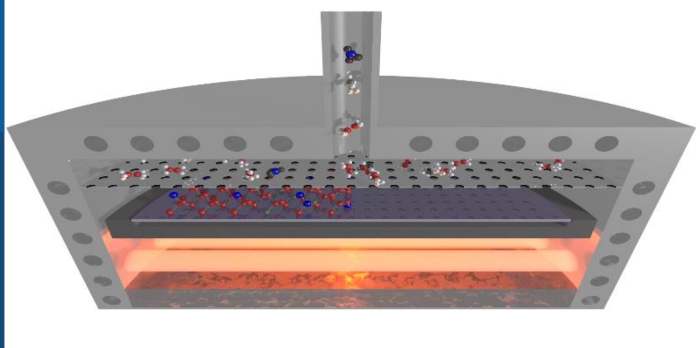
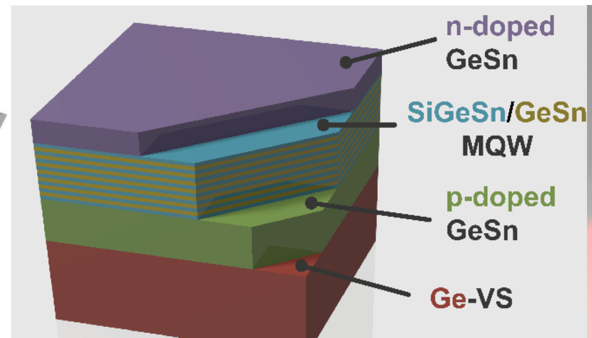
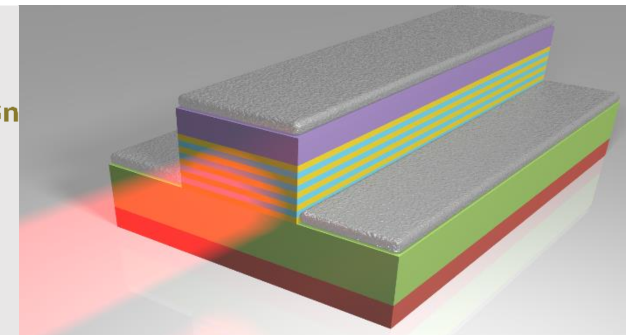
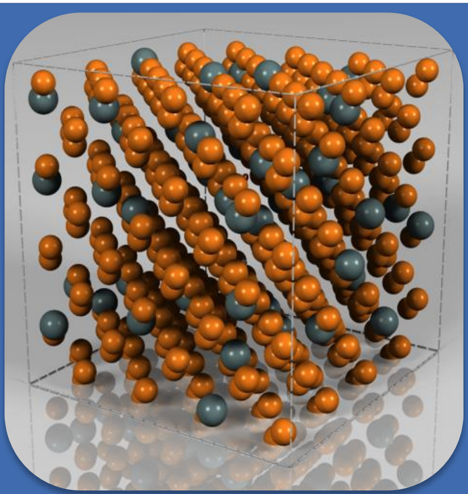
Jülich Aachen Research Alliance







Epitaxy and strain engineering of GeSn/SiGeSn for Optoelectronics



" Extending the Silicon "world"

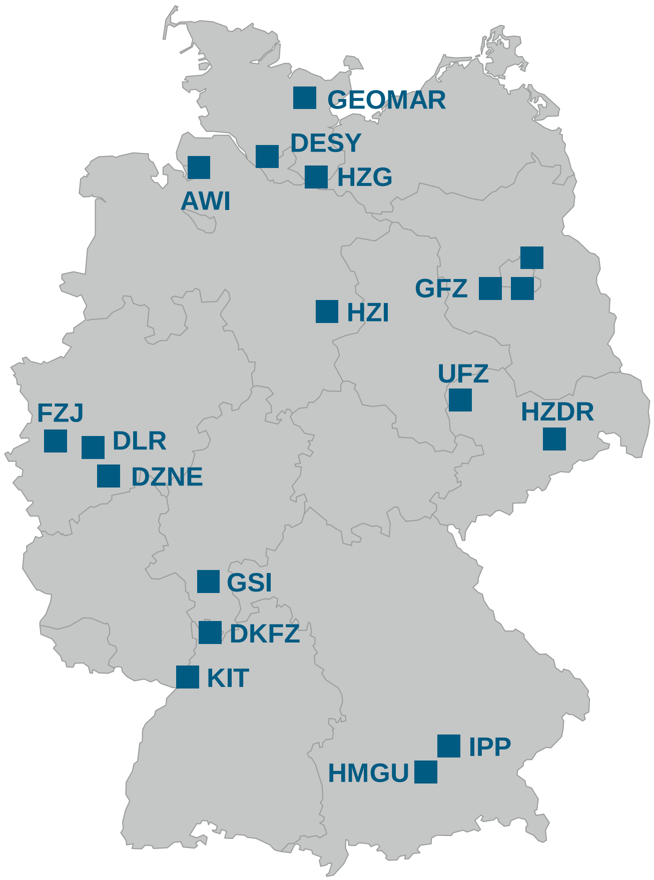
- Si-Ge-Sn a multifunctional alloy-

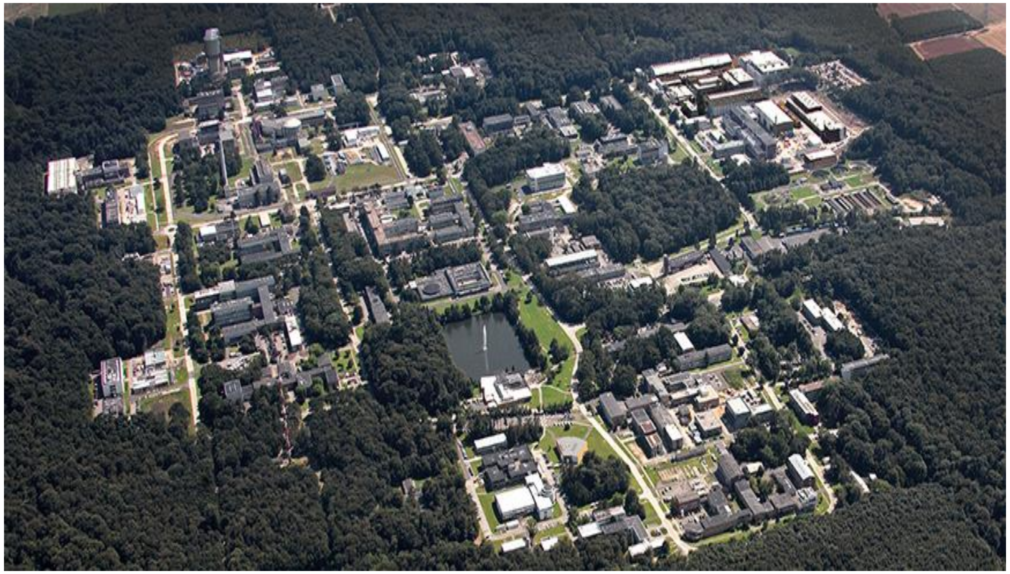
An introduction

Dan Buca, D. Grützmacher


Kiel
Rostock
Lübeck
Hamburg
Stettin
Bremen
Berlin
Amsterdam
Hannover
Wolfsburg
Braunschweig
Magdeburg
Den Haag
Niederlande
Dortmund
Leipzig
Dresden
Antwerpen
Köln
Deutschland
Brüssel
Lille
Belgien
Frankfurt am Main
Prag
Tschechien
Luxemburg
Mannheim
Nürnberg
Stuttgart
Straßburg
München
Österreich
Zürich

Member of the Helmholtz Association



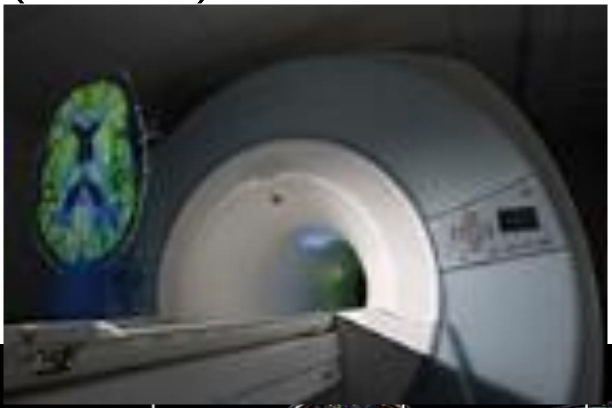


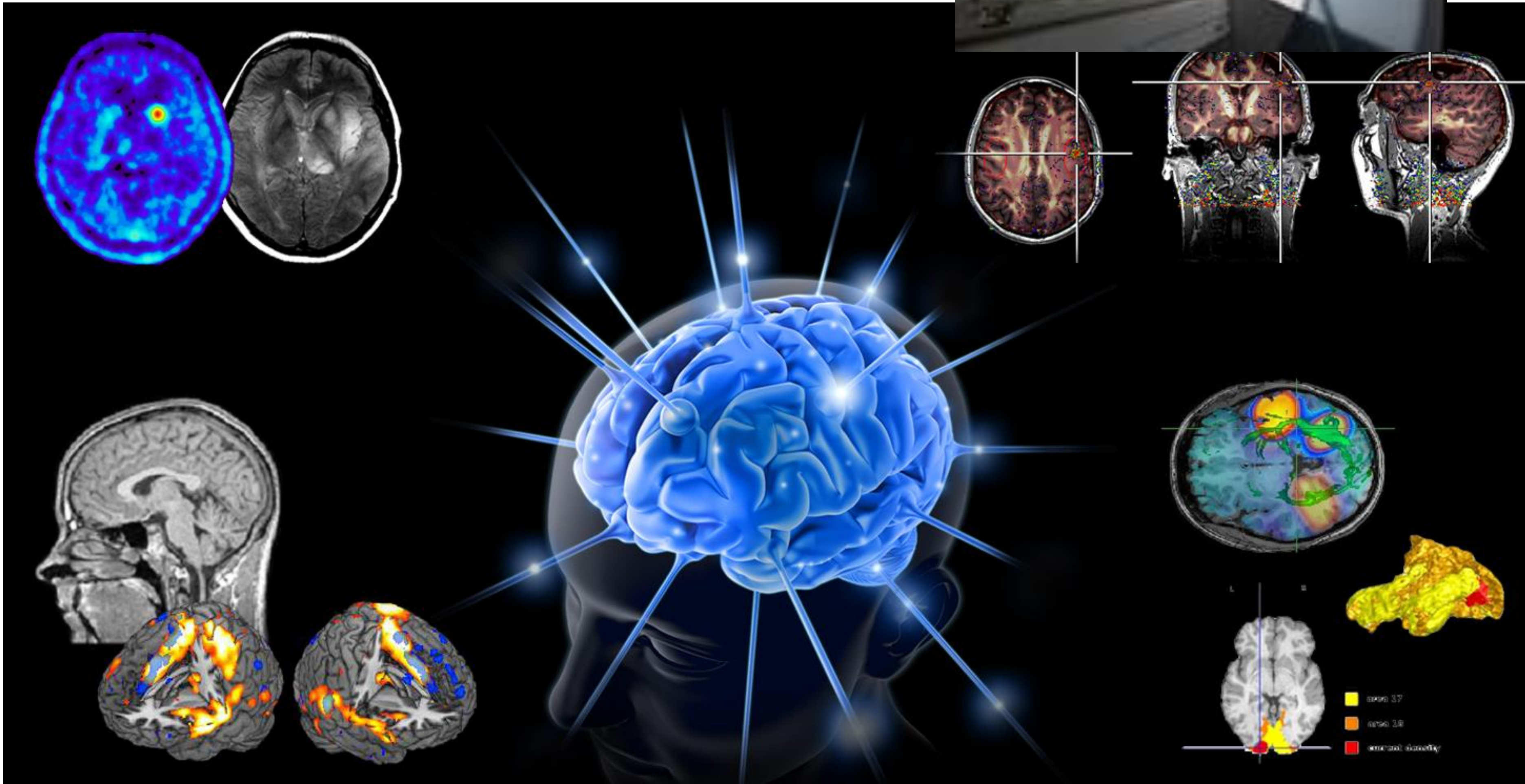
- **Facts and figures**
- Employees **38,237 (in 18 centres)**
- Budget **€ 4,45 billion**

of which more than 30 % is third-party funds

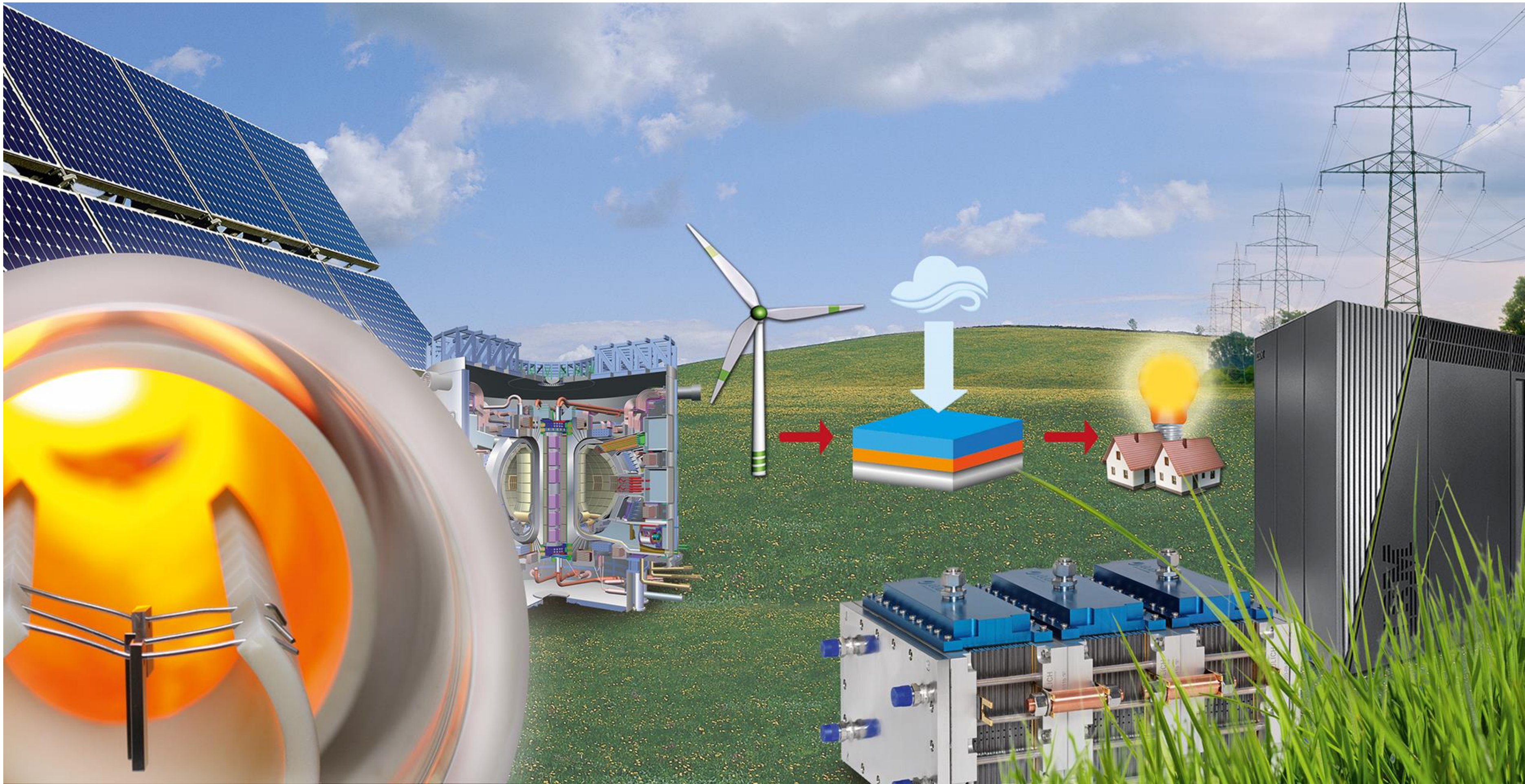
The brain

Imaging Core Facility (ICF)
(8T MRT)





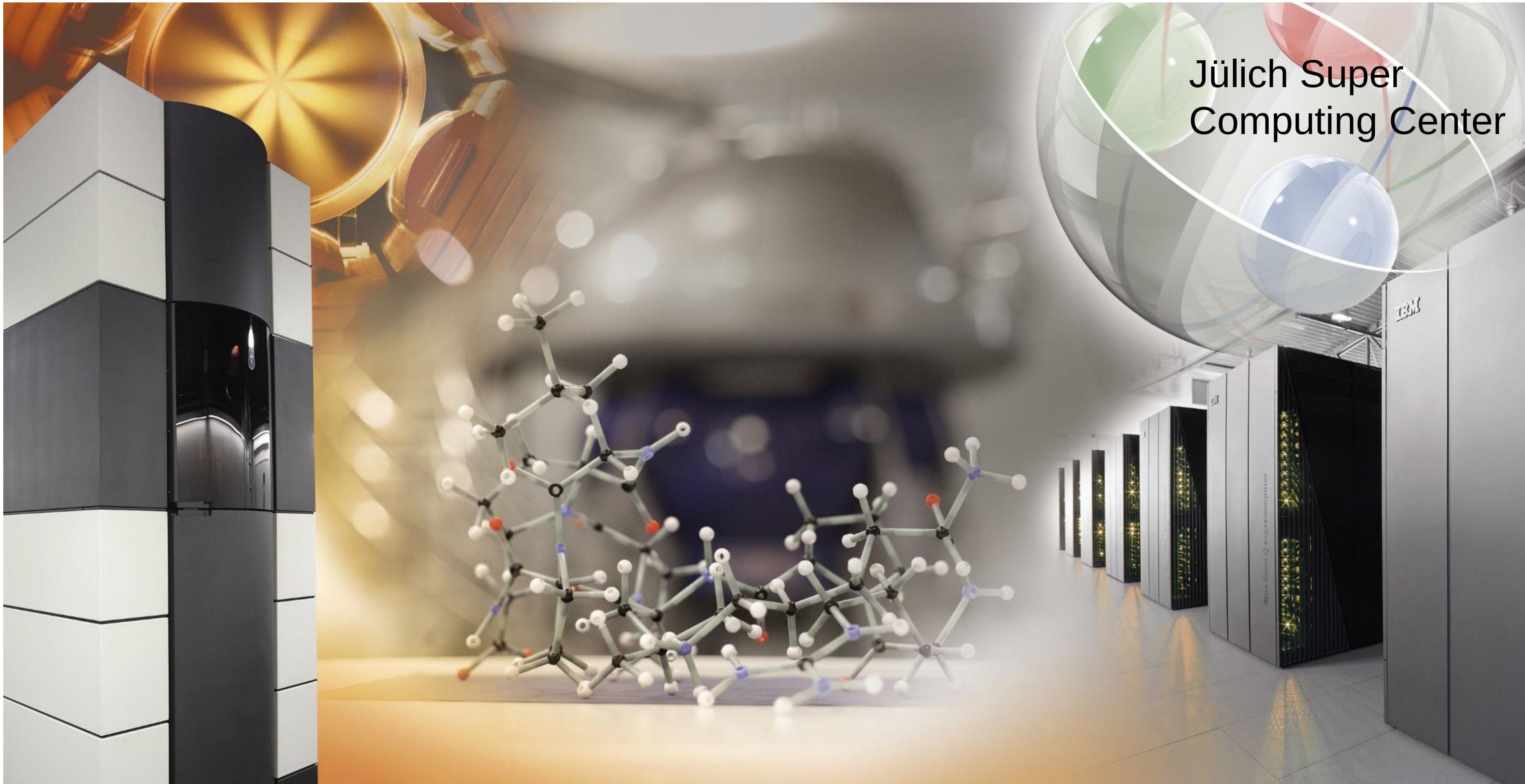
Energy



Atmosphere and climate

Key infrastructure facilities

Ernst Ruska Center
for electron microscopy



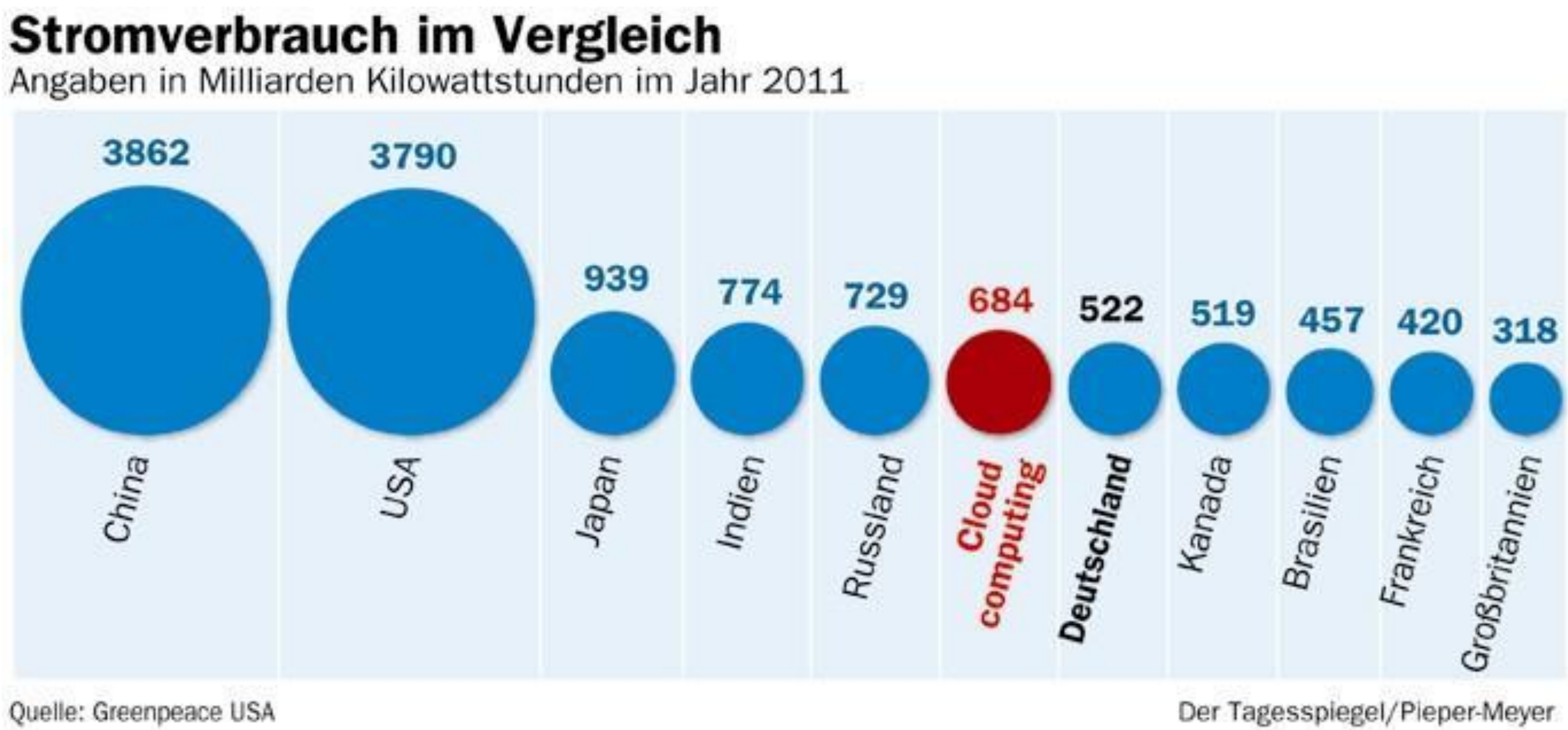
Jülich Super
Computing Center

Information Technology

Biggest problems of information society:

Data security

Electrical power consumption



Energy!

- **Electrical Power Consumption of IT Products** in comparison to the total electrical power consumption of the world:
- < 1% in 2000
- ~ 1.5% in 2006
- > 10% in 2012

- **within 10 years** we will consume the equivalent of **100% of todays electrical power** only for **IT products**, or only for the internet by 2030

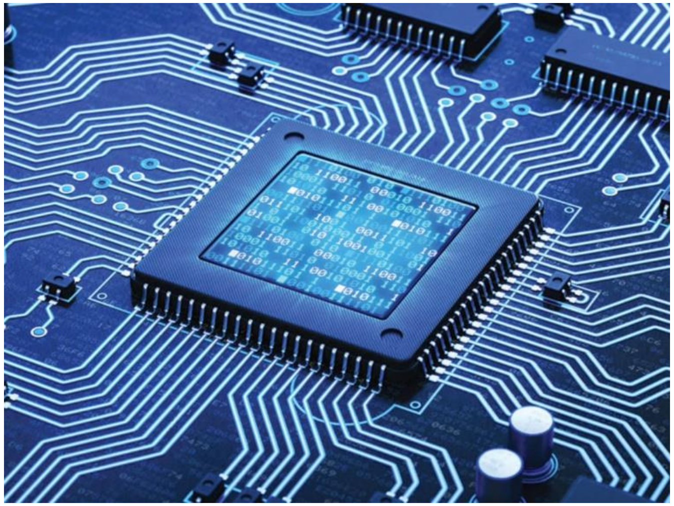
(My daughter „uses“ >30 Gb /month)

Today there are more IT products connected to the internet than people on earth

Forecast says that will **increase by a factor of 10 within the next 5 years**
Predictions before COVID : digital schooling

=> Enormous increase data volume => Problems: **energy and bandwidth**

Electronics



energy efficiency of the most advanced microelectronics
pJ/bit

information “carrier”
is an **electron**
(energy dissipation)

Driving force for µ-e evolution:

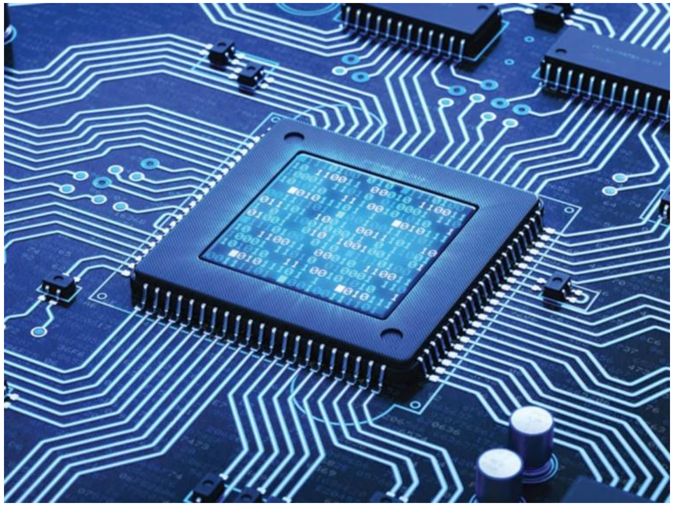
- Increase performance (scaling)
- Reduce power consumption

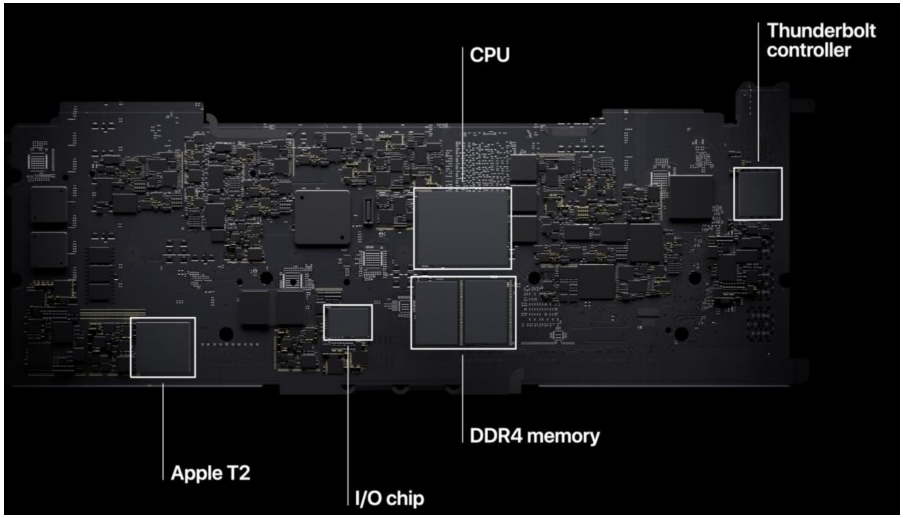
  TFETs

  NW electronics

„Green IT“

Electronics



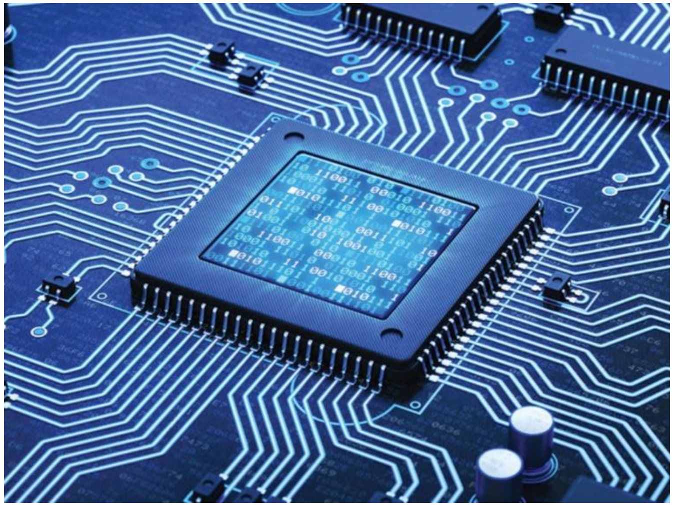


energy efficiency of the most advanced microelectronics
pJ/bit

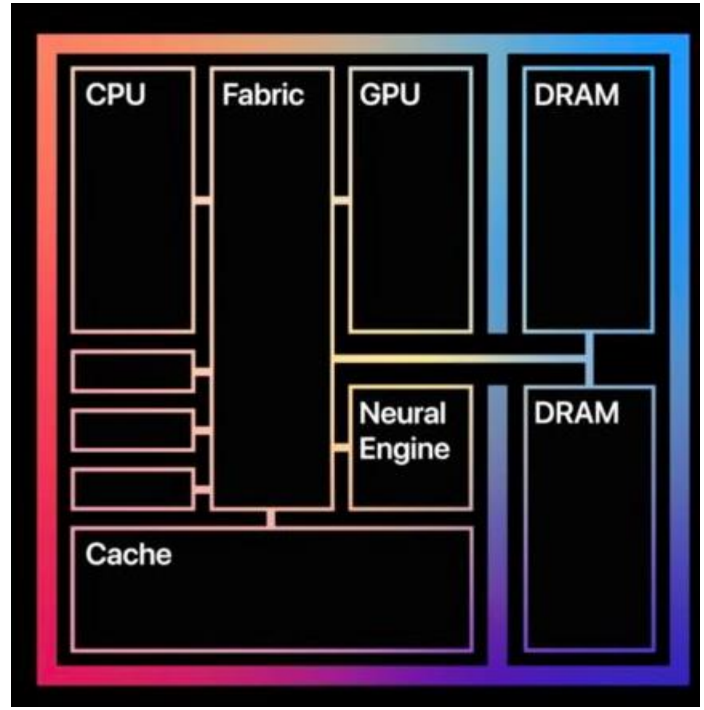
information “carrier” is an **electron (energy dissipation)**

Large losses: „transport“ of information

Electronics



energy efficiency of the most advanced microelectronics
pJ/bit



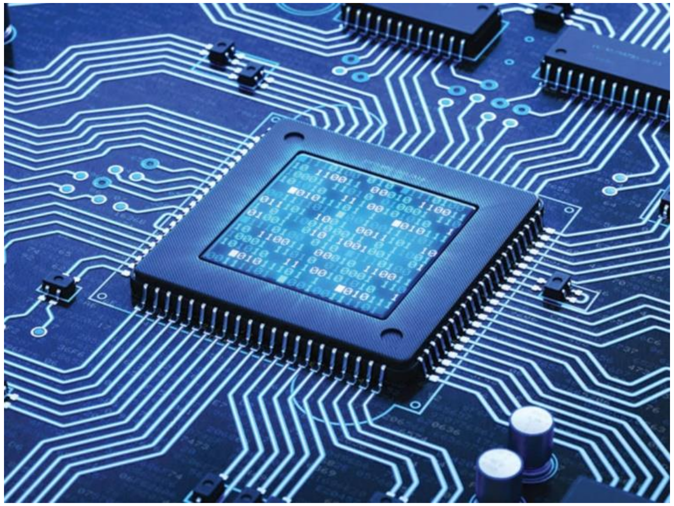
Large losses: „transport“ of information

information “carrier” is an **electron (energy dissipation)**

Design/architecture (Apple M1)

system on chip (SoC)

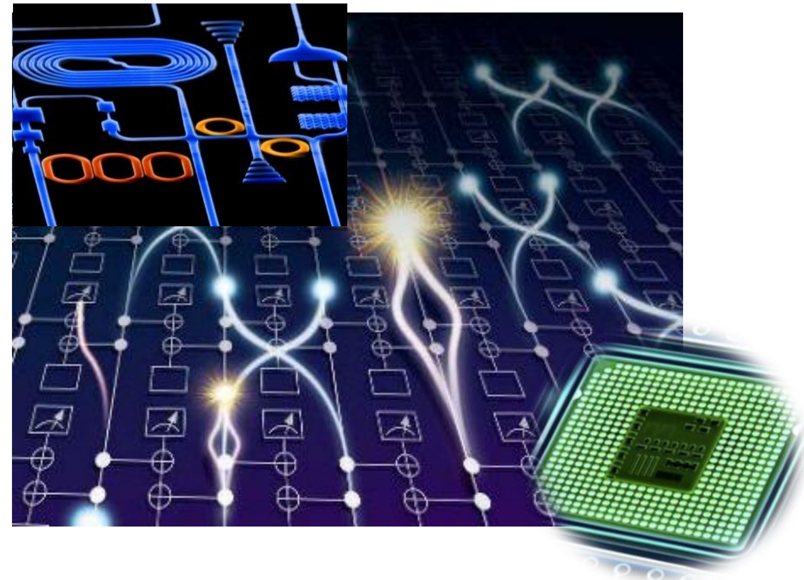
Electronics



energy efficiency of the most advanced microelectronics **pJ/bit**

information "carrier" is an **electron (energy dissipation)**

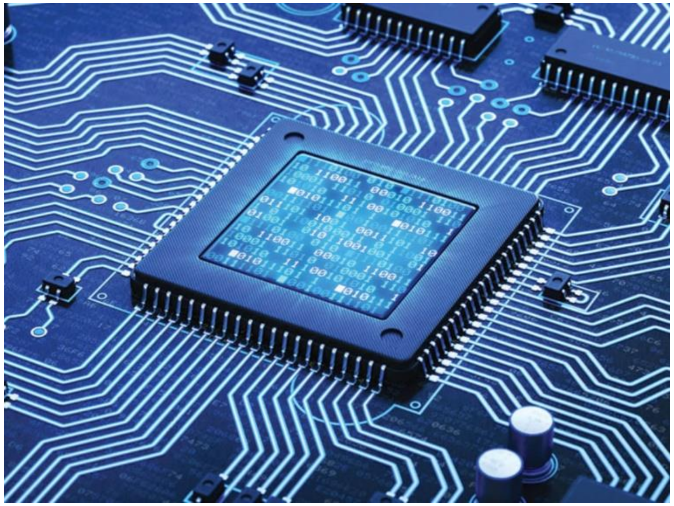
Si-Photonics



photon-based technologies the energy budget is **< fJ/bit**

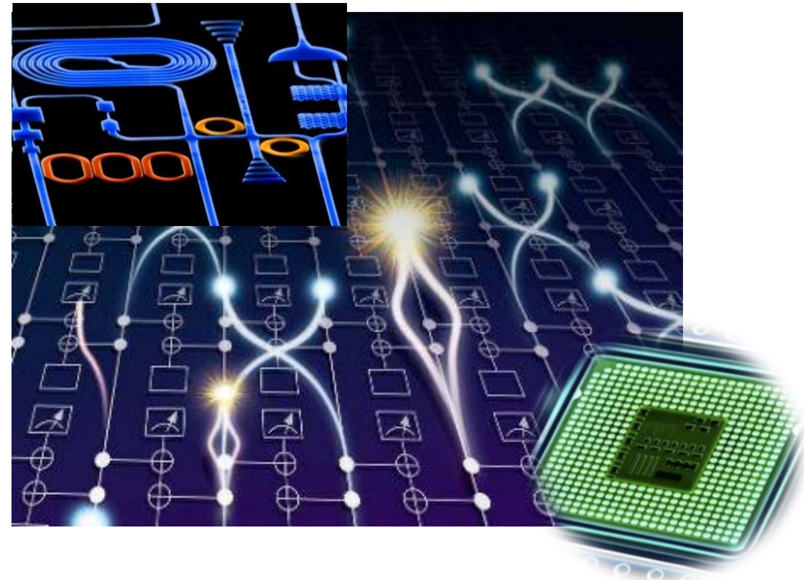
information "carrier" is a **photon**

Electronics



energy efficiency of the most advanced microelectronics **pJ/bit**

Photonics



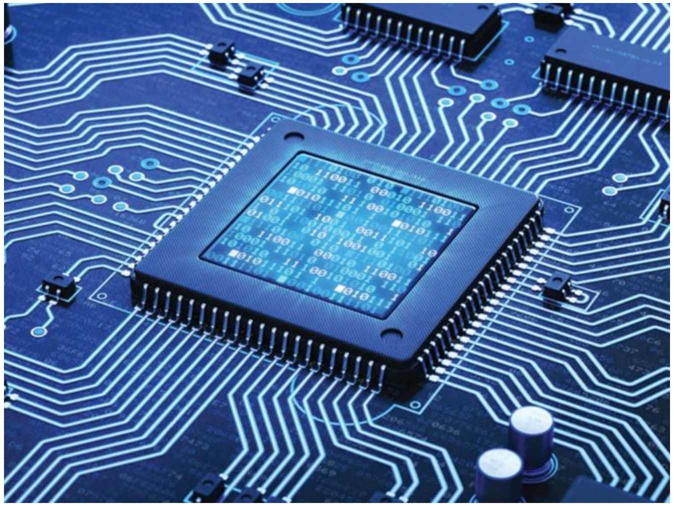
photon-based technologies the energy budget is **< fJ/bit**

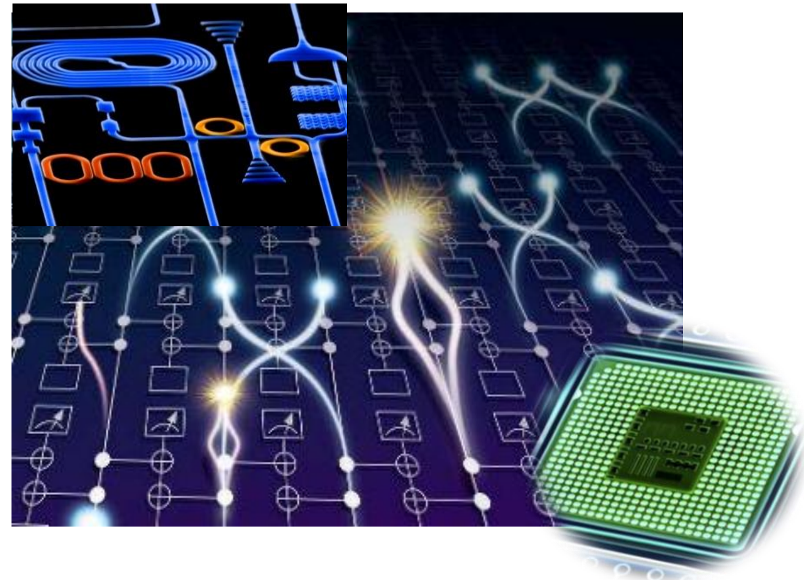
Frequency spectrum is ~10,000 higher for photons than electrons

Photonic chip: more data and far more energy efficiently

Electronics

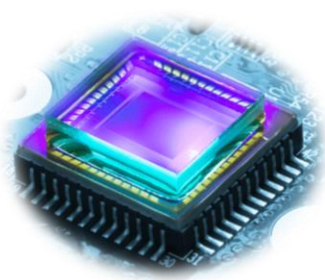
Photonics





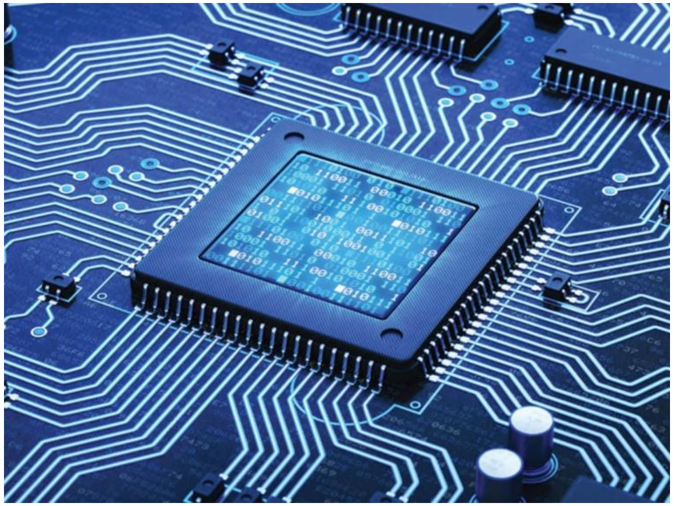
energy dissipation

photon-based technologies
the energy budget is **< fJ/bit**



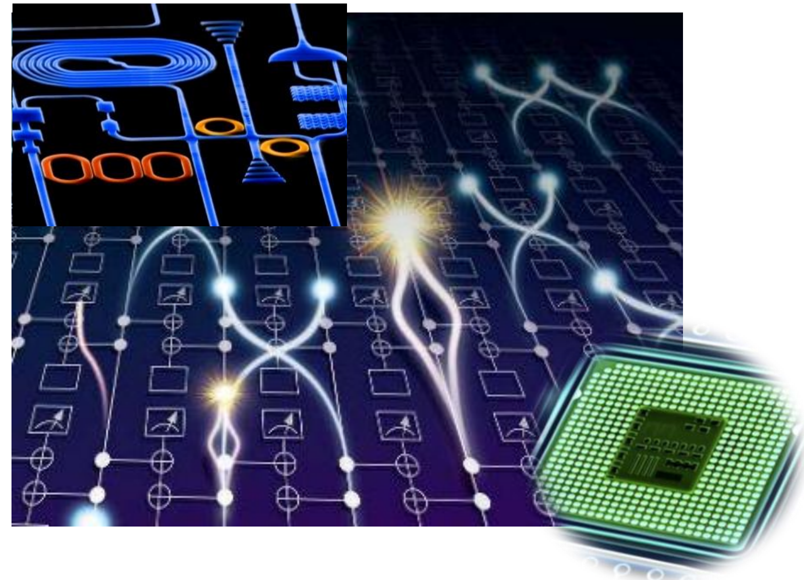
Energy harvesters – thermoelectric

Electronics



energy dissipation

Photonics



photon-based technologies
the energy budget is **< fJ/bit**

Energy harvesters – thermoelectric

Smart Home ???

Stays on the heater but powered by battery !!!!!

Electronics

Si -best material
mass-production
circuits

Photonics

Si dominates

Si has the highest optical losses (10 x **InP**)

Si- no light emitters (indirect bandgap)

InP – efficient laser but technology is not CMOS

Why we always need another material for different application?

Monolitical integration not possible?

Energy harvesters – thermoelectric

SiGe good **> 900°C**

20°-100°C: Bi2Te3, PbTe

Electronics

High mobility chanels
Low contact resistance

Go down in group IV

strained Si
SiGe
Ge
GeSn

Si-Photonics

Laser is missing

Direct bandgap semiconductor

Go down in group IV

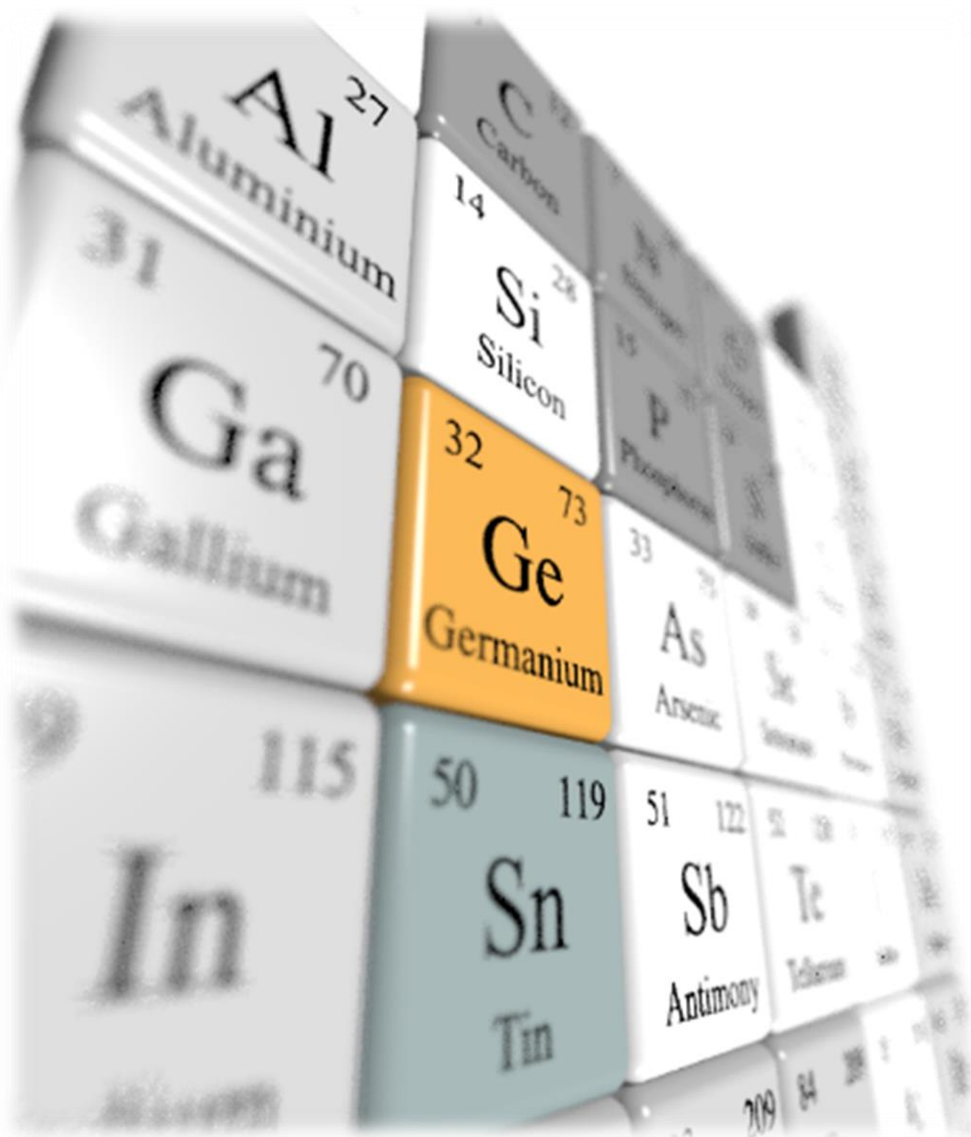
Strained Ge
GeSn

Si-group alloys

Energy harvesters – thermoelectric

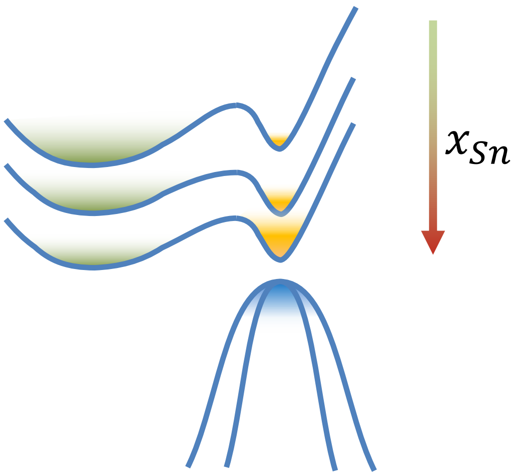
Low thermal conductivity (strong phonon scattering)
Good electrical conductance

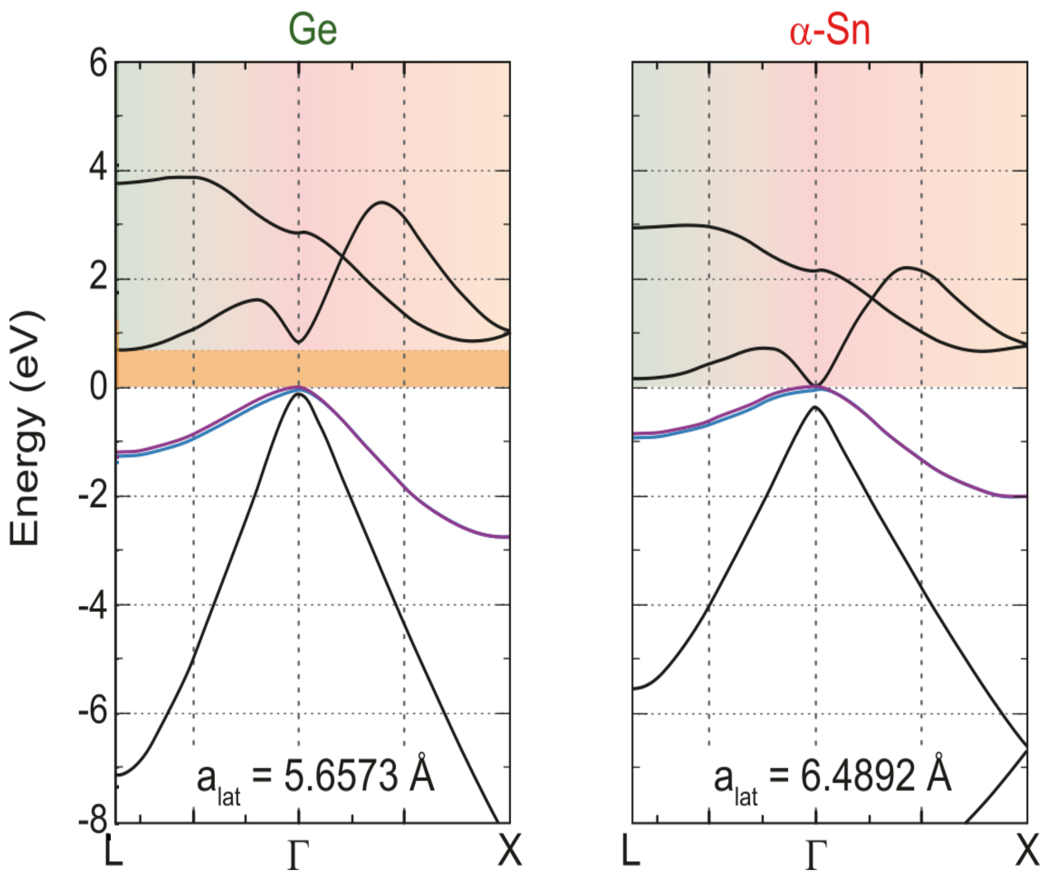
Take all group IV elements: SiGeSn or CSiGeSn alloys



Si-Ge-Sn
A Multifunctional Alloy

GeSn Alloys – Band Structure

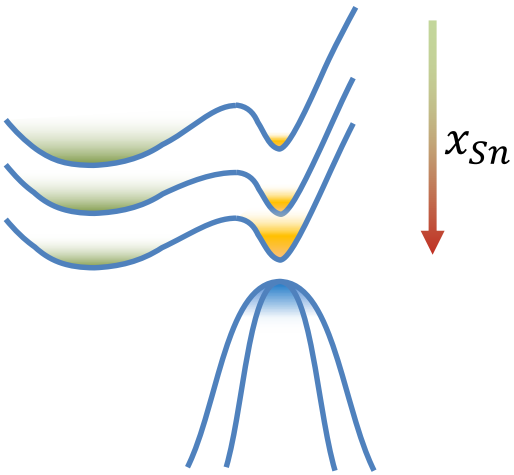




Bandgap	Ge	α-Sn
$E_{g,\Gamma}$ (eV)	0.8	-0.4
$E_{g,L}$ (eV)	0.66	0.1

$$E_g = E_{Ge}x_{Ge} + E_{Sn}x_{Sn} - b_{GeSn}x_{Ge}x_{Sn}$$

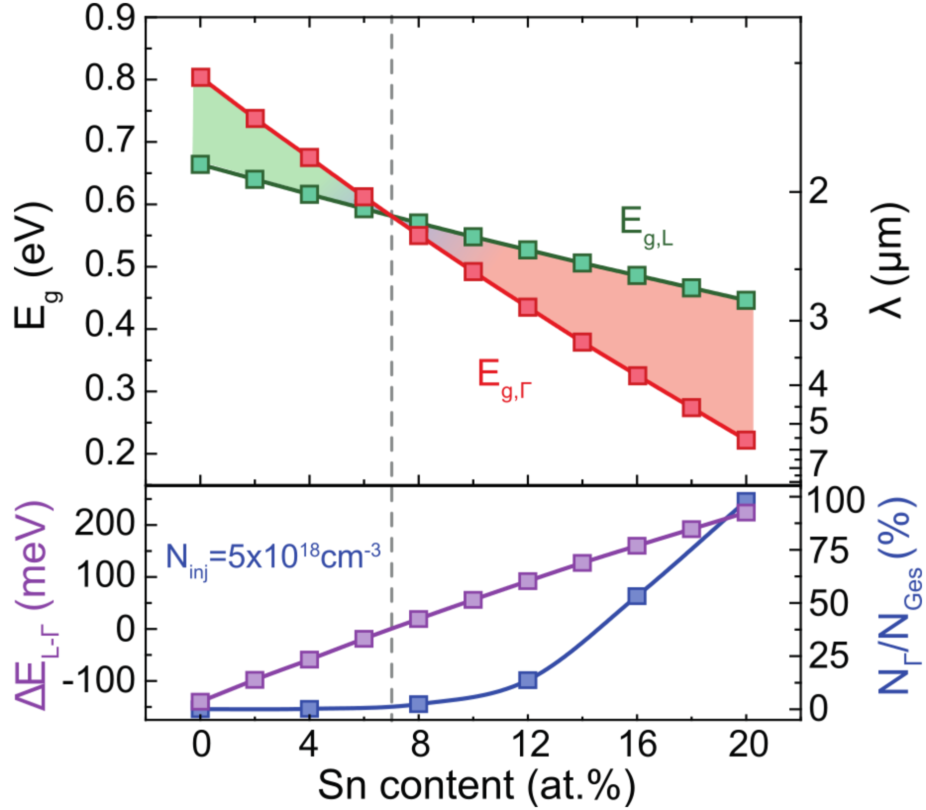
GeSn Alloys – Band Structure



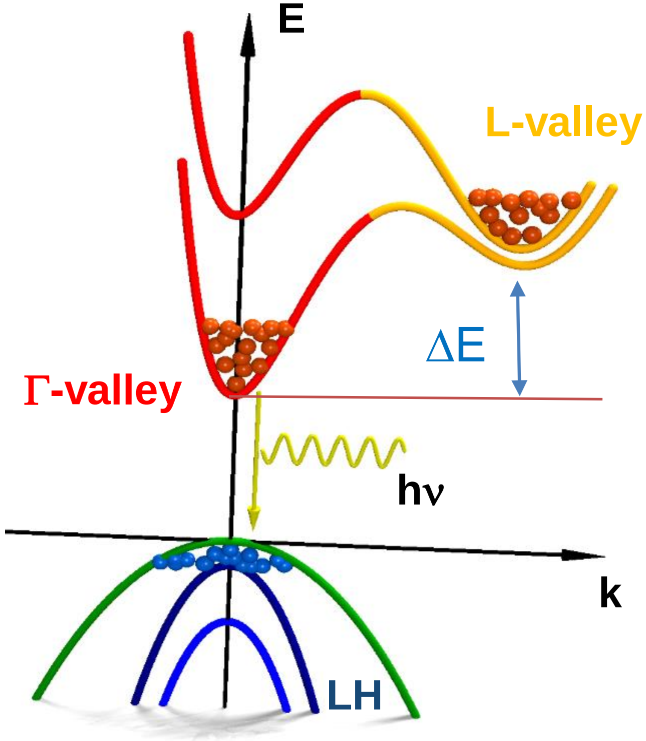
Bandgap	Ge	α-Sn
$E_{g,\Gamma}$ (eV)	0.8	-0.4
$E_{g,L}$ (eV)	0.66	0.1

$$E_g = E_{Ge}x_{Ge} + E_{Sn}x_{Sn} - b_{GeSn}x_{Ge}x_{Sn}$$

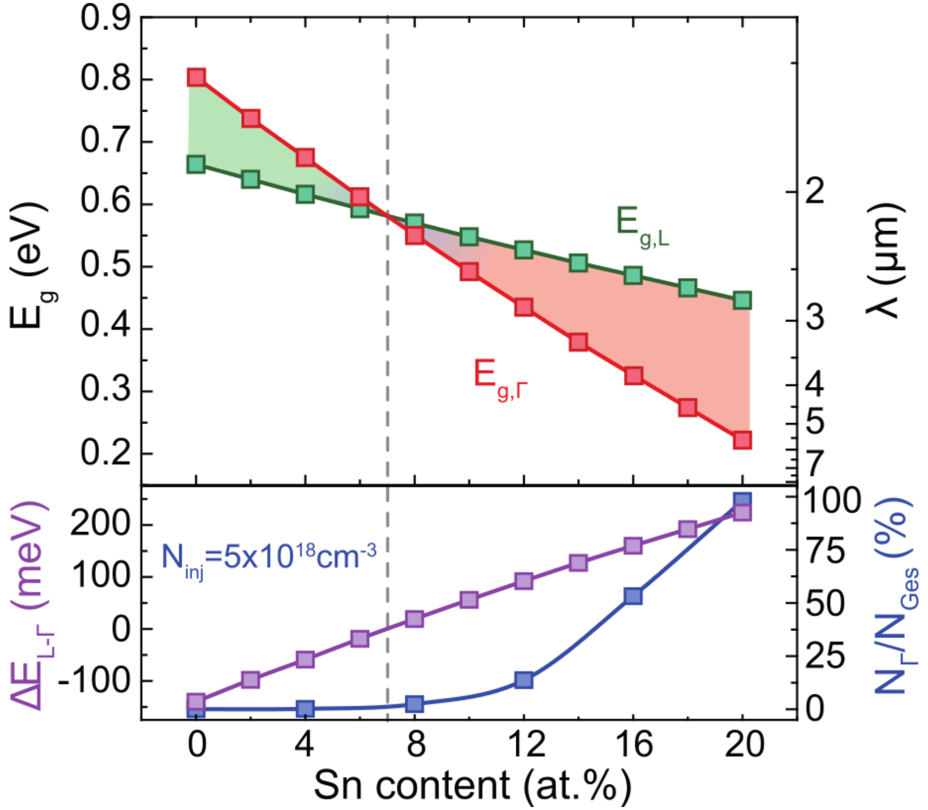
8-band k·p calculations



GeSn Alloys – Band Structure

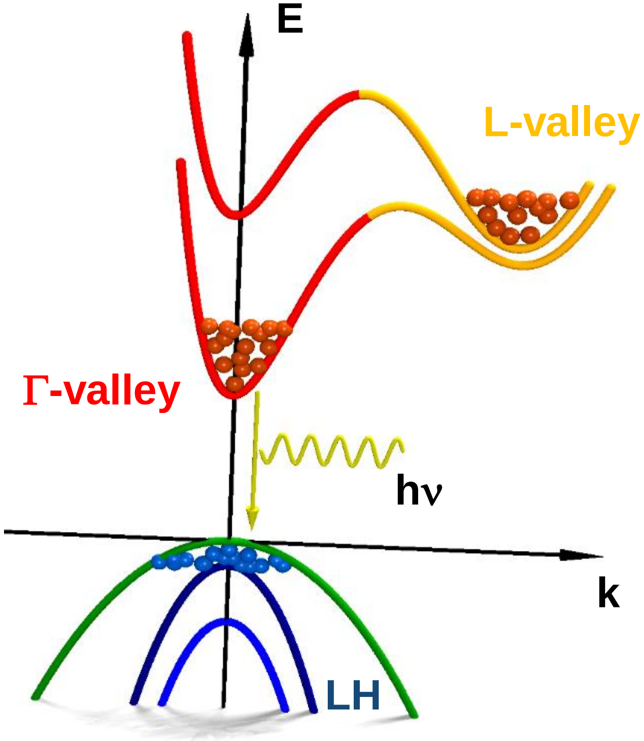


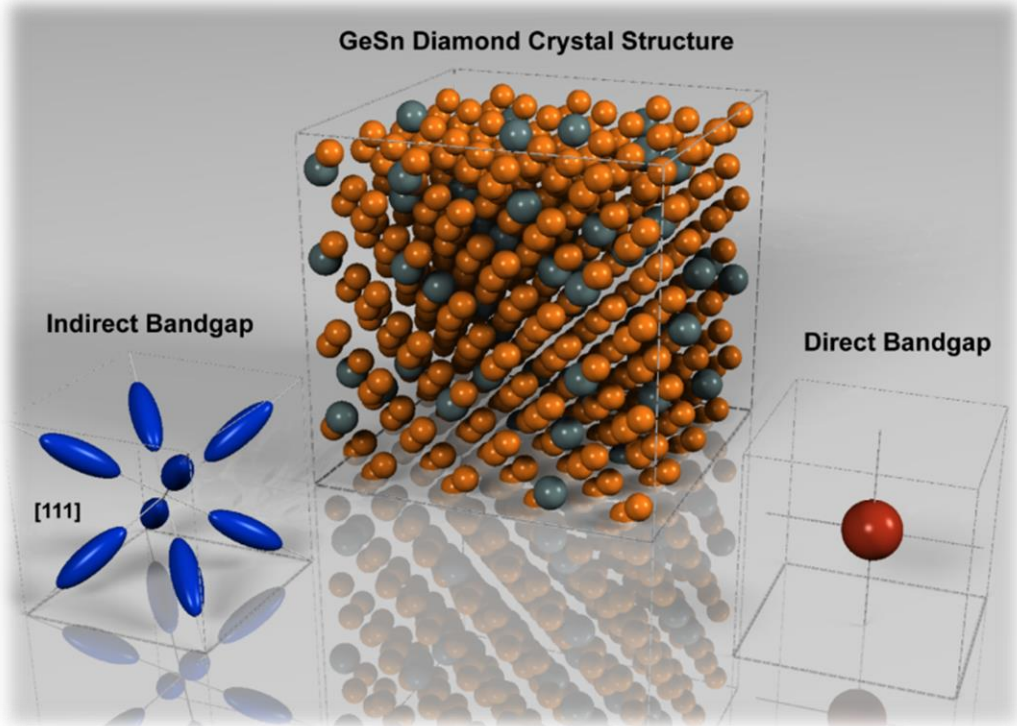
8-band k·p calculations



$$E_g = E_{Ge}x_{Ge} + E_{Sn}x_{Sn} - b_{GeSn}x_{Ge}x_{Sn}$$

GeSn Alloys – Band Structure

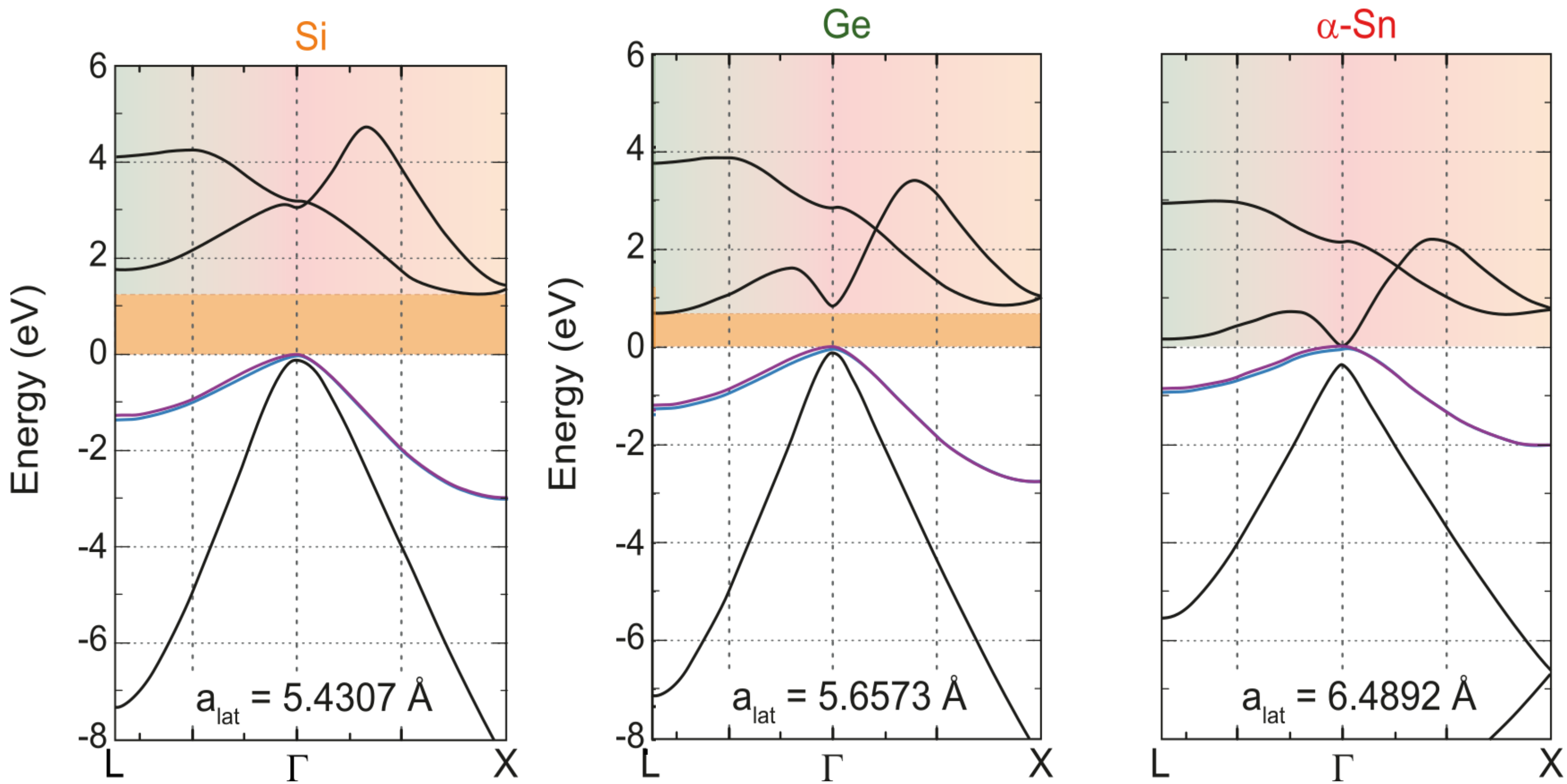




Sn < 7 at.%
Fundamental **indirect**
Electrons in **L band**

Sn > 7 at.%
Fundamental **direct**
Electrons in Γ **band**

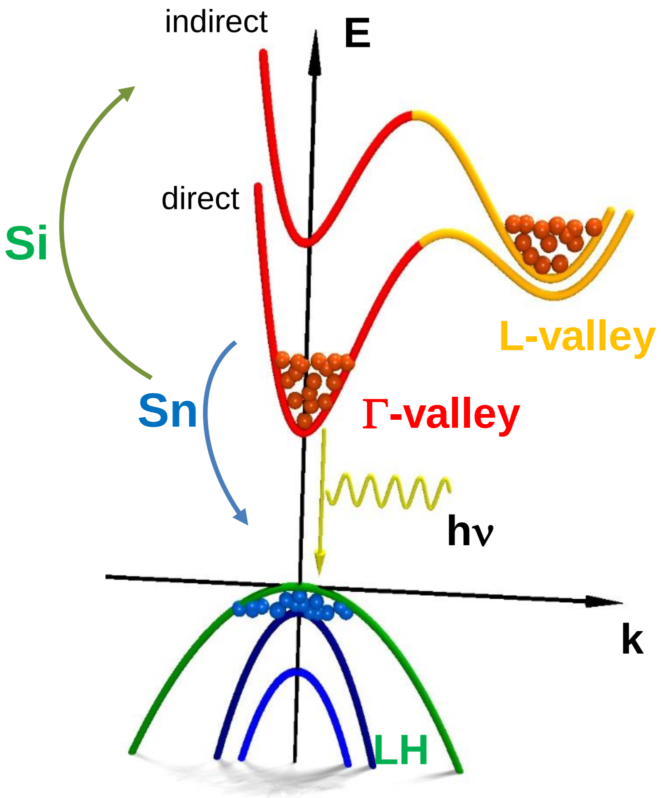
SiGeSn Alloys – Band Structure

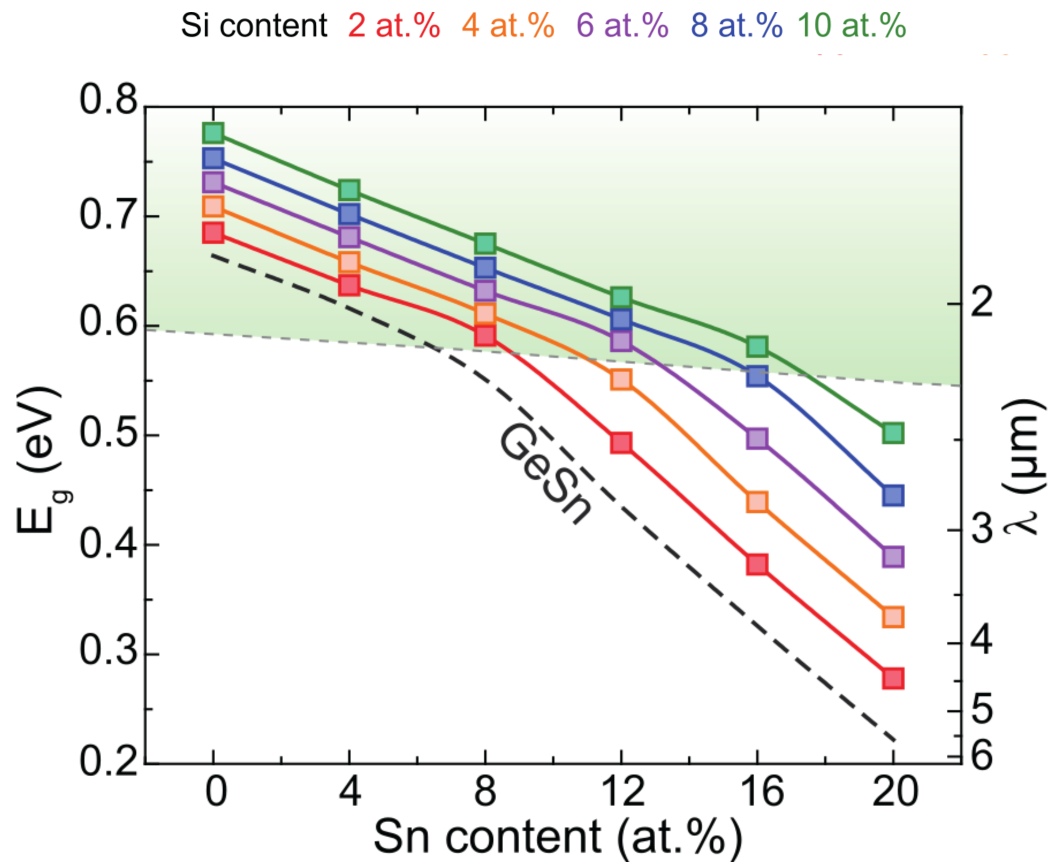


$$E_g = E_{Ge}x_{Ge} + E_{Si}x_{Si} + E_{Sn}x_{Sn} - b_{GeSn}x_{Ge}x_{Sn} - b_{SiGe}x_{Ge}x_{Si} - b_{SiSn}x_{Si}x_{Sn}$$

$$= E_{GeSn}(x_{Ge}, x_{Sn}) + x_{Si}(E_{Si} - b_{SiGe}x_{Ge} - b_{SiSn}x_{Sn})$$

SiGeSn Alloys – Band Structure





$$E_g = E_{Ge}x_{Ge} + E_{Si}x_{Si} + E_{Sn}x_{Sn} - b_{GeSn}x_{Ge}x_{Sn} - b_{SiGe}x_{Ge}x_{Si} - b_{SiSn}x_{Si}x_{Sn}$$

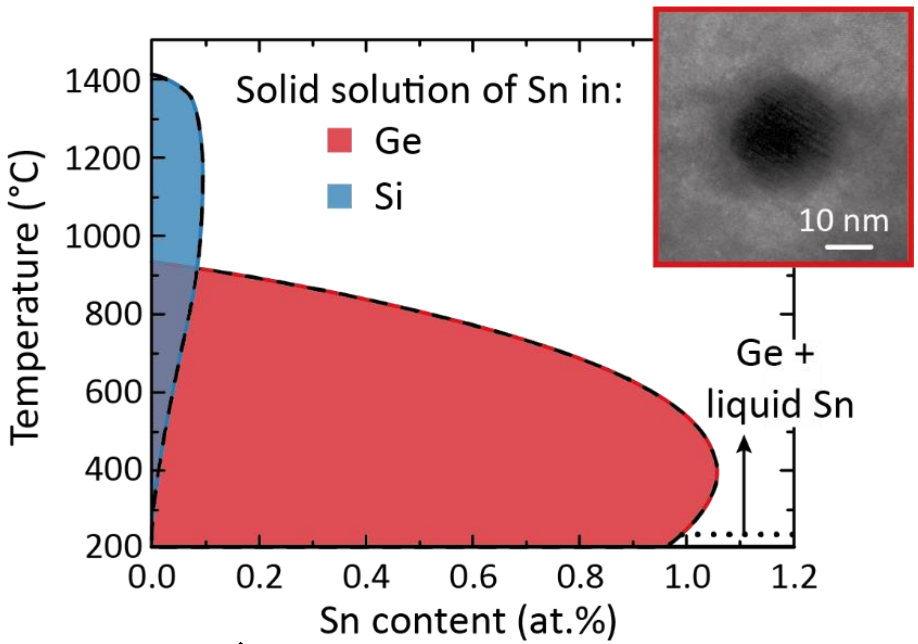
$$= E_{GeSn}(x_{Ge}, x_{Sn}) + x_{Si}(E_{Si} - b_{SiGe}x_{Ge} - b_{SiSn}x_{Sn})$$

tunability

Si-Ge-Sn group IV alloys

challenges:

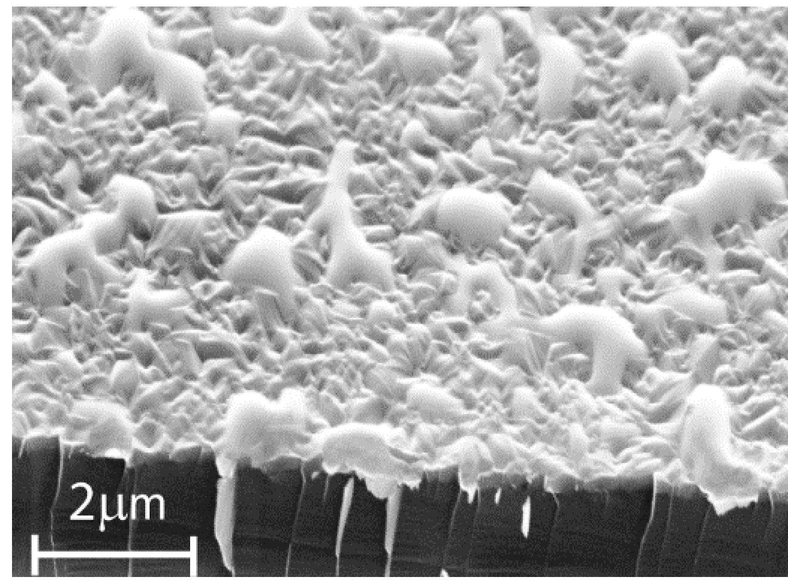
- **low solid solubility** of Sn (< 1 at.%)



~~Thermodinamic equilibrium~~

Sn segregation

(β-Sn) during growth

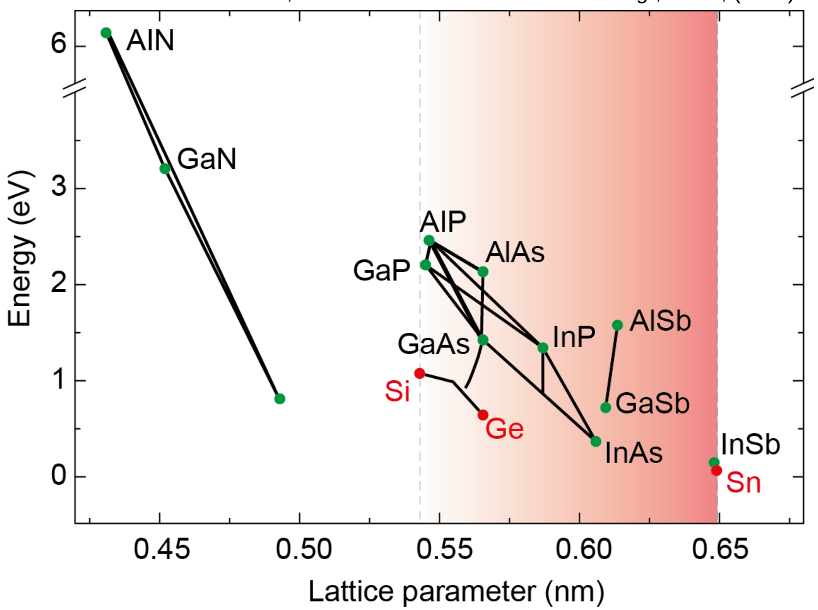


S. Wirths *et al.*, *JSST* **2**(5), N99 (2013)

Si-Ge-Sn group IV alloys

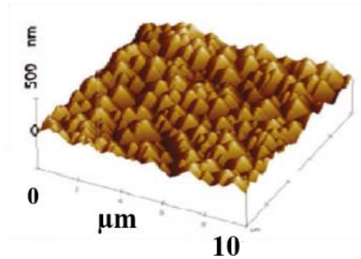
Lattice Constants

T. F. Kuech *et al.*, *Ann. Rev. of Chem. and Biomol. Eng.*, **4**:187, (2013)



Large lattice mismatch (~ 15%)

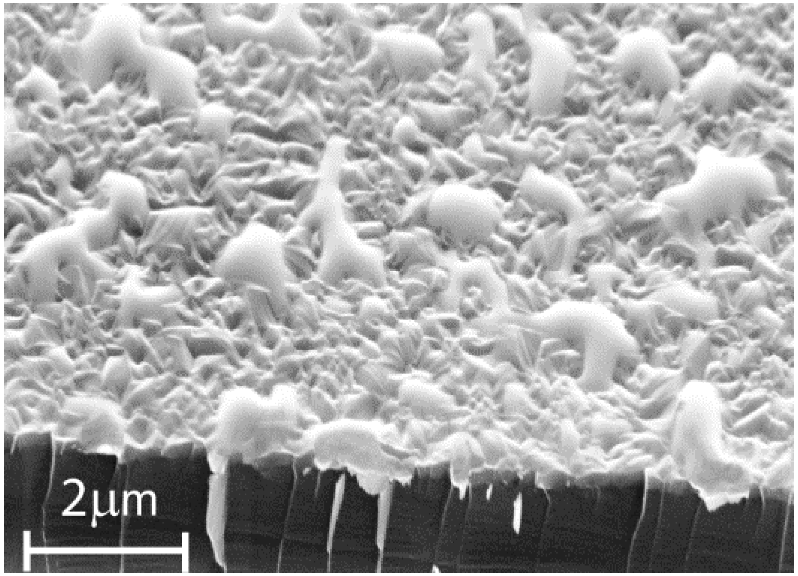
Surface roughening & epitaxial breakdown



F. Gencarelli *et al.*,
JSST **2**(4), P134 (2013)

Sn segregation

(β-Sn) during growth

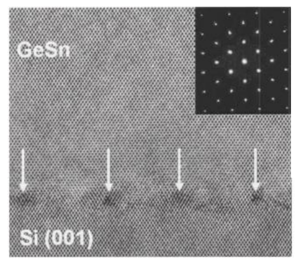


S. Wirths *et al.*, *JSST* **2**(5), N99 (2013)

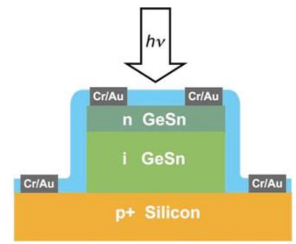
GeSn – Timeline

C. Goodman, *IEE Proc. I SS&E Dev.* **129** (1982),
S. Oguz *et al.*, *APL* **43** (1983),
S. Shah *et al.*, *J. of Cryst. Gr.*, **83** (1987),
E. A. Fitzgerald *et al.*, *J. of Electr. Mat.* **20**, (1991),
M. Taylor and G. He, *JAP* **80** (1996),
R. Ragan and H. Atwater, *APL* **77** (2000),
M. Bauer *et al.*, *APL* **81** (2002),
R. Soref *et al.*, *J. Mater. Res.* **22** (2007),
J. Mathews *et al.*, APL **95** (2009),
B. Vincent *et al.*, *APL* **99** (2011),
M. Oehme *et al.*, *IEEE Phot. Techn. Let.* **23** (2011),
S. Wirths & R. Geiger *et al.*, *Nat. Phot.* **9** (2015).

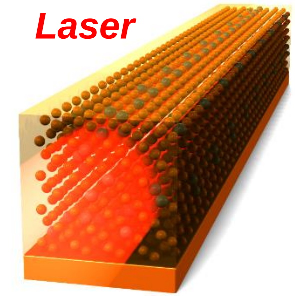
CVD-grown GeSn

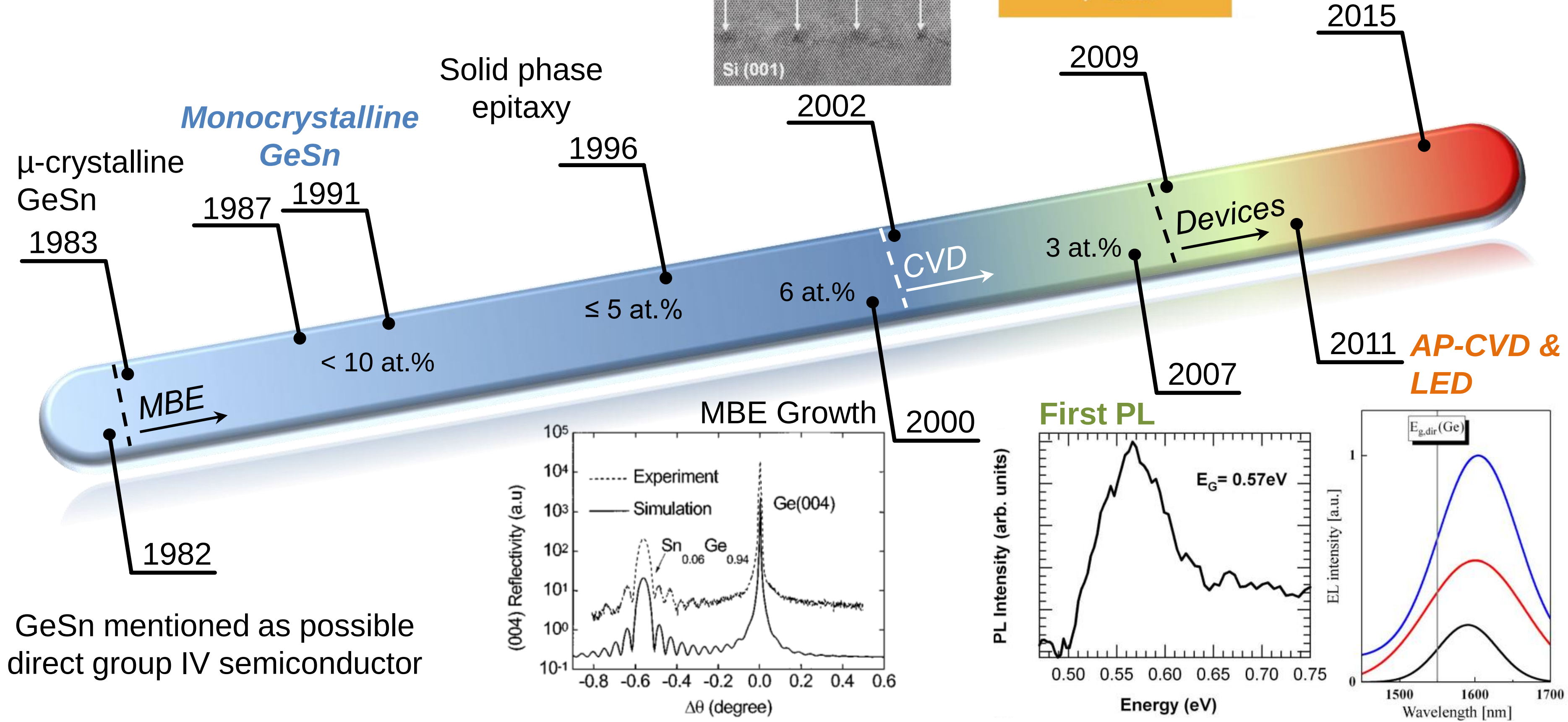


Photodetector



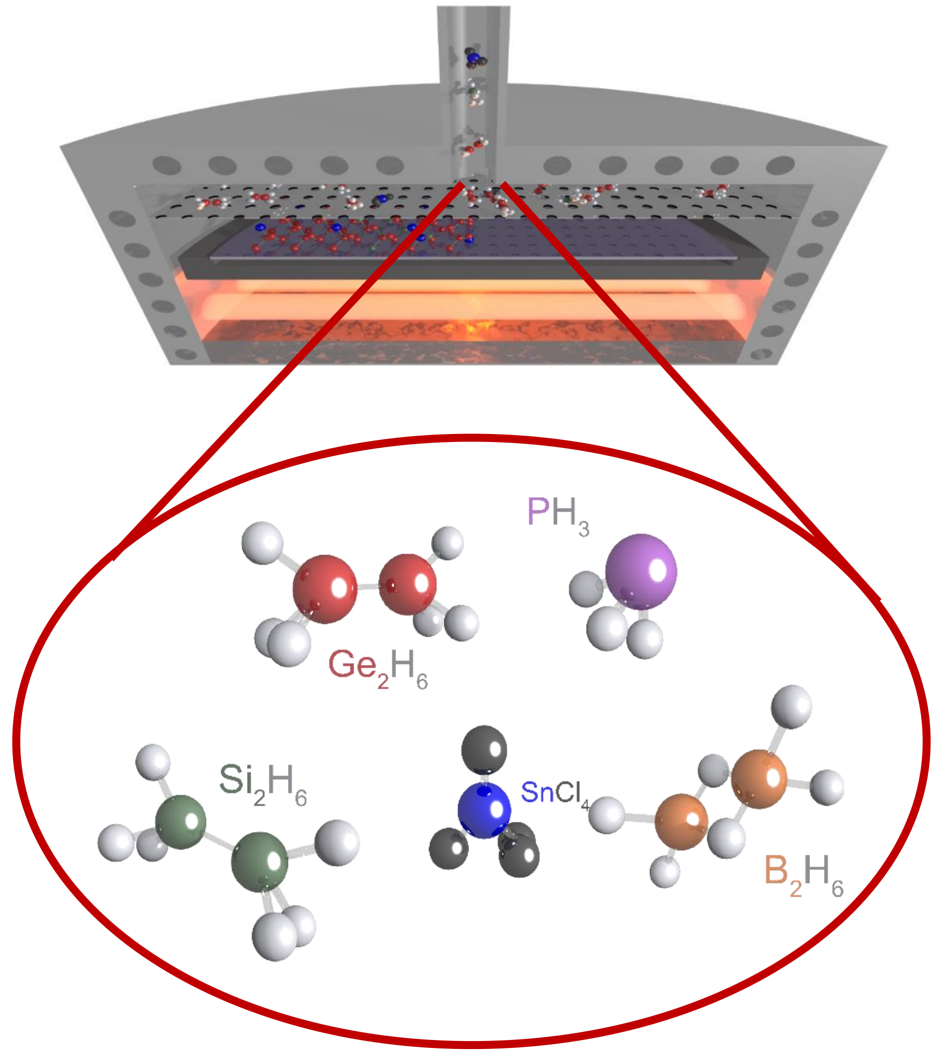
Laser





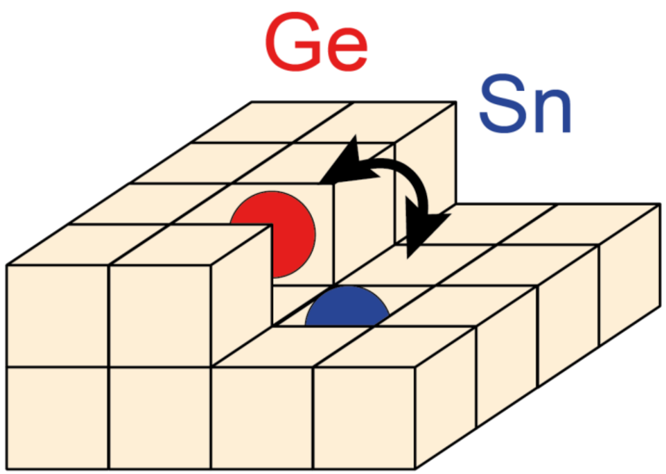
Si-Ge-Sn group IV alloys

200 mm Cold-Wall Reduced Pressure Reactor (RPCVD)

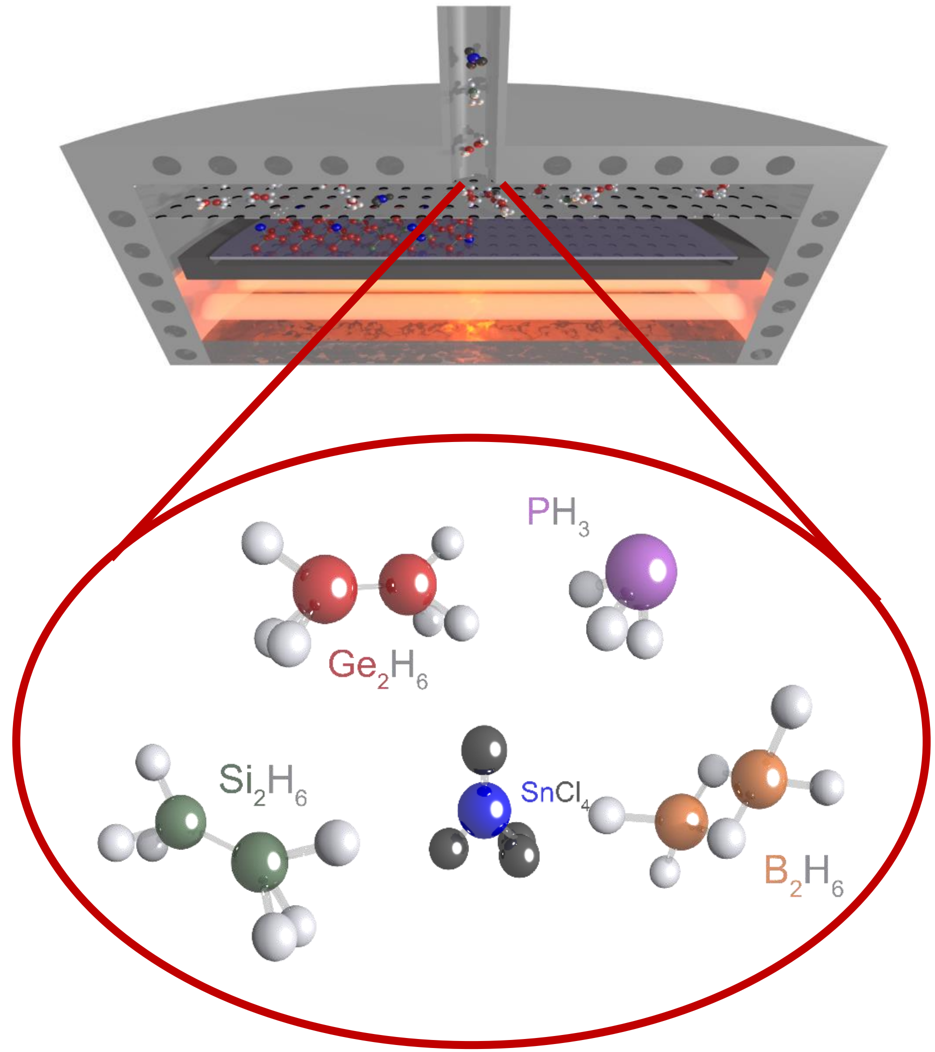


- *Showerhead* technology
- Precursors: Ge_2H_6, $SnCl_4$, Si_2H_6

Si-Ge-Sn group IV alloys



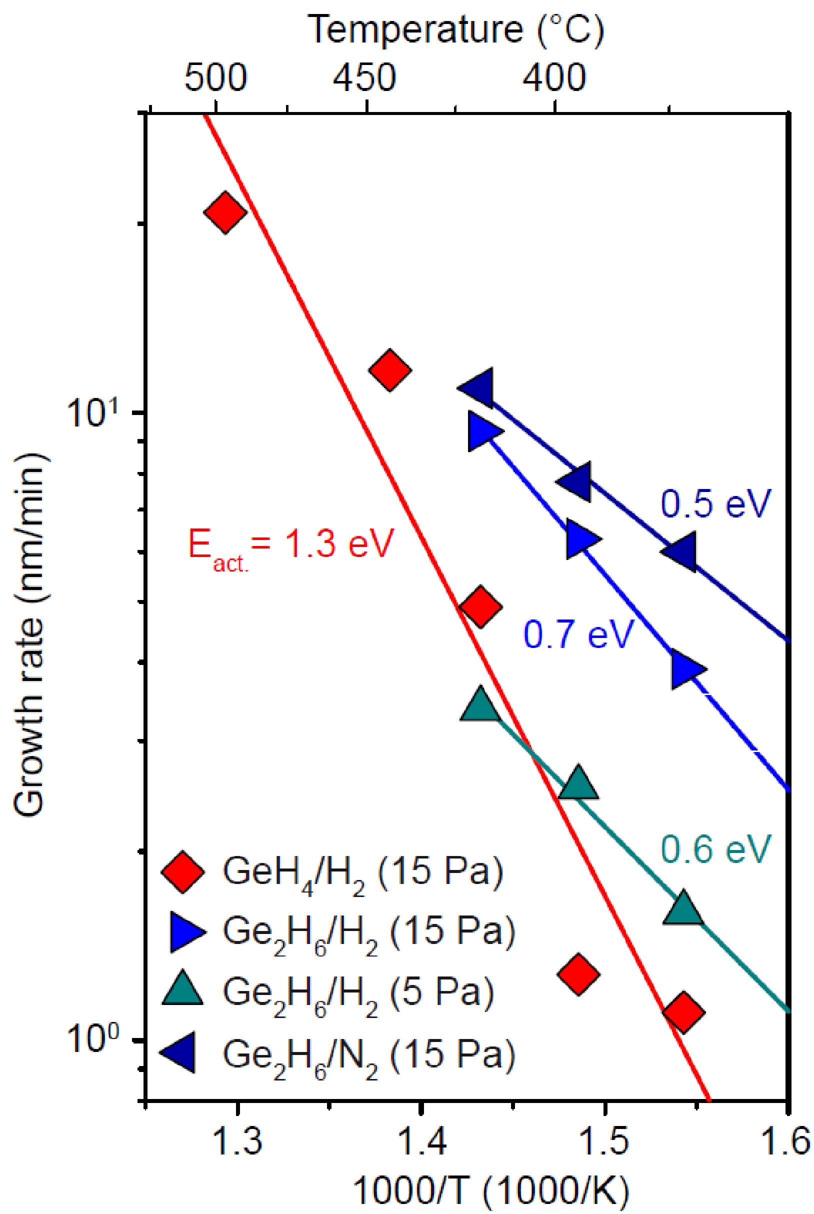
$$\Delta_s \propto \frac{1}{\sqrt{R}} e^{-1/k_B T}$$



Low Growth Temperature &

High Growth Rate

Growth rate of Ge on Si (100)



GeH_4 => Ge_2H_6

E_{act} ↓ ➔ ↑ growth rate at low T

15 Pa => 5Pa

E_{act} ~ constant, growth rate ↓ a factor of 3

Radicals:

$Ge_2H_6 + H_2$ => $2GeH_3• + H_2$ => $2GeH_4$

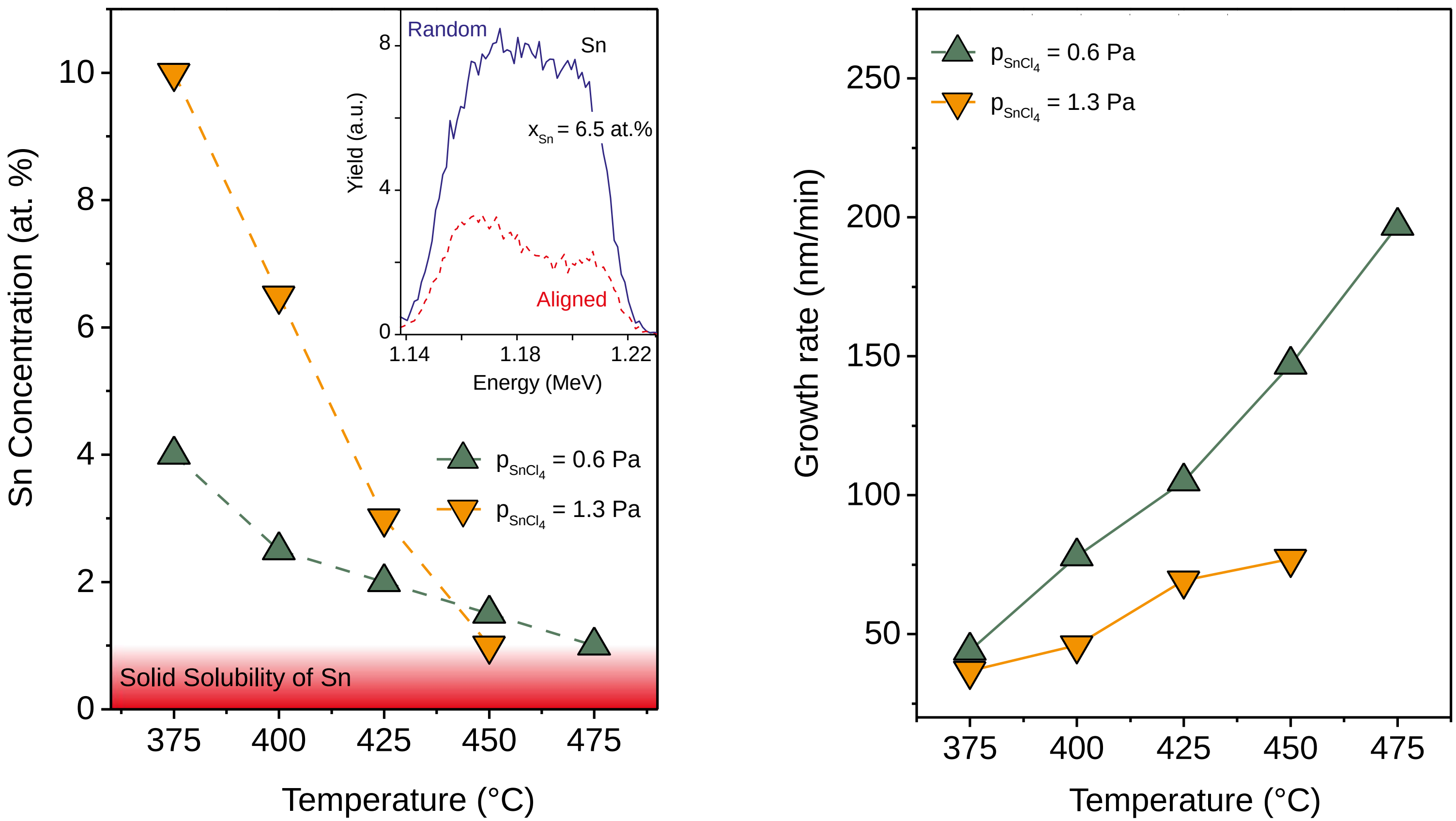
$Ge_2H_6 + N_2$ => $2GeH_3• + N_2$

E_{act} ↓ and growth ↑ at low T

Supply of hydride radicals to the surface is a key element

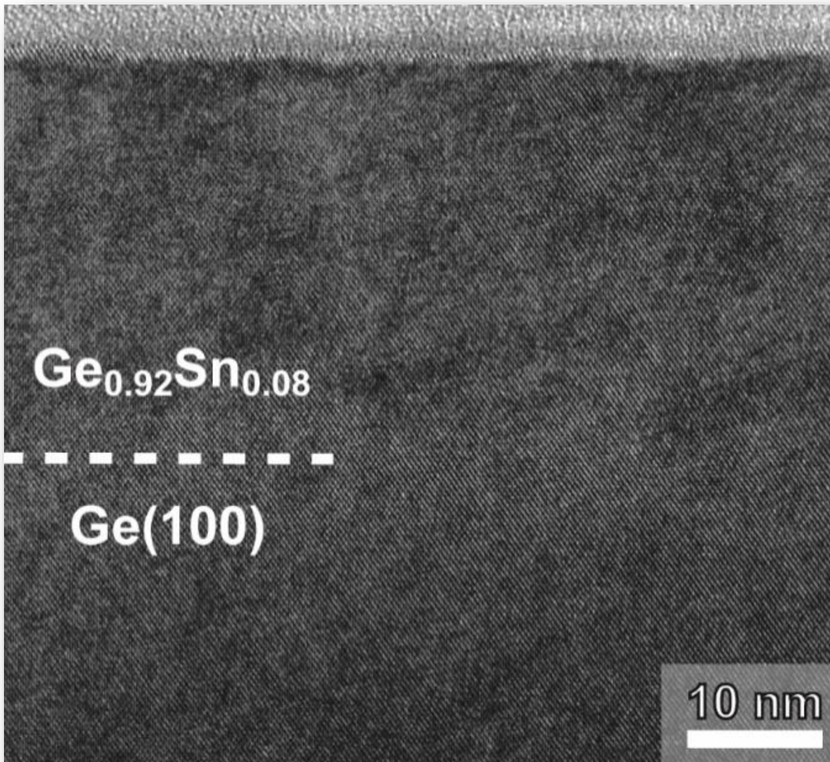
GeSn/Si(001) Growth Kinetics

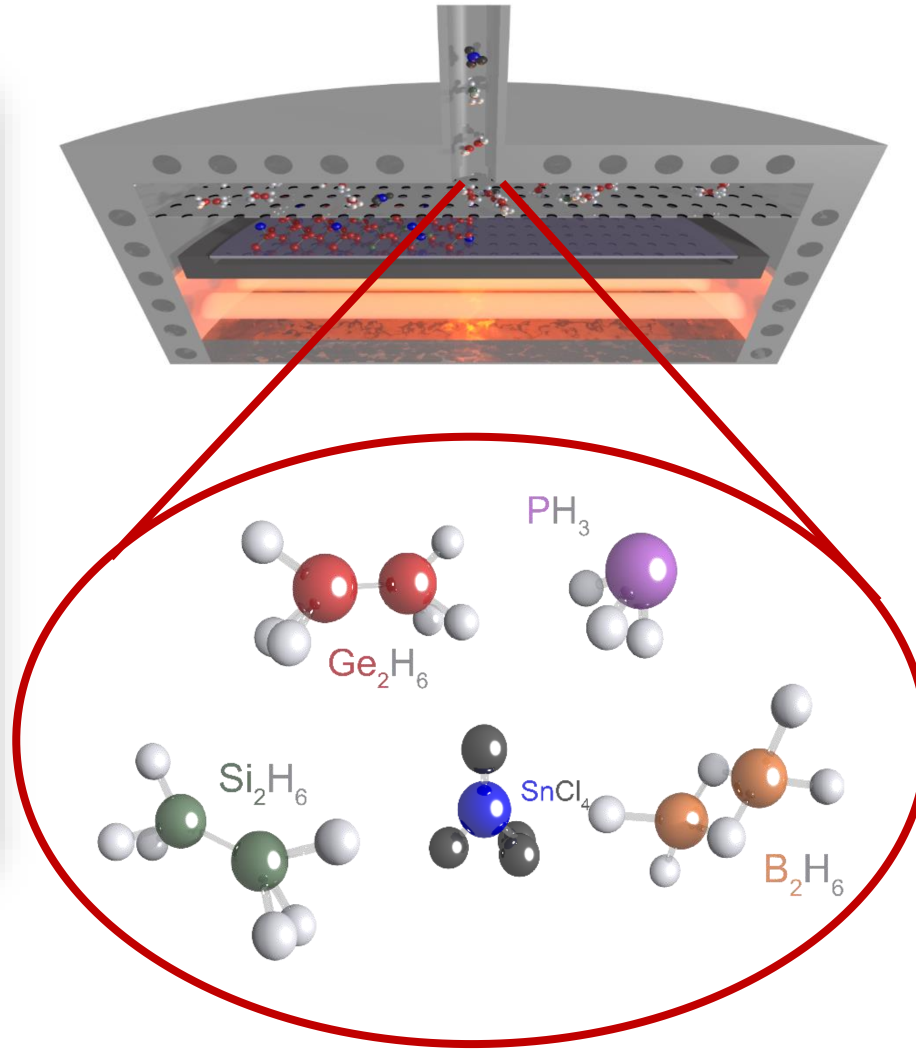
Growth Temperature



Solid solubility limit can be exceeded for $T_{growth} \leq 450$ °C

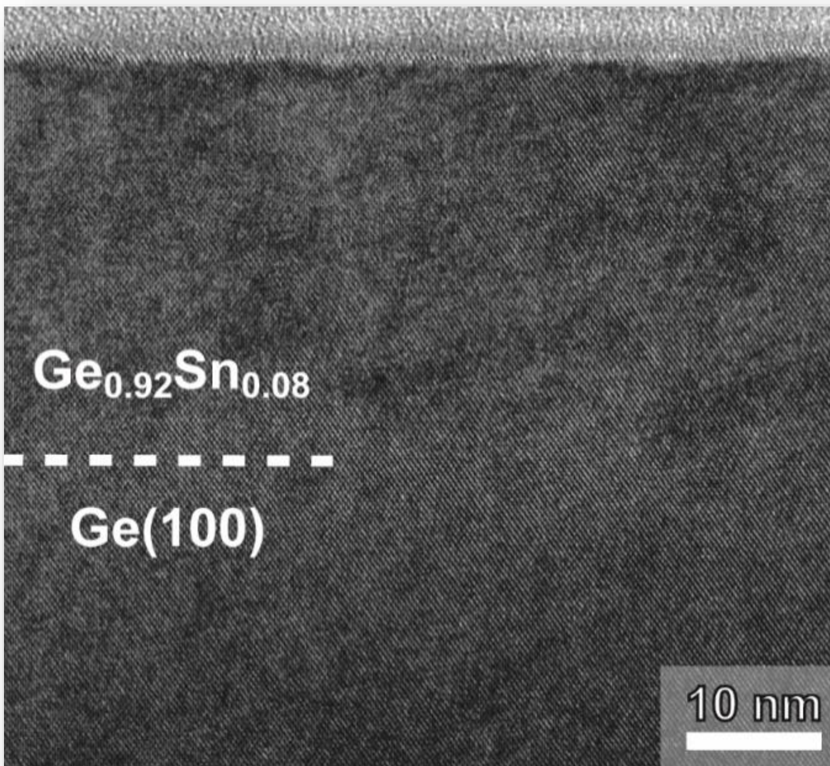
Si-Ge-Sn group IV alloys



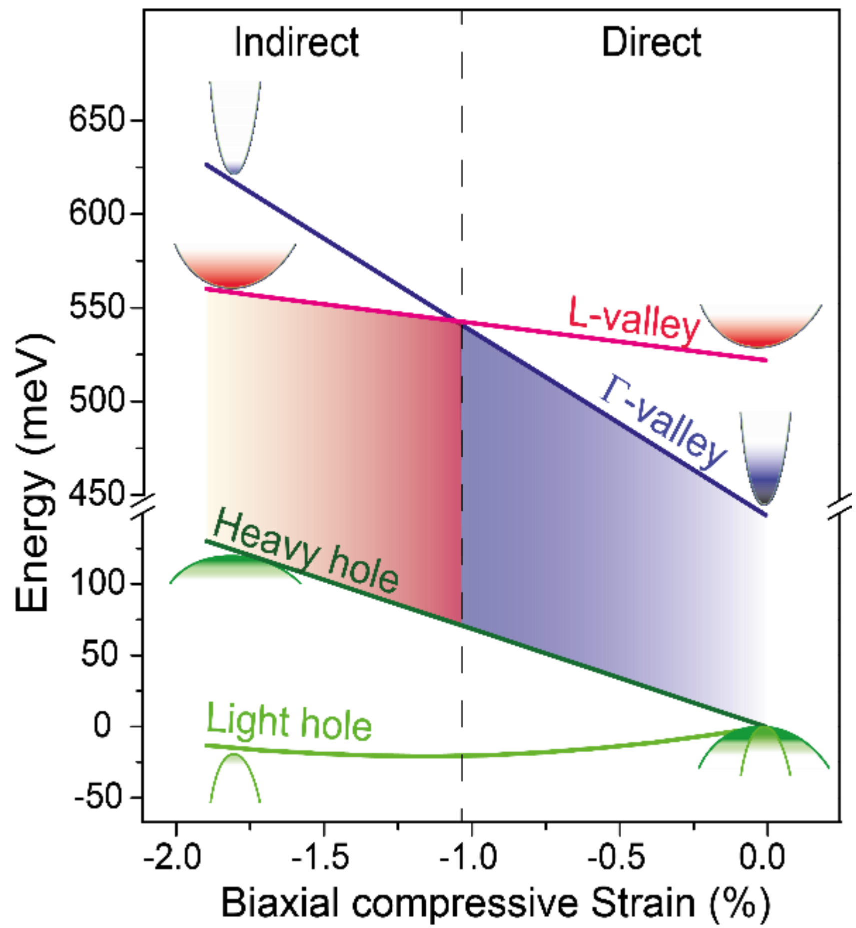


- Very *high* crystall quality

Si-Ge-Sn group IV alloys

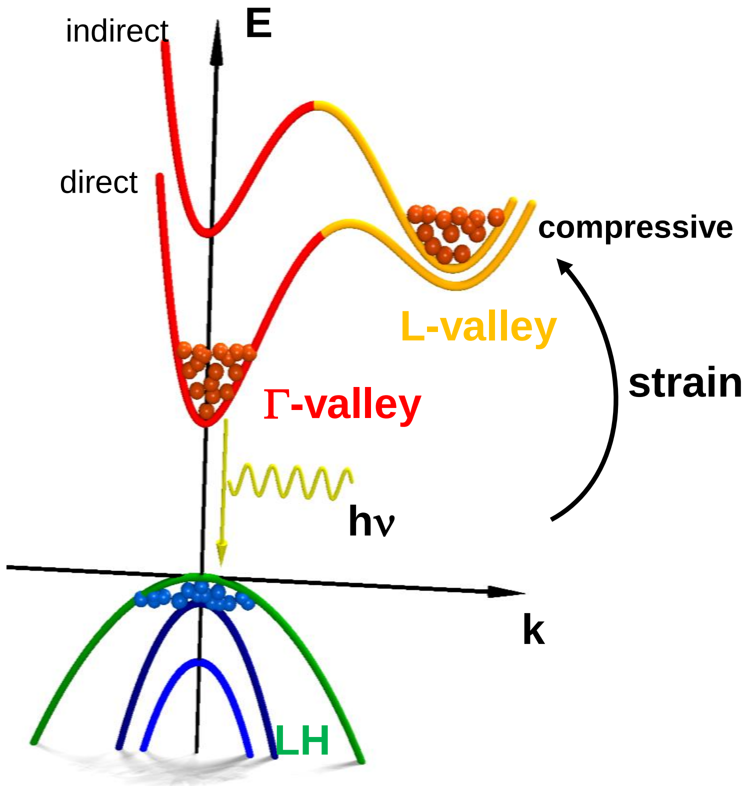


GeSn 12at.%

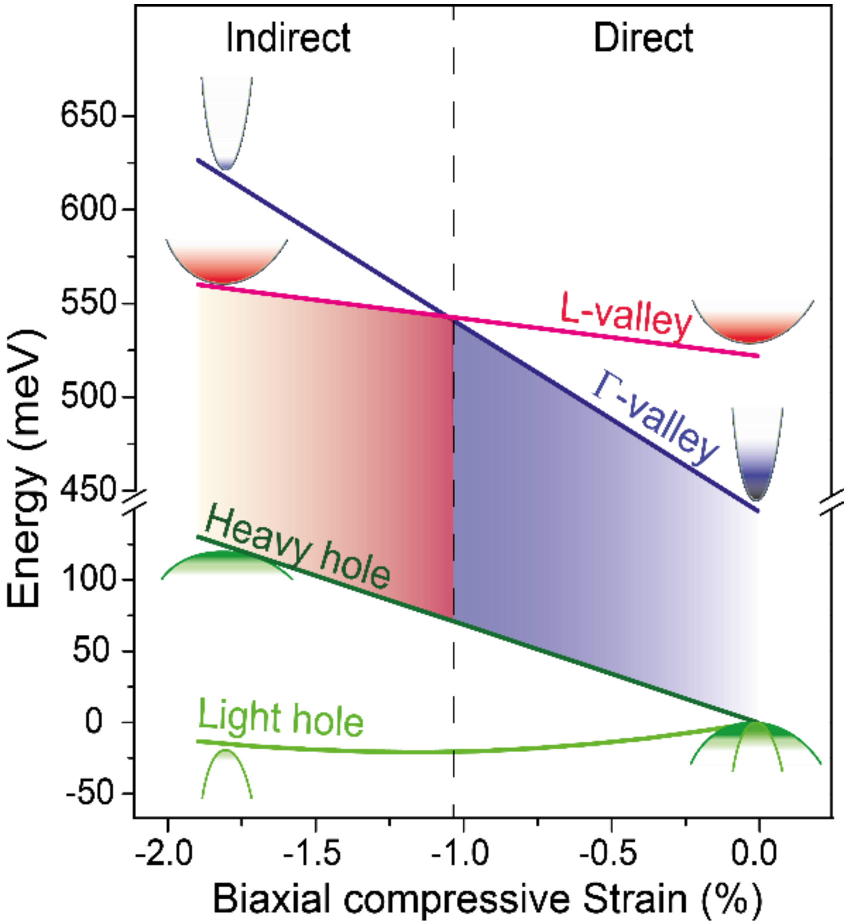


Huge lattice strain!!!

Si-Ge-Sn group IV alloys

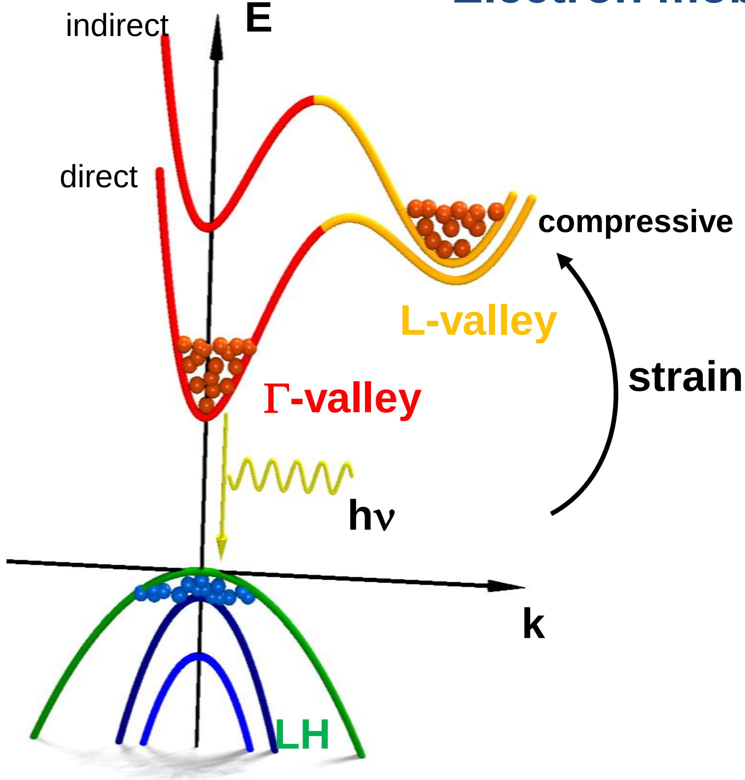


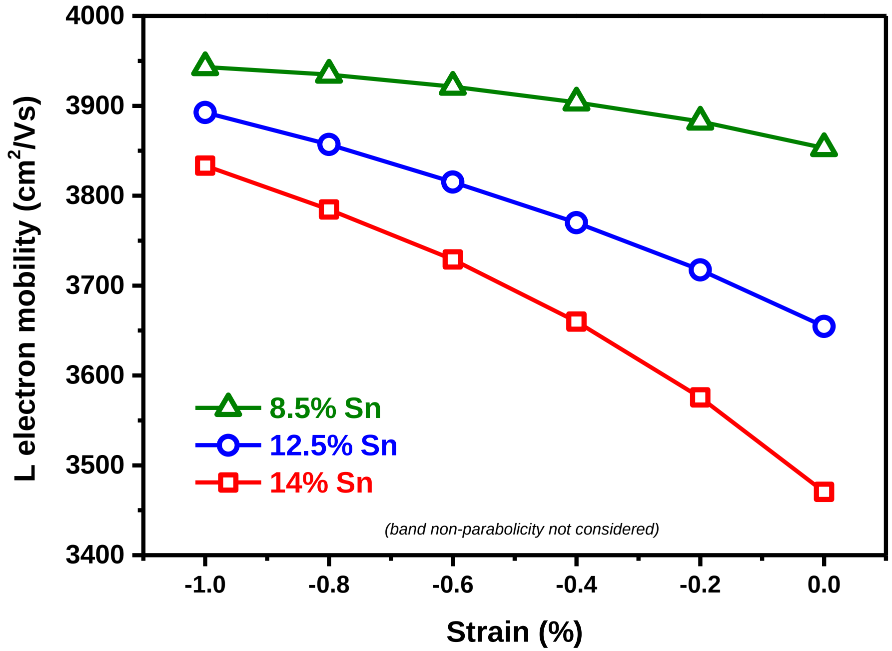
GeSn 12at.%

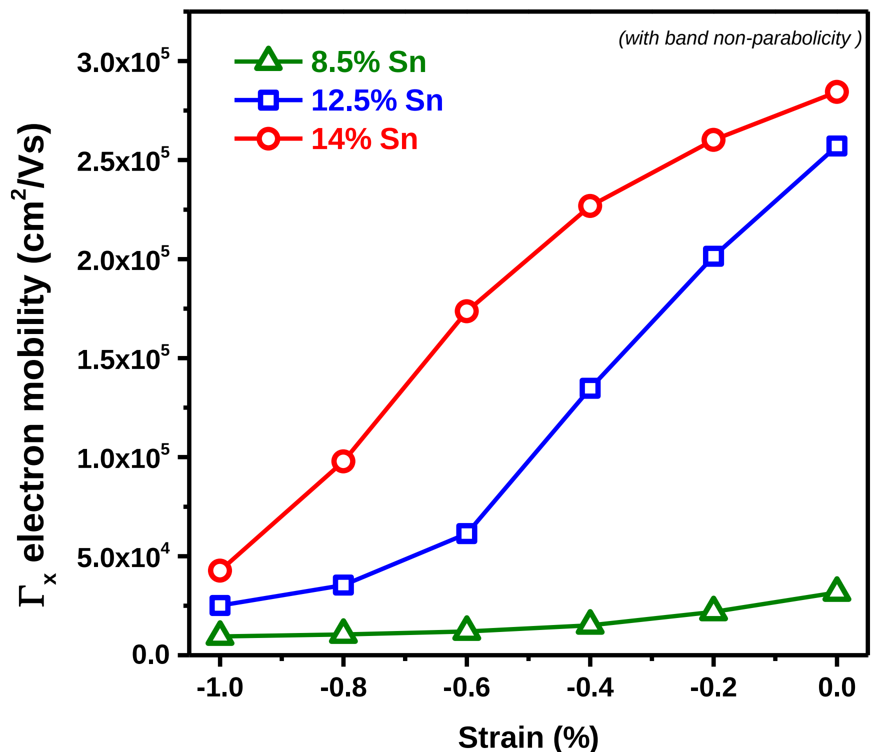


Si-Ge-Sn group IV alloys

Electron mobility





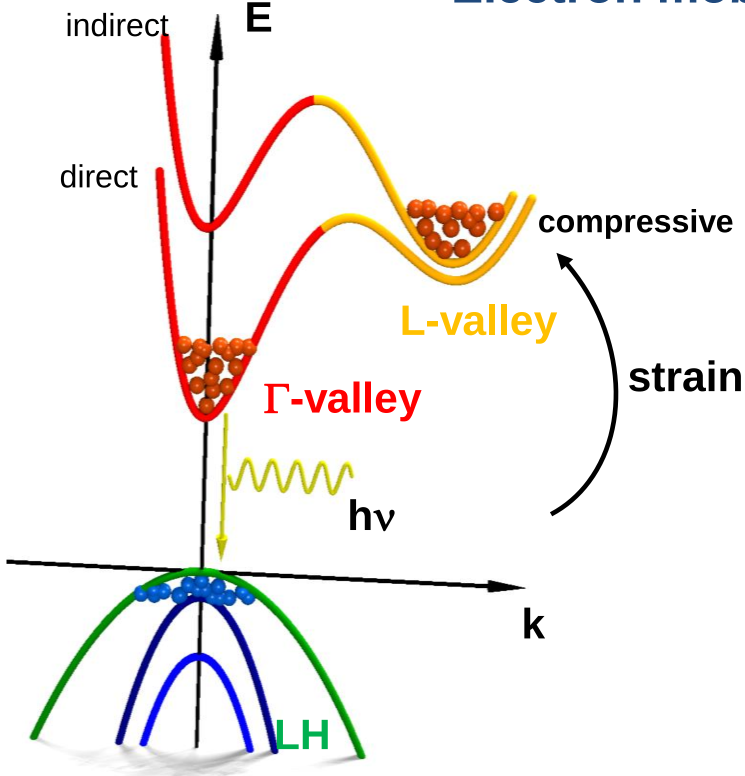


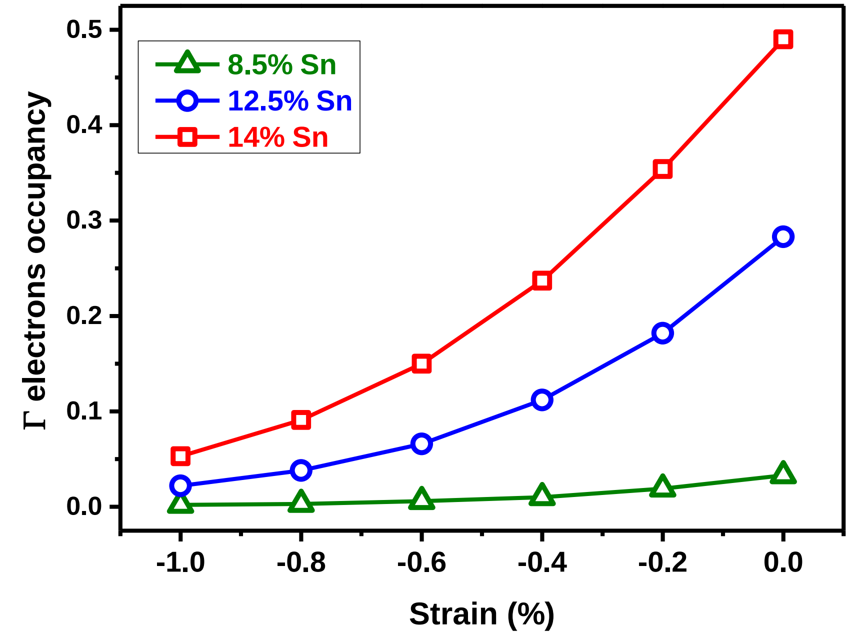
μ Similar to III-V

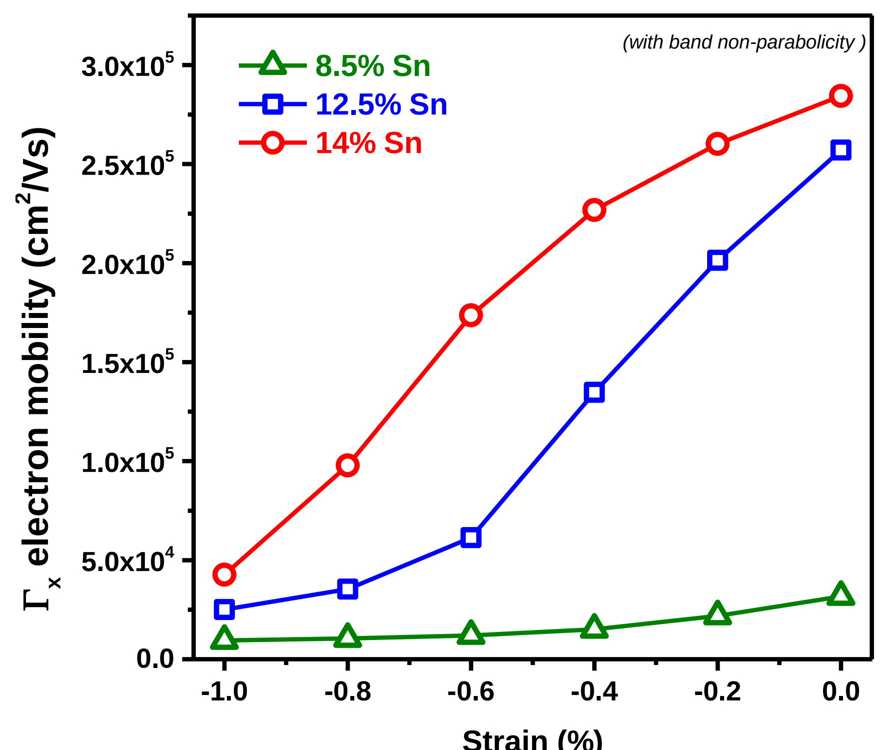
Conductivity mass $$\mu \sim \frac{1}{m_{eff}} = \frac{\partial^2 E}{\partial k^2}$$

Si-Ge-Sn group IV alloys

Electron mobility







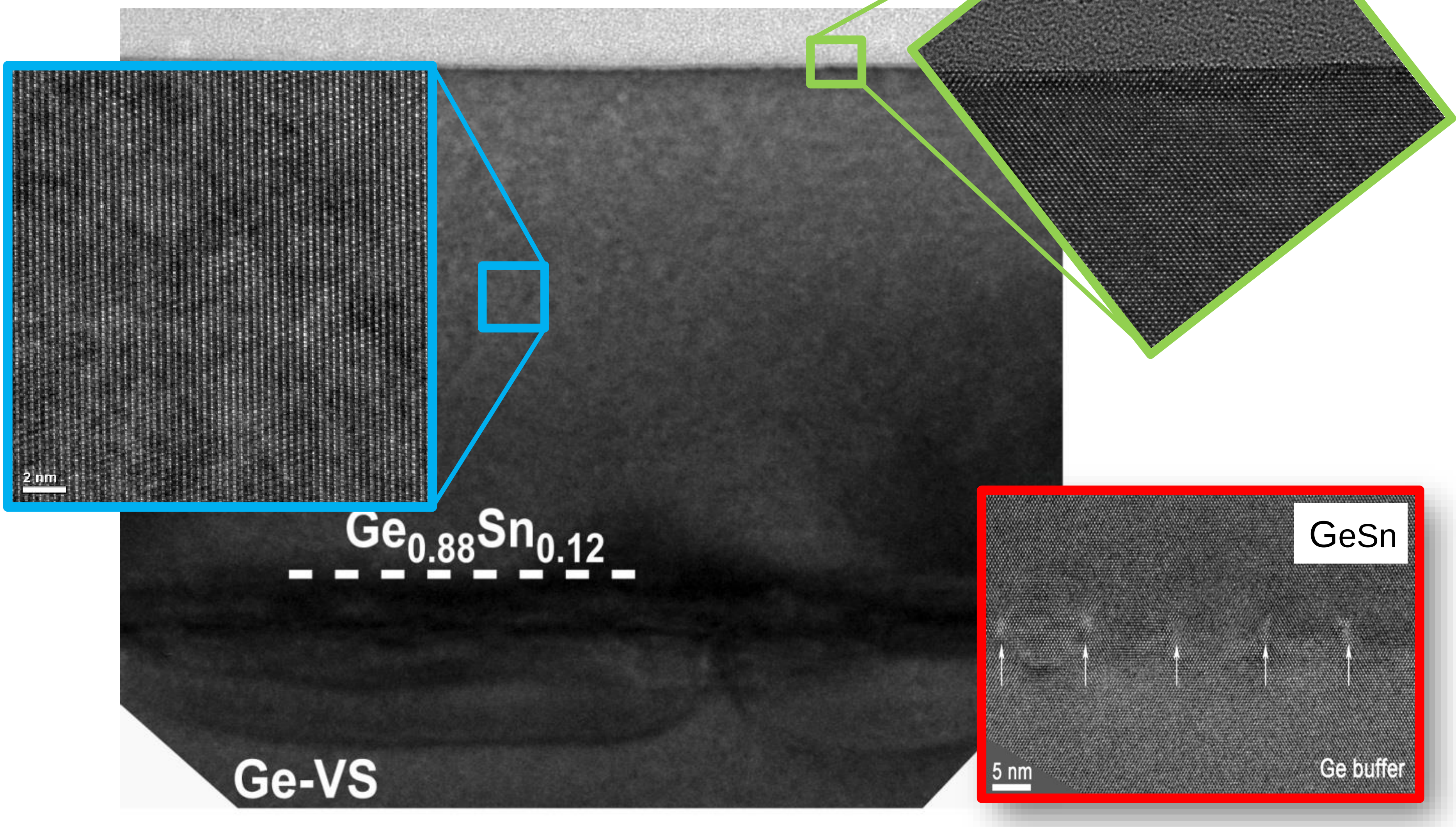
μ Similar to III-V

$$\mu \sim \frac{1}{m_{eff}} = \frac{\partial^2 E}{\partial^2 k}$$

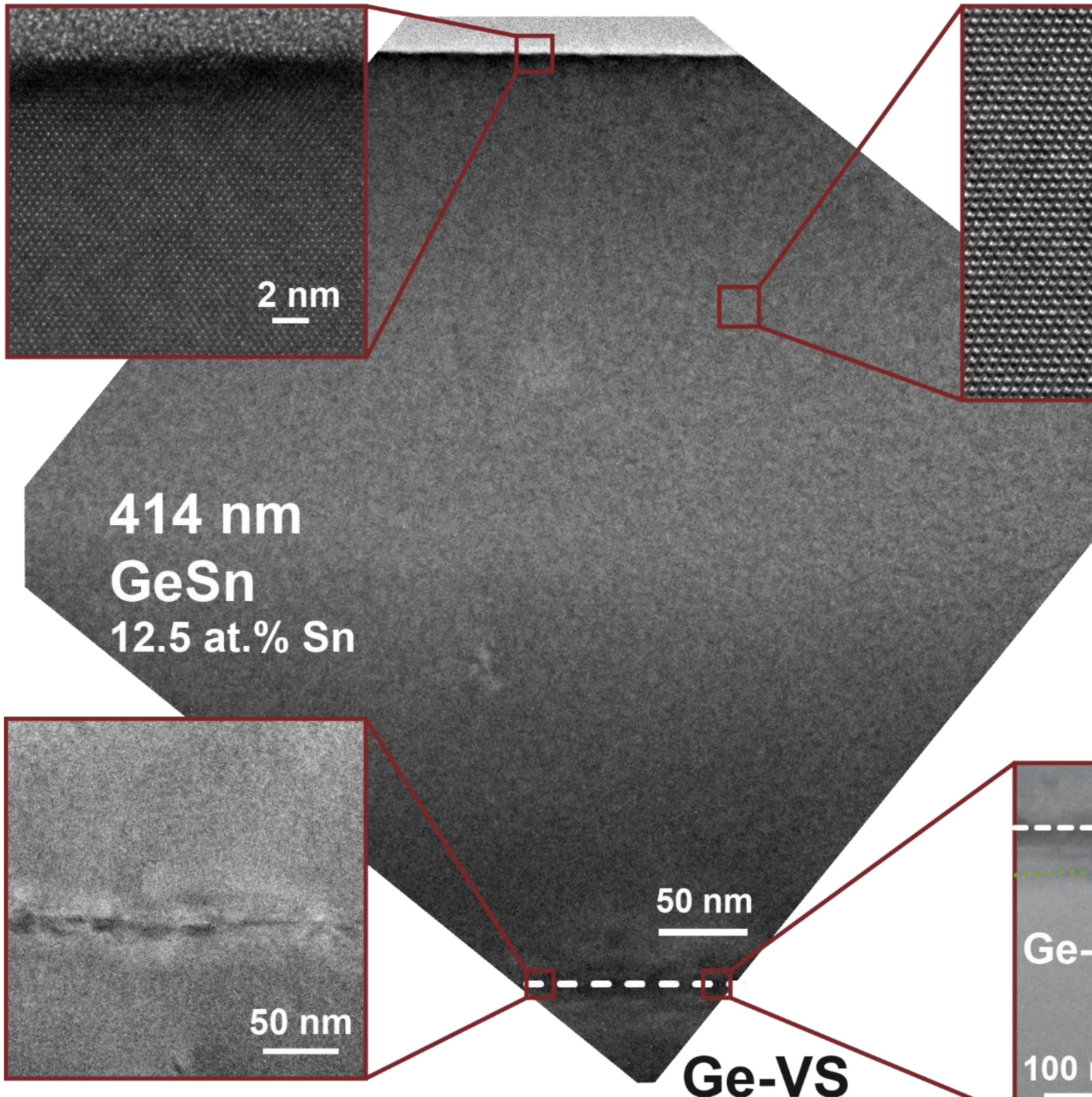
Conductivity mass

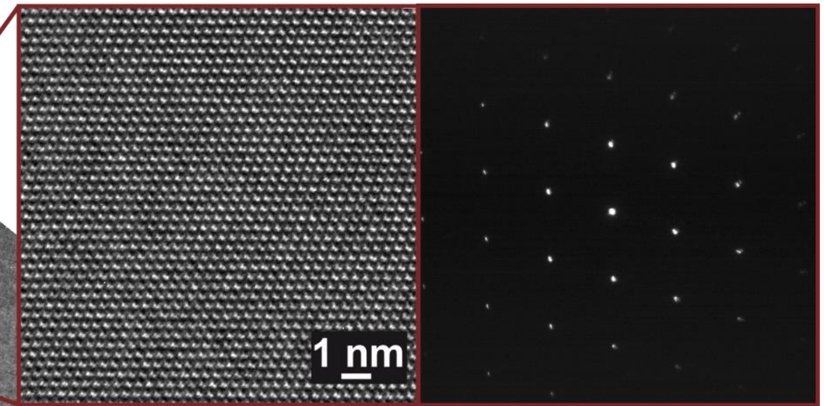
(Si)GeSn Epitaxy

Very high crystalline quality

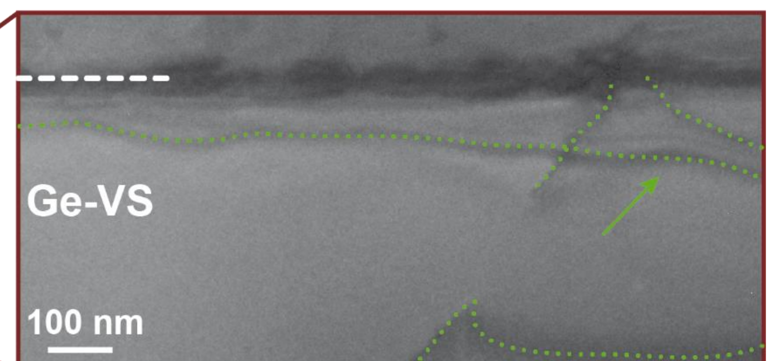


GeSn – Defect Formation





- high crystalline quality
- low threading dislocation density ($< 5x10^{6}$ cm^{-2})
- MD network near interface



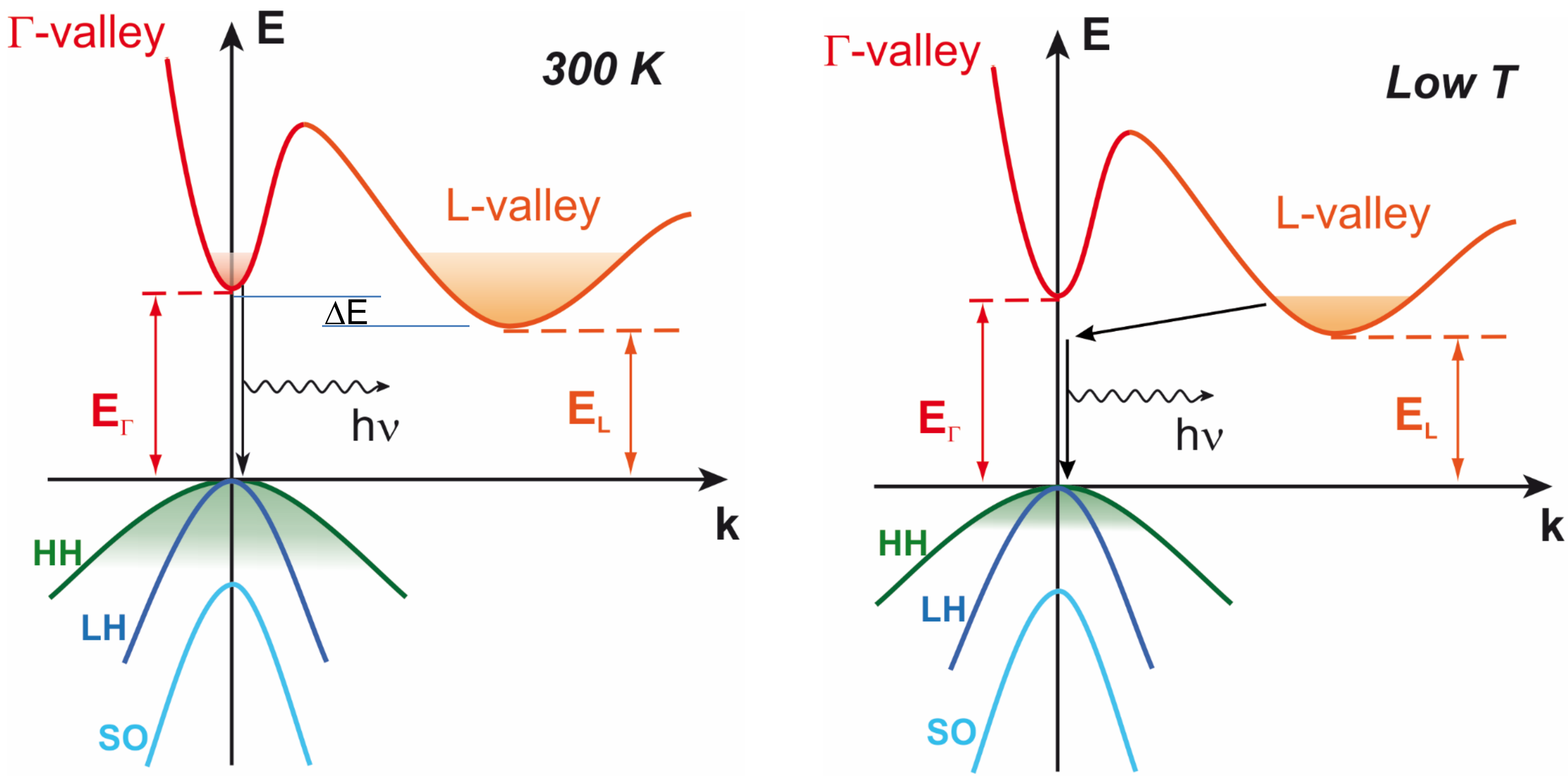
How can we differentiate between FACTS and *alternative facts* (fake news)?

Using knowledge

and Experimental physics

Temperature Dependent PL

Fundamental Indirect Bandgap



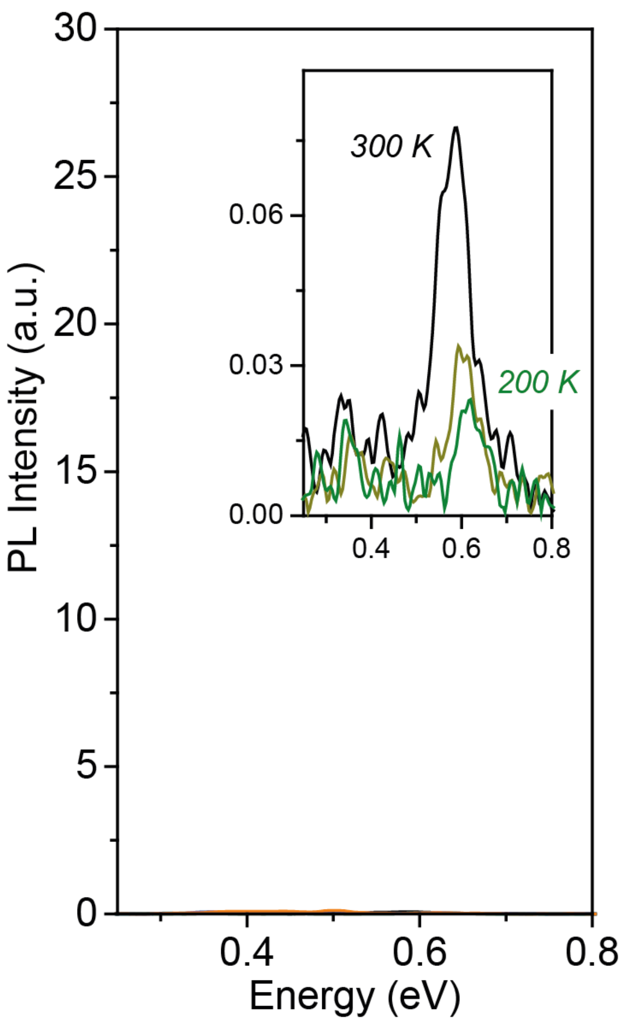
L-valley filled up with electrons and phonon scattering helps populate the Γ-valley at 300 K

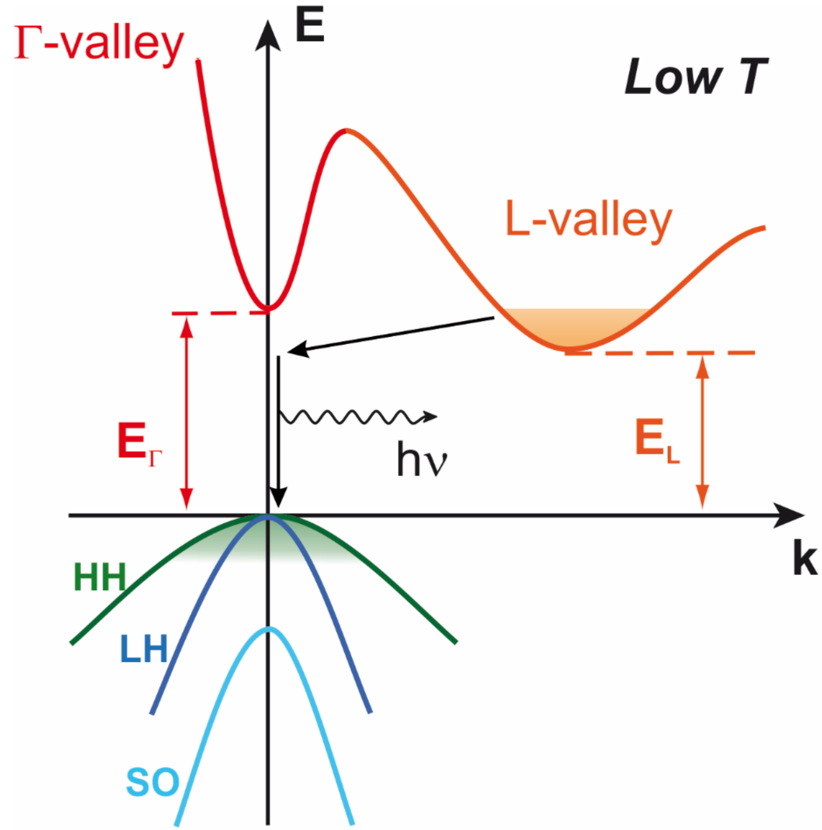
Condensation in L-valley and phonon scattering freeze

Decreasing PL for decreasing Temperature

Temperature Dependent PL

Fundamental Indirect Bandgap



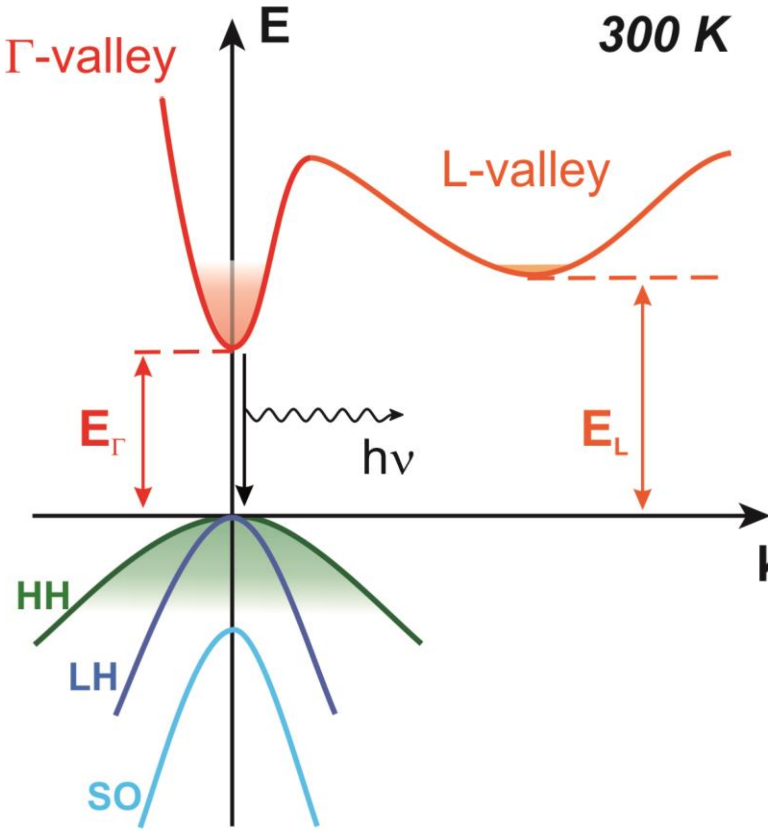


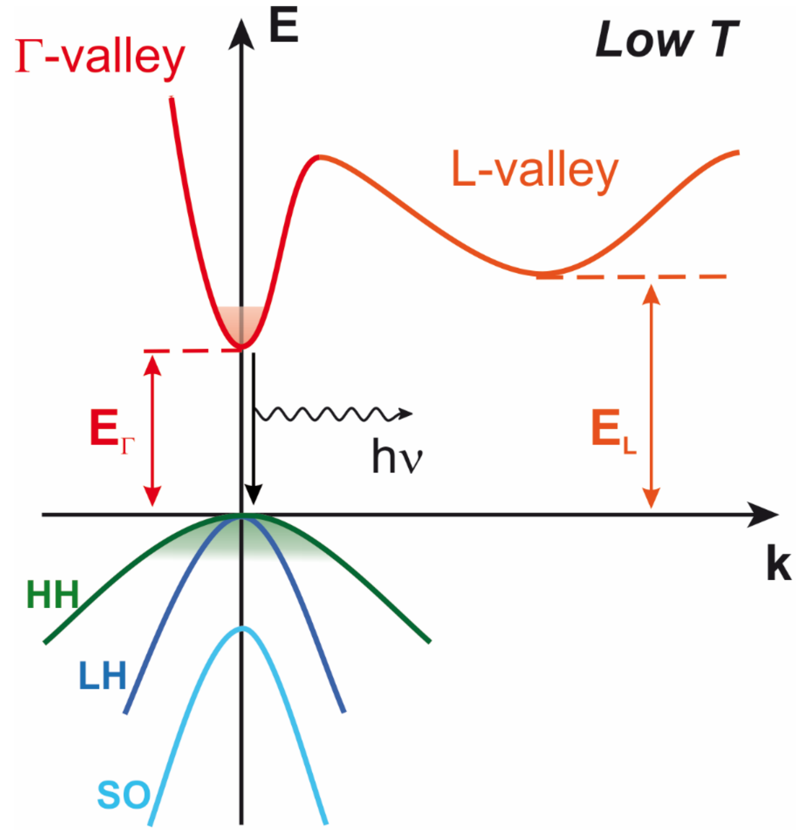
Condensation in L-valley and phonon scattering freeze

Decreasing PL for decreasing Temperature

Temperature Dependent PL

Fundamental Direct Bandgap





Γ-valley is filled up

BUT large L-valley DOS

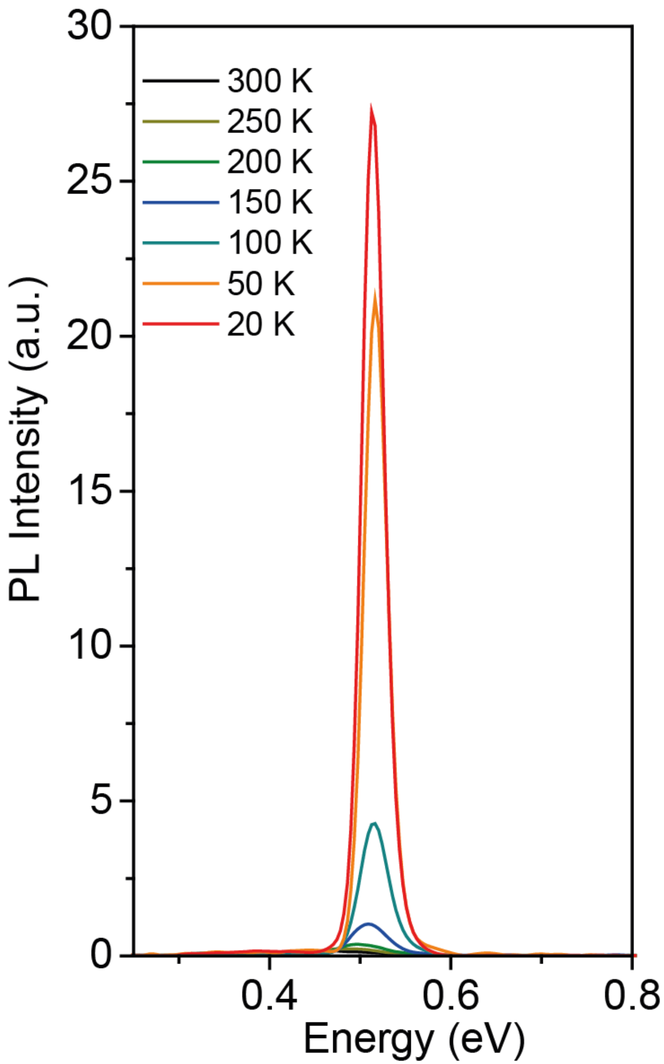
Condensation in Γ-valley ;

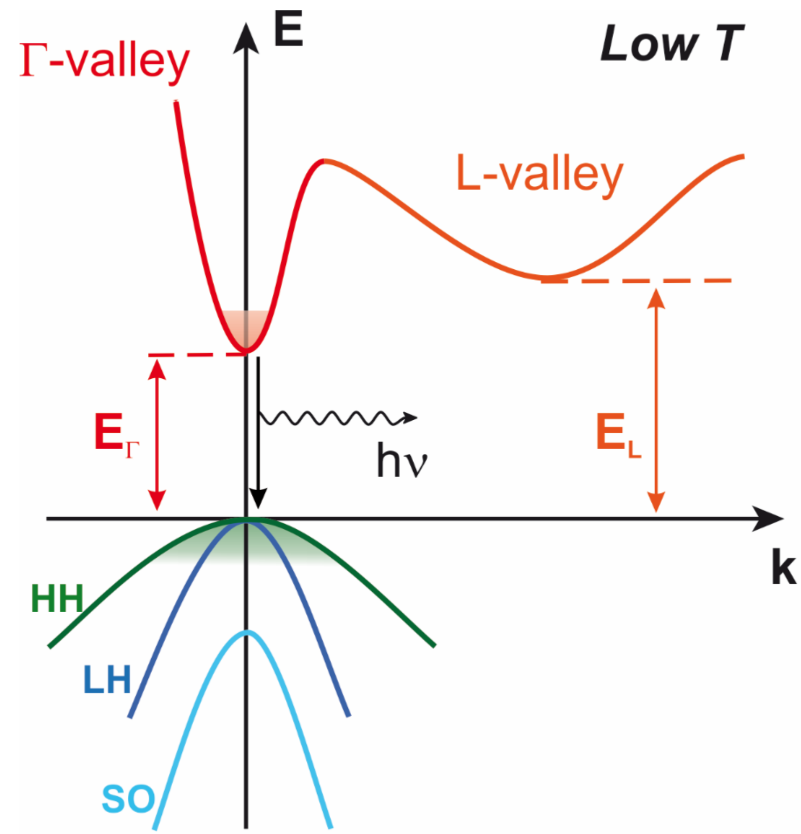
scattering to L-valley decrease

STRONG increase PL for decreasing Temperature

Temperature Dependent PL

Fundamental Direct Bandgap



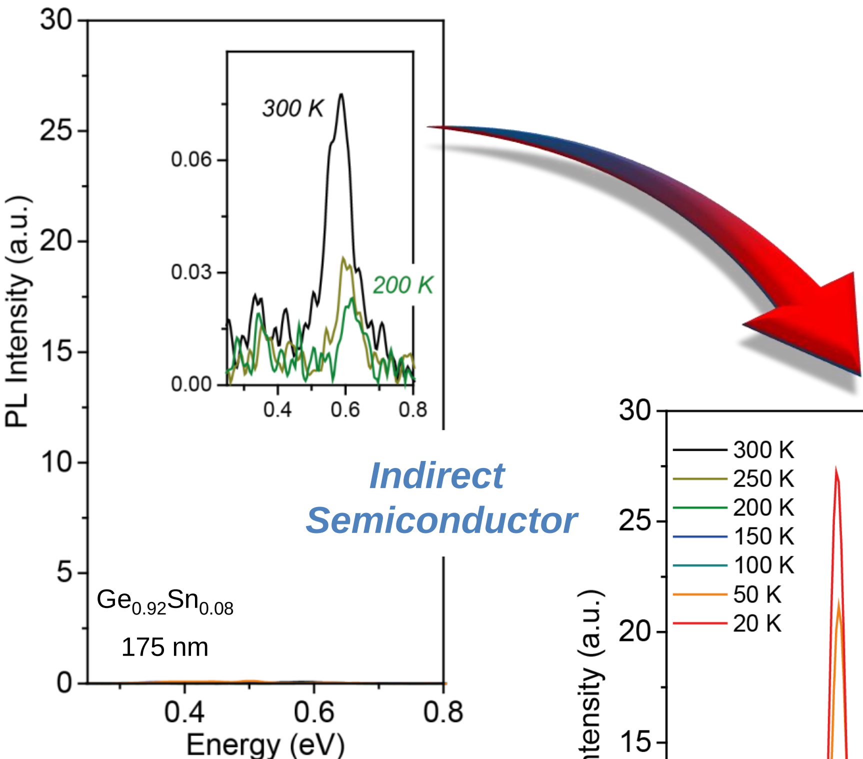


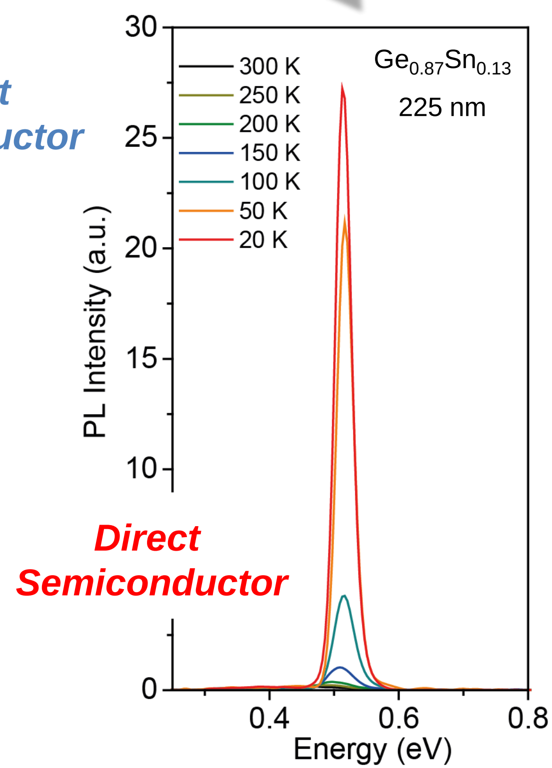
Condensation in Γ-valley ;

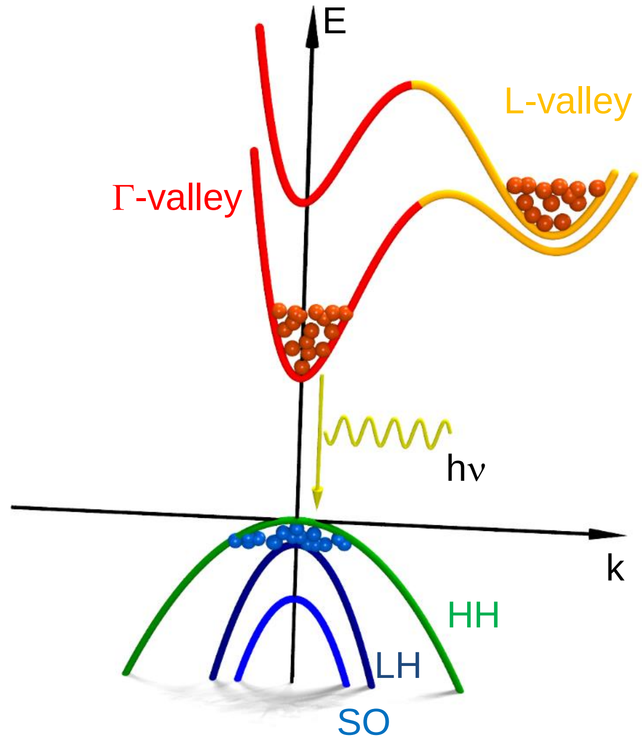
scattering to L-valley decrease

STRONG increase PL for decreasing Temperature

Indirect-to-Direct Transition



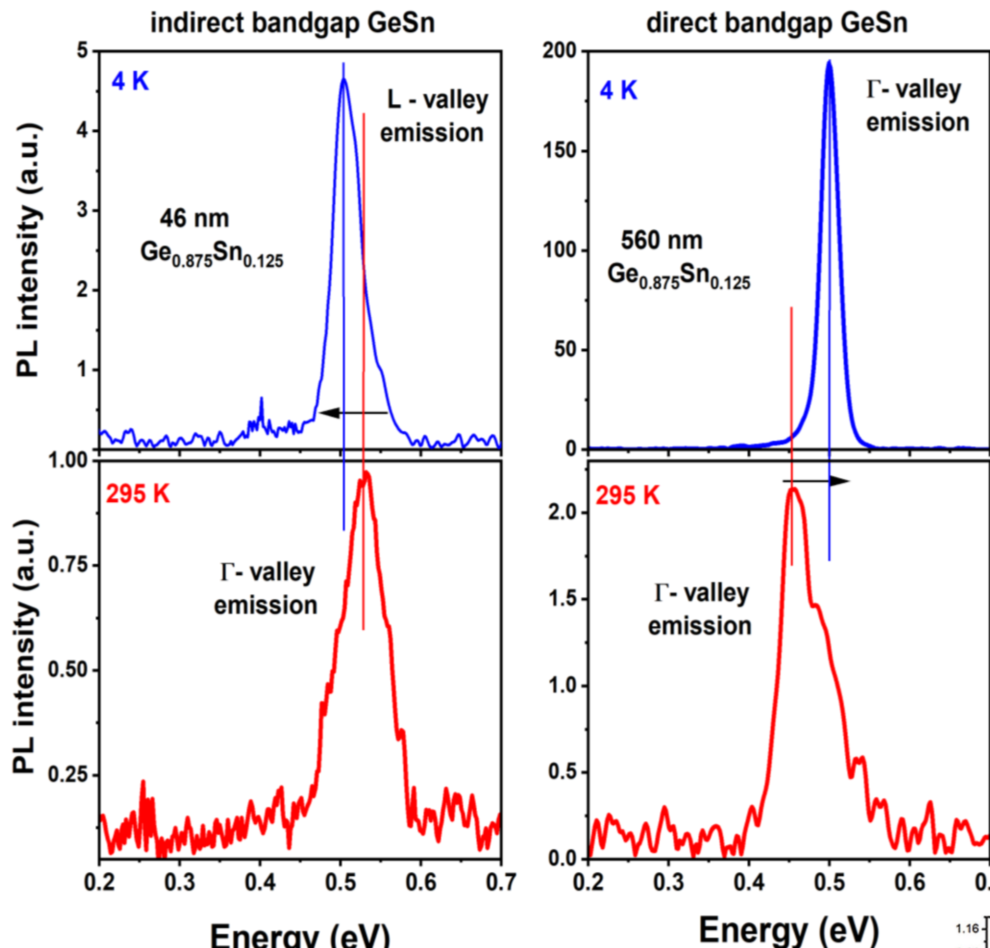


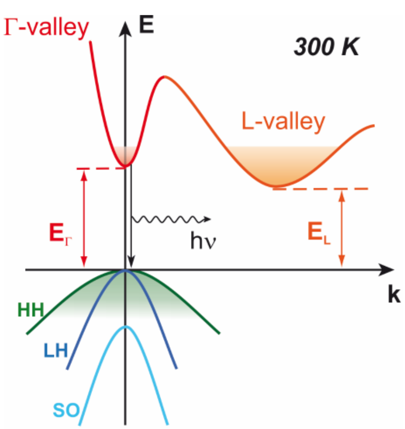


Peak intensity decreases (increases) for indirect (direct) for ***decreasing T***

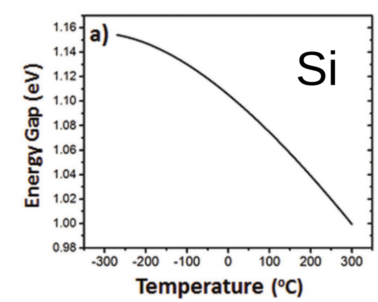
S. Wirths and R. Geiger *et al.*, *Nat. Phot.* **9**, 88 (2015)

Indirect-to-Direct Transition

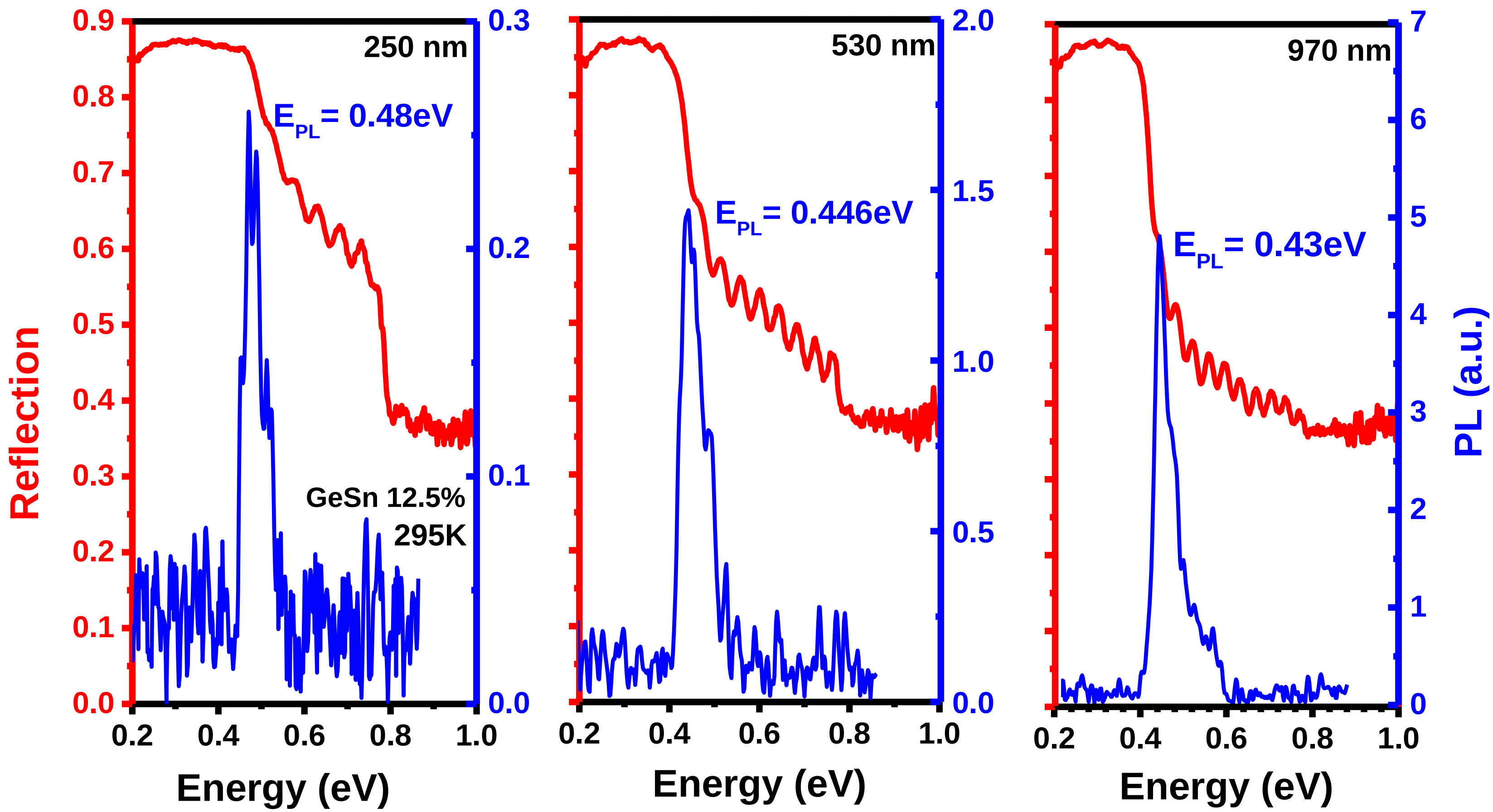




Si Bandgap change with temp



Direct gap determination



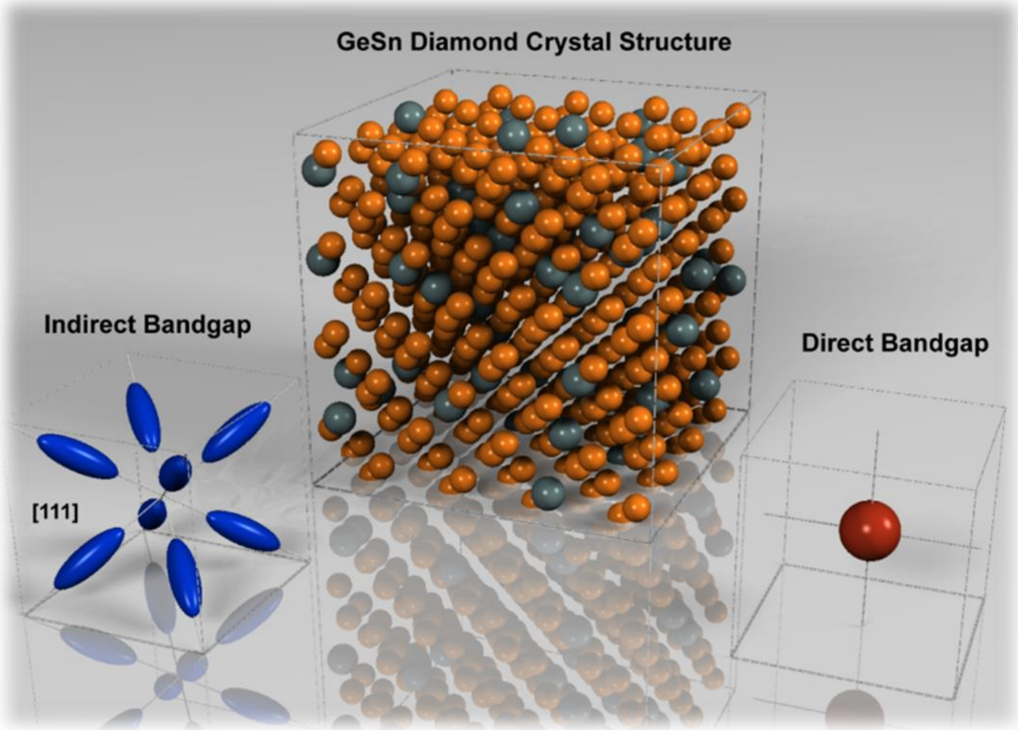
The **PL emission** takes place at the **strong absorption edge**

What comes „new“ with GeSn

The physics of **JUST** direct semiconductors.

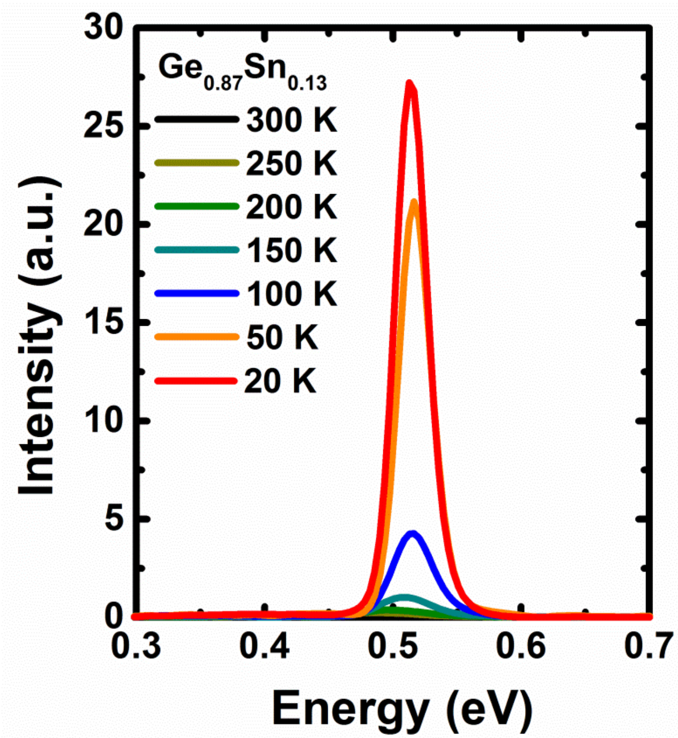
The physics at transition

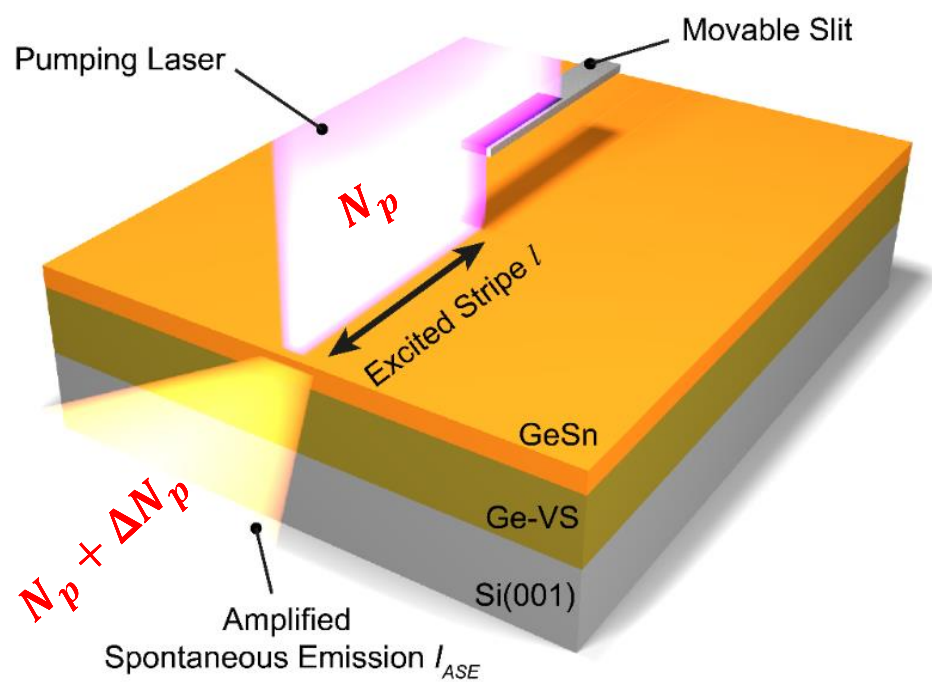
No such experiments were possible before GeSn



No Si group laser demonstration (as bulk semiconductor)

Variable Stripe Length (VSL) Method





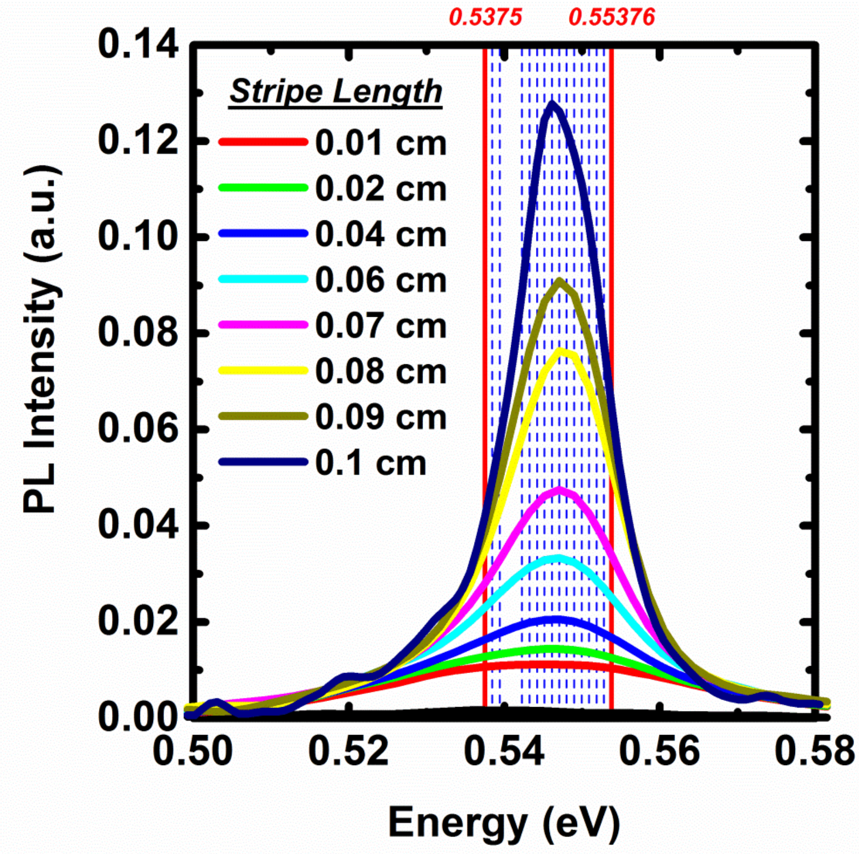
- *Measure the light amplification within a direct bandgap material via VSL*
- *Gain is a measure of how well a medium amplifies photons by stimulated emission*

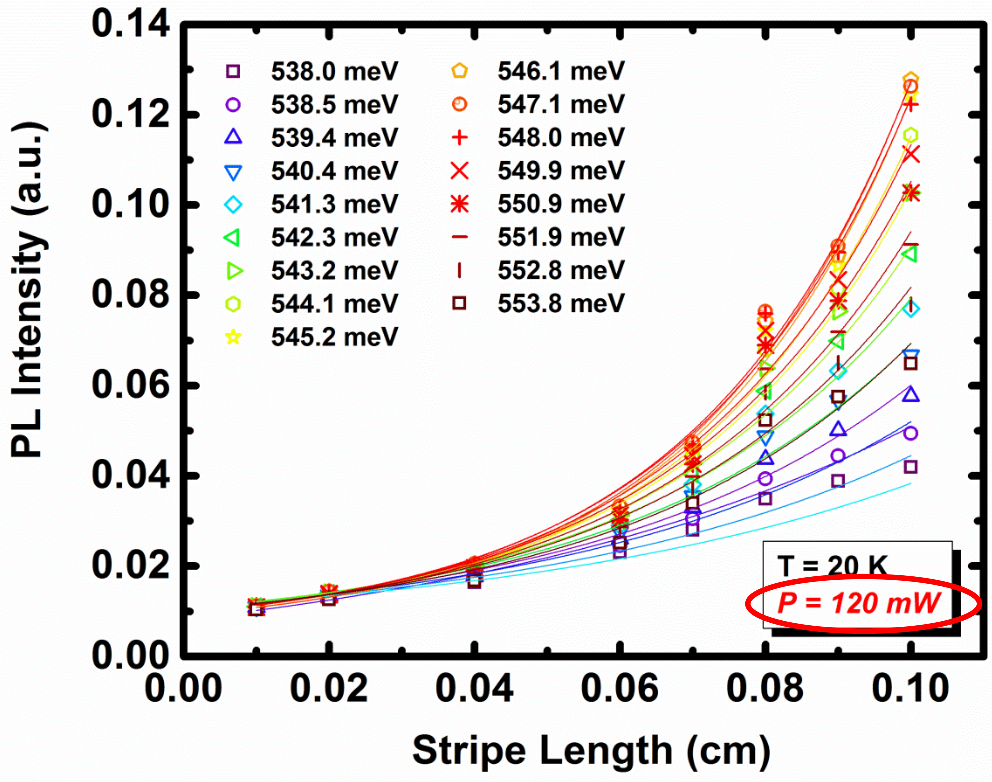
Photon density:

$$N_p + \Delta N_p = N_p e^{g\Delta l}$$

Variable Stripe Length (VSL) Method

Above lasing threshold

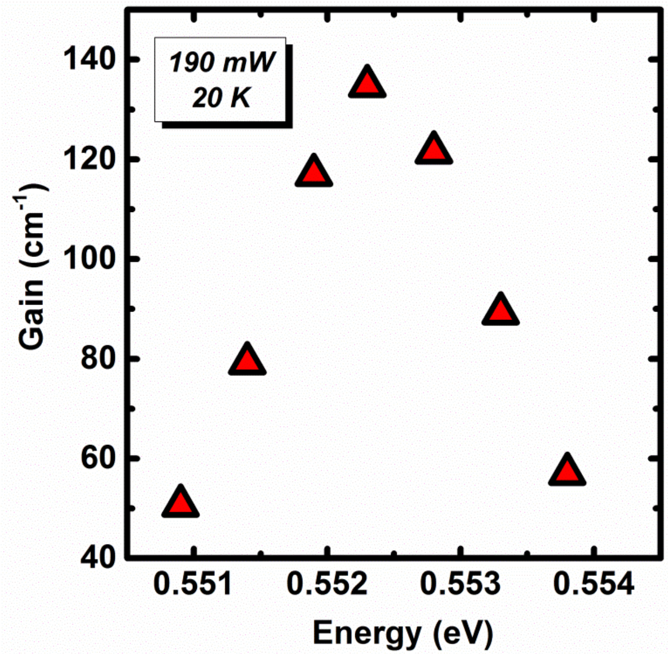


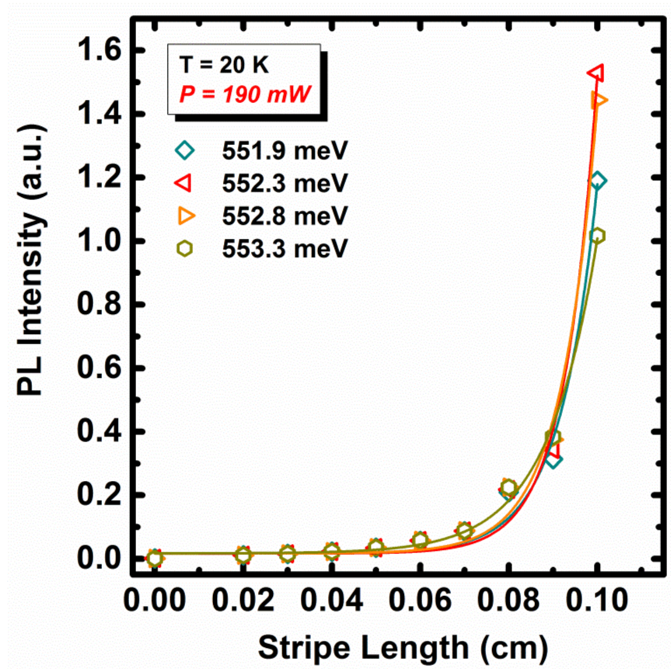


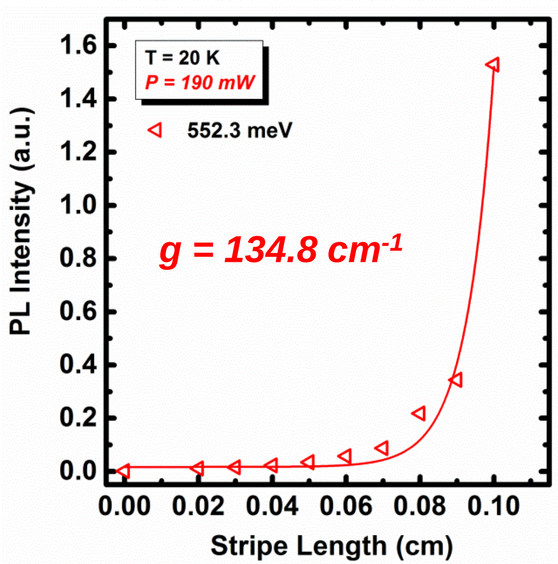
- **Exponential fit to determine gain *g***
- **Fixed y_0 (0.00531) used for fitting**

$$I_{ASE} \propto \frac{I_{spont} \cdot l}{g}\left(e^{g \cdot l} - 1\right)$$

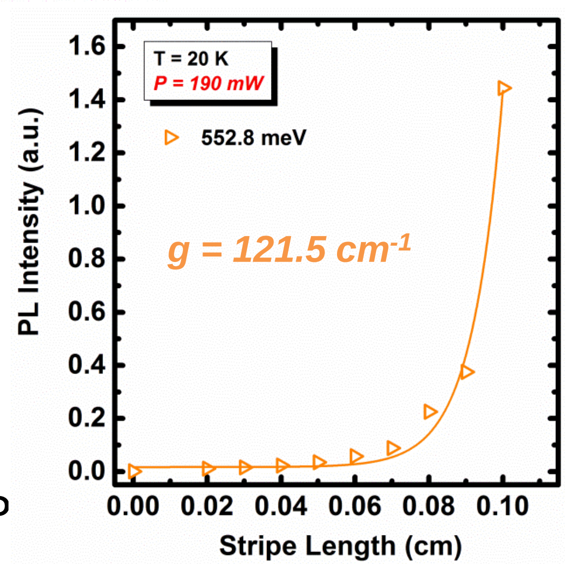
Variable Stripe Length (VSL) Method

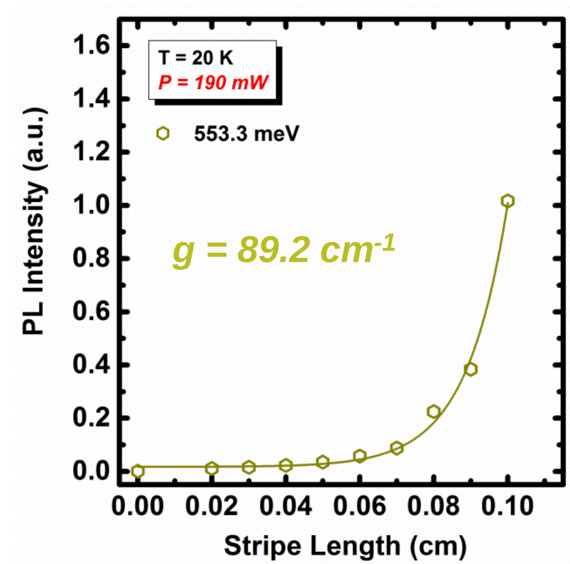




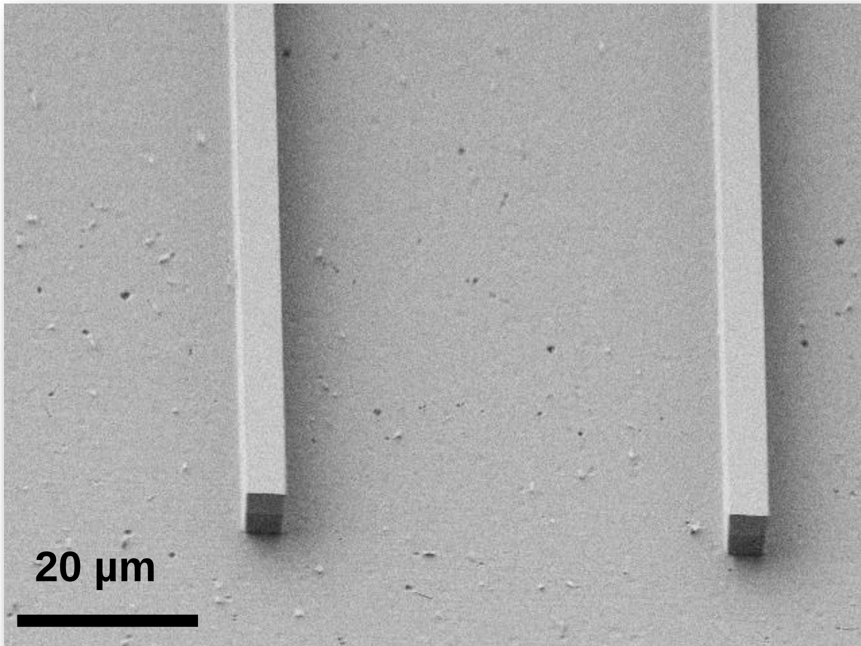


P



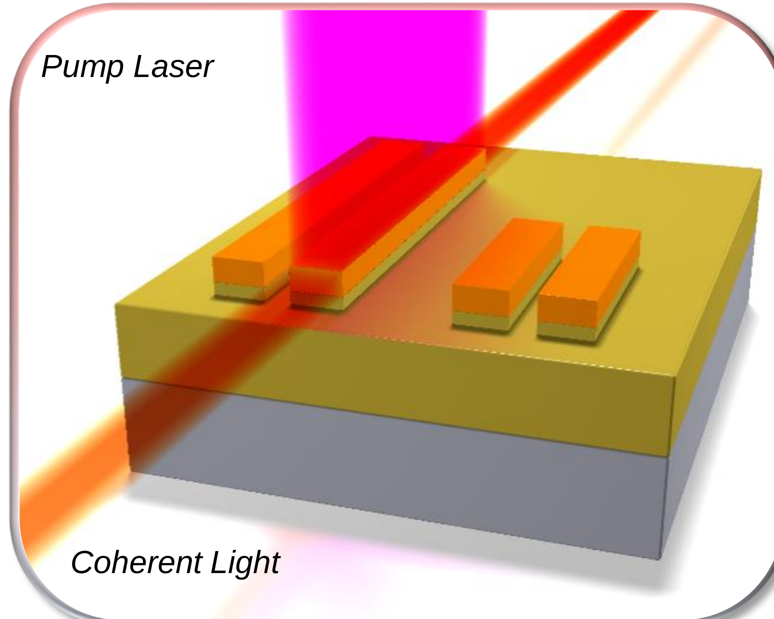


First Optically Pumped GeSn Lasers (2015)



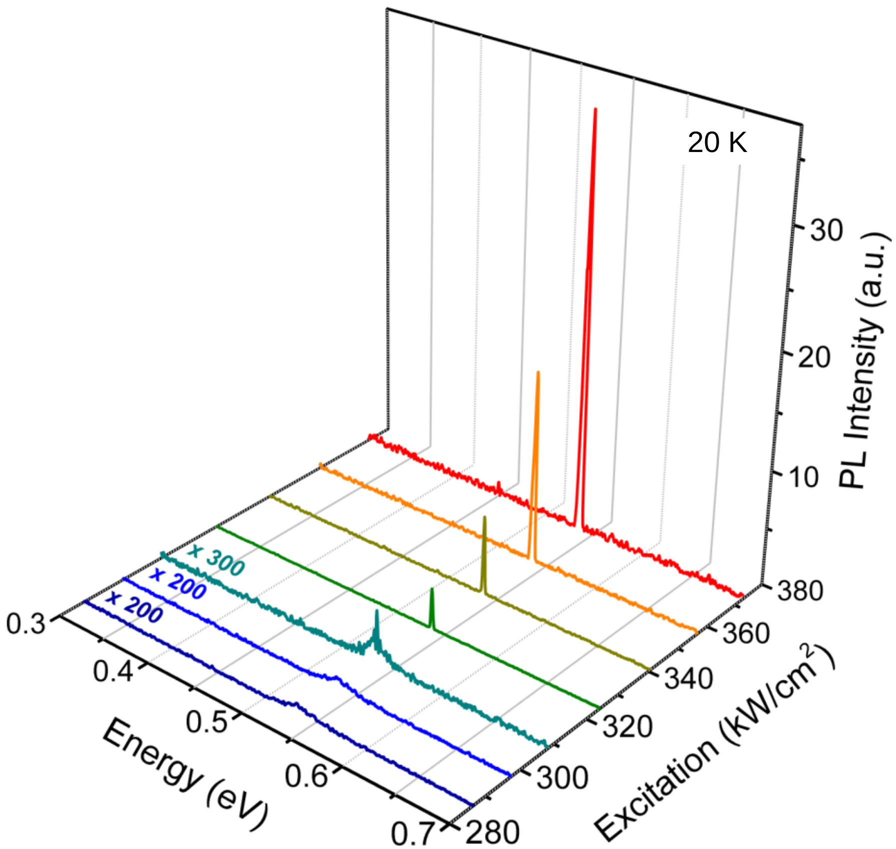
Waveguide structure….

Optical Pumping

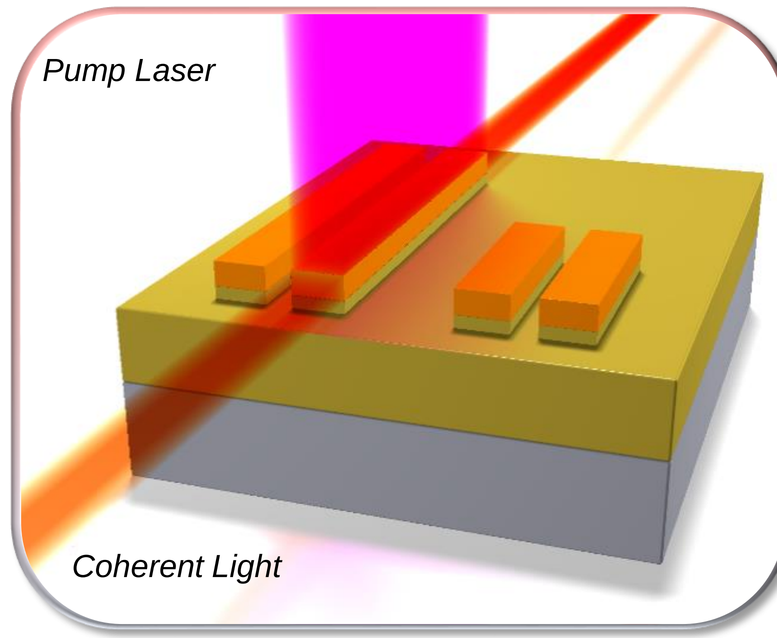


First Optically Pumped GeSn Lasers (2015)

Power Dependence



Optical Pumping

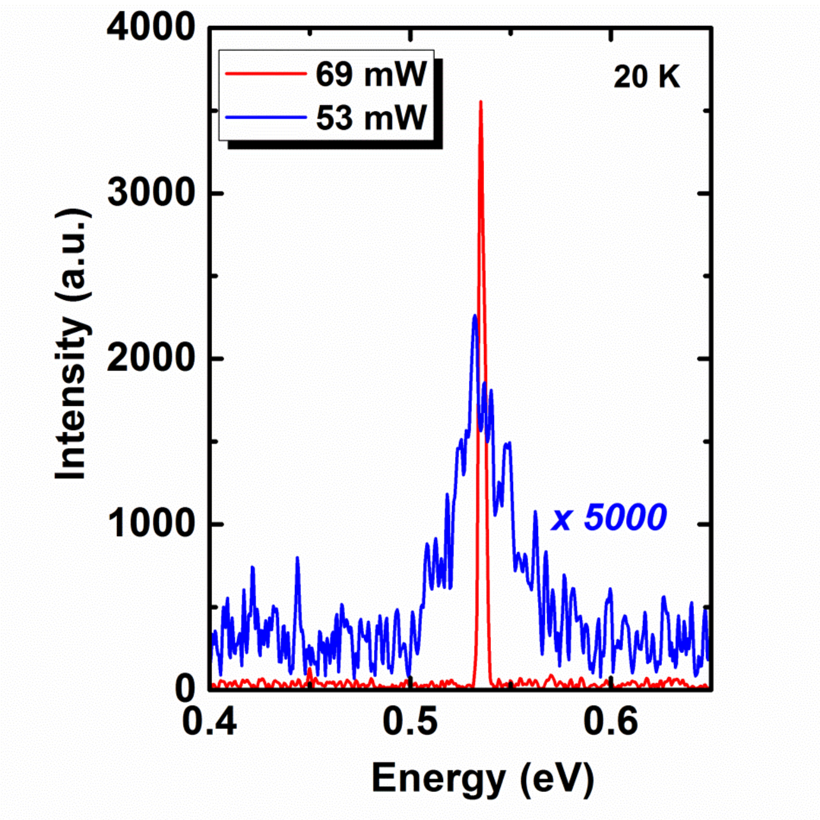


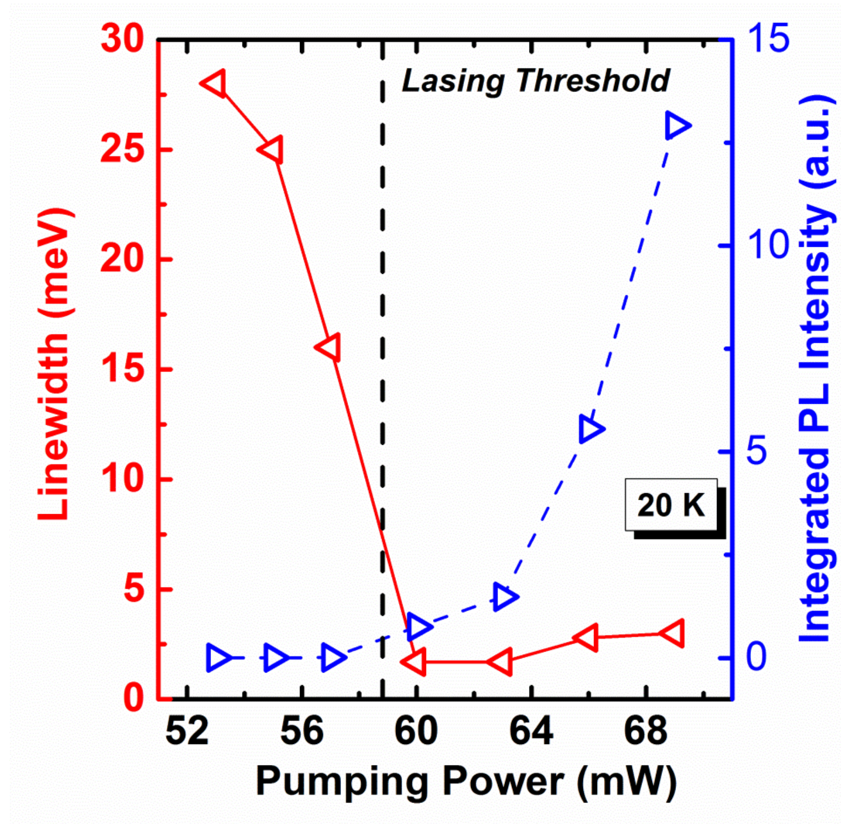
- GeSn laser at 20 K
- At 2.5µm
- max temp 100K

Details on the physics, problems, solutions ….maybe other time

How to recognize the laser effect:

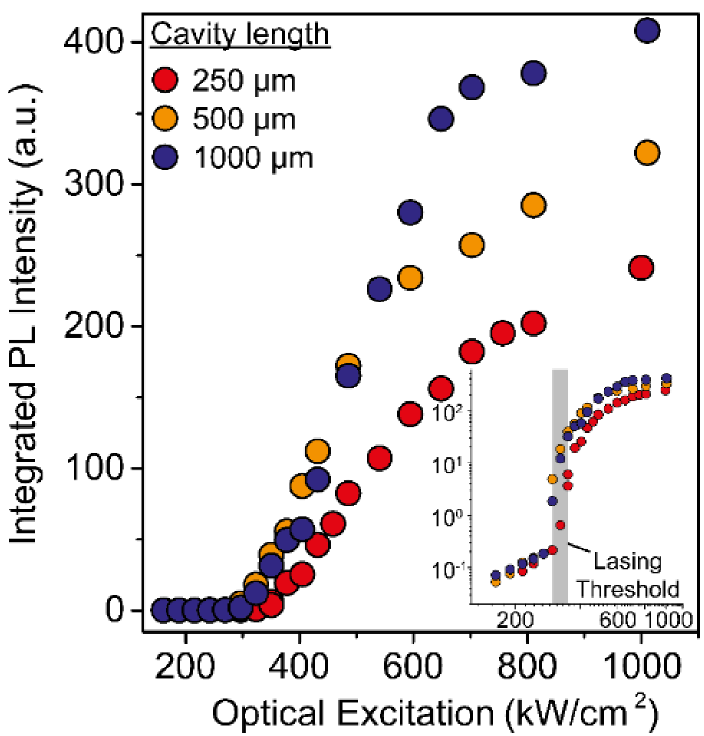
1. Linewidth colapse

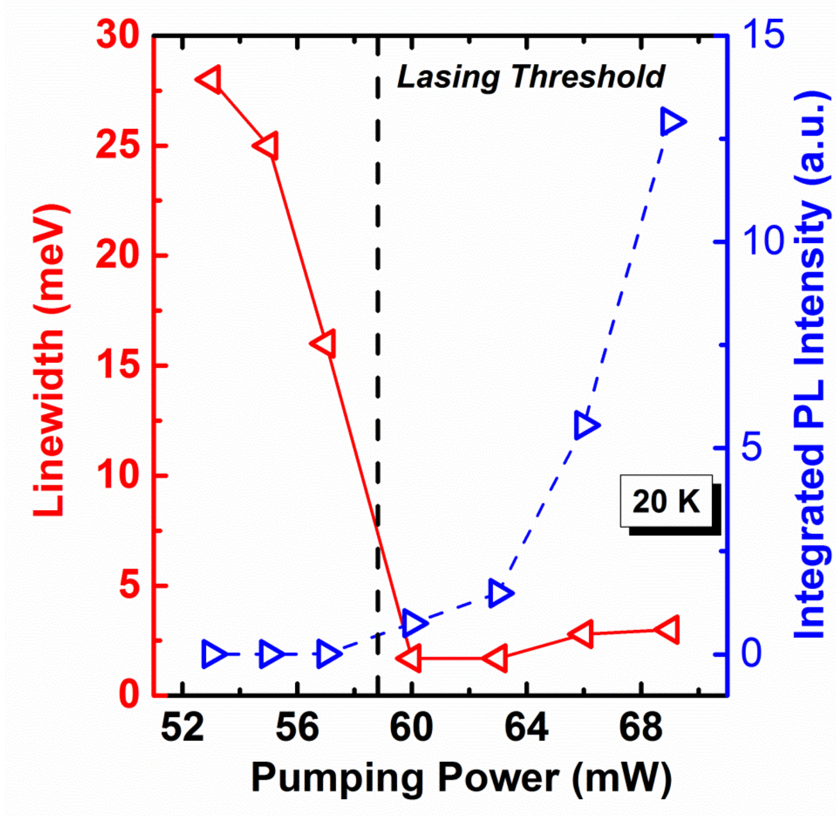




How to recognize the laser effect:

2. Exponential PL Intensity increase
   Clear treshold

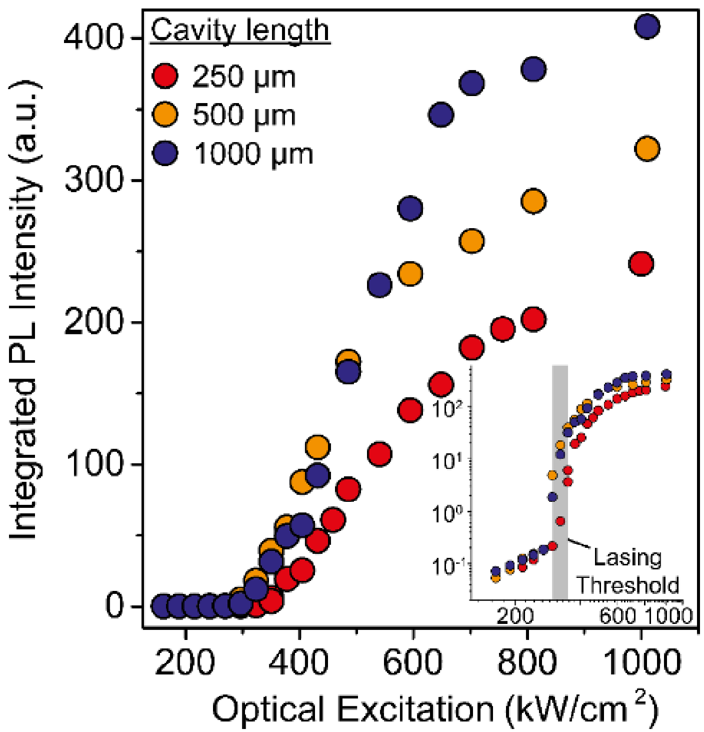




PL saturation (gain saturation)

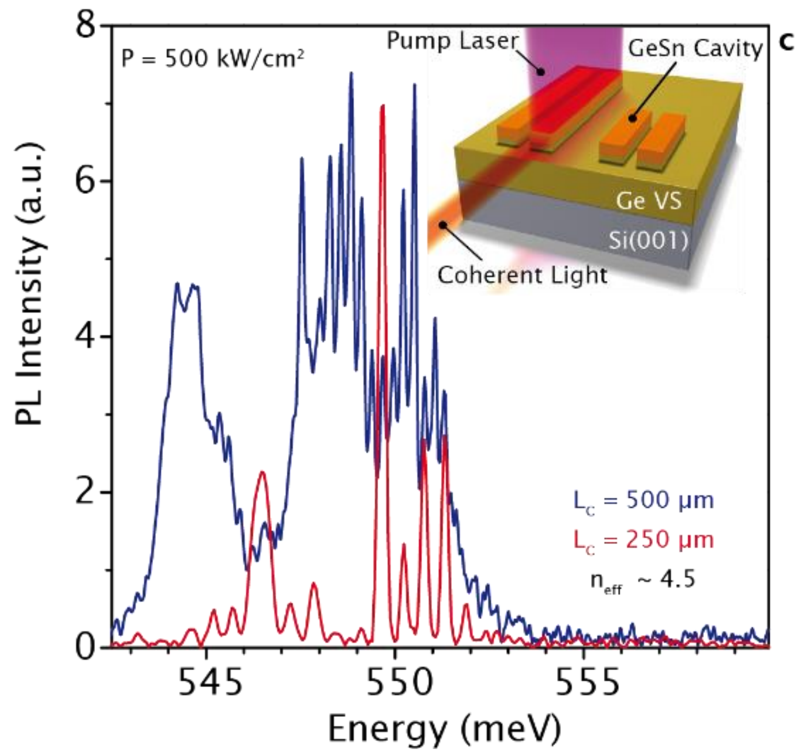
How to recognize the laser effect:

2. Exponential PL Intensity increase
Clear treshold

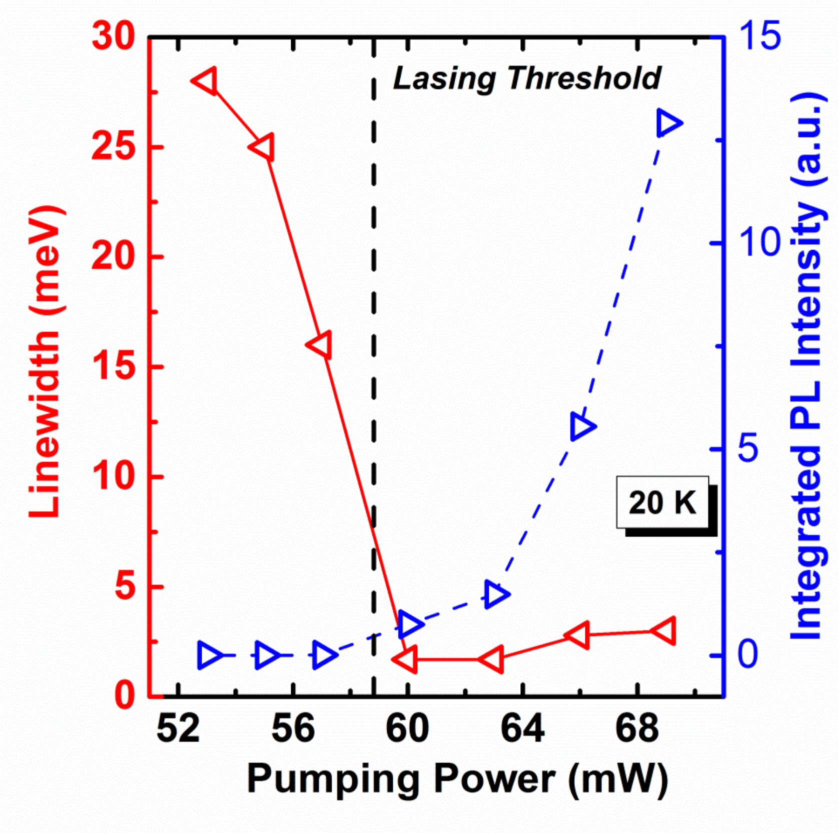


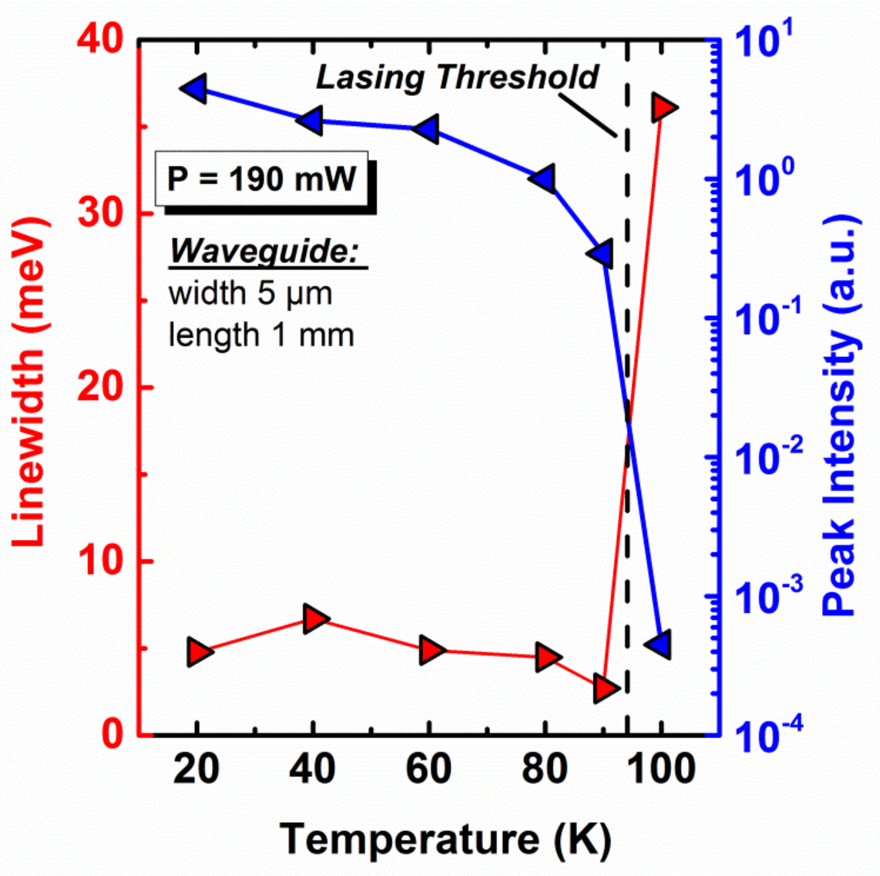
PL saturation (gain saturation)

3. Optical modes are cavity characteristic



How to recognize the laser effect:

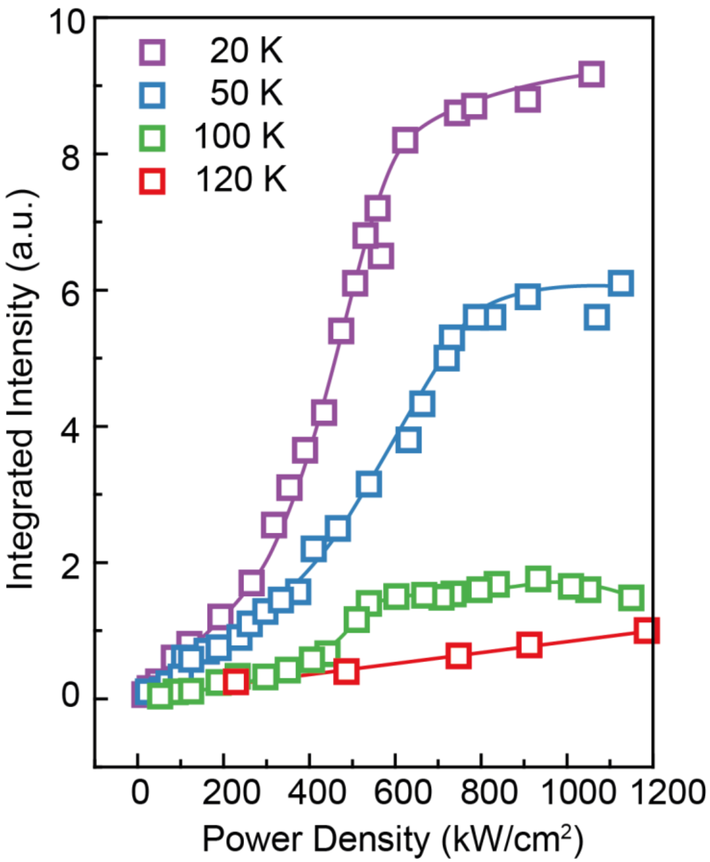


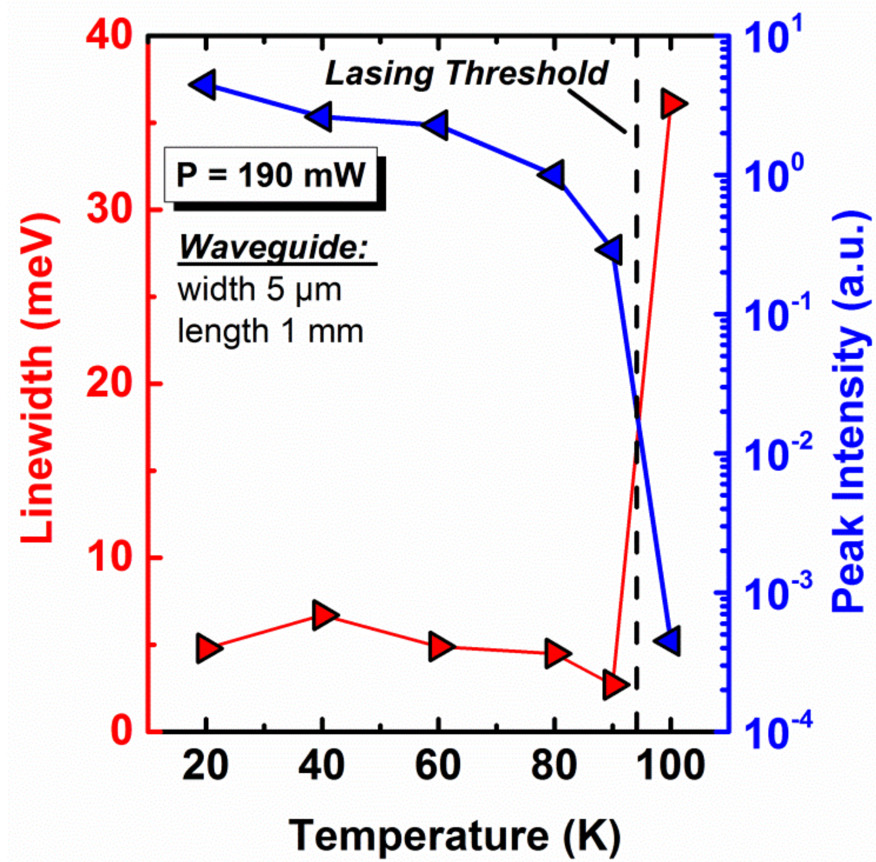


Laser starts

Laser stops

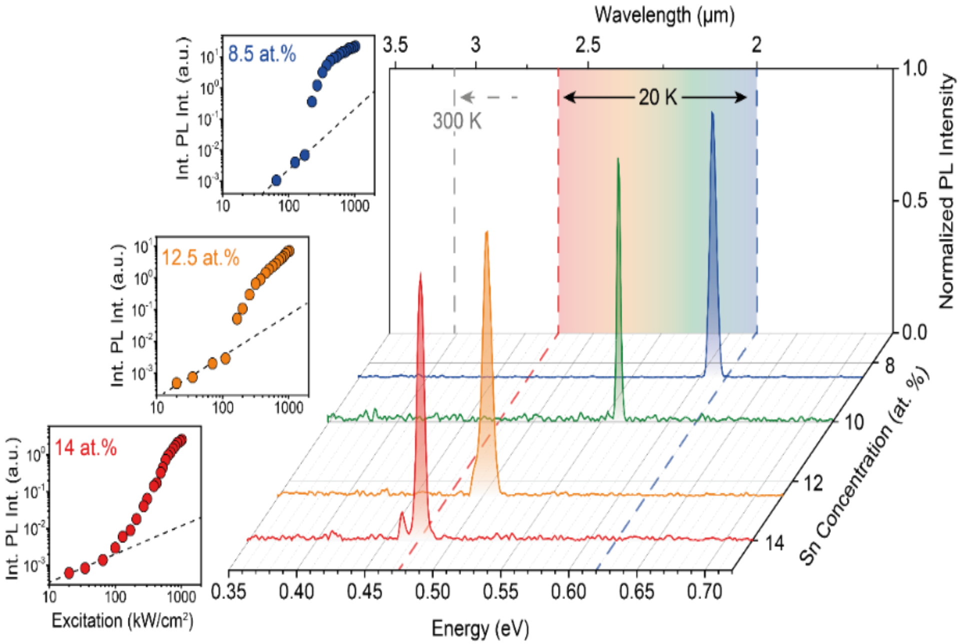
How to recognize the laser effect:

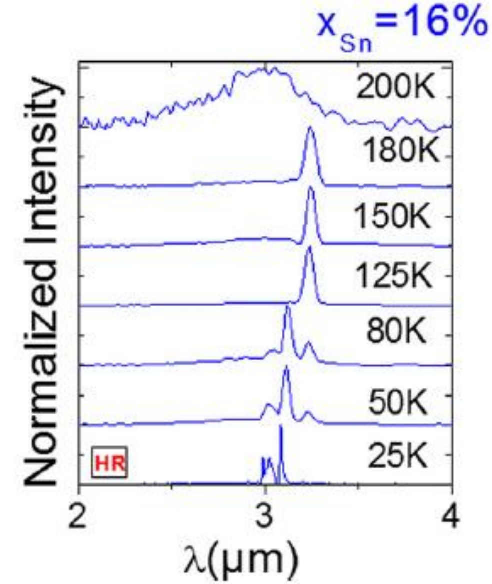




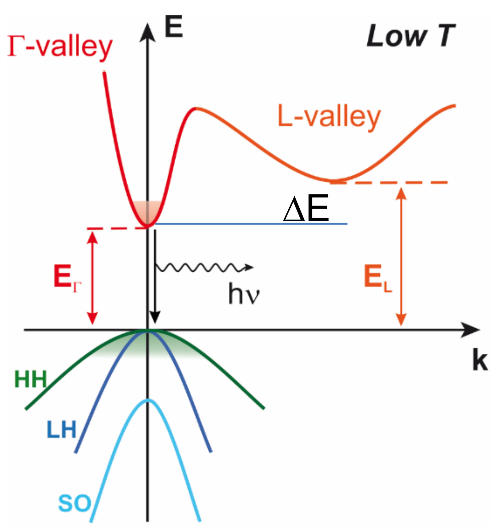
Laser stops

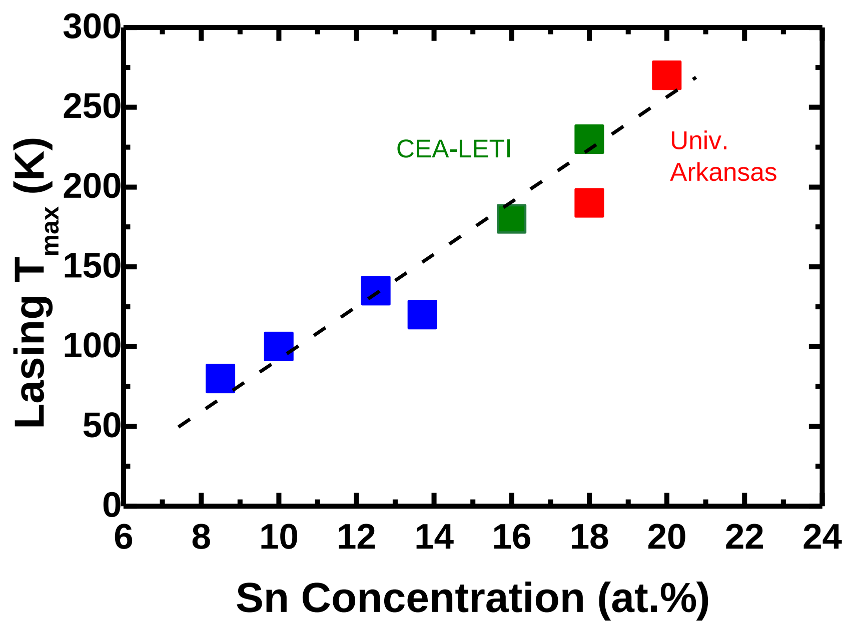
GeSn Laser evolution:



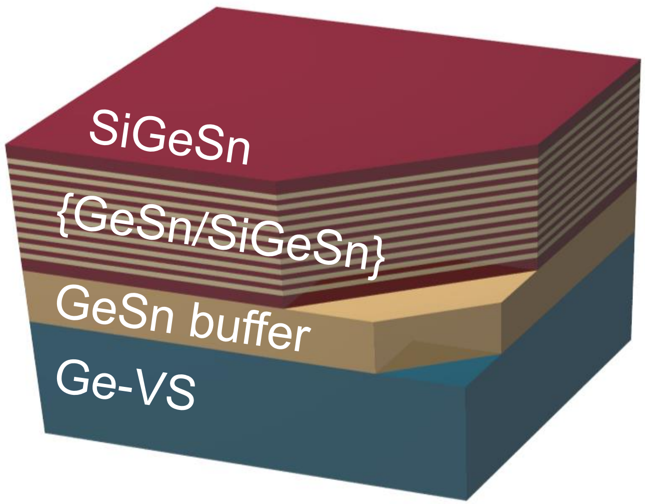


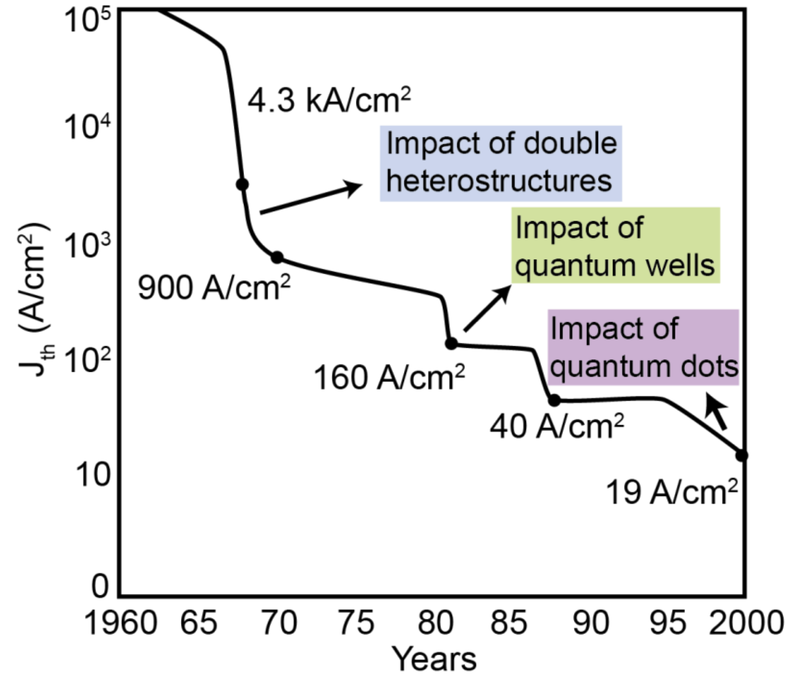
CEA-Leti (2018)



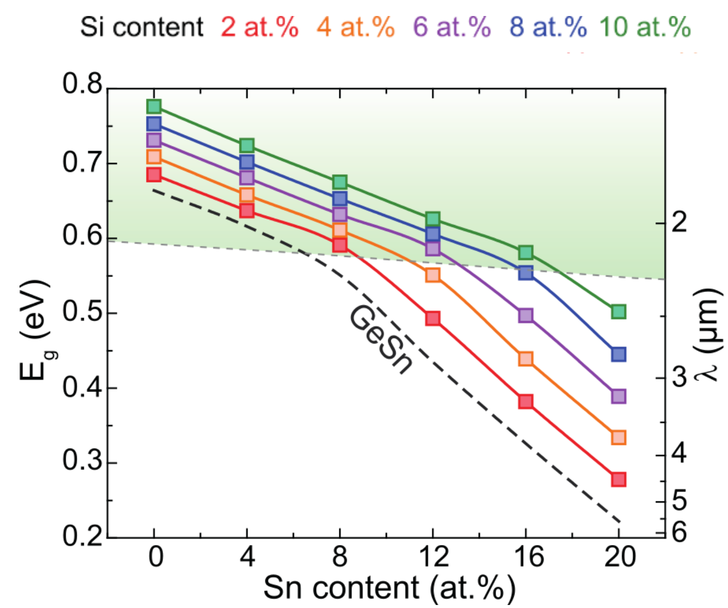


Heterostructure history

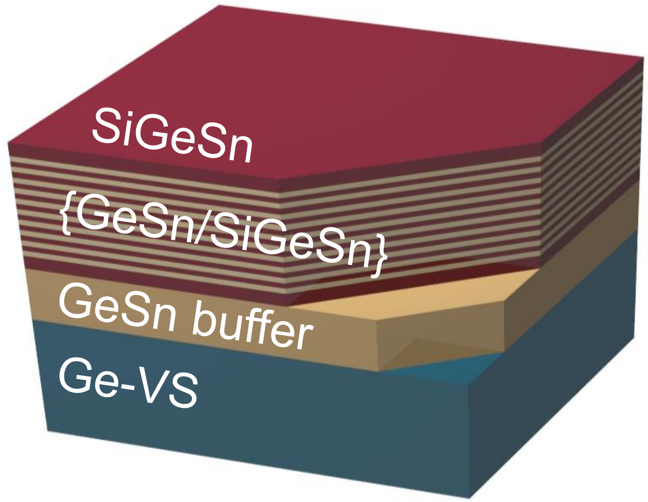


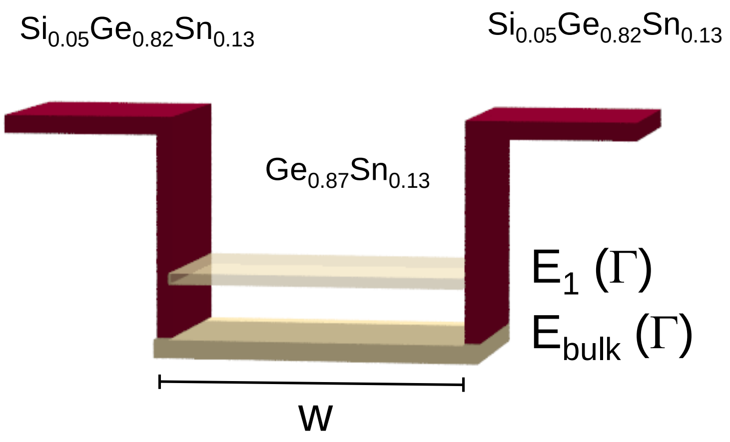


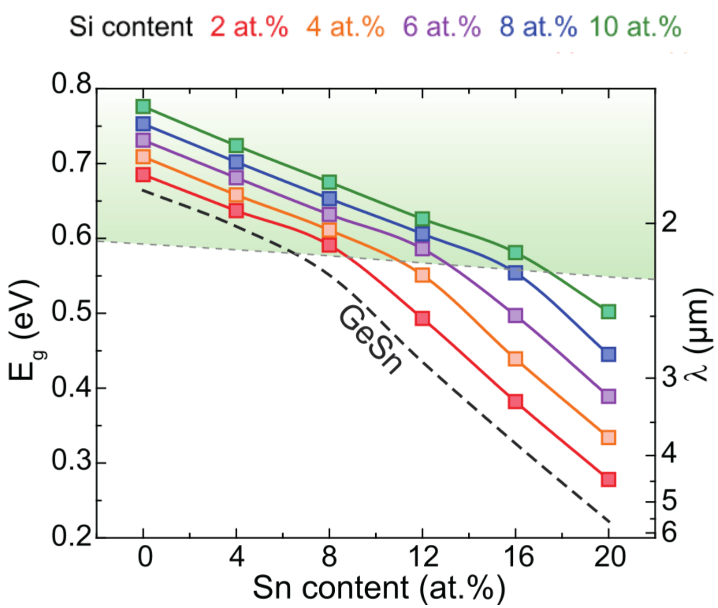
Z. Alferov, IEEE J. Sel. Top. Quantum Electron. ***6****, 832 (2000)*



Heterostructure history

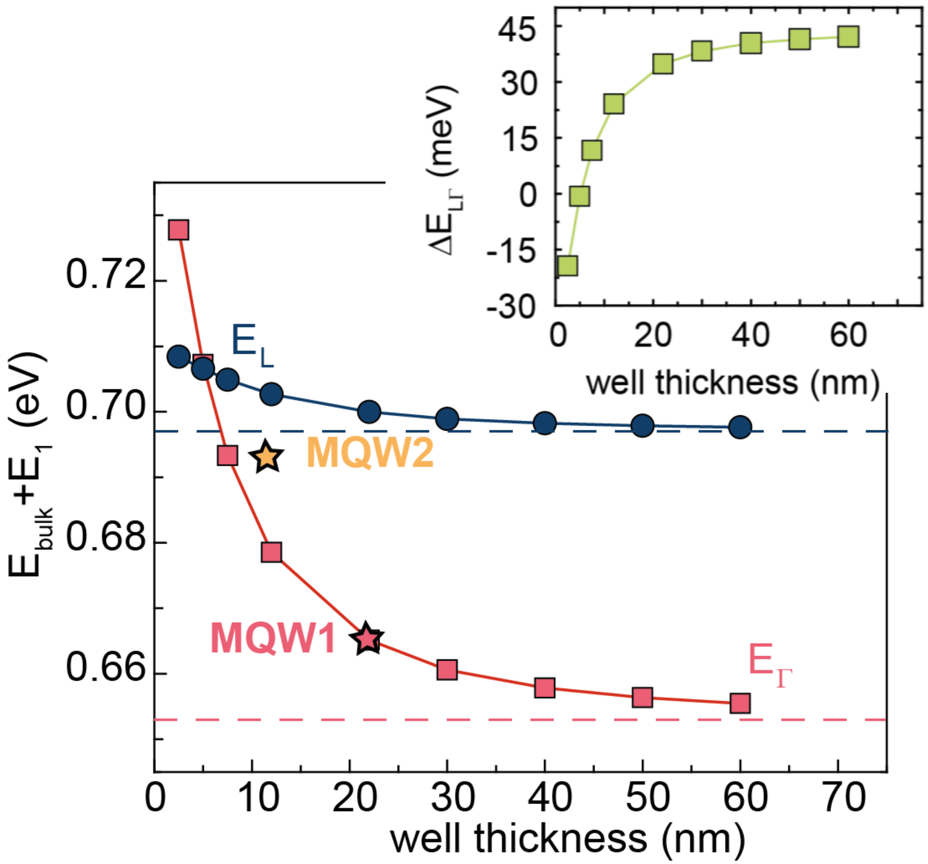


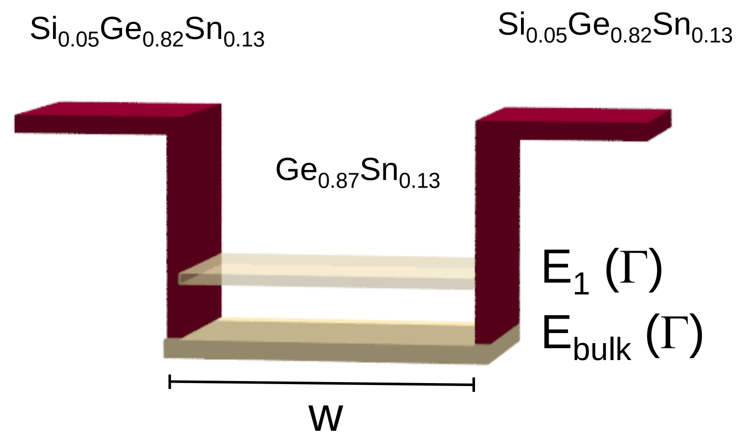




- 2D confinement in GeSn active layer
- Larger gap SiGeSn barrier
- reduced density of states

GeSn/SiGeSn MQW band structure





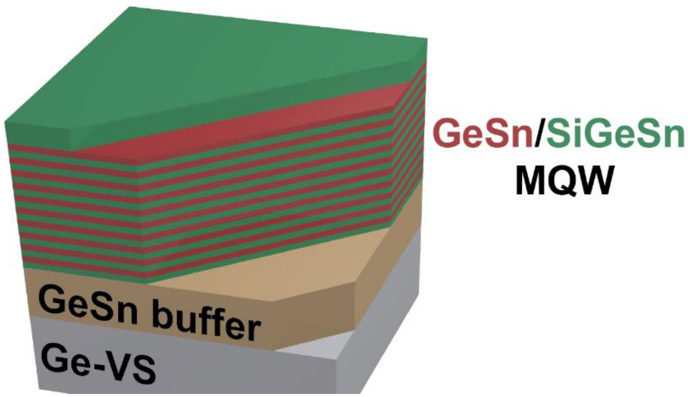
- $E_n \propto \frac{1}{w^2 m^*}$
- $m^*_\Gamma < m^*_L$

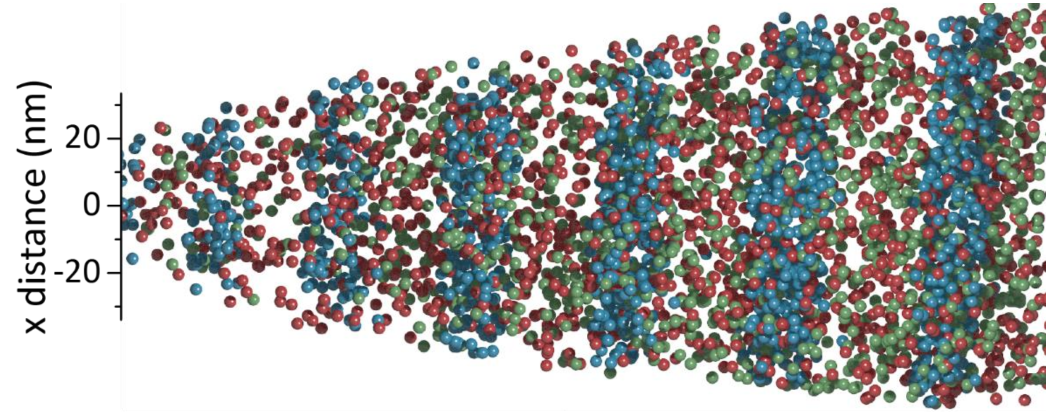
Required: **low quantization** energy for (i) **quantum confinement** but still (ii) **high directness**

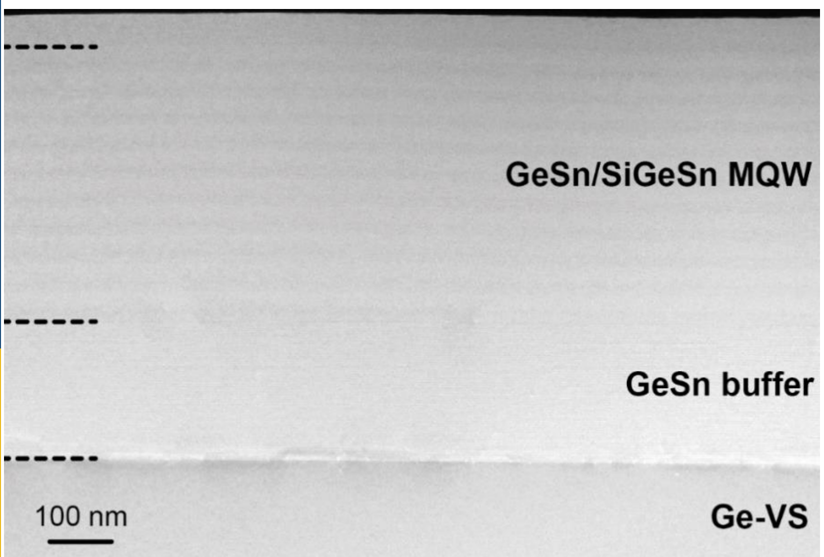
↓

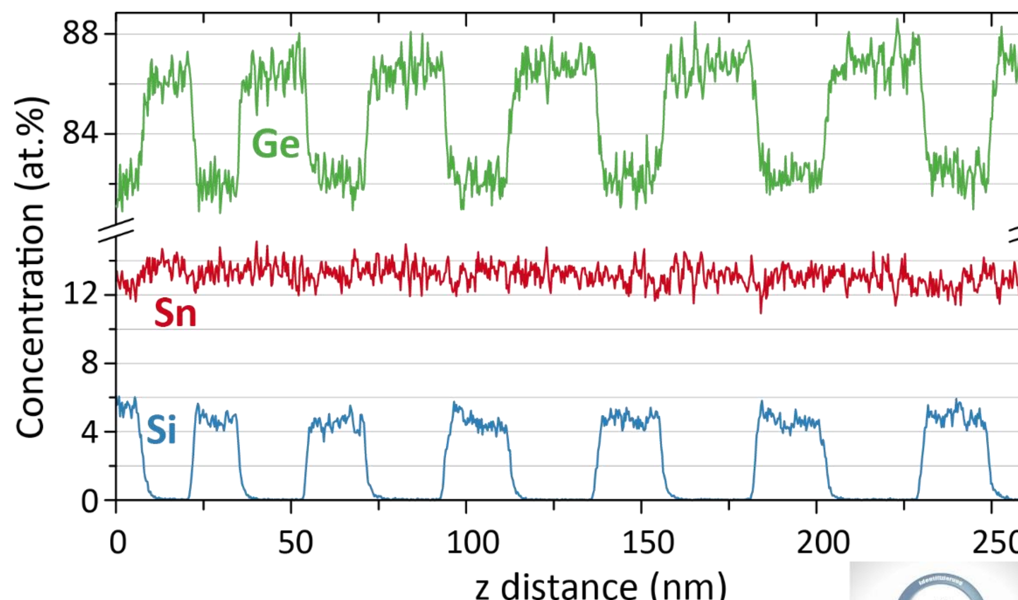
Specific for „JUST DIRECT" semiconductors (strained Ge, GeSn, SiGeSn)

Direct bandgap MQW heterostructures





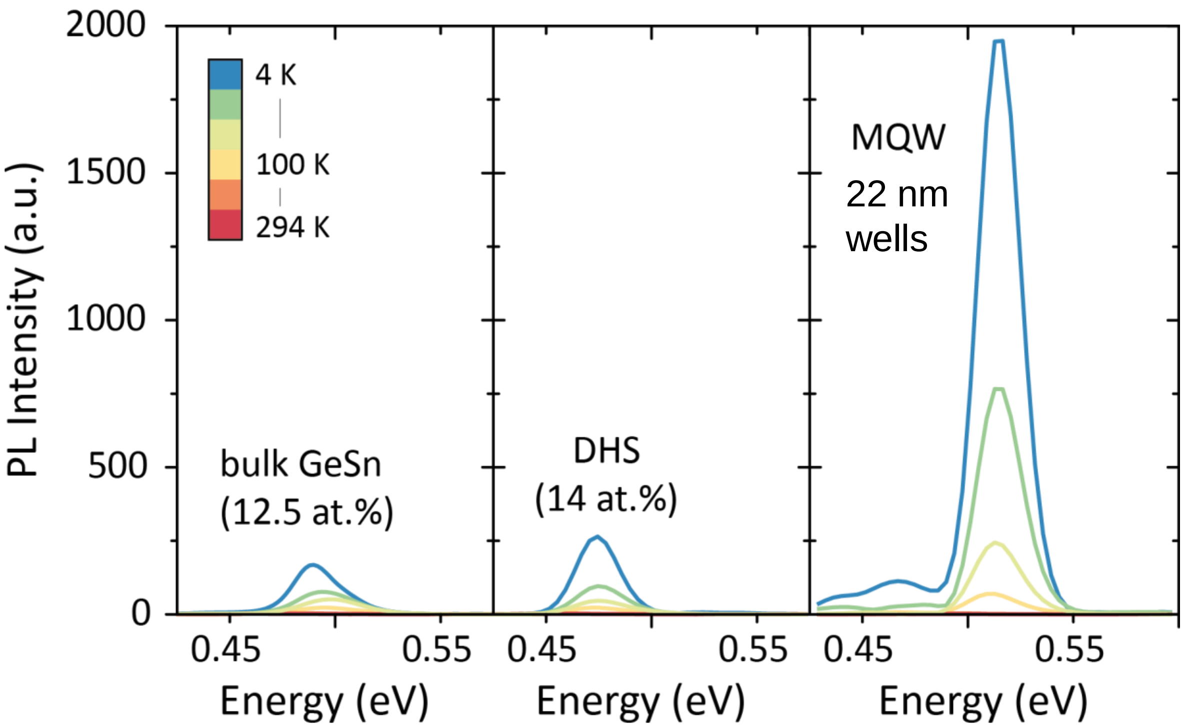


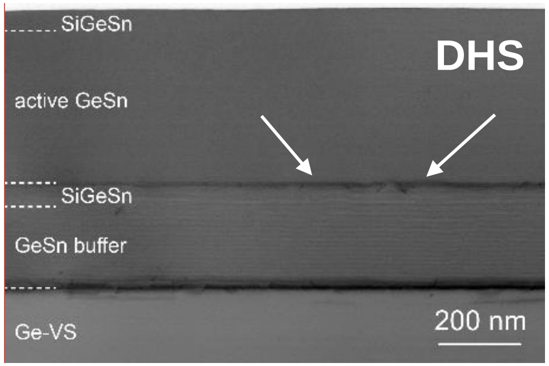


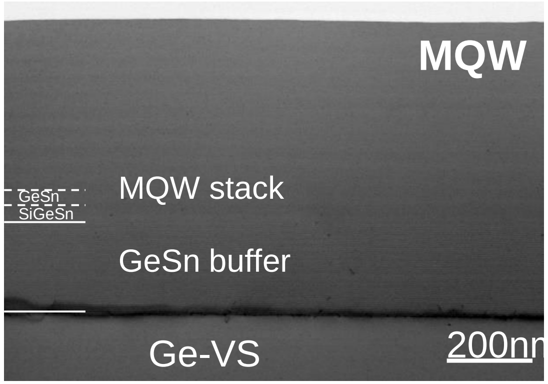
- 10x GeSn/SiGeSn MQW
- well thicknesses of 22 & 12 nm

- wells: ~ 13.3 at.% Sn
- barriers: ~13.0/5.0 at.% Sn/Si

Light emission

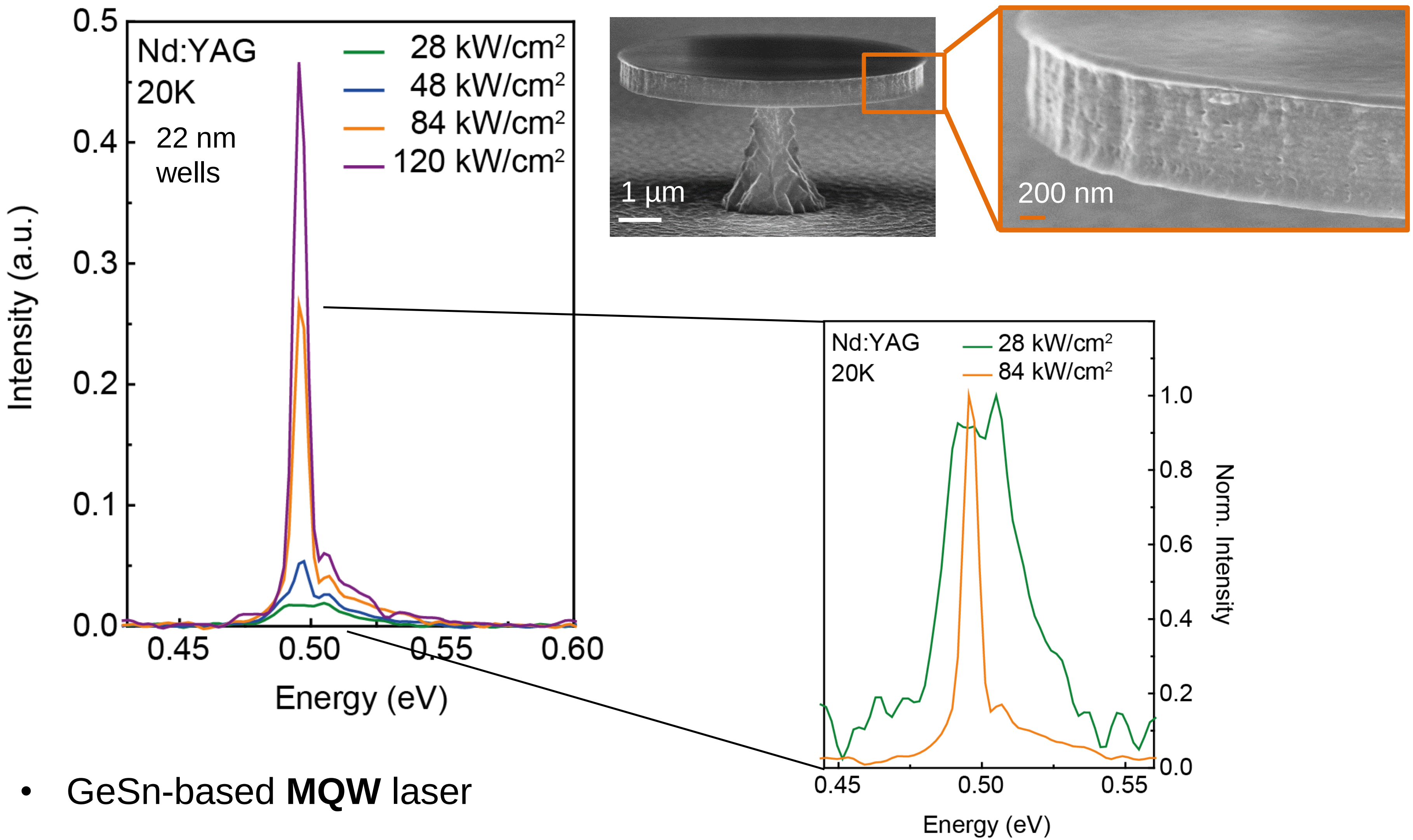






- emission in double heterostructures limited by presence of defects at active region
- screening of carriers from defects in MQW

MQW Laser

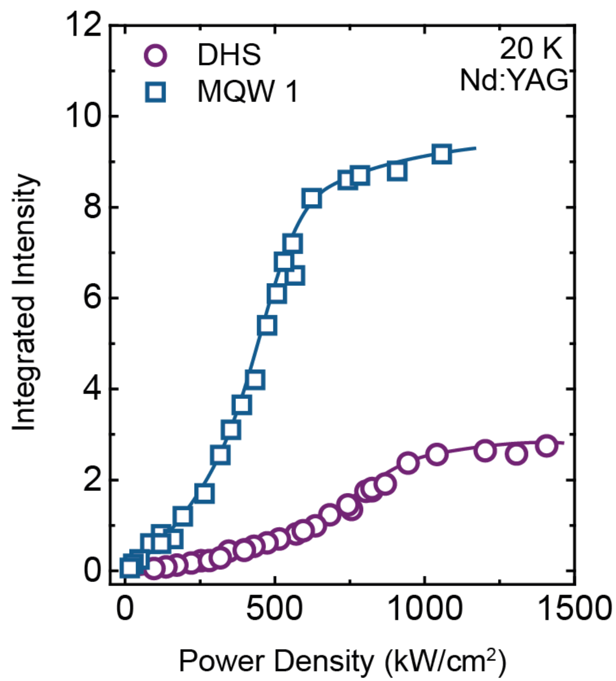


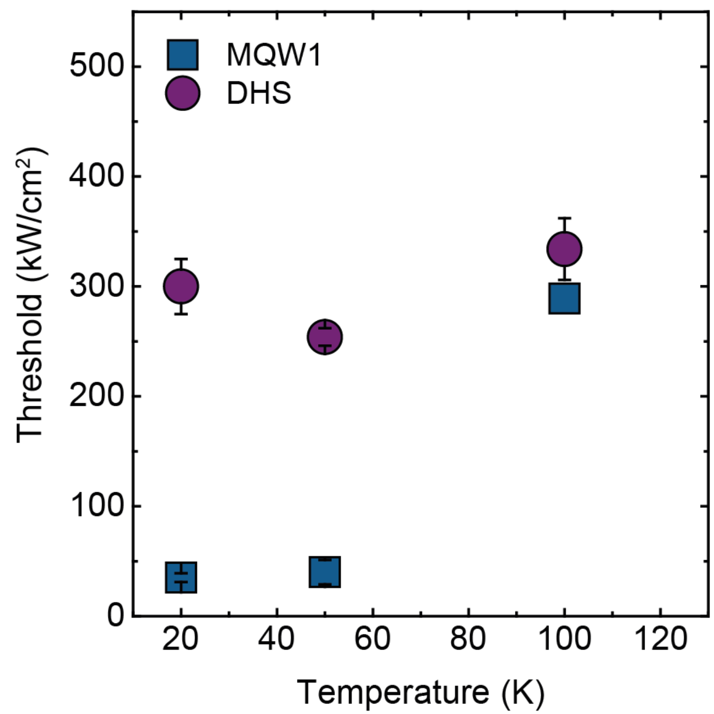
- GeSn-based **MQW** laser

MQW Laser – Threshold reduction

DHS: 377 nm active GeSn
MQW: 220 nm active GeSn

→ MQW: one order of magnitude lower threshold



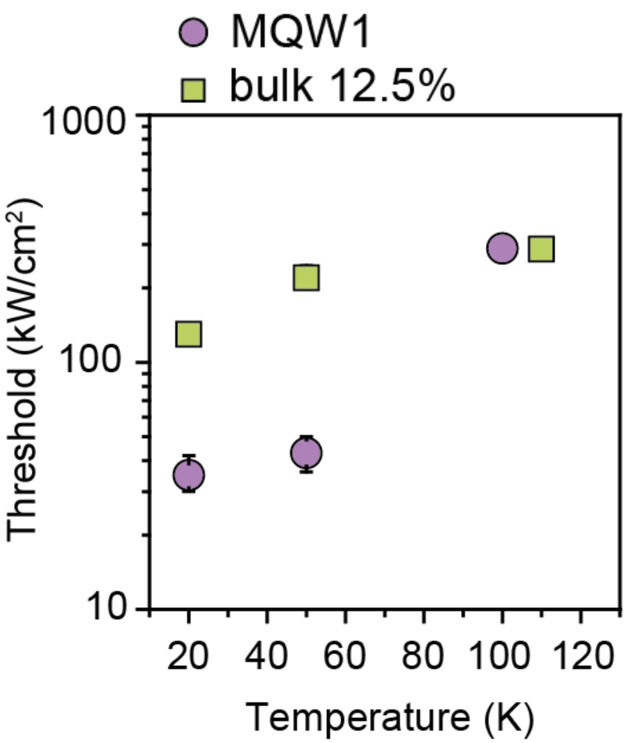


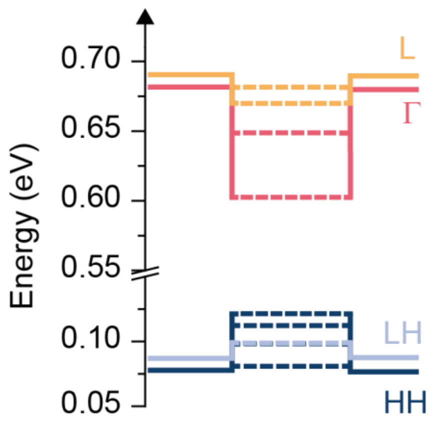
- screening of carriers from defects…

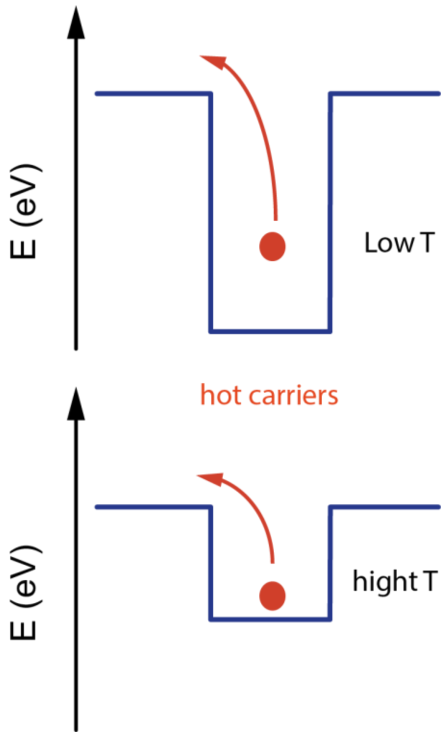
… **increases intensity**

… dramatically **decreases** (low temperature) **threshold** → No improvement in high temperature operation

Laser threshold comparison







Deceased laser threshold due to:

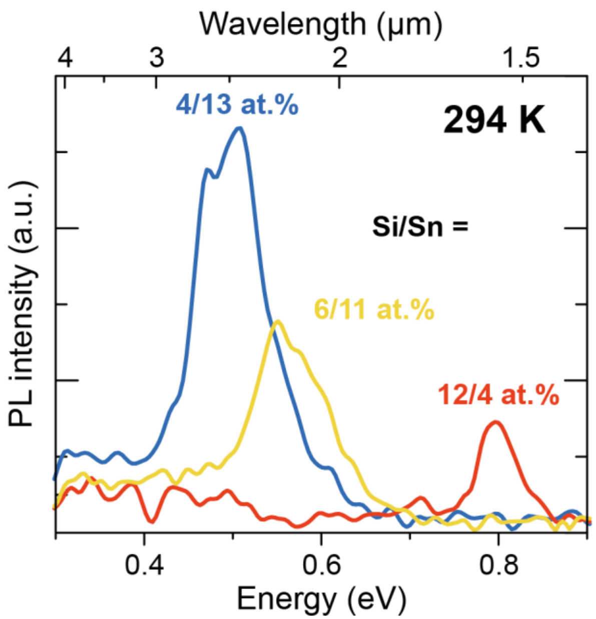
- carrier confinement
- 2D density of states

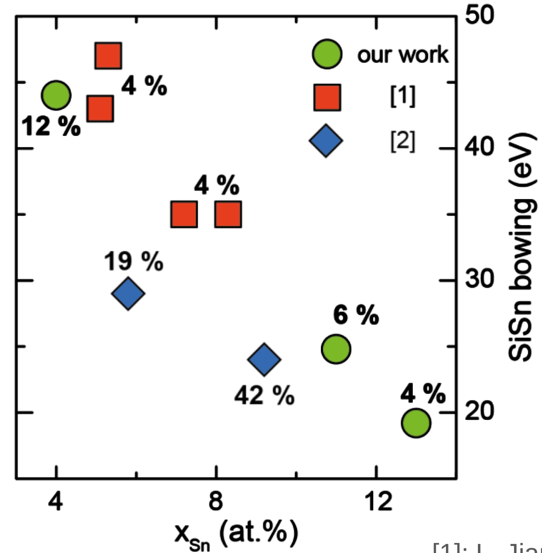
Temperature limitations due to

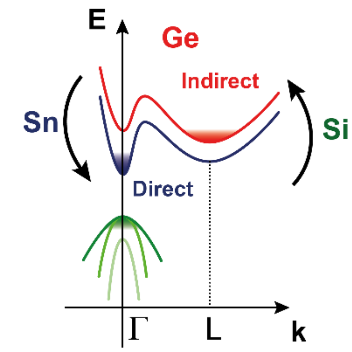
- moderate directness
- band offsets

SiGeSn modeling

N. von den Driesch *et al.*, Small **1603321** (2017)







[1]: L. Jiang et al. Chem. Mater. **26**, 2522 (2014)

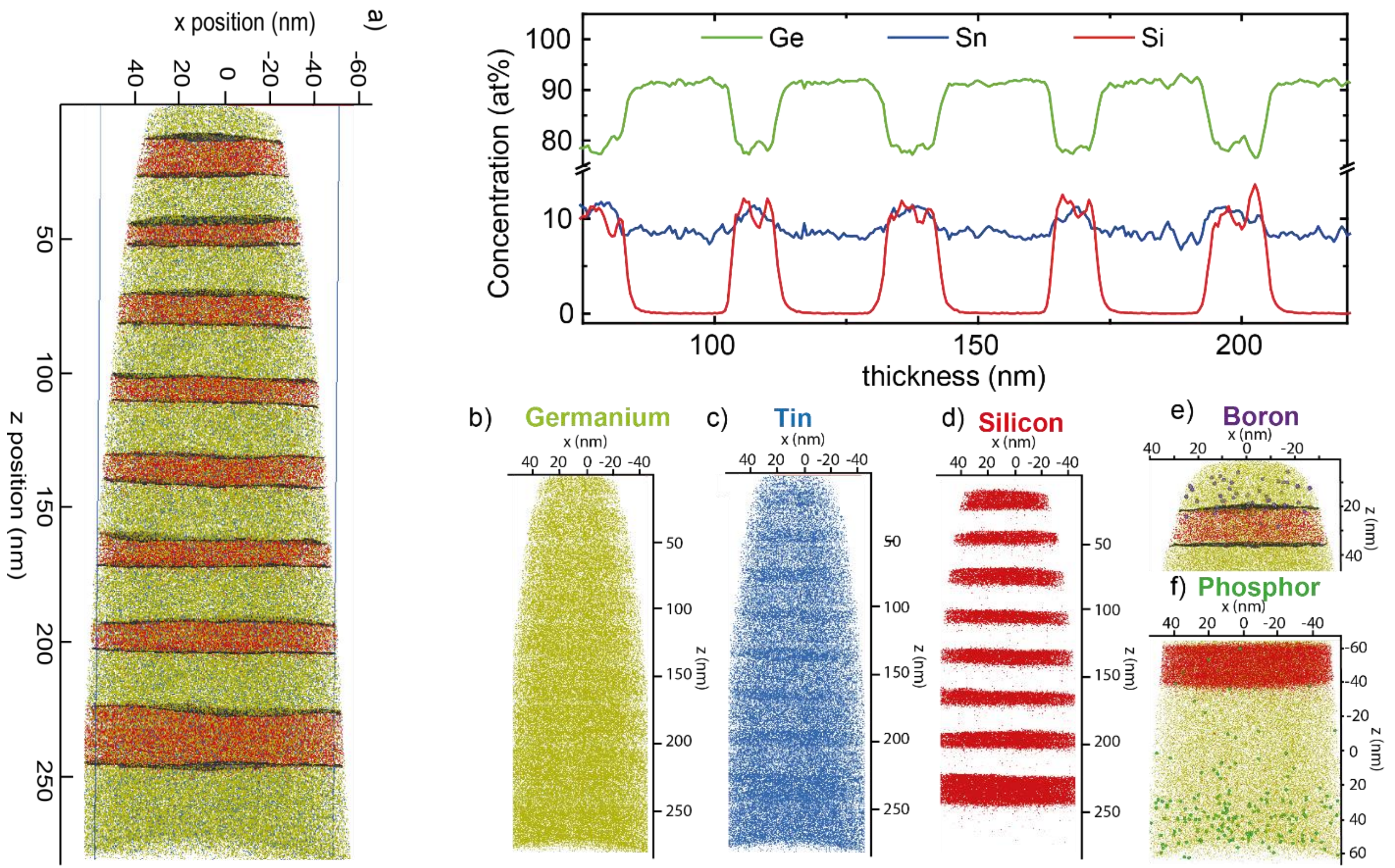
[2]: T. Wendav et al. APL **108**, 242104 (2016)

$\boldsymbol{Si_xGe_ySn_z}$:

$$E_\Gamma = E_\Gamma^{Si}x + E_\Gamma^{Ge}y + E_\Gamma^{Sn}z - b^{SiGe}xy - b^{GeSn}yz - b^{SiSn}xz$$

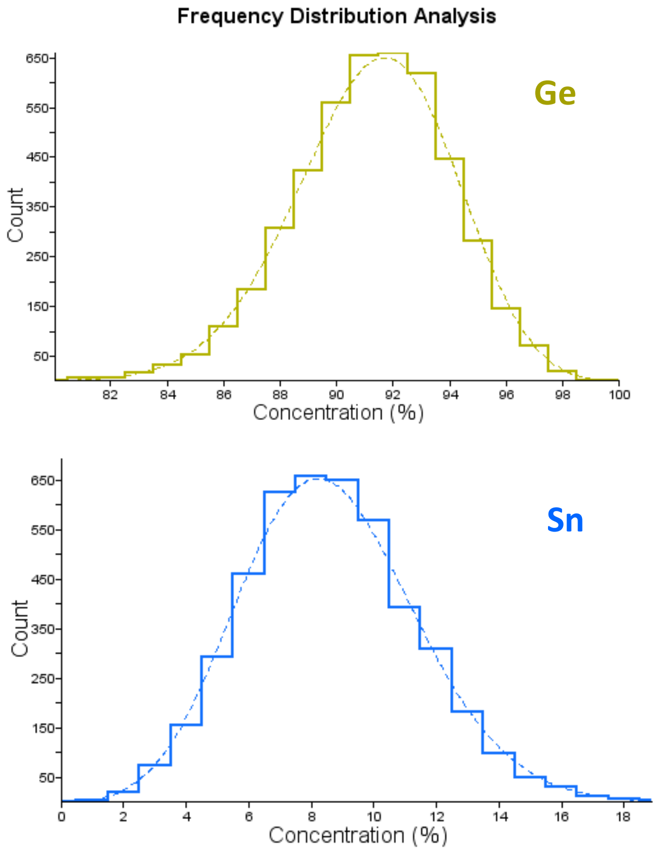
$\longrightarrow$ not a constant, but composition dependent

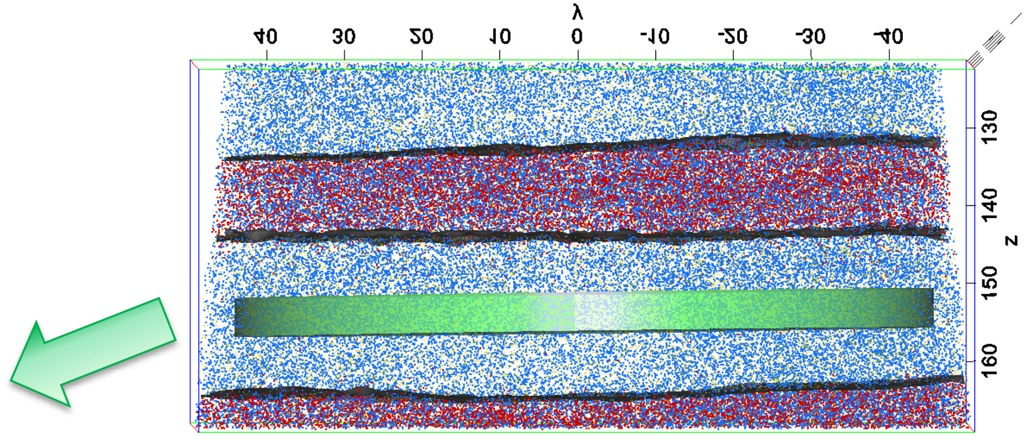
GeSn MQW



a)
x position (nm)
z position (nm)
Concentration (at%)
Ge
Sn
Si
thickness (nm)
b) Germanium
c) Tin
d) Silicon
e) Boron
f) Phosphor
x (nm)
z (nm)

Elemental distribution inside GeSn QW





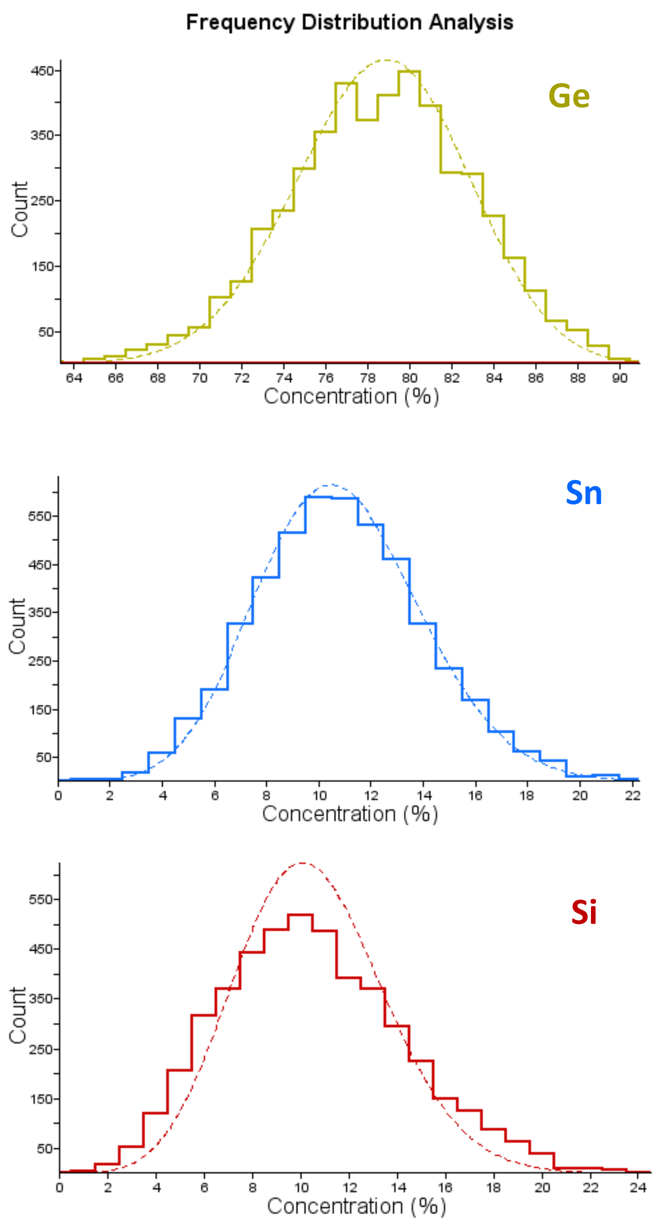
5 nm slice, 500k atoms

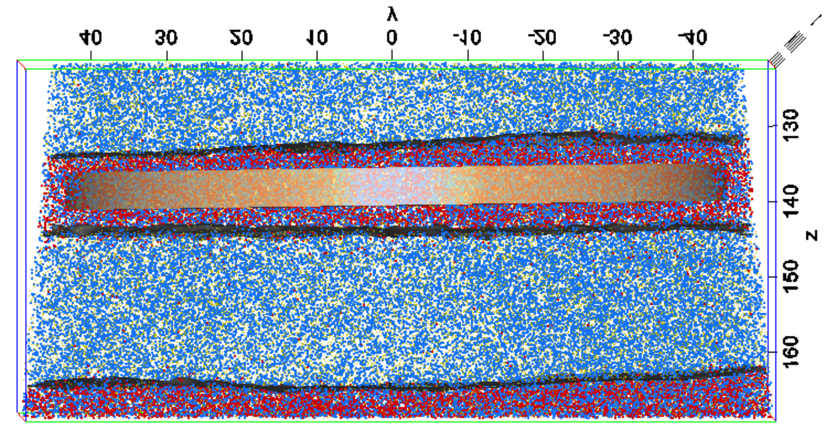
<u>Homogeneous</u>

<u>solid solution in GeSn QW volume</u>

Dataset is split into spatial subvolumes of 100 ions each:
<u>solid line:</u> measured number of blocks with given concentrations
<u>dashed line:</u> binomial (random) distribution

Elemental distribution in SiGeSn layers





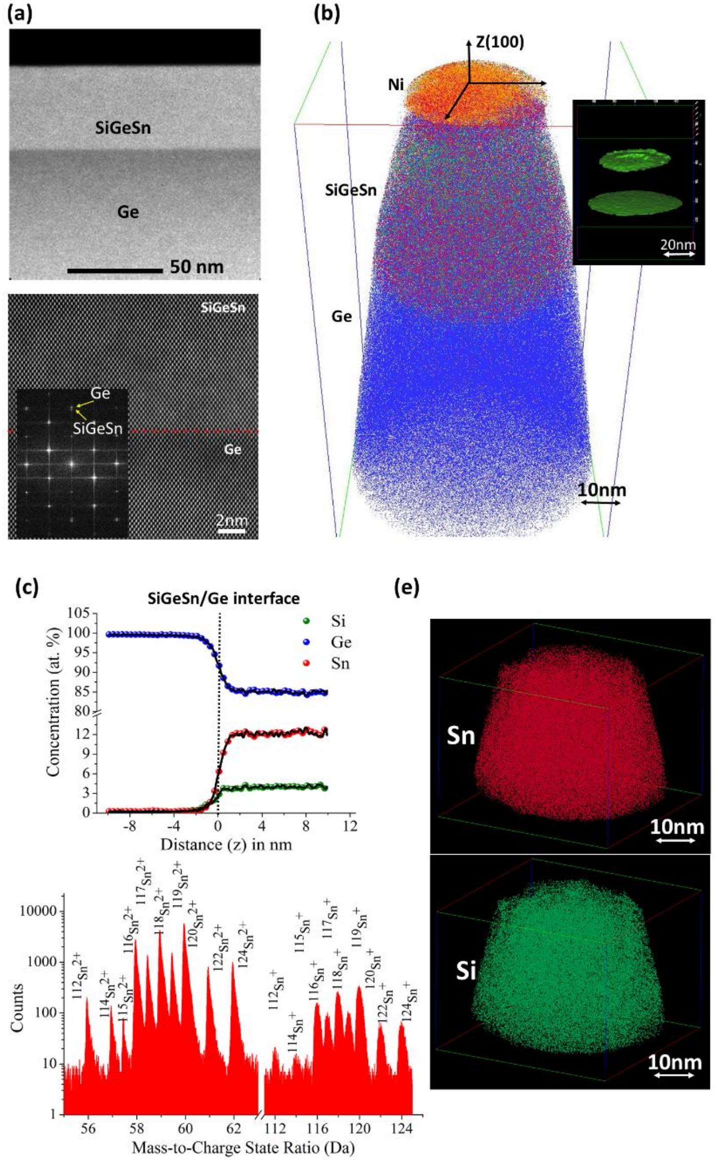
5 nm slice, 500k atoms

Non-homogeneous distribution in inter-QW regions <u>for Si</u>

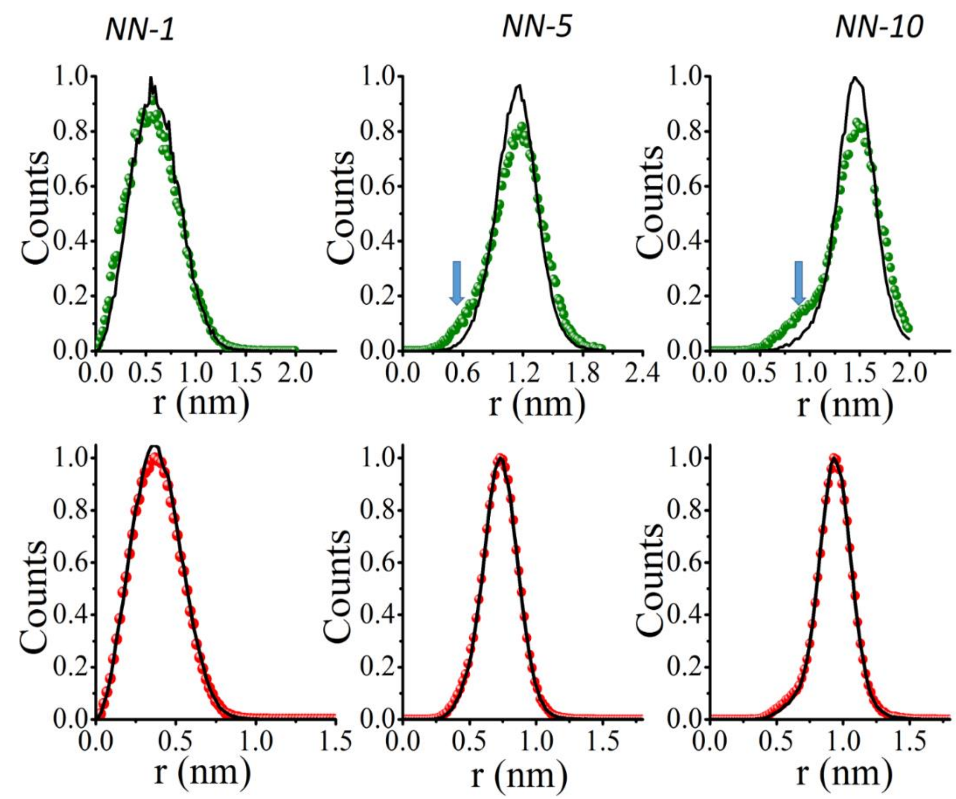
Element	at.%
Ge	78.6
Sn	**10.2**
Si	**10.5**

Atom probe tomography - SiGeSn

together with Prof. O. Moutanabbir group at Polytechnique Montréal, Cana



ordering effect for distant Si neighbours



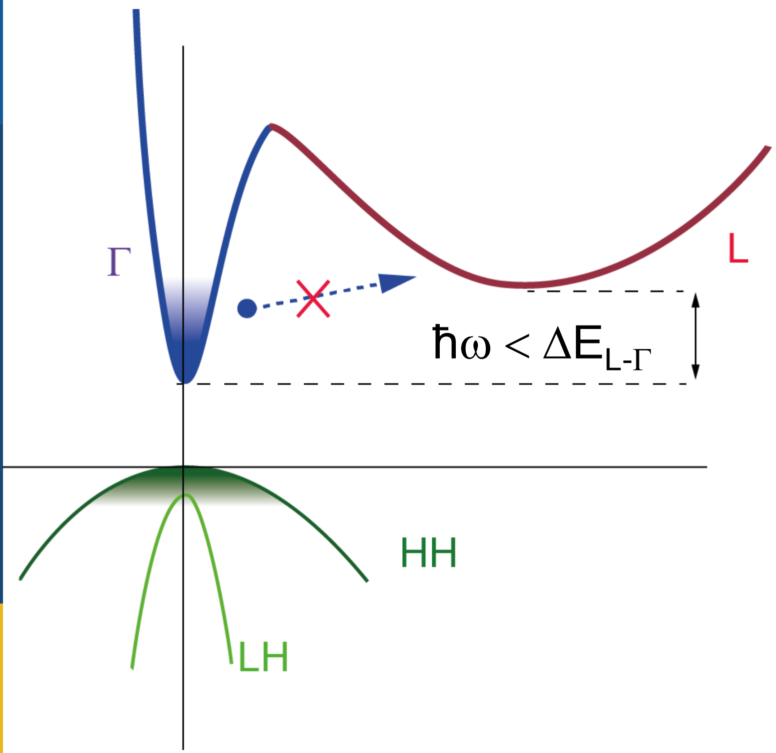
Atomic Order in Metastable Sn-rich SiGeSn Ternary Alloys
Phys. Rev. B, April 2017

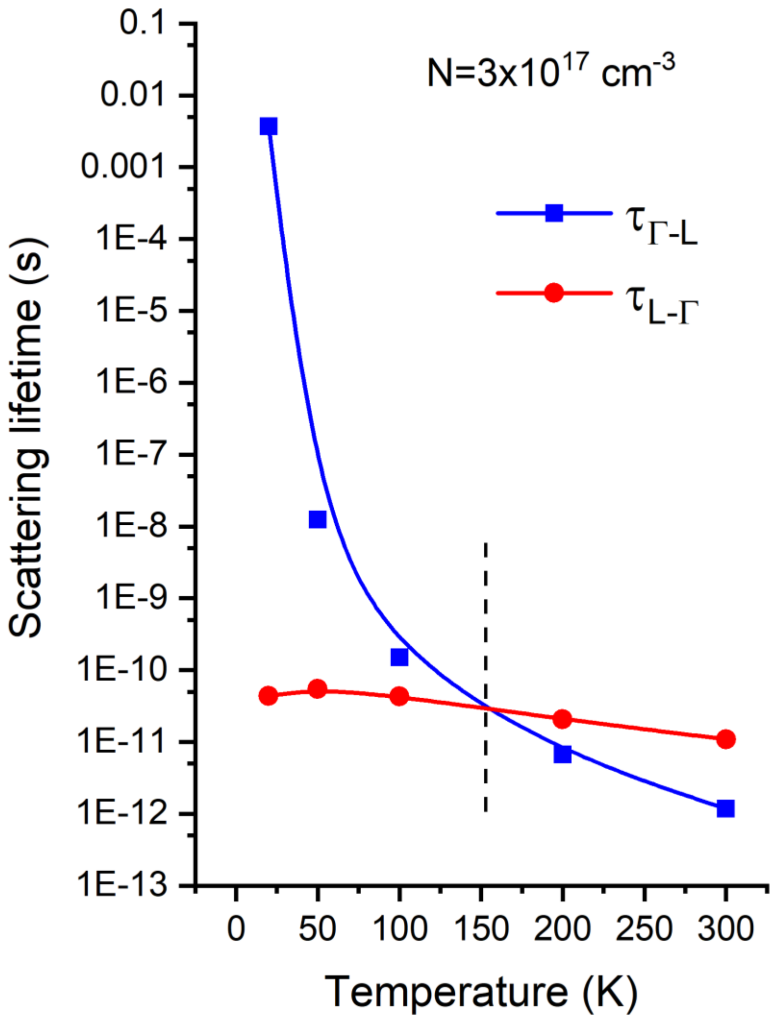
Challenges

Low Pumping Thresholds	$\Rightarrow$ Low defect density, minimize optical losses
SiGeSn QW	$\Rightarrow$ Band off-sets
Room Temperature Operation	$\Rightarrow$ Increase ΔE > 100 meV
CW-operation	$\Rightarrow$ Large ΔE and low defect density
Electrically pumped laser	

Carrier dynamics- Conduction band

Low T, low carrier density

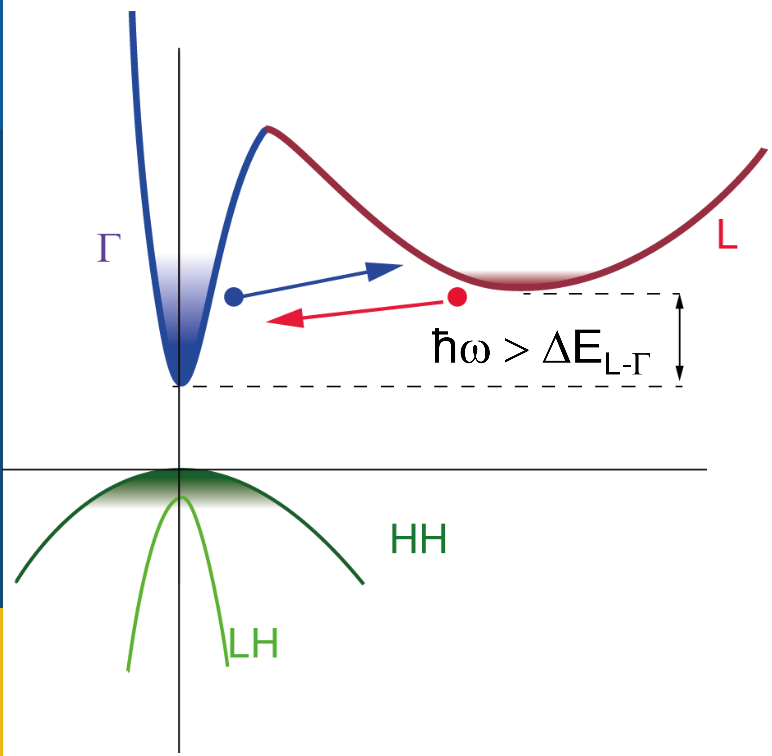


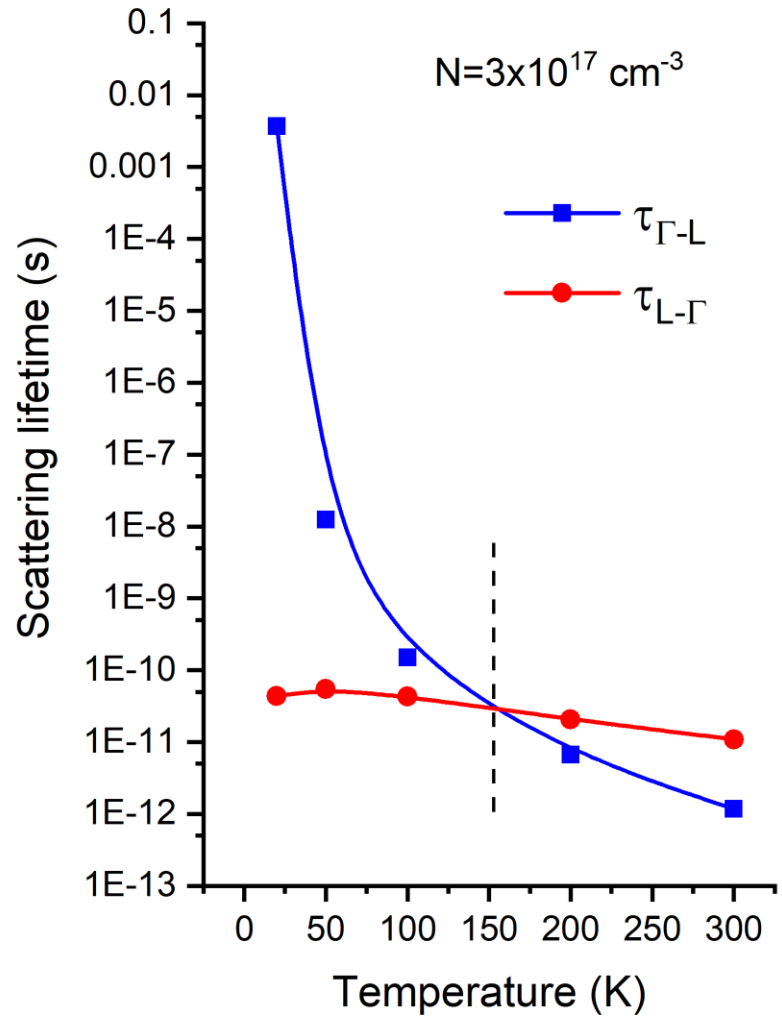


ħω~26meV

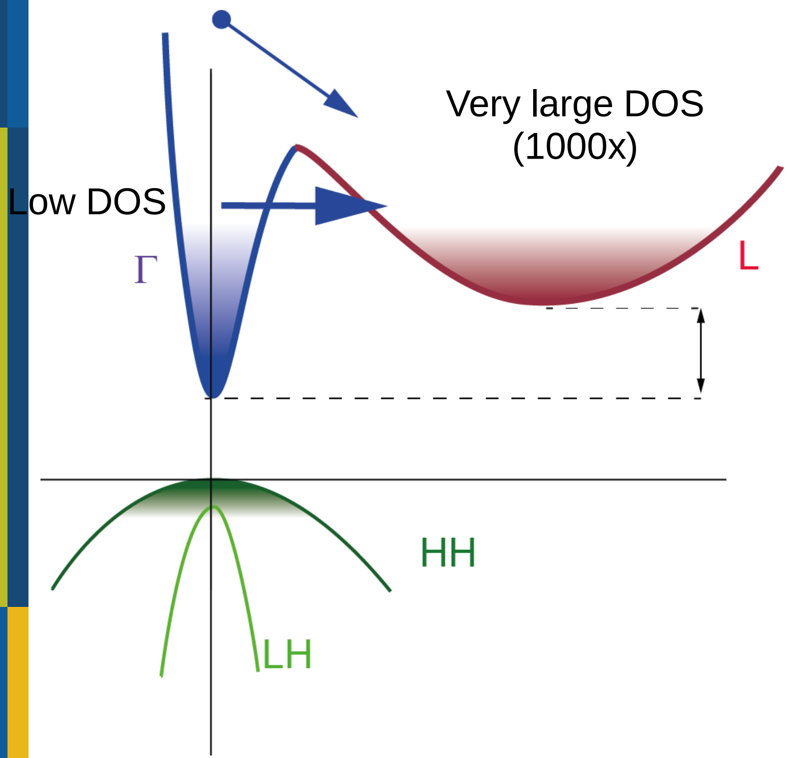
Carrier dynamics- Conduction band

$T \uparrow \Rightarrow \Delta E_{L\text{-}\Gamma} \downarrow$

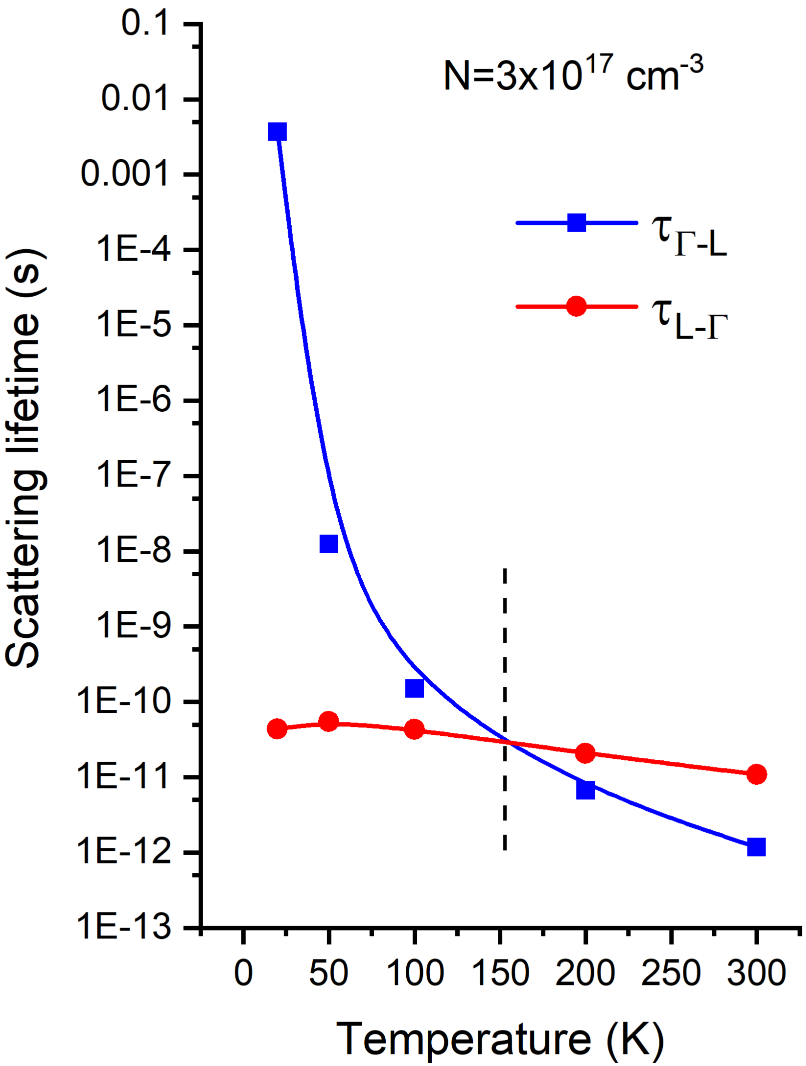




Carrier dynamics- Conduction band

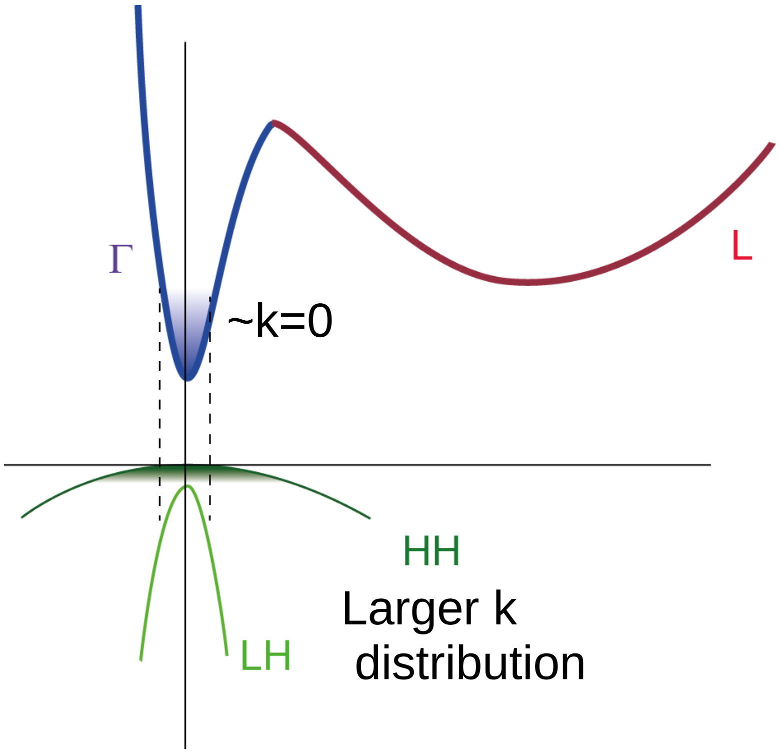


Need high $\Delta E_{\Gamma\text{-}L}$

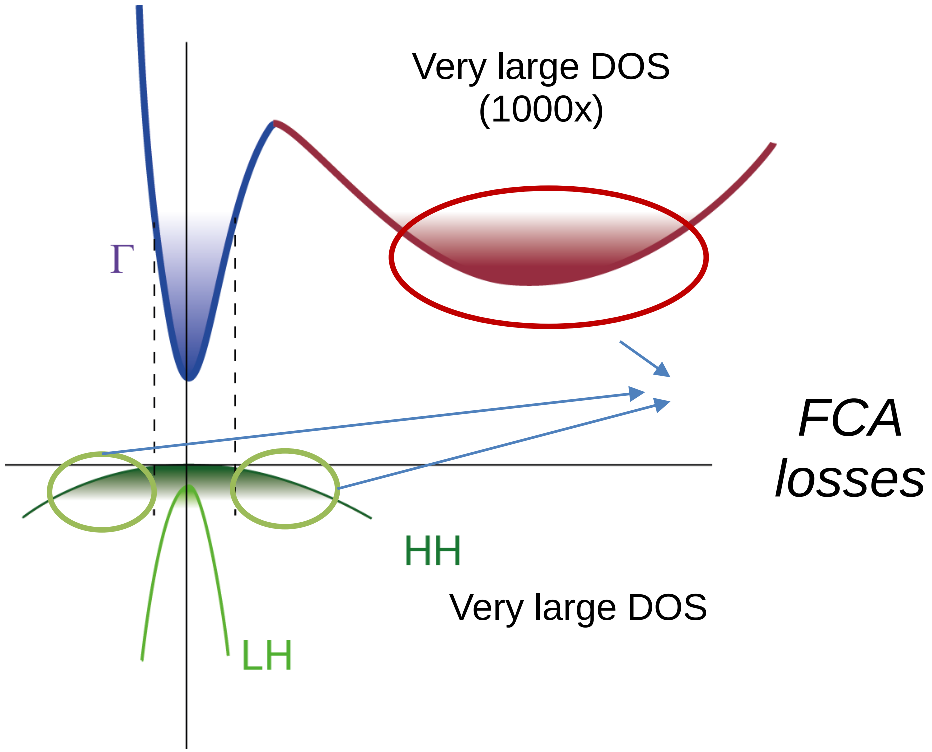


Carrier dynamics - power effect

Compressive strained layers



Carrier dynamics - Valence band



Pumping increases ➔

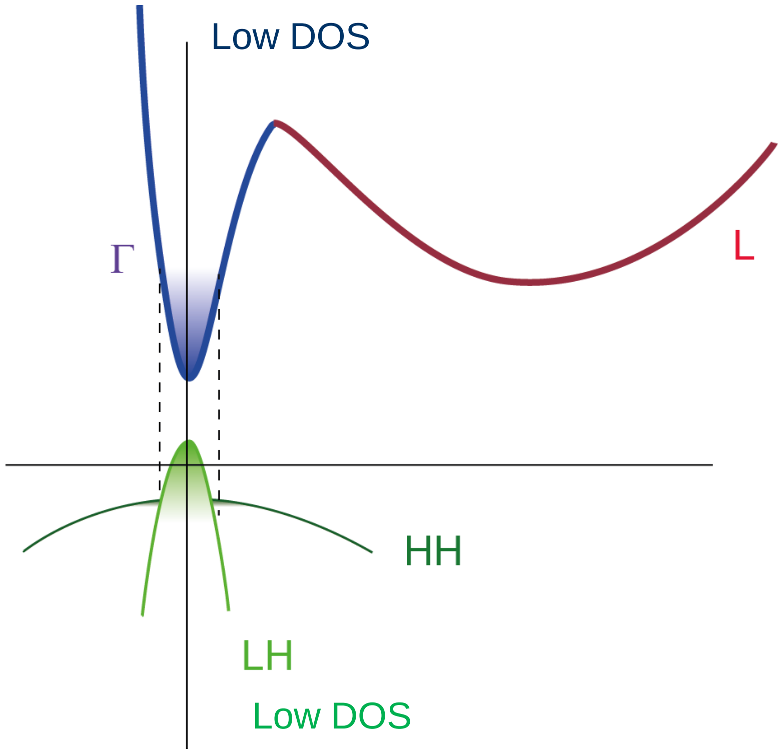
➔ scattering increases ➔

➔ losses increases (large threshold)

➔ more pumping ➔

➔ Laser quenching

Carrier dynamics - Valence band



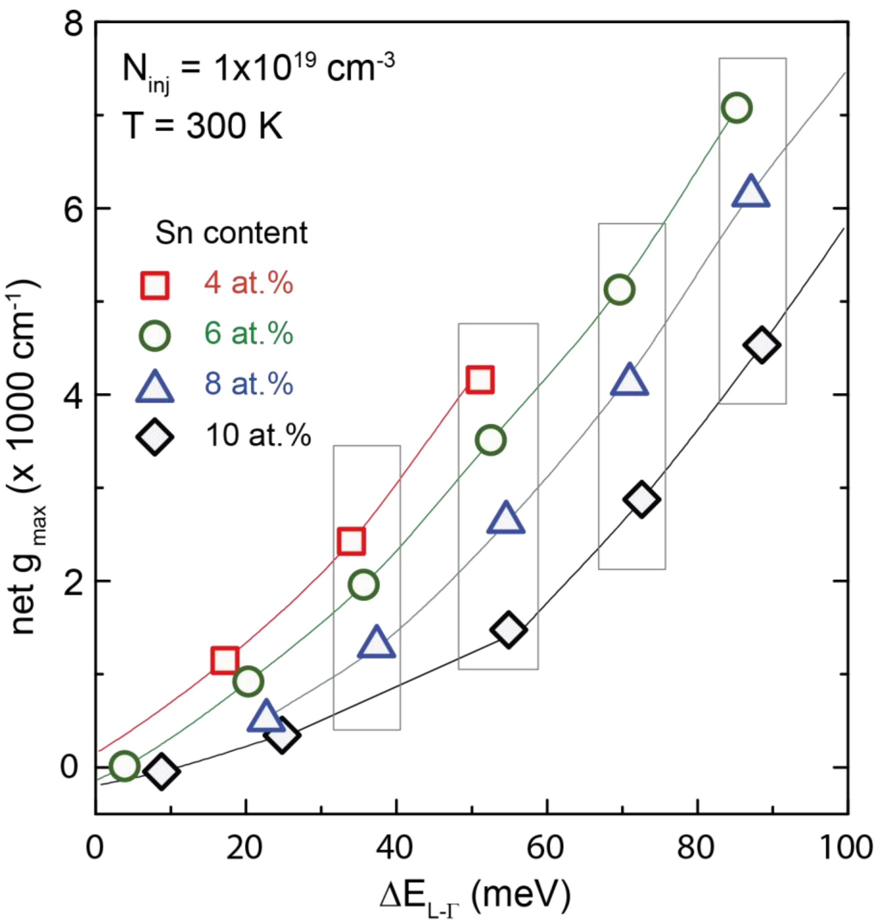
Tensile strain

BIAXIAL

Tensile strained GeSn

Net gain calculations :

D. Rainko et al., Scientific Reports 2019



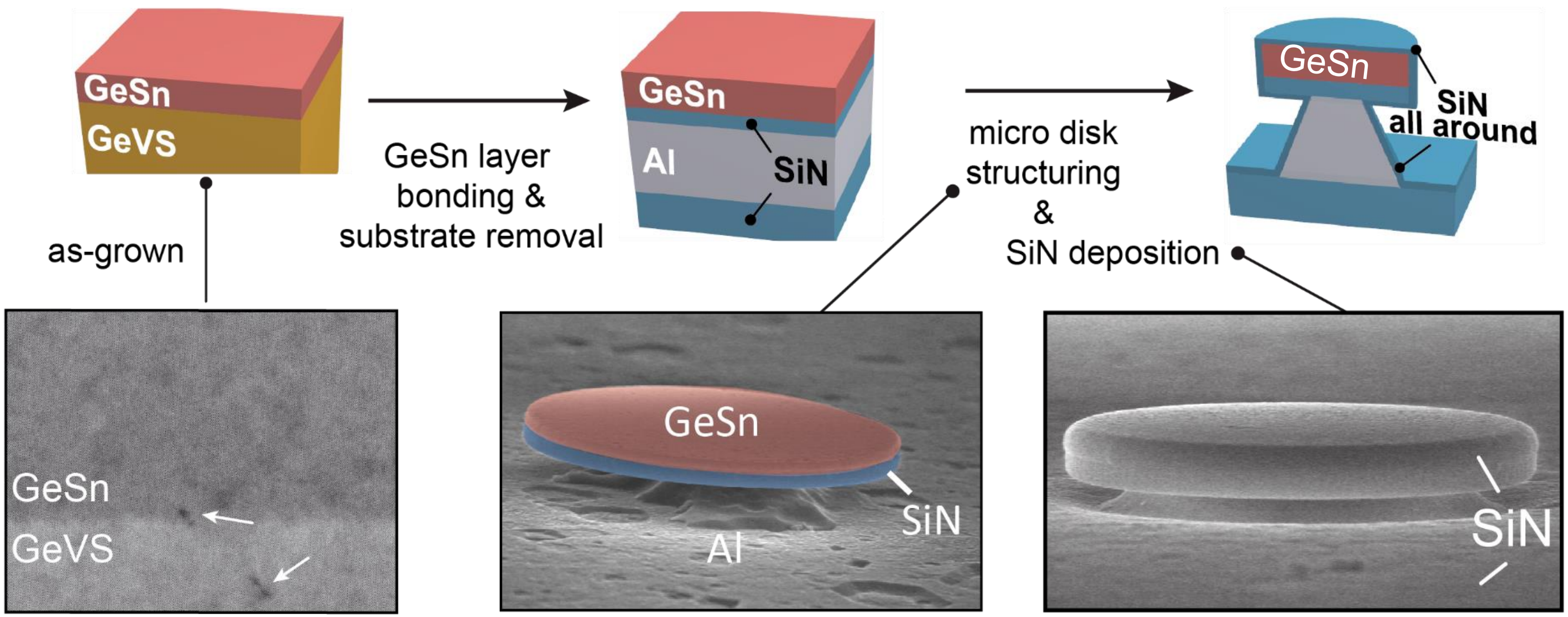
- Due to splitting of HH- and LH-bands majority of injected holes in LH
- optical transition matrix element for z-polarized radiation for LH-Γ transition (z-polarized) is larger (30 %) than the matrix element for HH-Γ (x-polarized) transition.

At the **same L to Γ** energy difference ➔

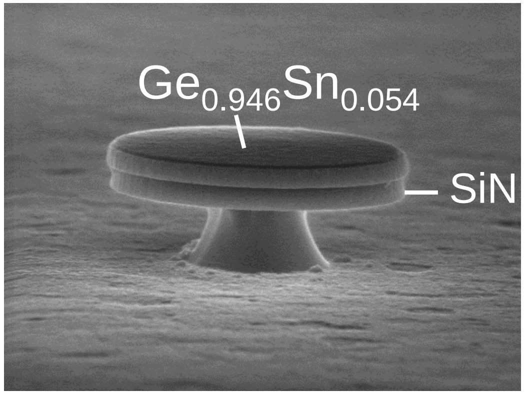
higher gain for lower Sn contents

Tensile strained GeSn

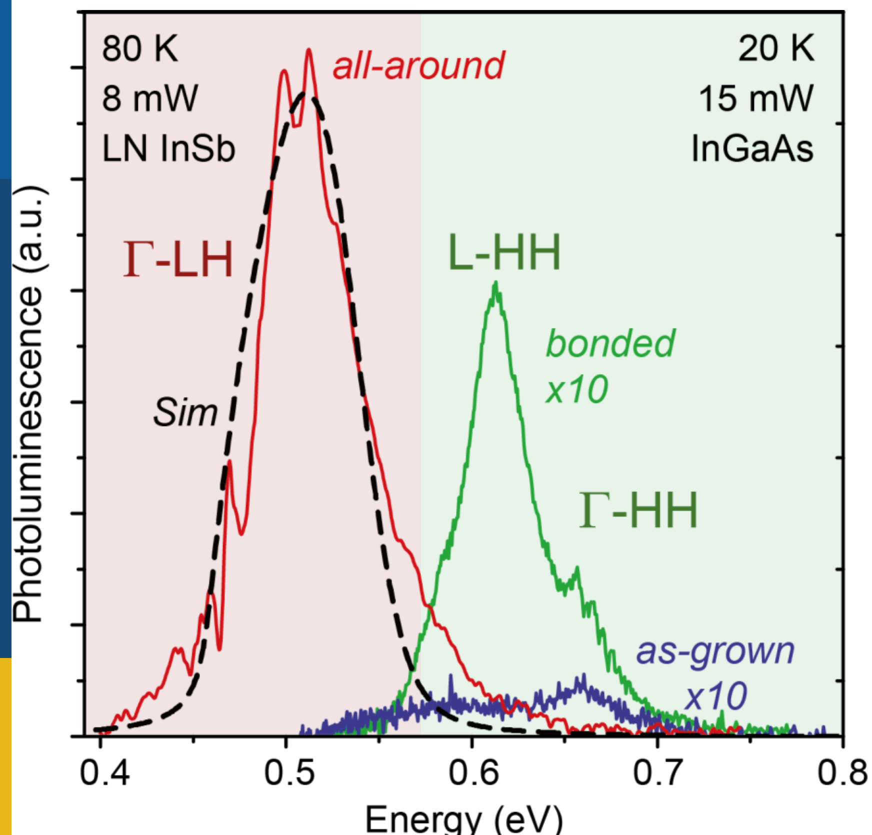
GeSn on Si_3N_4 by layer bonding

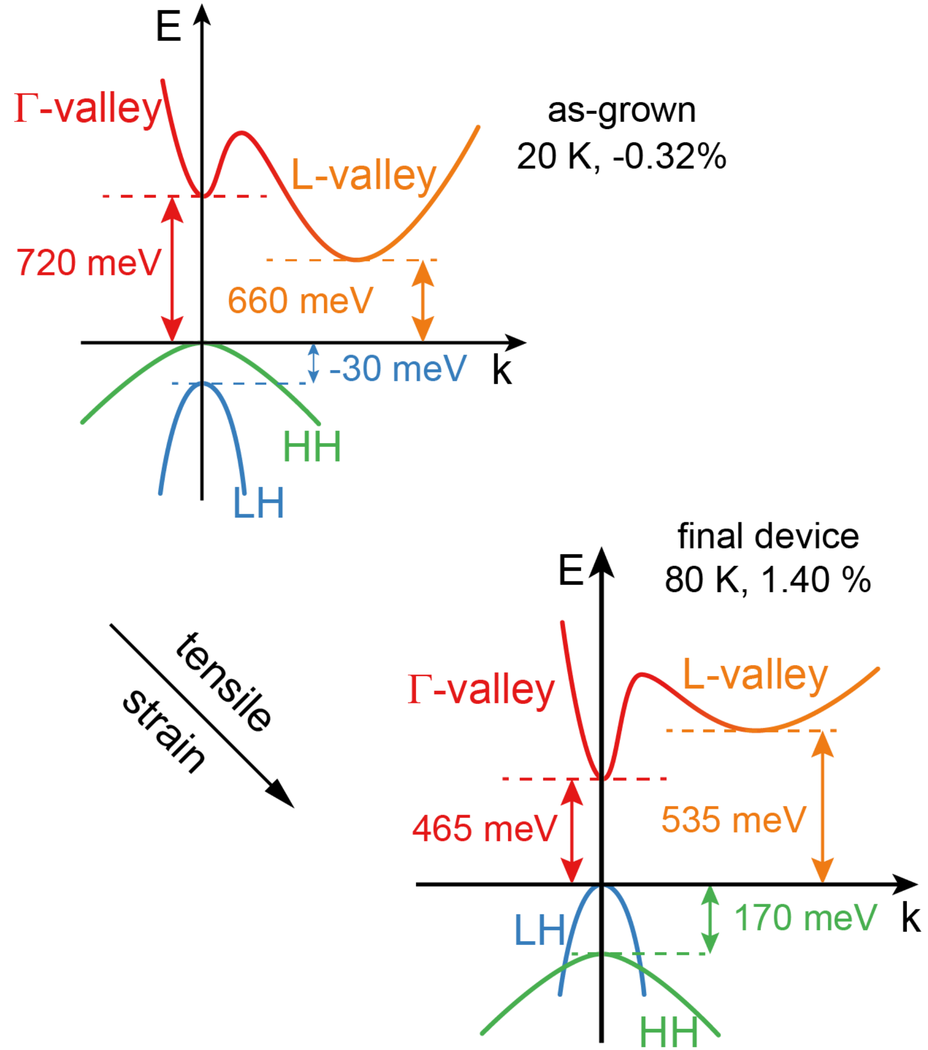


Nature Photonics, 16 march 2020

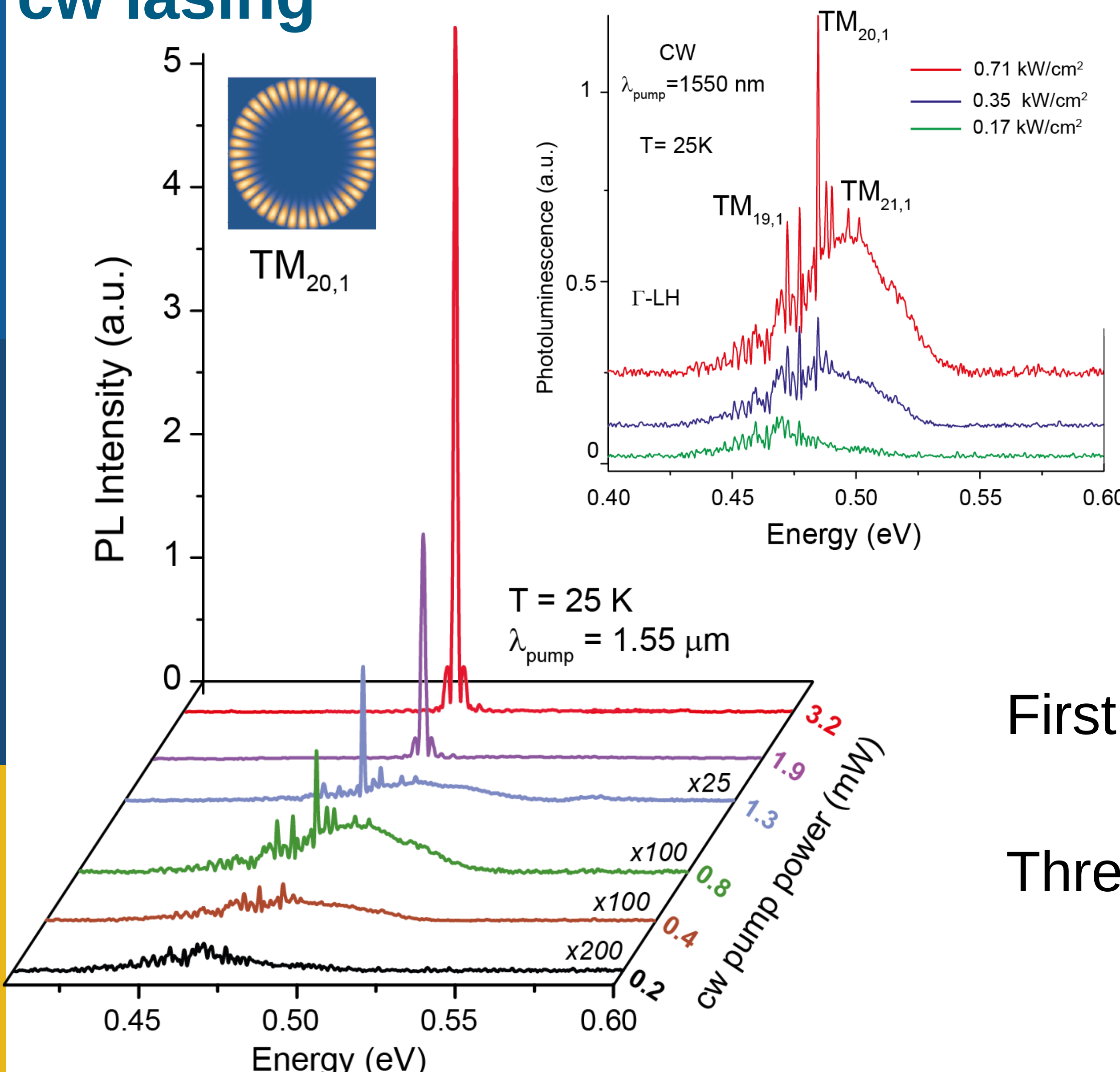


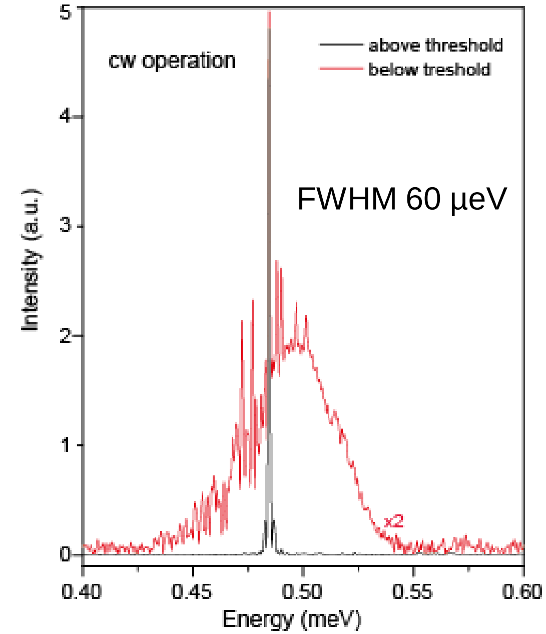
Tensile strained GeSn





cw lasing

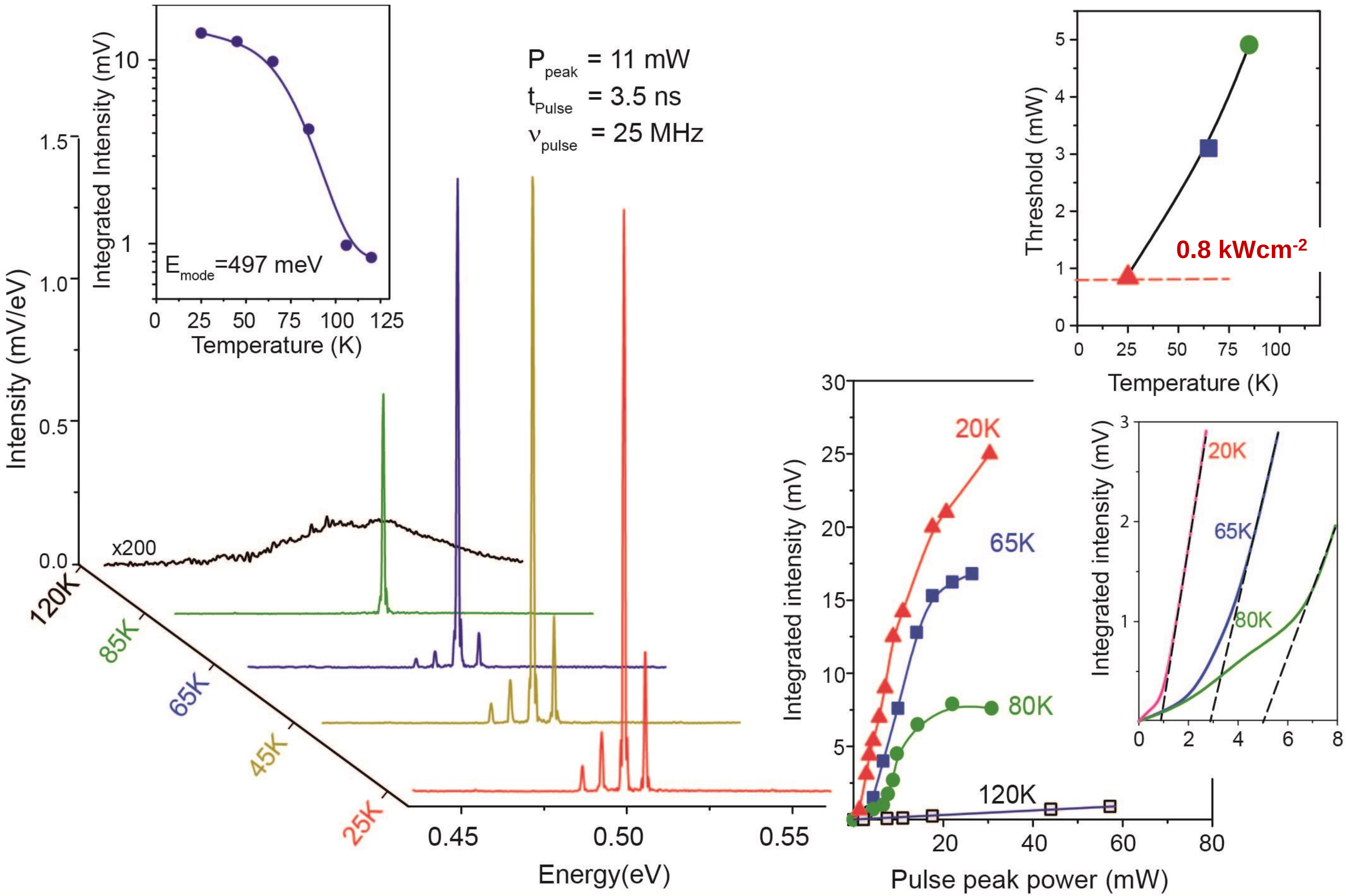




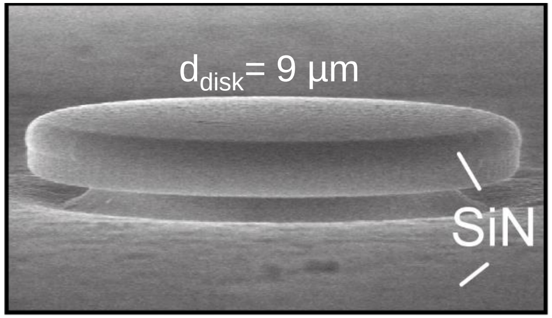
First cw group IV lasing

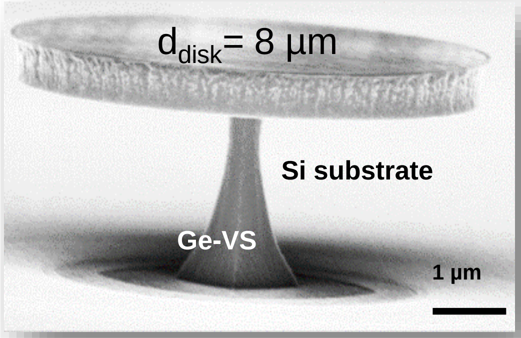
Threshold **1.1kW/cm²**

Multi-mode pulsed lasing



GeSn lasers -Benchmarking



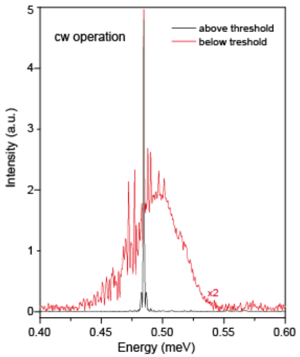


250 nm $Ge_{0.946}Sn_{0.054}$

Eg = 465 meV

$\Delta E_{L\text{-}\Gamma}$ ~ 70 meV

E_{LH}-E_{HH}=172 meV



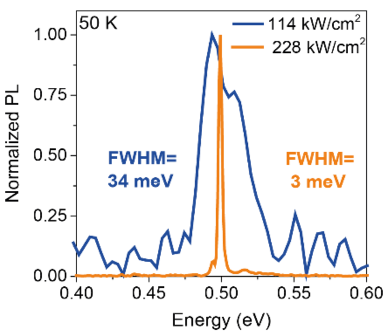
FWHM = 60 µeV

560 nm $Ge_{0.875}Sn_{0.125}$

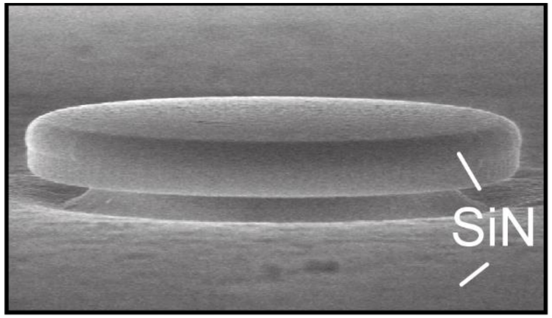
Eg = 460 meV

$\Delta E_{L\text{-}\Gamma}$ ~ 70 meV

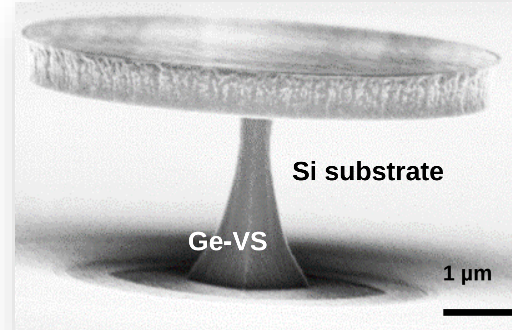
E_{LH}-E_{HH}= -20 meV



FWHM = 3 meV



Mode overlap factors



TM mode

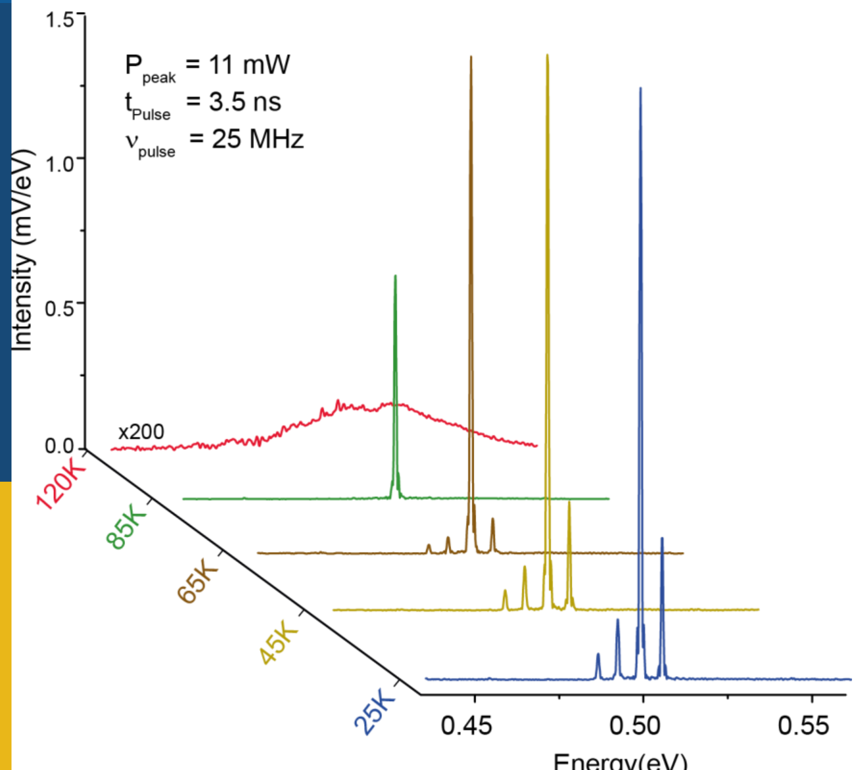
17%

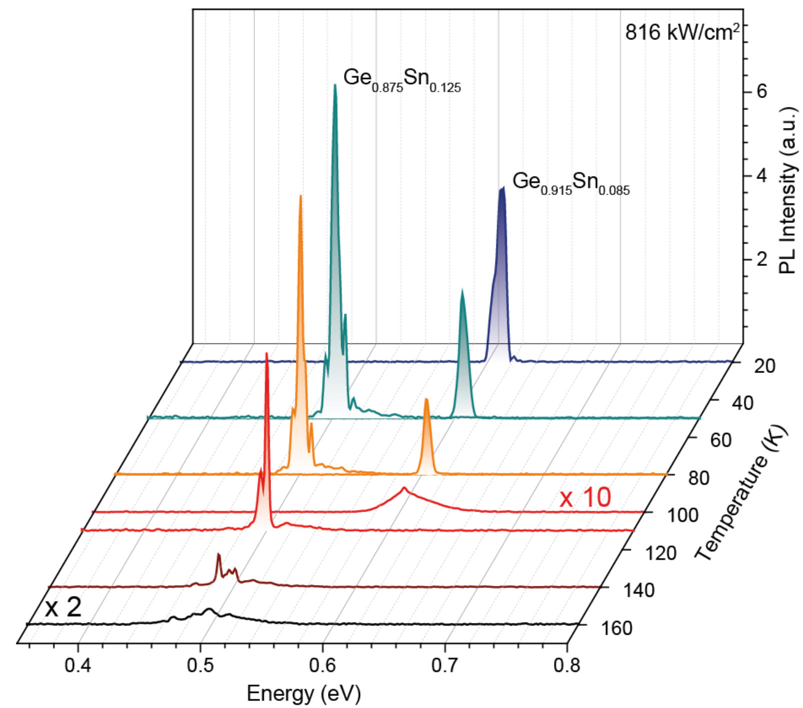
TE mode

70%

250 nm $Ge_{0.956}Sn_{0.054}$

560 nm $Ge_{0.875}Sn_{0.125}$





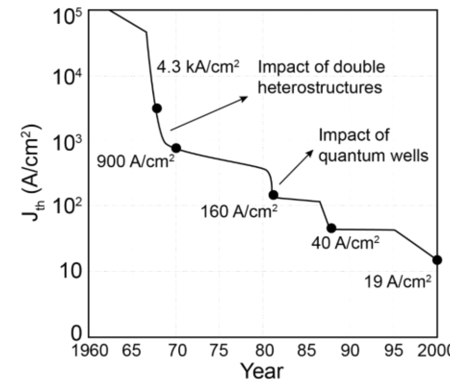
GeSn lasers - Benchmarking

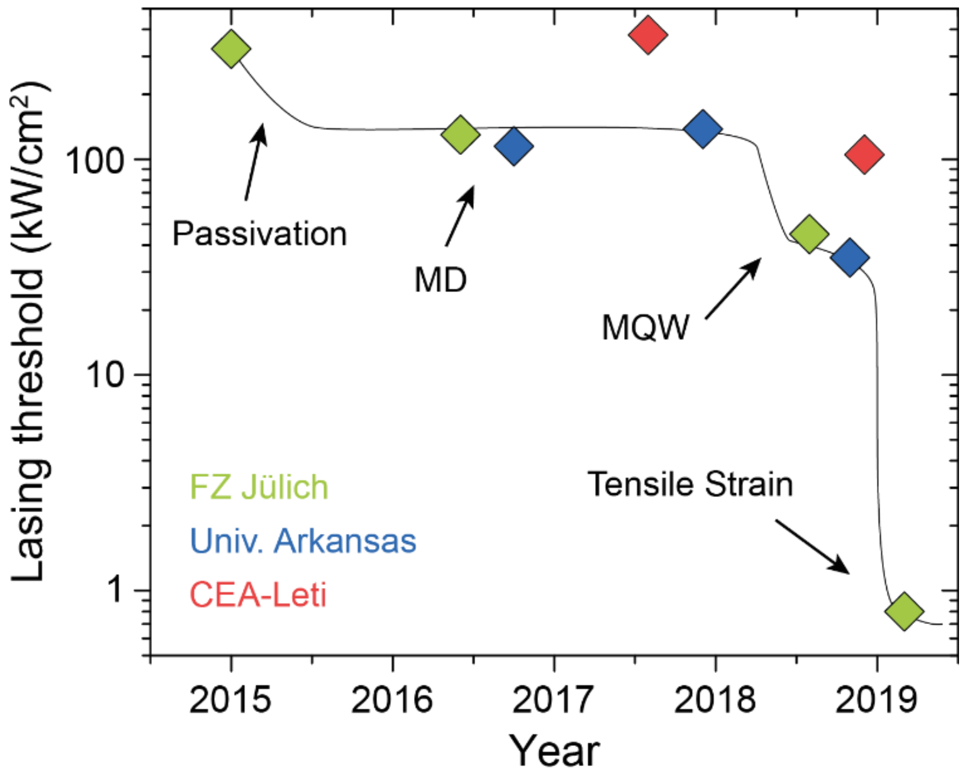
Laser Threshold

	20K	150K	270K	Puls laser	cw laser
High **Sn/comp. Strain** /Bulk	100-200 kW/cm^2	300-800 kW/cm^2	**3-4 MW/cm^2**	YES	NO
Medium Sn/ MQW	30 - 40 kW/cm^2	*300 - 400 kW/cm^2*		YES	NO
low Sn/ **Tensile biaxial strain**	**1 kW/cm^2**	**4 kW/cm^2**		YES	YES

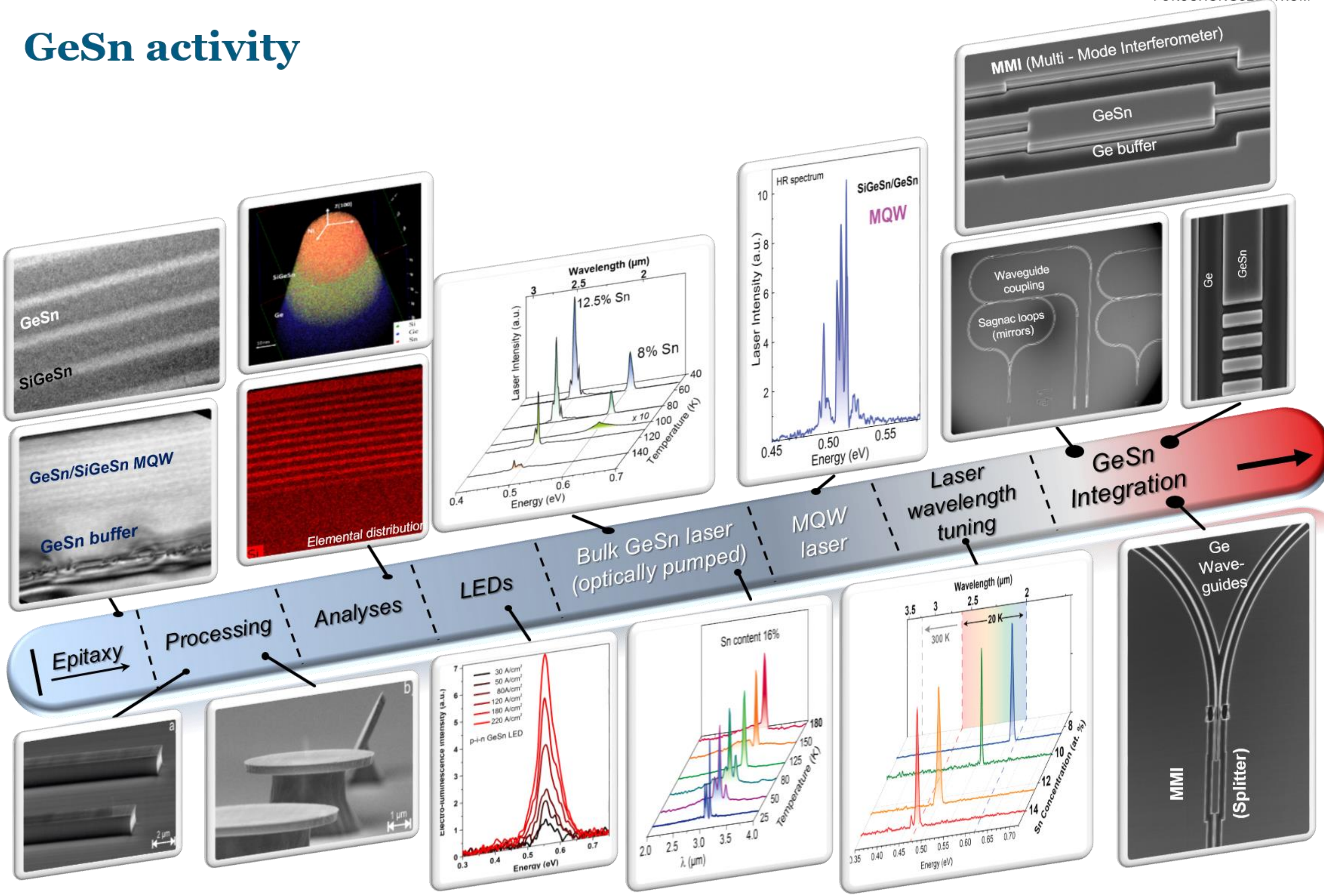
cw mono-mode
puls multi-mode

Pulsed lasing in strained micro disks





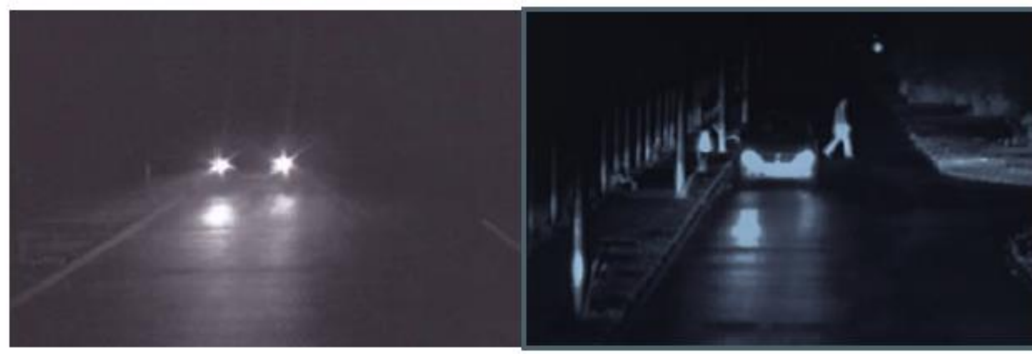
GeSn activity



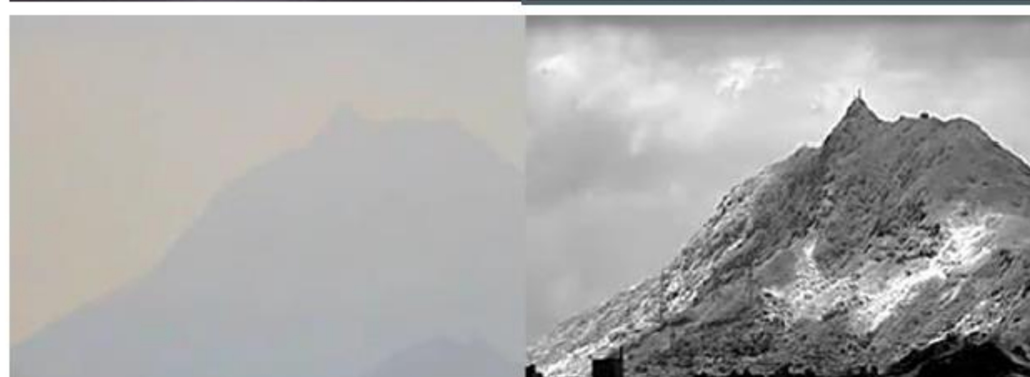
Short Wave Infrared (SWIR) imaging

Applications:
_Spectroscopy
_Imaging

Enhanced night vision

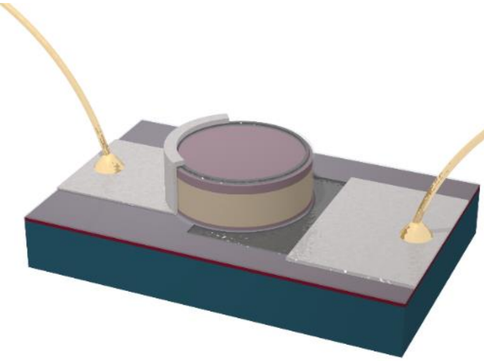


>> Penetration depth in high scattering mediums

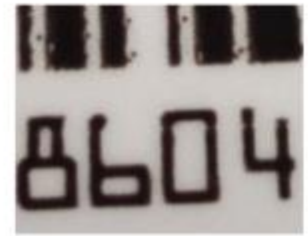
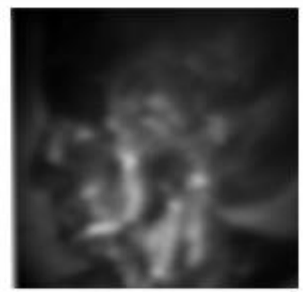


JÜLICH FORSCHUNGSZENTRUM

GeSn Mid infrared imaging

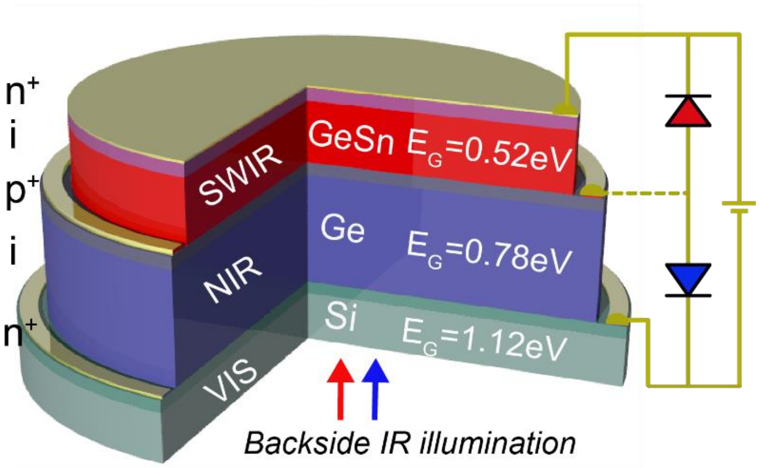


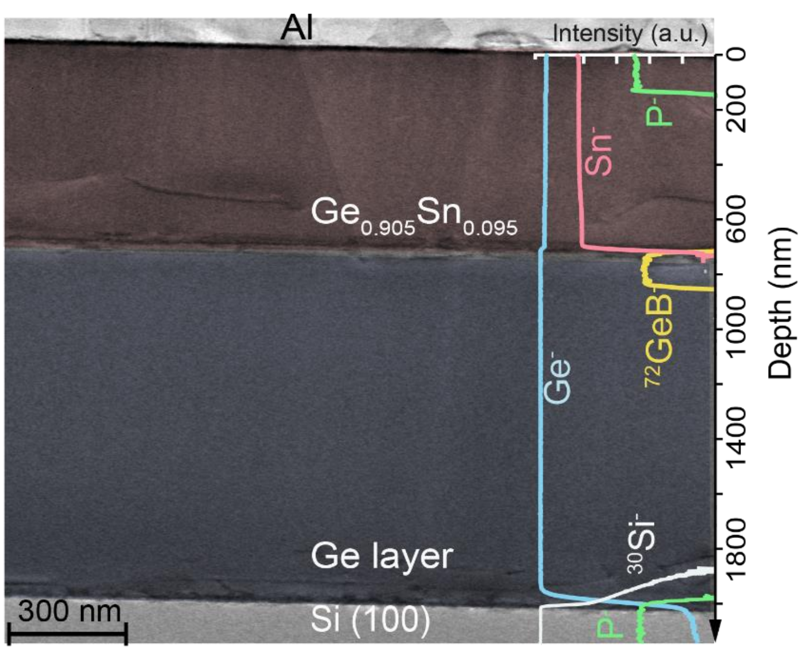
p-i-n homojunction

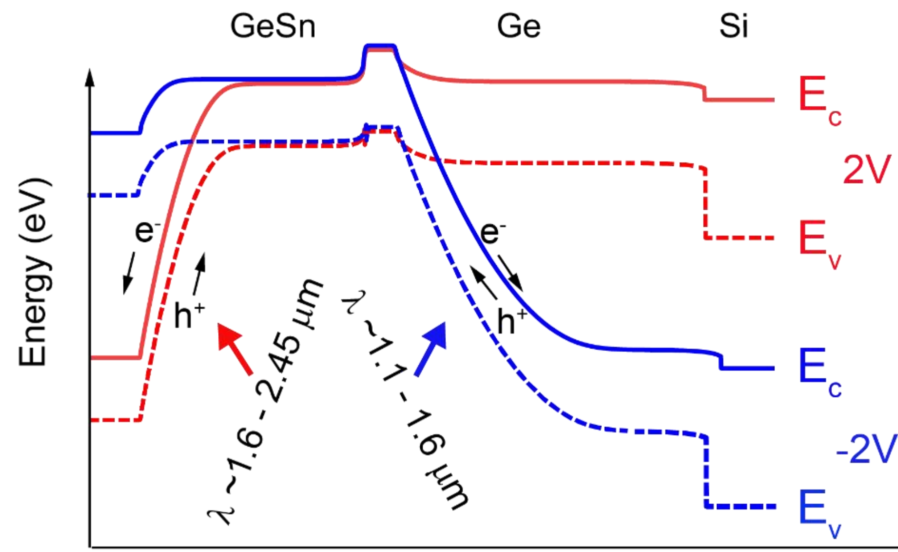
Objects		
GeSn Diode (11%Sn)		
PbSe Single Detector		

Department of Electrical Engineering, University of Arkansas

Dual band Mid infrared imaging

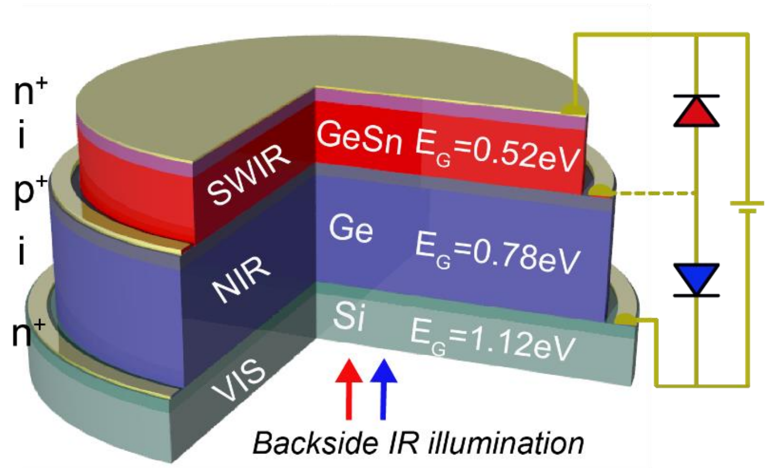


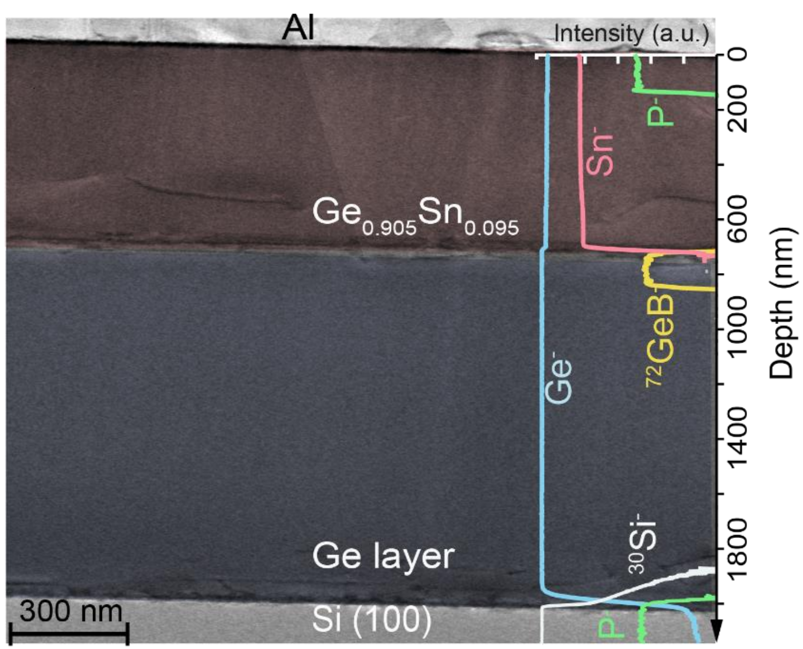


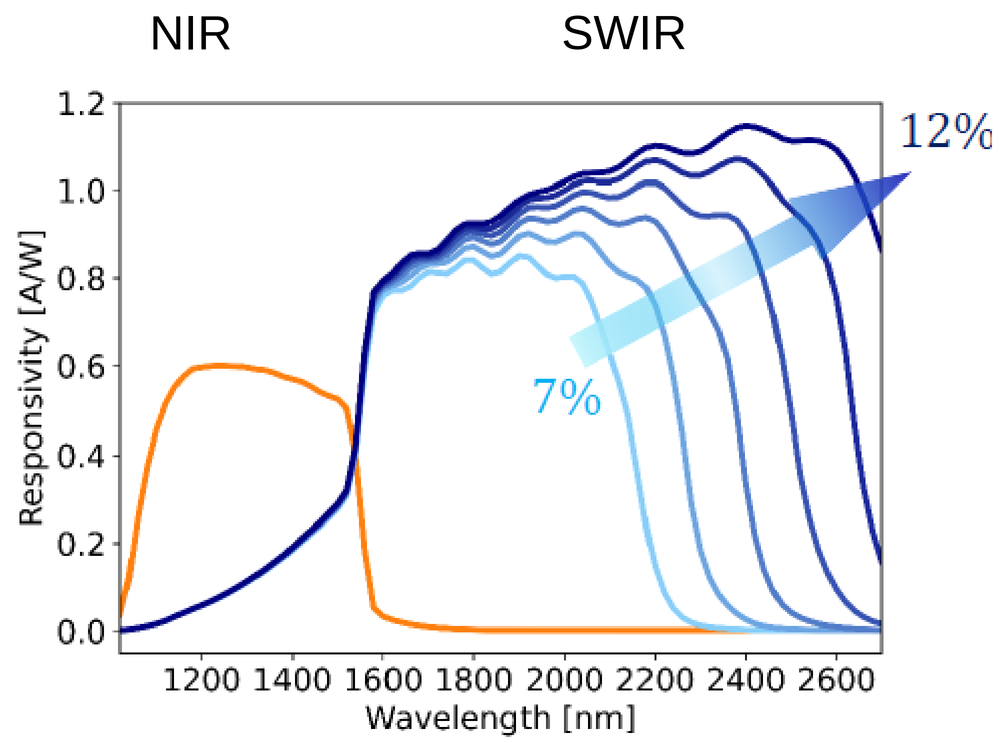


Prof. Giovanni Isella

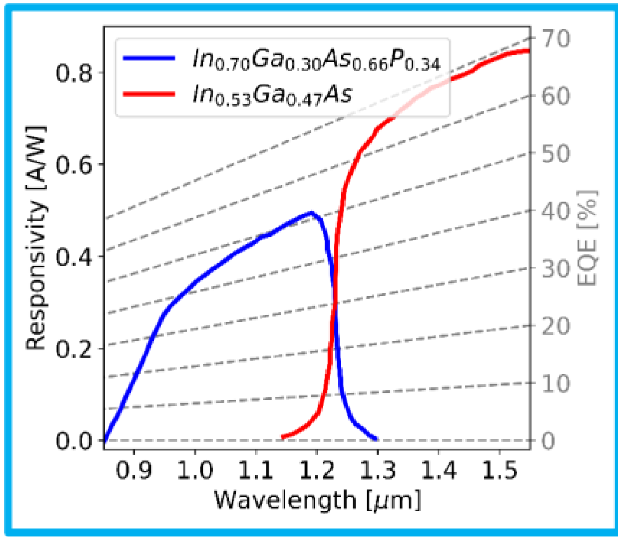
Dual band Mid infrared imaging



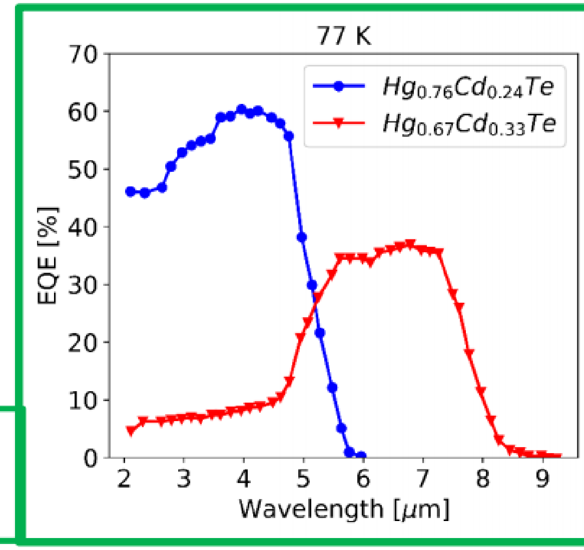




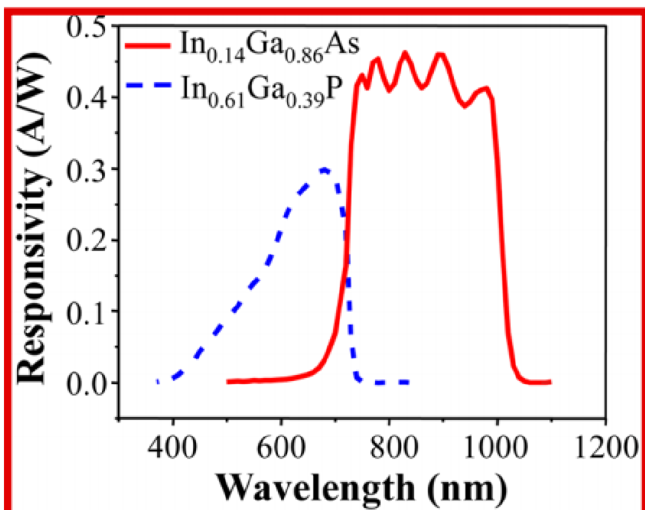
Prof. Giovanni Isella



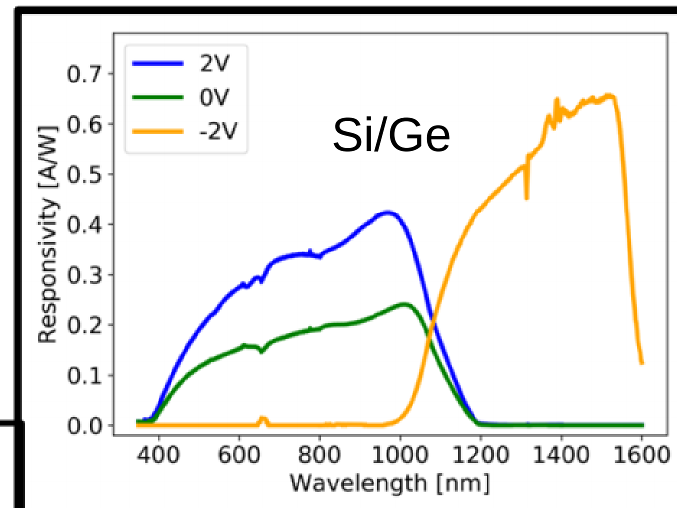
J. C. Campbell et al.
IEEE J. Quantum
Electron. 16, (1980).



E. R. Blazejewski et al.
J. Vac. Sci. Technol. B
10, (1992).

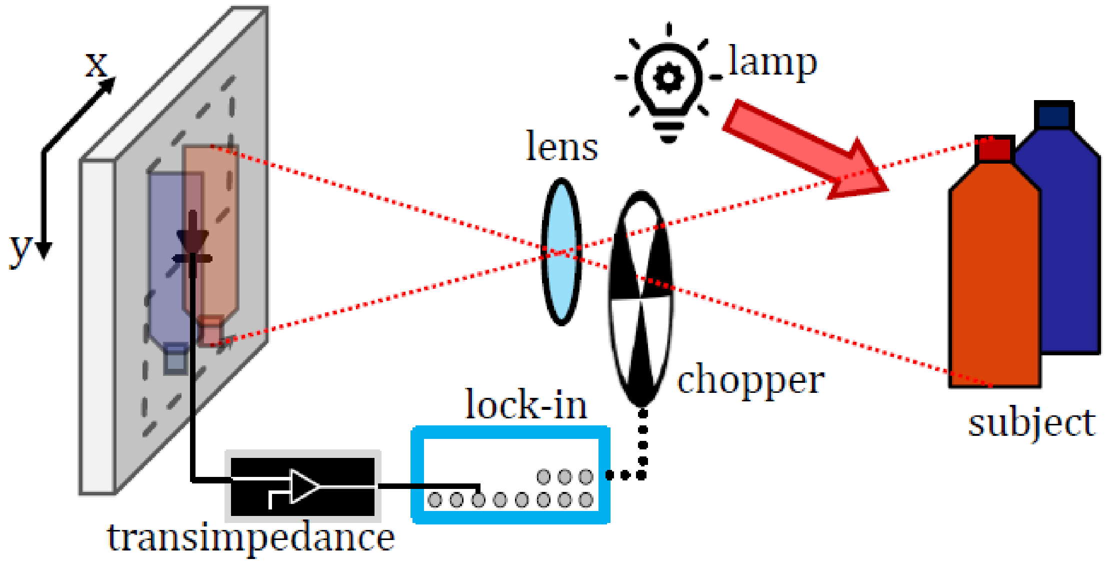


K. Swaminathan et al.
J. Appl. Phys. 110,
(2011).



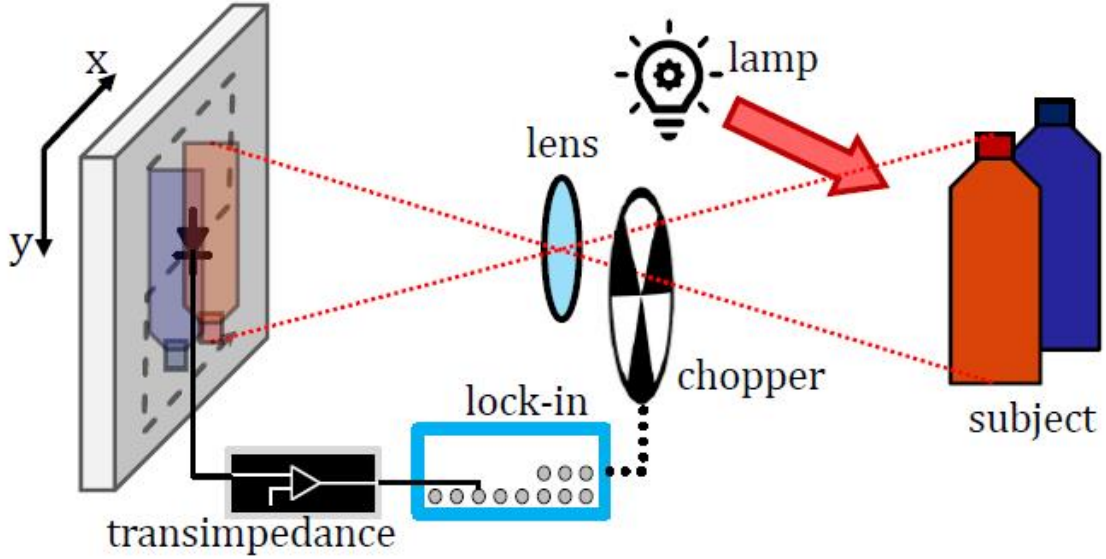
E. Talamas Simola et al.
Opt. Express 27, (2019).

„BORING“ infrared imaging



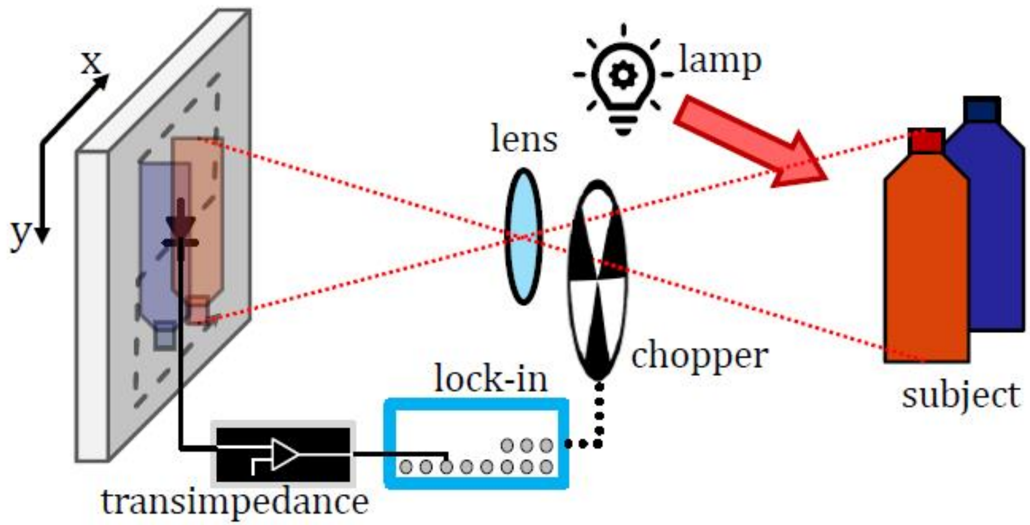
ink

„BORING“ infrared imaging



ink

Imaging


x
y
lamp
lens
chopper
lock-in
transimpedance
subject


IPA
TOLUENE
KAUTEX


-0.3V
+0.3V
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5

ACS Photonics

pubs.acs.org/journal/apchd5

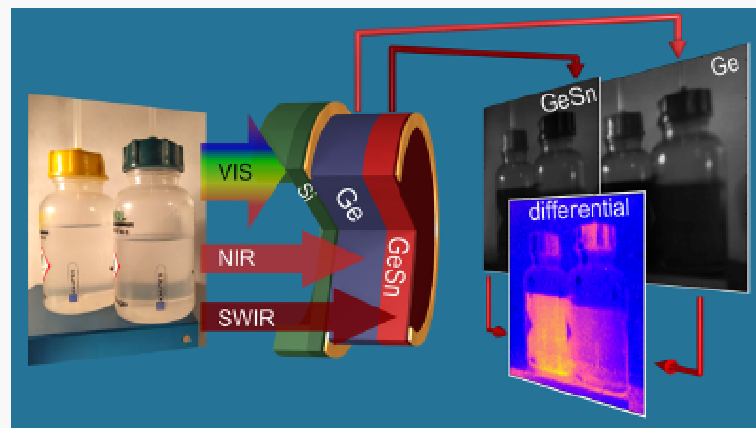
Article

CMOS-Compatible Bias-Tunable Dual-Band Detector Based on GeSn/Ge/Si Coupled Photodiodes

Enrico Talamas Simola,* Vivien Kiyek, Andrea Ballabio, Viktoria Schlykow, Jacopo Frigerio, Carlo Zucchetti, Andrea De Iacovo, Lorenzo Colace, Yuji Yamamoto, Giovanni Capellini, Detlev Grützmacher, Dan Buca,* and Giovanni Isella

Cite This: https://doi.org/10.1021/acsphotonics.1c00617

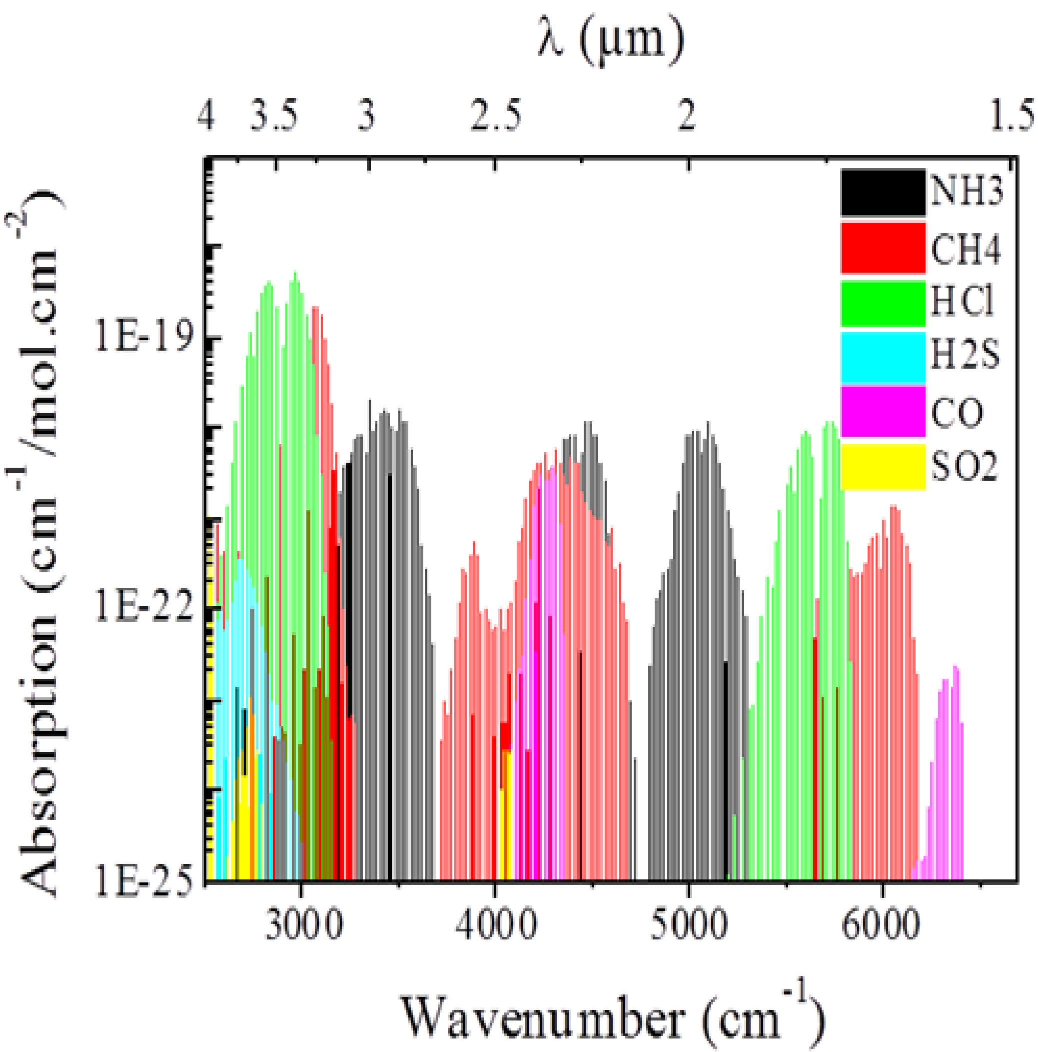
ABSTRACT: Infrared (IR) multispectral detection is attracting increasing interest with the rising demand for high spectral sensitivity, room temperature operation, CMOS-compatible devices. Here, we present a two-terminal dual-band detector, which provides a bias-switchable spectral response in two distinct IR bands. The device is obtained from a vertical GeSn/Ge/Si stack, forming a double junction *n-i-p-i-n* structure, epitaxially grown on a Si wafer. The photoresponse can be switched by inverting the bias polarity between the near and the short-wave IR bands, with specific detectivities of 1.9×10^{10} and 4.0×10^{9} cm·(Hz)$^{1/2}$/W, respectively. The possibility of detecting two spectral bands with the same pixel opens up interesting applications in the field of IR imaging and material recognition, as shown in a solvent detection test. The continuous voltage tuning, combined with the nonlinear photoresponse of the detector, enables a novel approach to spectral analysis, demonstrated by identifying the wavelength of a monochromatic beam.

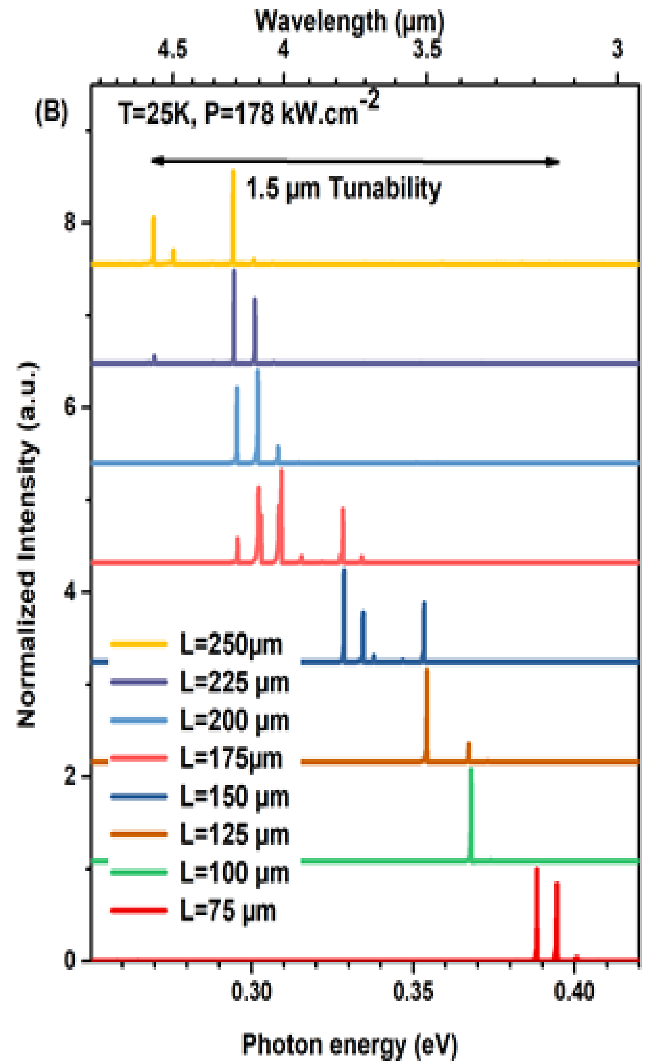


KEYWORDS: *GeSn, Geo-on-Si, dual-band photodetector, infrared imaging*

Gas sensing

Gases absorption lines in GeSn emission range

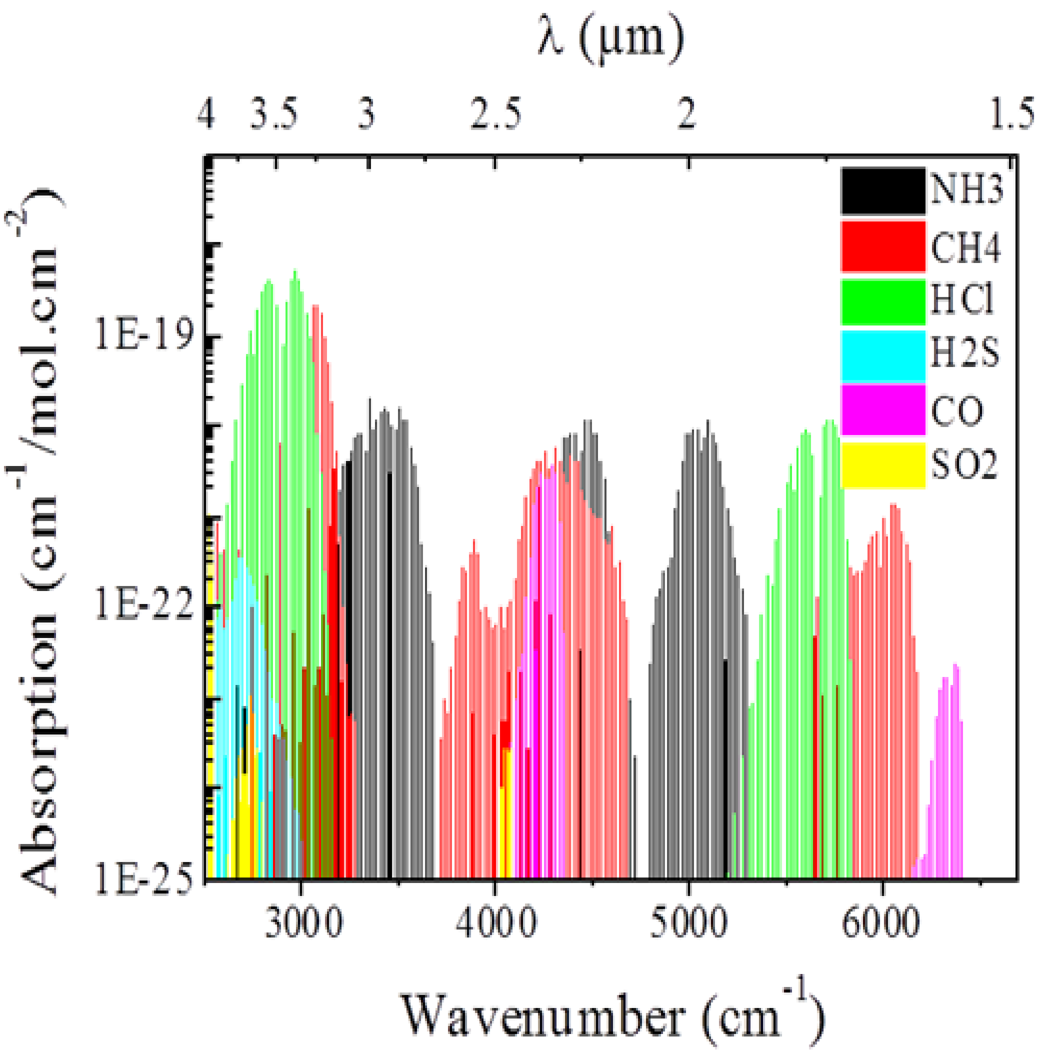


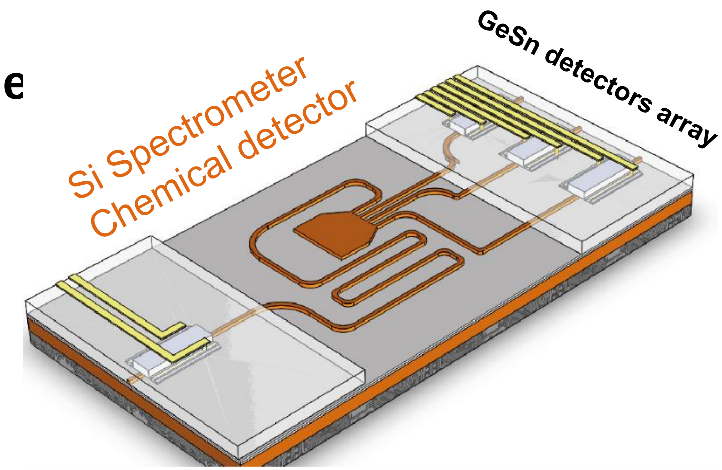


CEA LETI

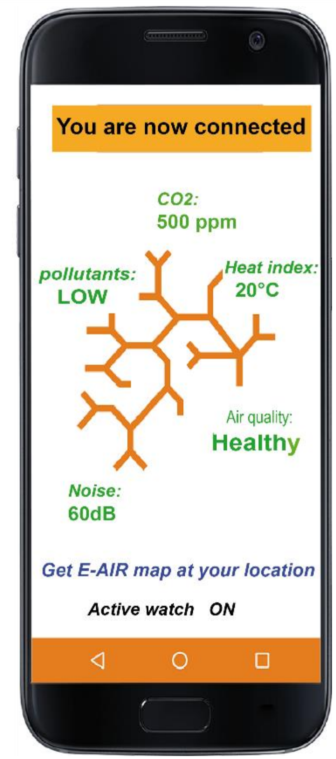
Gas sensing

Gases absorption lines in GeSn emission range



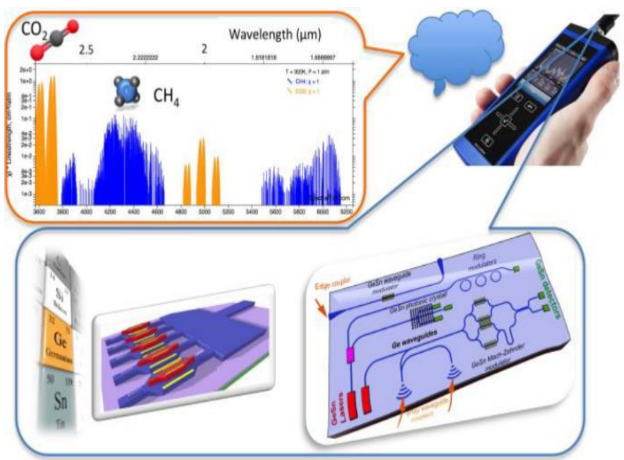


Smart „phone“



Optical detection in human breath

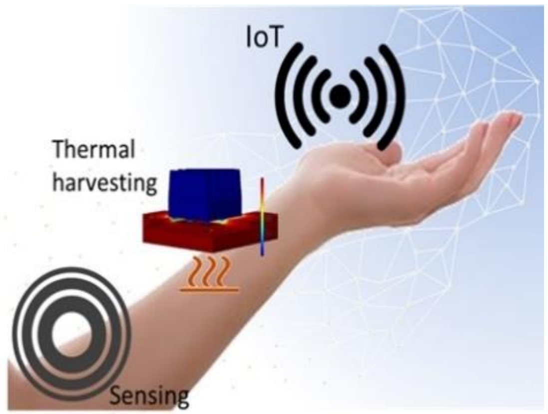
Gas detected in Mid-IR	Disease
Acetone (C_3H_6O)	Diabetis
Carbon Monoxide (CO)	Liver diseases, asthma, cholesterol
Pentane (C_5H_{12})	Schizofrenia, infarct miocardic
Ammonia (NH_3)	kidney diseases
Nitric oxide (NO)	Lung Inflammation, Bronchitis
Benzene (C_6H_6)	Lung cancer



Optical detector integrated in a Si chip connected to a smartphone

Si-based energy harverstors

Target: Wearable thermoelectric harvesters of human body heat for IoT /AI

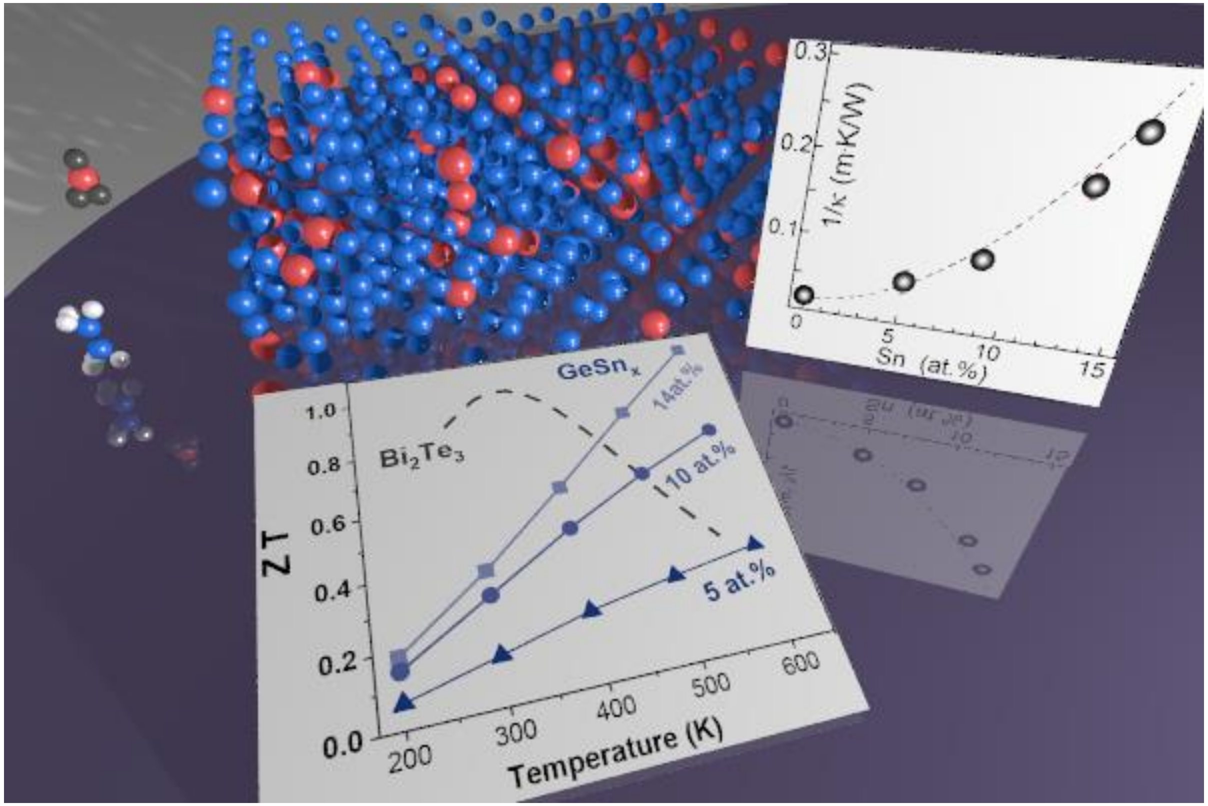


TEG for powering sensors

Device	Typical Power
TEG for Seiko wristwatch: drive a watch (1 μW) and battery recharge	22.5 μW
pulse oximeter	62÷100 μW
powered wireless electrocardiography (ECG) system in a shirt	0.8÷1.0 mW 0.4 down to 0.1 mW
ECG/ EEG energy harvesting body sensor fabricated using 130 nm CMOS technology	60÷200 μW
cardiac pacemakers	70÷100 μW
Cardiac defibrillator	30–100 μW
Neurological stimulator	30 μW to several mW
Drug pump	100 μW–2 mW
Glucose monitor	>10 μW

$$ZT = \frac{S^2\sigma}{\kappa}T, \quad \kappa = \kappa_e + \kappa_L$$

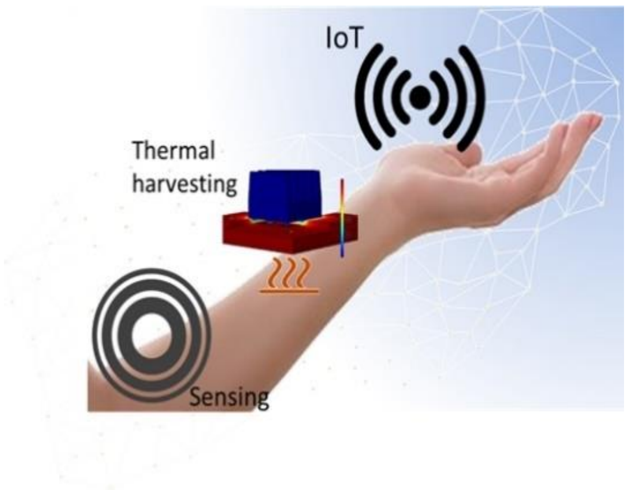
Si-based energy harverstors for wearables



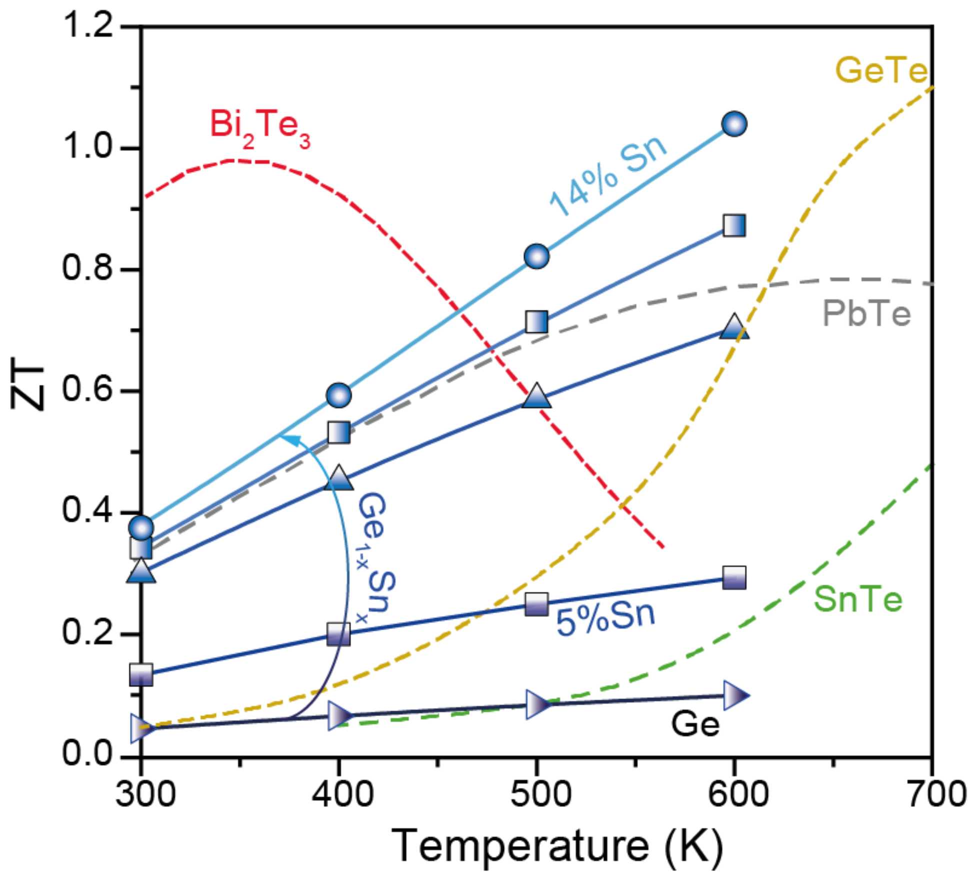
D.Spirito et al., ACS Appliend Energy Materials, in press

$$ZT = \frac{S^2\sigma}{\kappa}T, \ \kappa = \kappa_e + \kappa_L$$

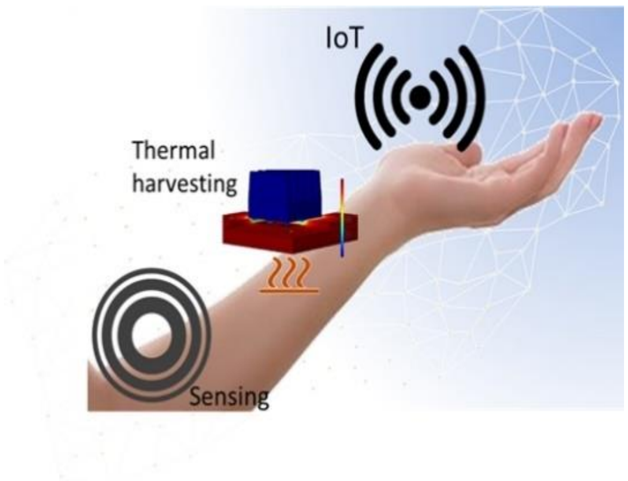
Si-based energy harverstors for wearables



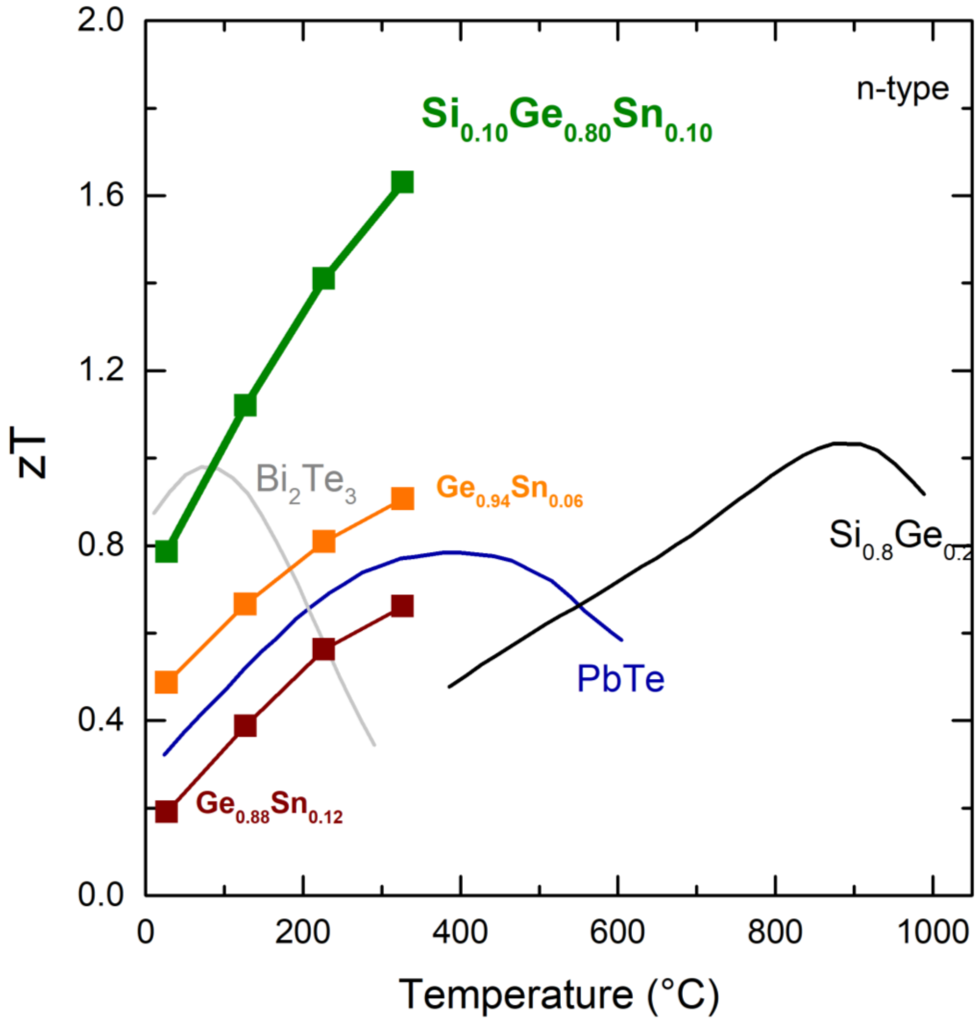
TEG for powering sensors



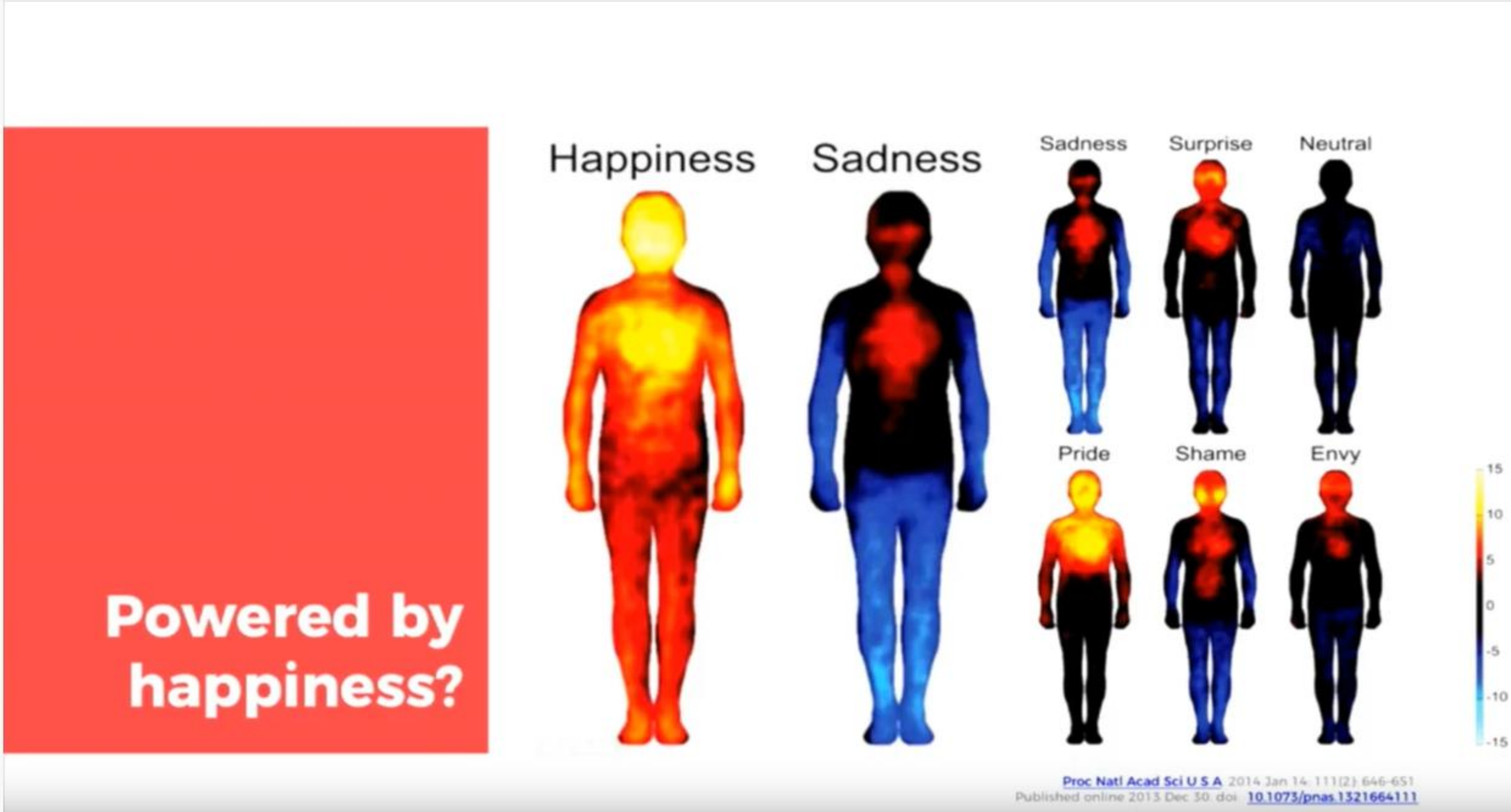
Si-based energy harverstors for wearables



TEG for powering sensors



SiGeSn TE performances (ZT=1; k=27000 μWcm^{-1} K^{-1}), maximum efficiency with Tc~Th; at 300K



Professor Jun Chen | *Wearable tech: turning body heat in to electricity*