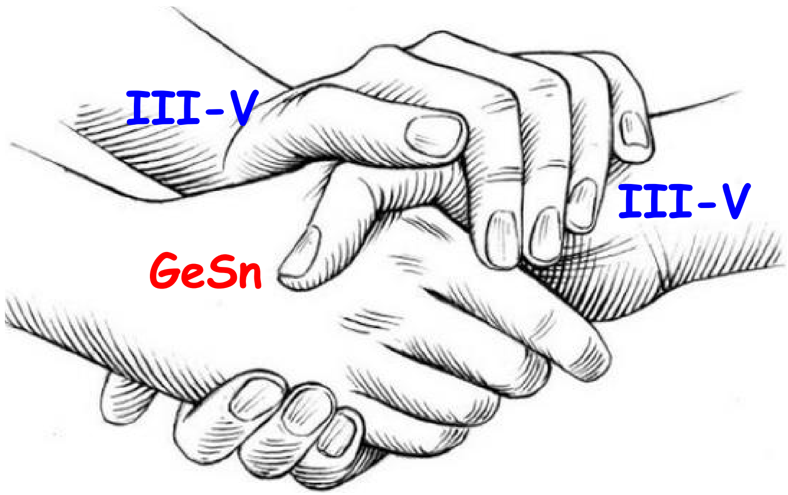
M. Clavel, et al, [Multi-Valley Electron Conduction at the Indirect-Direct Crossover Point in Highly-Strained Germanium](). *Phys. Rev. Appl.*, **2022**, *18*, 064083-1-12

Epitaxial GeSn: Address Lattice Mismatch

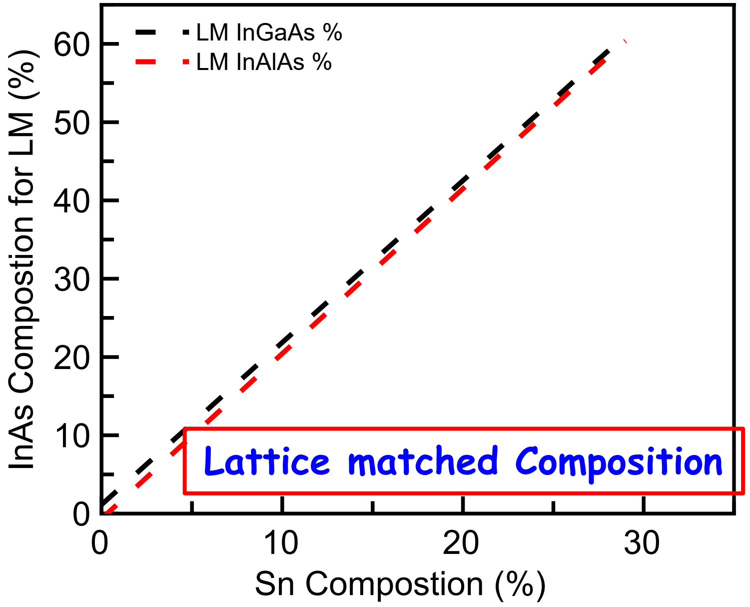


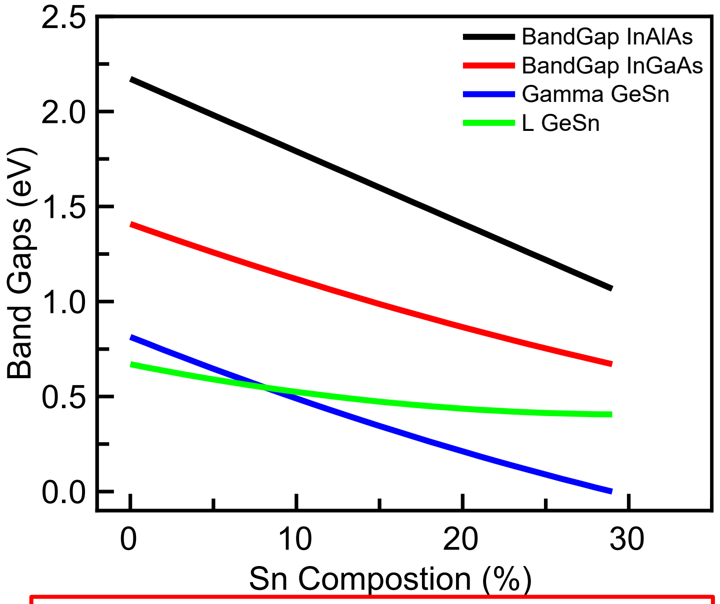
- ✓ **InAlAs or InGaAs** lattice matched layer to **GeSn**
- ✓ **GeSn/In(AlGa)As** heterostructures, *e.g.*, Sn = 12% & In ~ 24%

III-V/GeSn/III-V Heterostructure for Laser

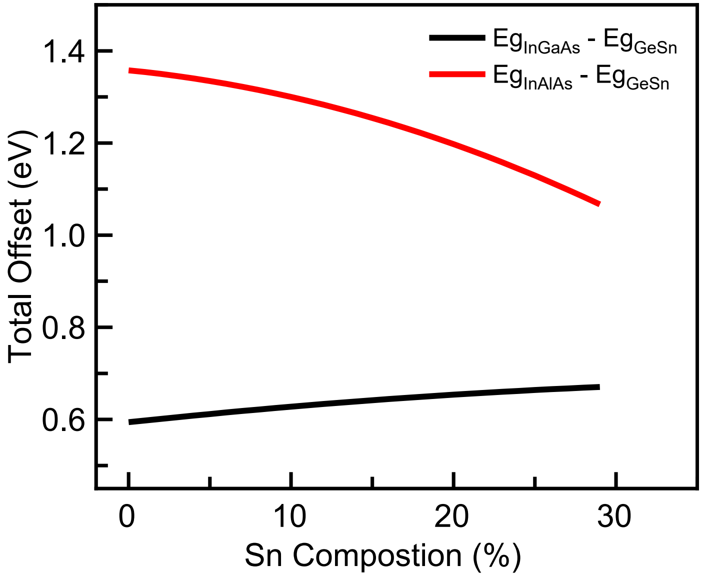


$In_x(AlGa)_{1-x}As$
$Ge_{1-y}Sn_y$
$In_x(AlGa)_{1-x}As$





Bandgap vs. Sn composition



Total available band offsets

R. Joshi, S. Johnston, S. Karthikeyan, L. F. Lester, and M. K. Hudait, "Monolithically Integrated strained-Ge/$In_xGa_{1-x}As$ Quantum Well Laser Design: Experimental and Theoretical Investigation", IEEE Journal of Selected Topics in Quantum Electronics 1-15 (2023) (early access).

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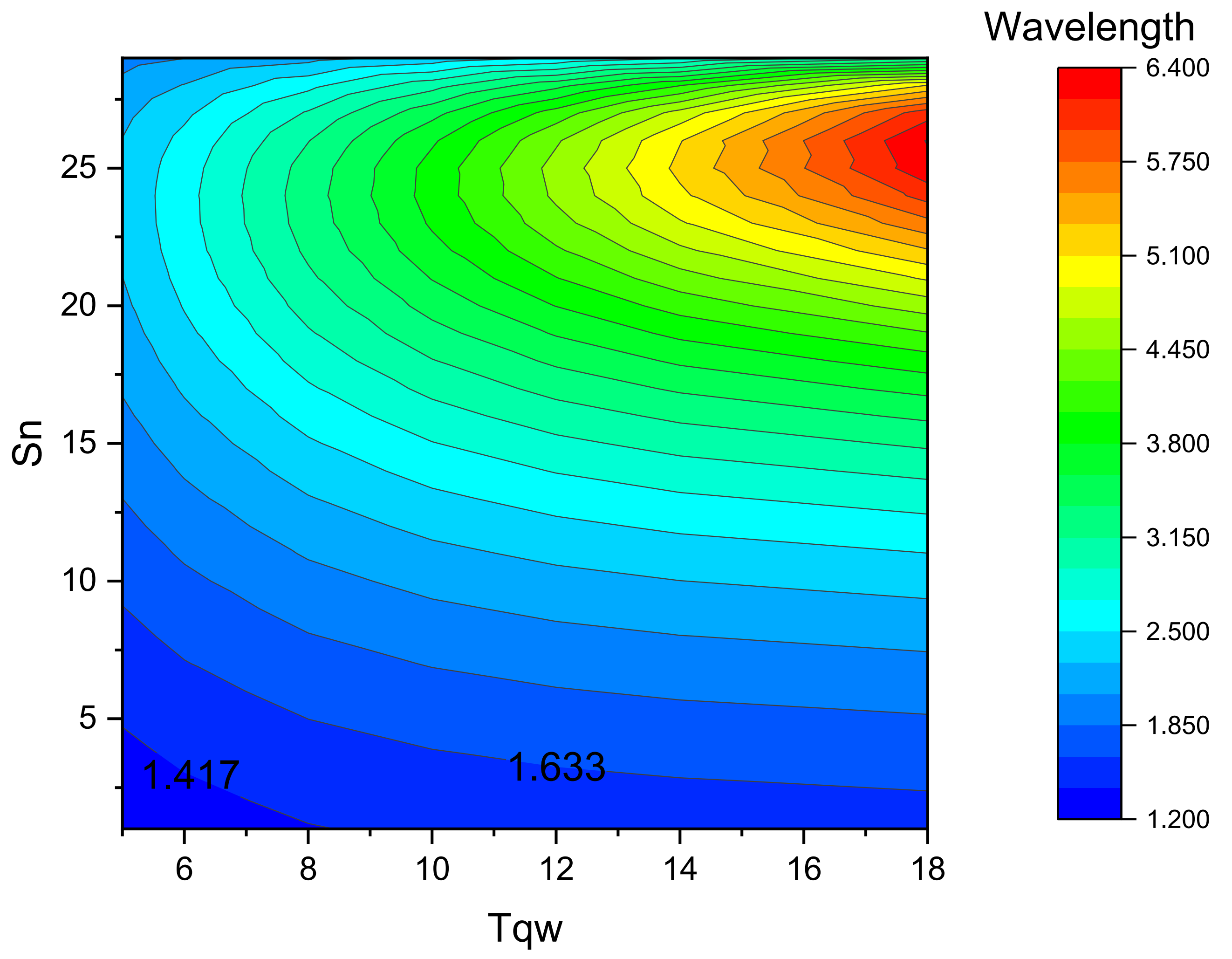
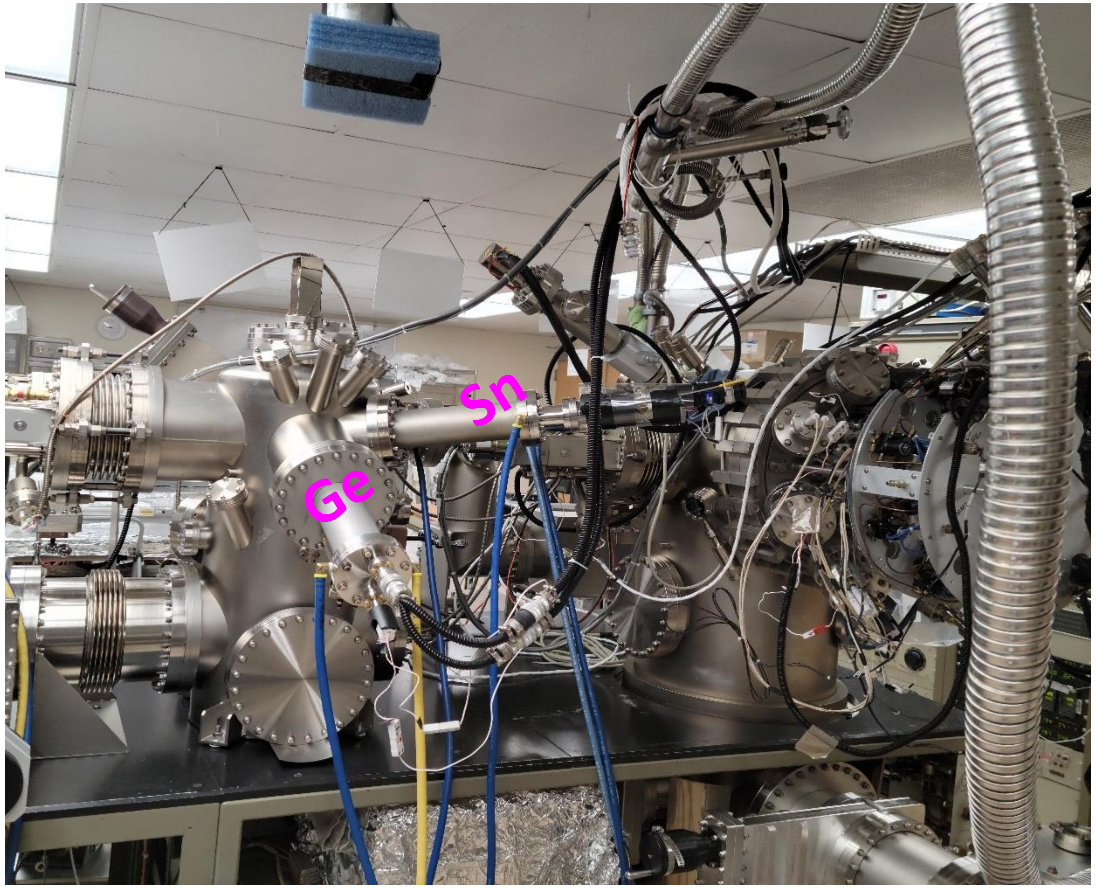
III-V/GeSn/III-V Heterostructure for Laser



Dual Chamber MBE for III-V and Ge @ ADSEL



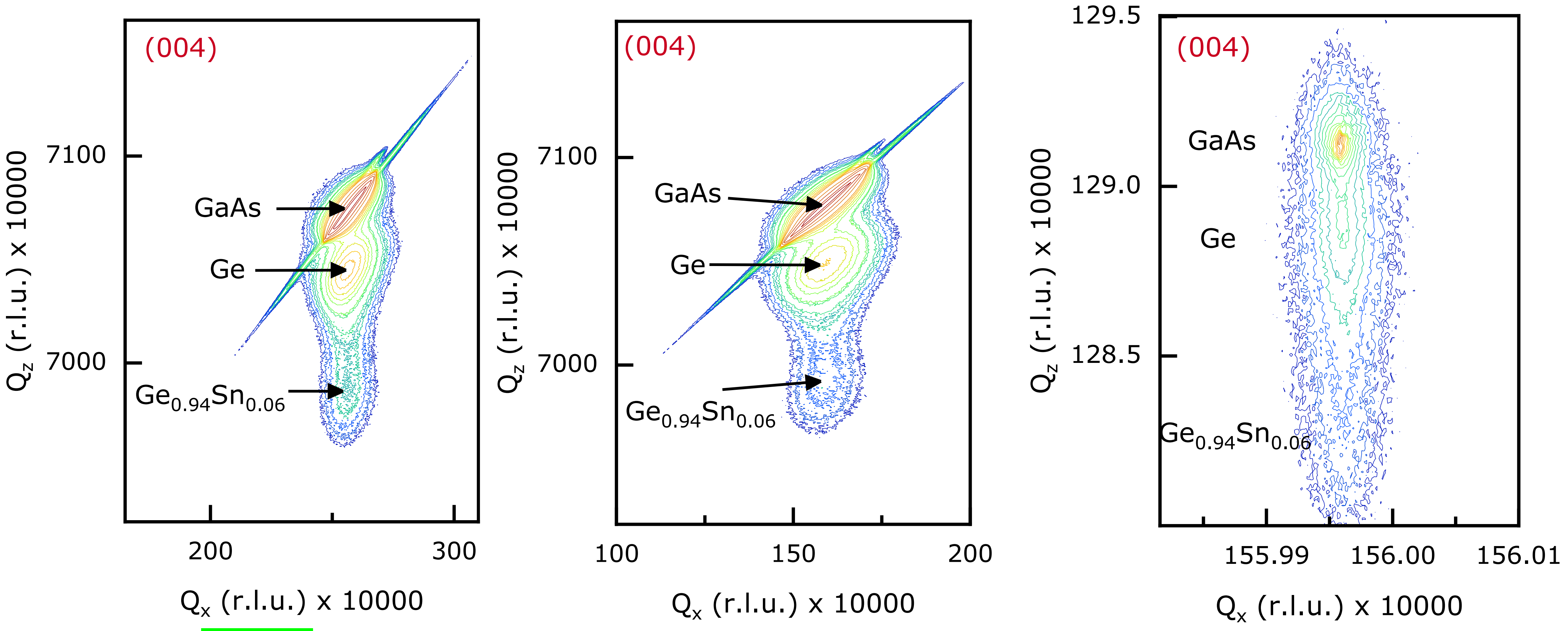
- ❑ Compound semiconductor and GeSn MBE growth systems are vacuum interconnected

Epitaxial GeSn Material Synthesis on Oriented GaAs Substrates

[A]	[B]	[C]	[D]
$Ge_{0.94}Sn_{0.06}$ 50 nm	$Ge_{0.94}Sn_{0.06}$ 100 nm	$Ge_{0.94}Sn_{0.06}$ 100 nm	$Ge_{0.94}Sn_{0.06}$ 100 nm
Ge 50 nm	Ge 27 nm	Ge 27 nm	Ge 27 nm
GaAs 250 nm	GaAs 500 nm	GaAs 500 nm	GaAs 500 nm
(100)/6° GaAs S.I. substrate	(100)/2° GaAs S.I. substrate	(100)/6° GaAs S.I. substrate	(110) GaAs S.I. substrate
Adsel 302	Adsel 305	Adsel 305	Adsel 305
(100)/6°	**(100)/2°**	**(100)/6°**	**(110)**

Material Characterization: X-ray analysis $GeSn_{0.06}$

Reciprocal Space Maps of Symmetric (004) scans

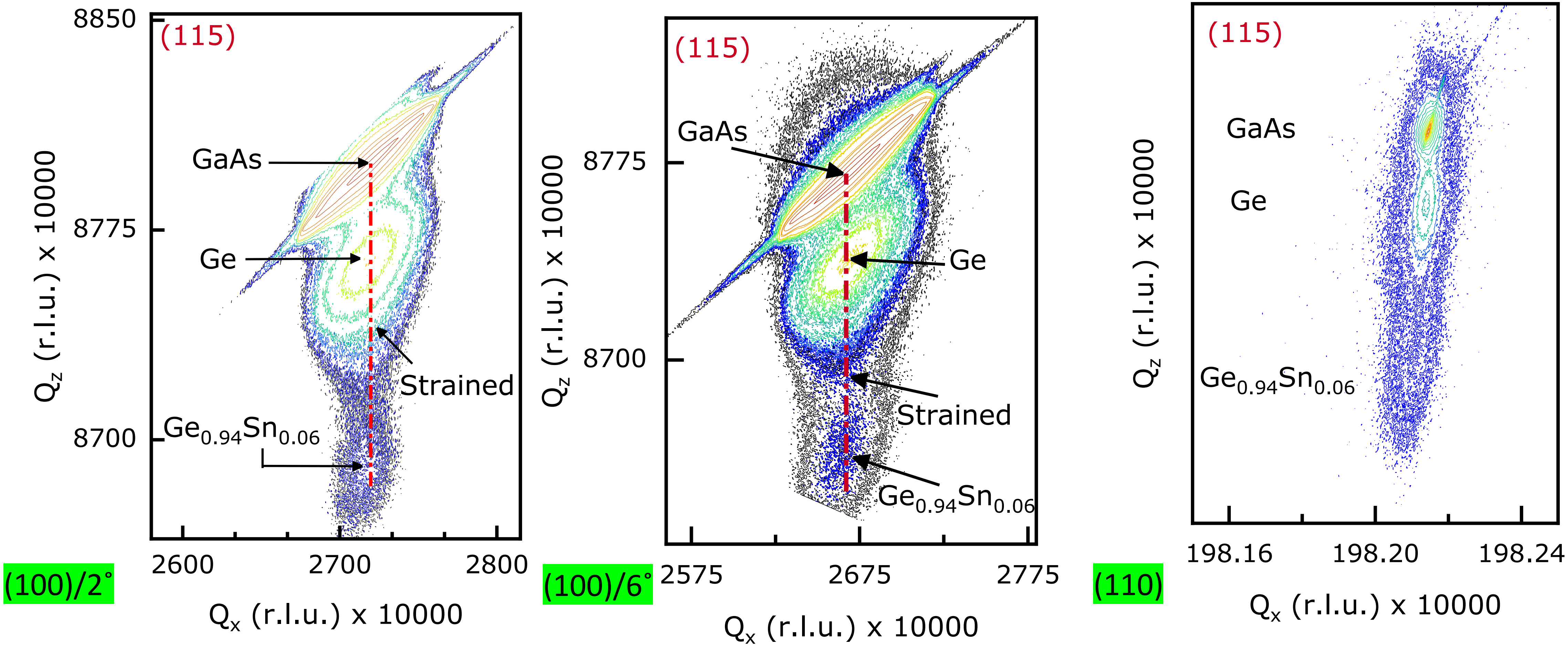


(100)/2˚ | (100)/6˚ | (110)

- GeSn on (110) oriented GaAs shows broad RSM spectrum

Material Characterization: X-ray analysis $GeSn_{0.06}$

Reciprocal Space Maps of Asymmetric (115) scans

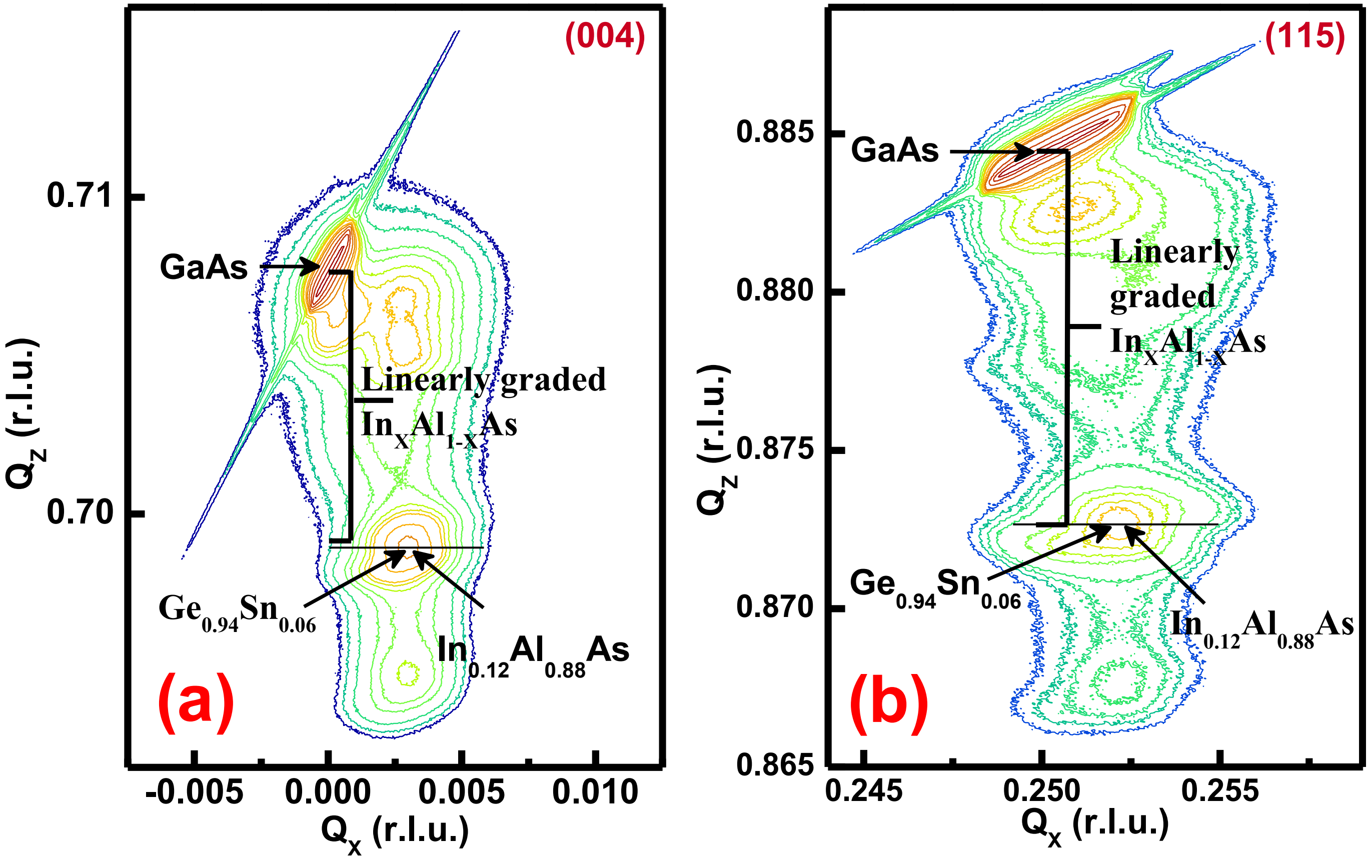


- GeSn layers are compressively strained wrt to Ge or GaAs substrates

S. Karthikeyan *et al.*, to be submitted to *JMC-C (2023)*.

Material Characterization: X-ray Analysis

Lattice matched



- $Ge_{0.94}Sn_{0.06}$ overlapping with $In_{0.12}Al_{0.88}As$

  ↓

  lattice matched

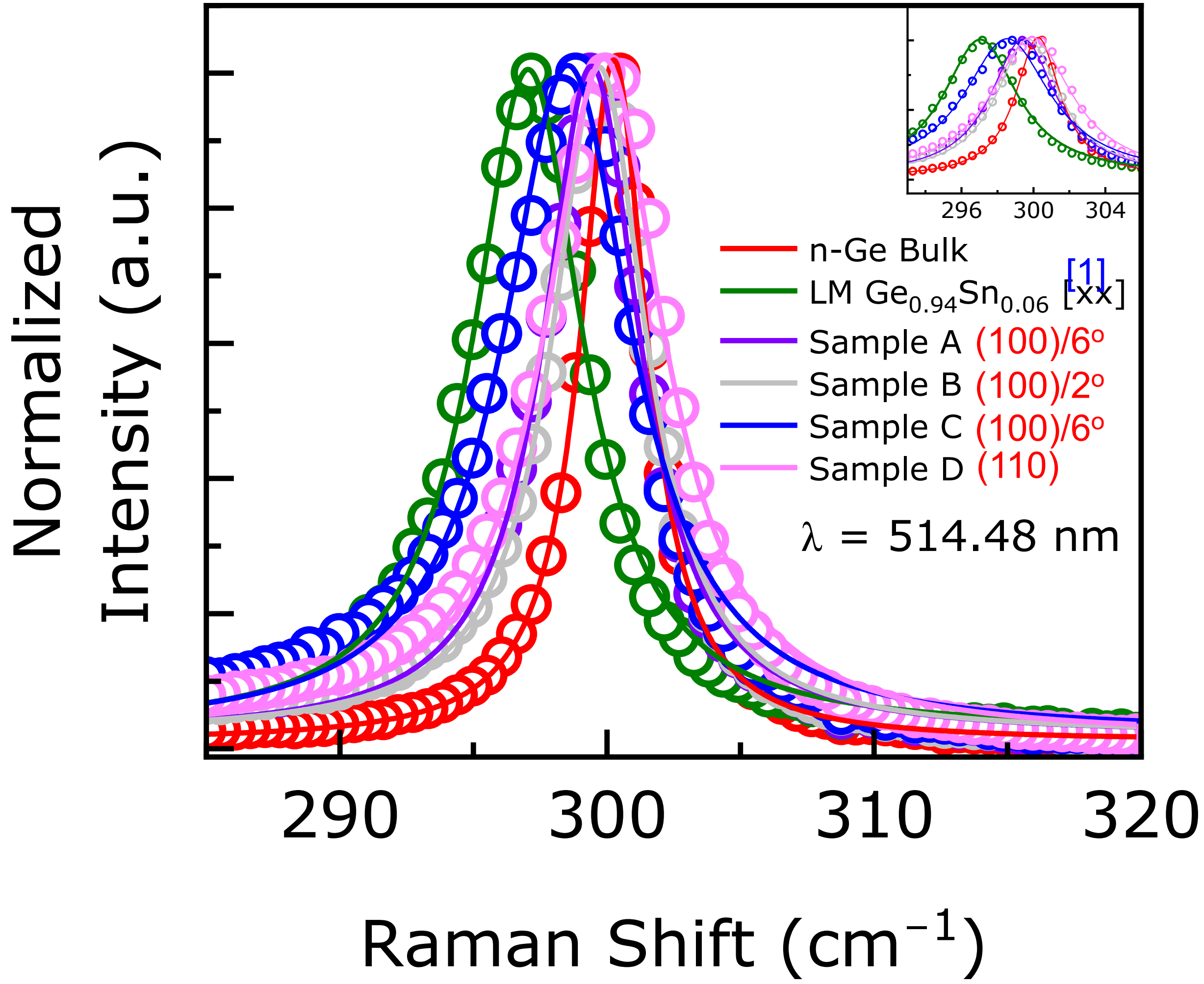
  ($a_{Ge_{0.94}Sn_{0.06}}$ = 5.70786 Å at 300 K)

- Q_z and Q_x symmetricity at $Ge_{0.94}Sn_{0.06}$ shows no defects.
- $In_xAl_{1-x}As$ linearly graded buffer constraints mismatch induced defects.

5th Tri-Service GeSn and SiGeSn workshop

Hudait *et al., J. Materials Chemistry C 10 (29): 10530-10540 (2022)*

Material Characterization: Raman analysis of $GeSn_{0.06}$



- ❑ No significant change of the peak position shift of each GeSn layer

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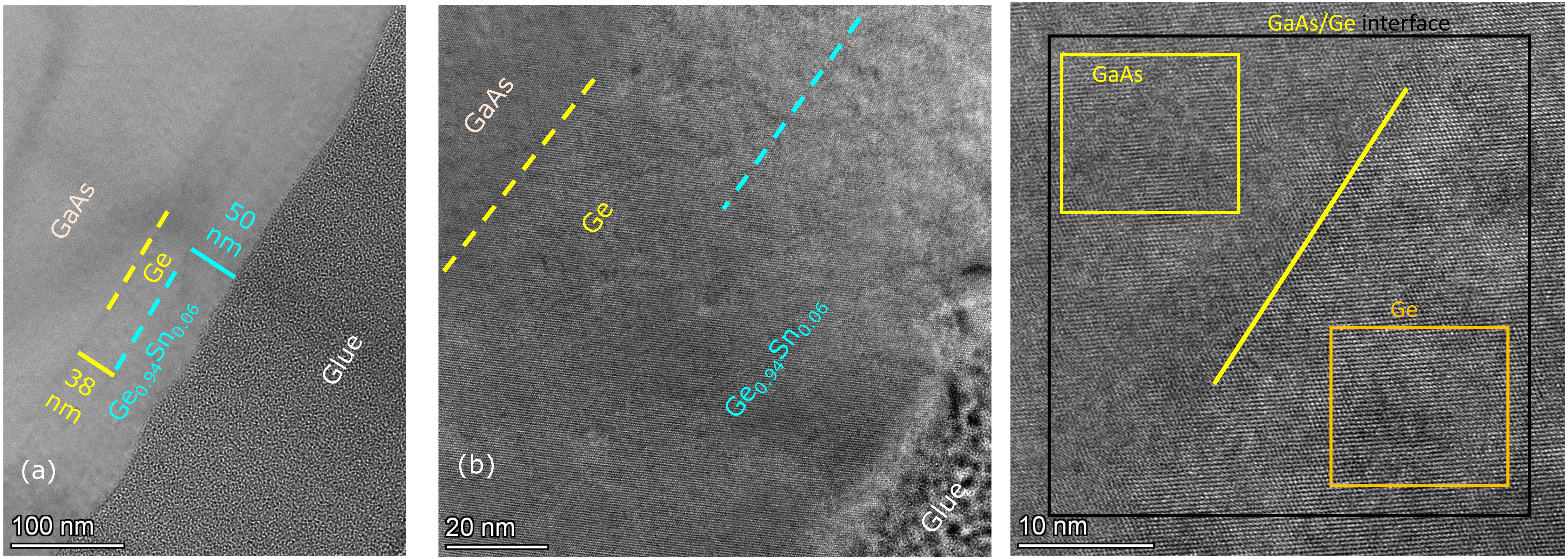
Material Characterization: XTEM analysis of $GeSn_{0.06}$



- $GeSn_{0.06}$ is compressively strained with Ge/(100)2° GaAs, as expected

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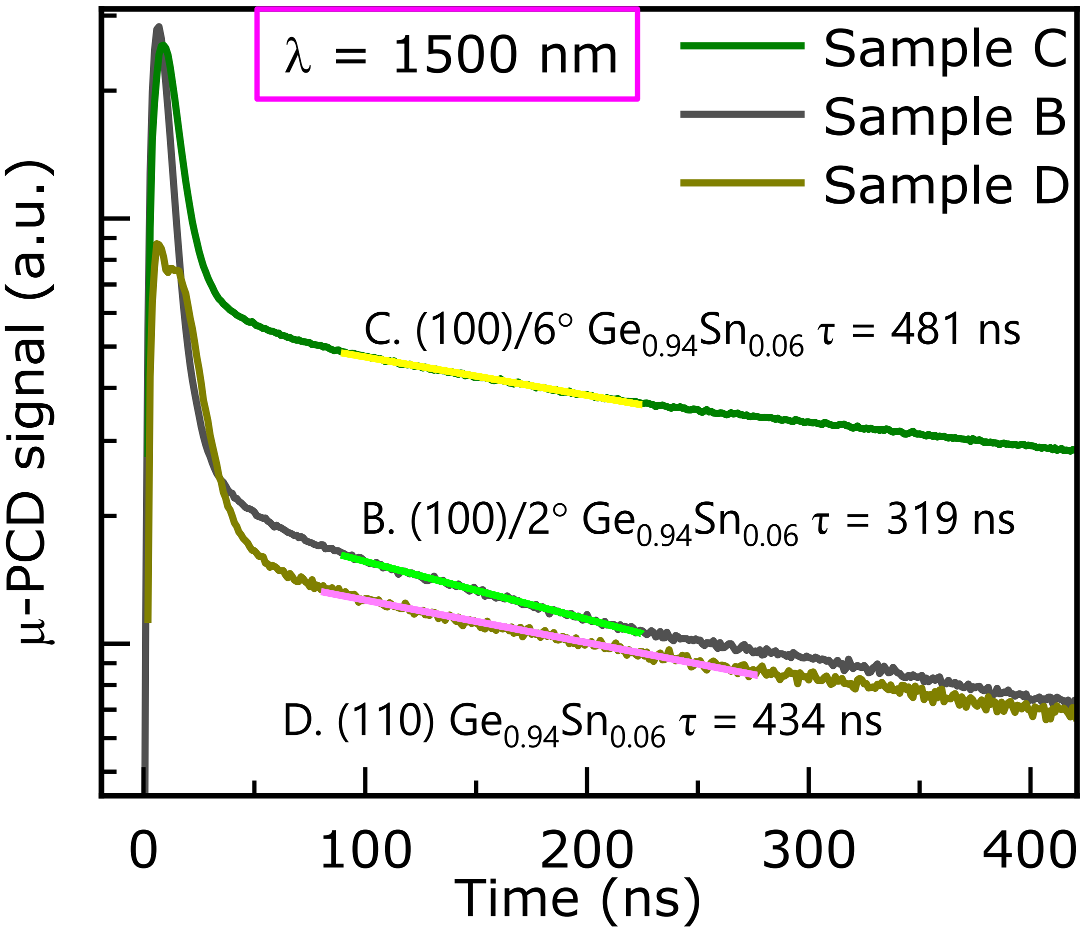
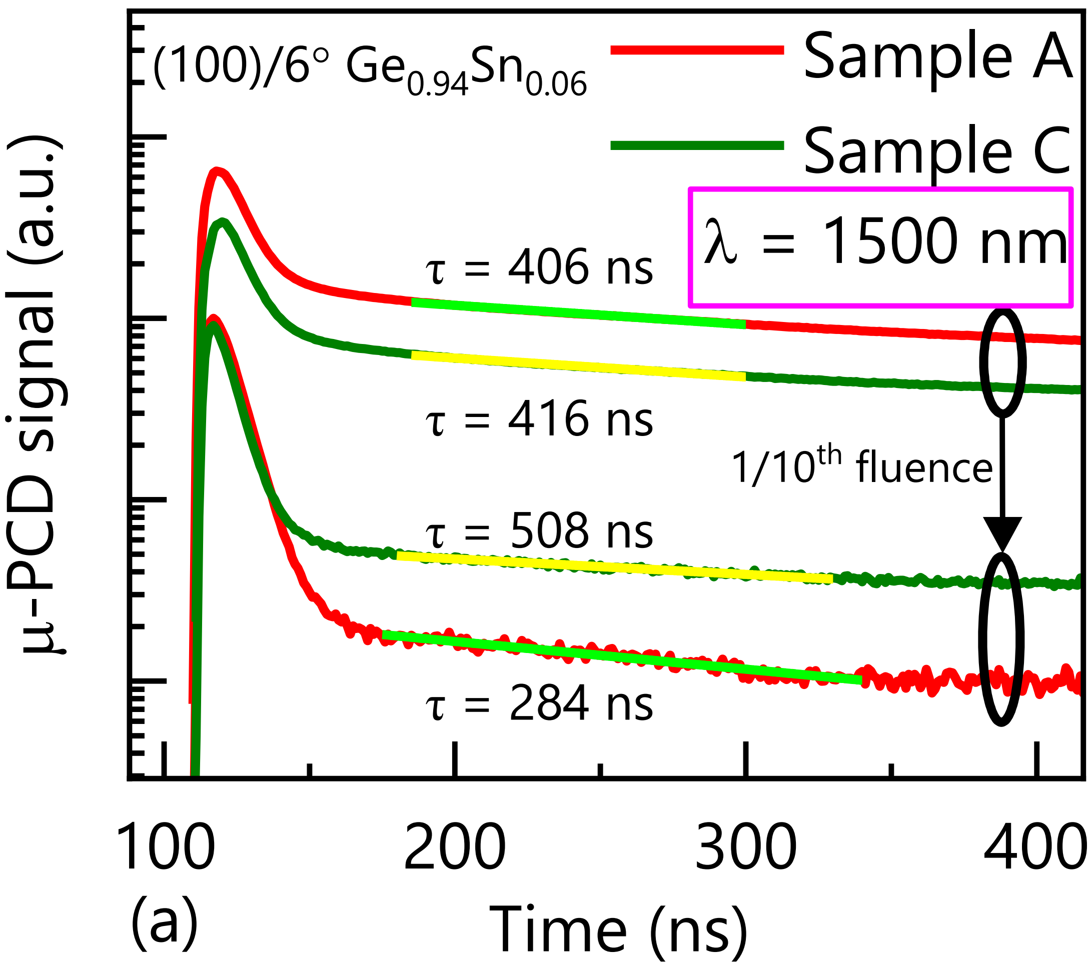
Minority Carrier Lifetimes of $GeSn_{0.06}$

P = 10 mW





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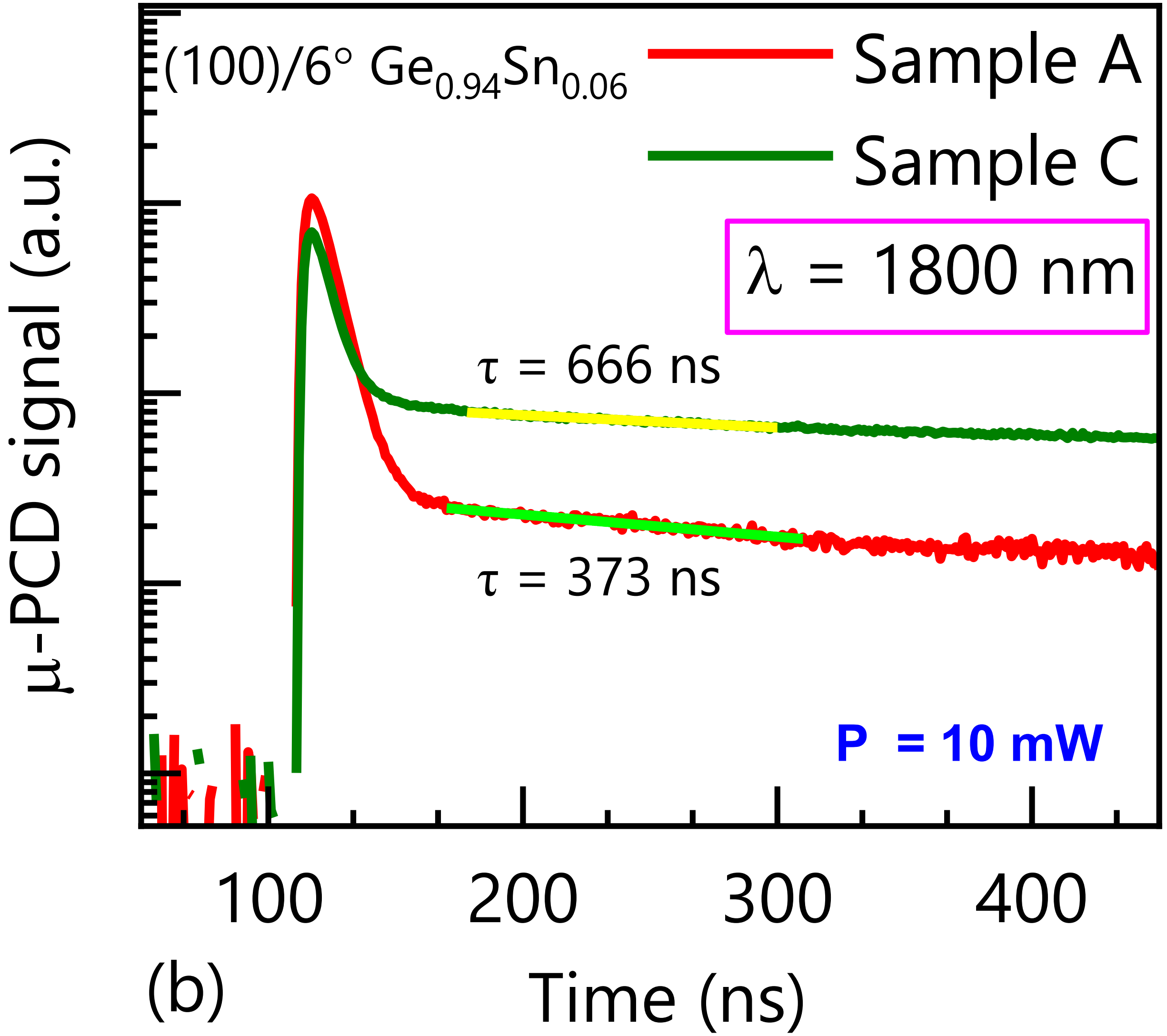
NREL

Minority Carrier Lifetimes of GeSn$_{0.06}$



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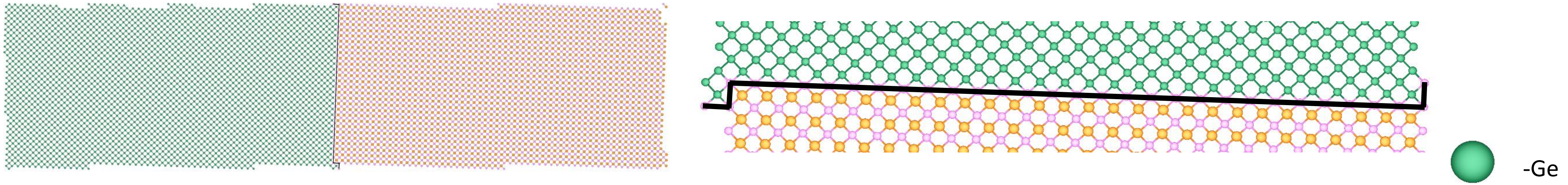
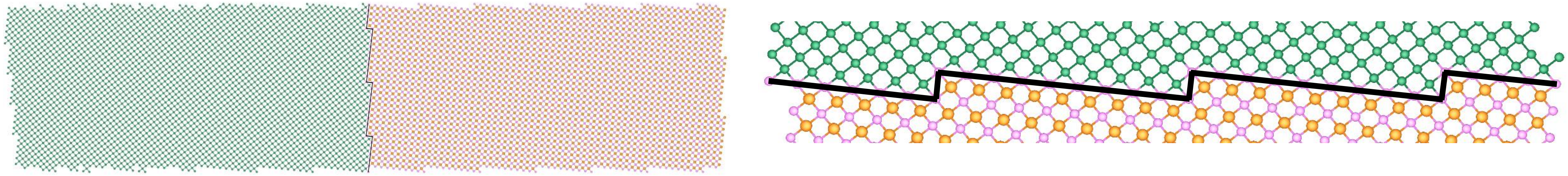
Ge/GaAs Interface Investigation: QuantumATK



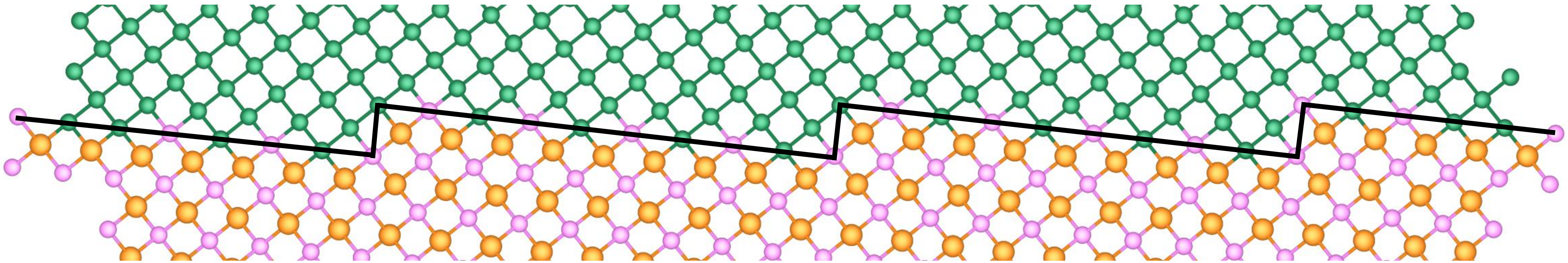
6280 atoms

(a) Ge-GaAs (100)/2˚



6280 atoms

(b) Ge-GaAs (100)/6˚



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Ge/GaAs Interface Investigation: QuantumATK

TOTAL ENERGY	Ge-GaAs (100)/2˚	Ge-GaAs (100)/6˚	6280 atoms
Without "As" termination	6.19 eV	5.30 eV	ΔE = 0.89 eV
With "As" termination, charged interface	3.38 eV	1.89 eV	ΔE = 1.49 eV
With "As" termination, neutral interface	2.77 eV	2.31 eV	ΔE = 0.46 eV

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Summary

- Device quality epitaxial ε-Ge and GeSn can be realized by interconnected MBE chambers
- Defects and dislocations can be confined in the buffer layer by growing lattice matched GeSn
- Effect of GaAs substrate orientations:
  - ✓ $GeSn_{0.06}$ layer on (100)/6° GaAs shows higher carrier lifetime than other orientations
  - ✓ Excitation dependent carrier lifetime at 1800nm is higher than 1500nm due to lower Auger recombination
  - ✓ Large band offsets (ΔE_V = 0.91 eV, $\Delta E_{C,\,G\text{-}X}$ = 0.64 eV)
  - ✓ Abrupt interface
- Required Sn source re-configuration for higher Sn (> 6%) compositional GeSn materials