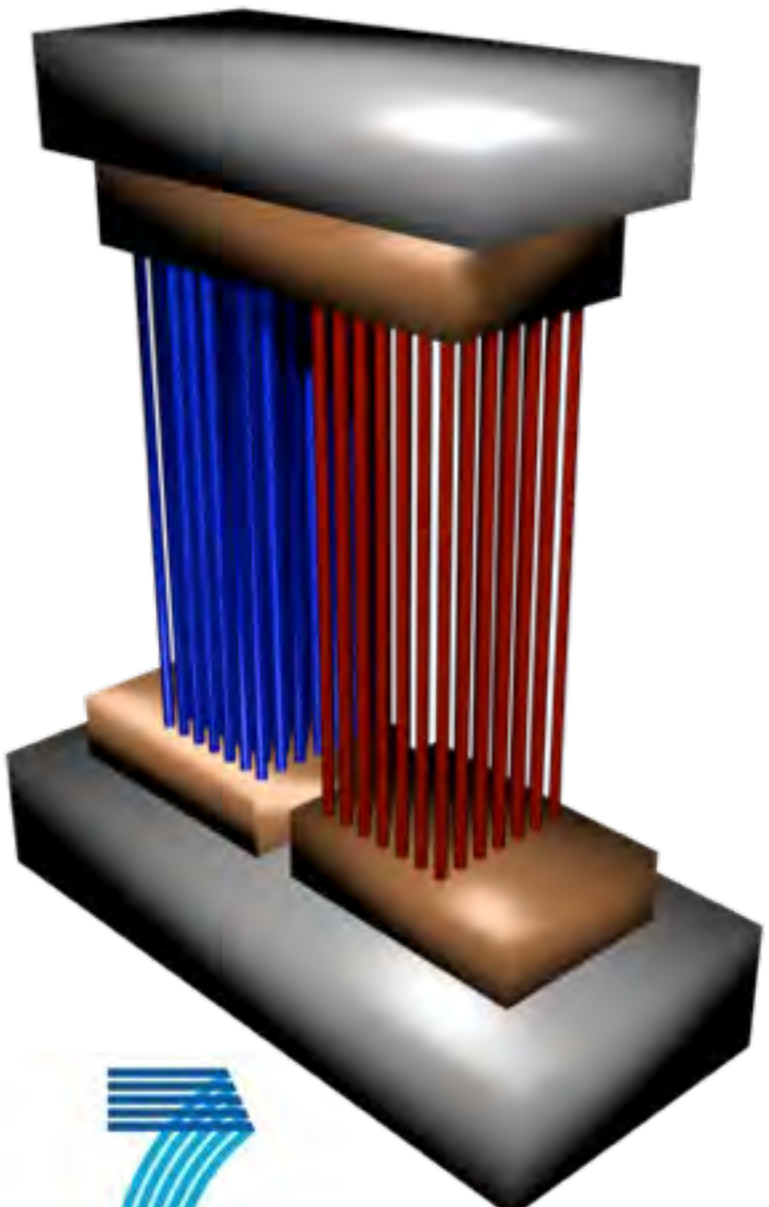
Generate Renewable Energy Efficiently using Nanofabricated Silicon (GREEN Silicon)



L. Ferre Llin, F. Mirando, A. Samarelli, A. Odia, J.M.R. Weaver & P. Dobson, D.J. Paul

University of Glasgow, U.K.

S. Cecchi, G. Isella, D. Chrastina

L-NESS, Politecnico de Milano, Como, Italy

T. Etzelstorfer & J. Stangl

University of Linz, Austria

E. Müller Gubler

ETH Zürich, Switzerland

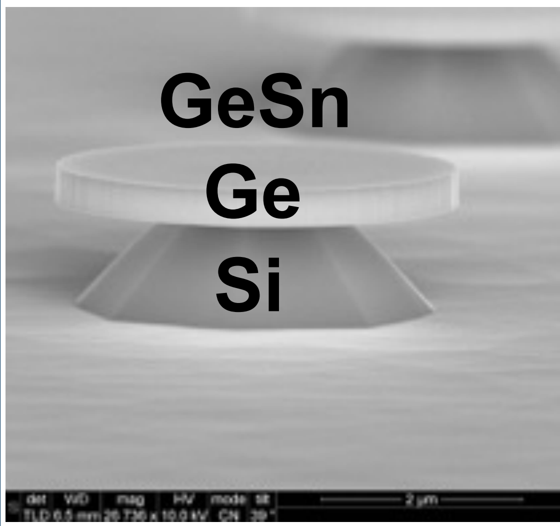
SEVENTH FRAMEWORK PROGRAMME

http://www.greensilicon.eu/GREENSilicon/index.html

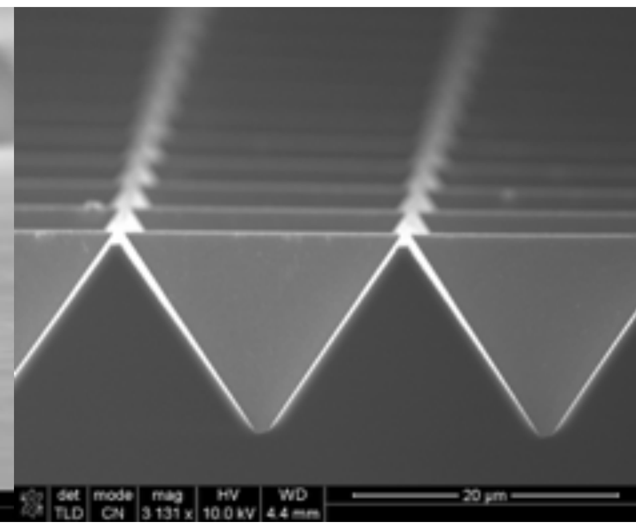
University of Glasgow

Semiconductor Device Group

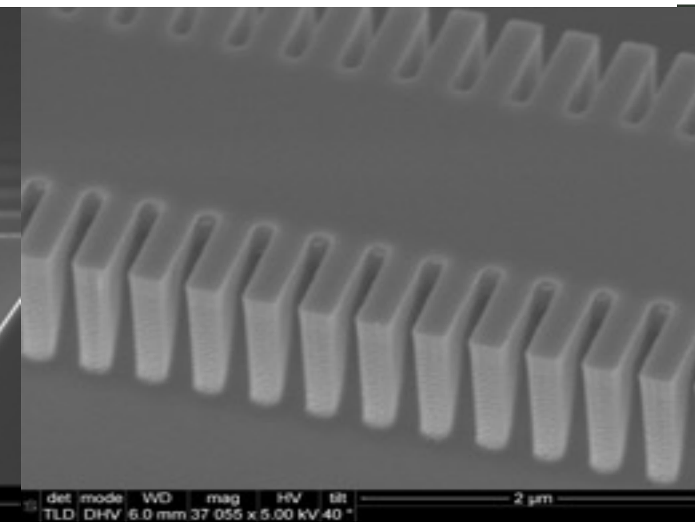
Si Photonics



Si thermal photovoltaics



Miniature cold atom systems



MEMS gravimeters

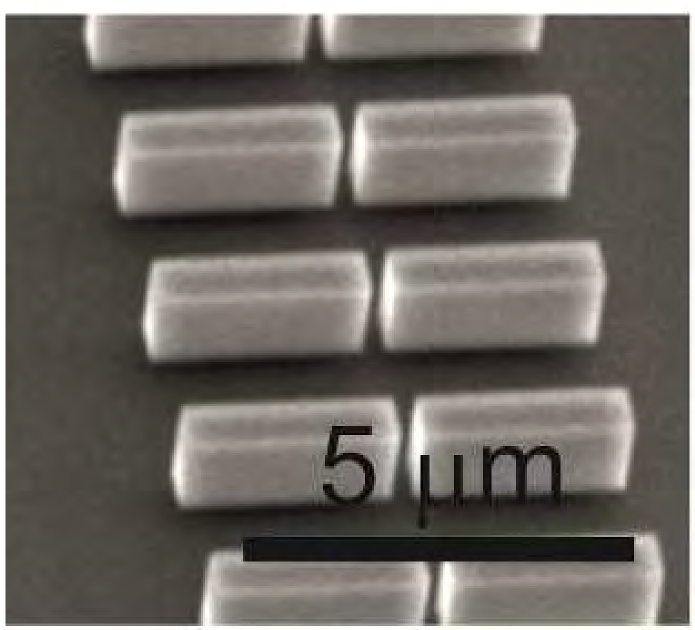
SEVENTH FRAMEWORK PROGRAMME

EPSRC Engineering and Physical Sciences Research Council

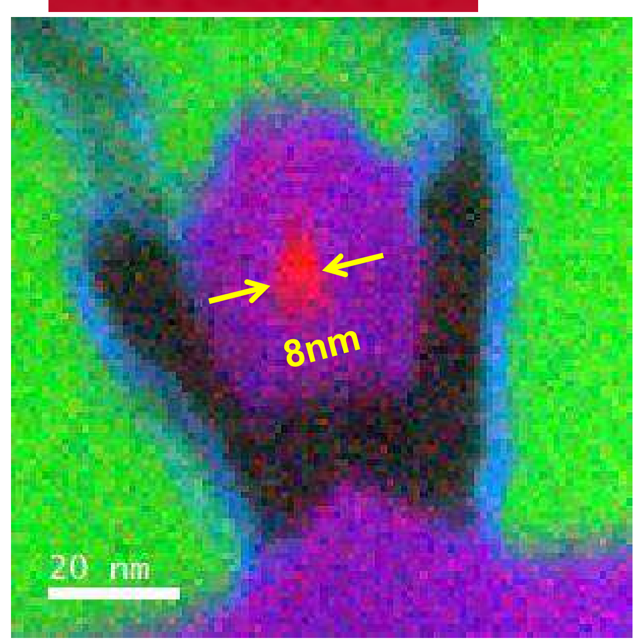
THE ROYAL SOCIETY

Science & Technology Facilities Council

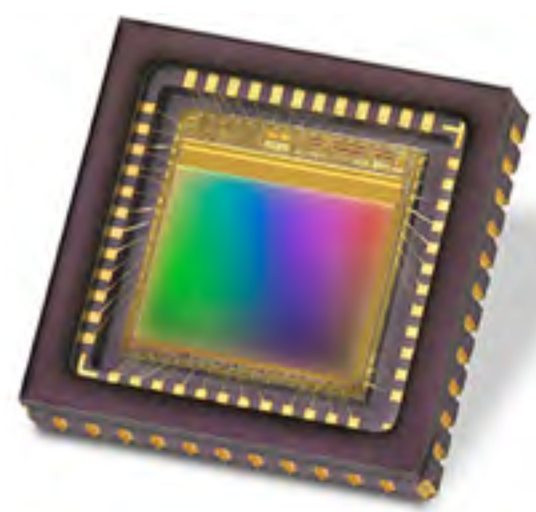
[dstl]



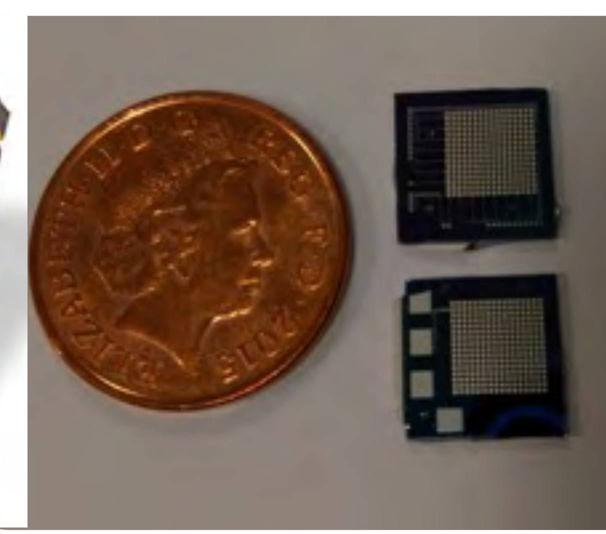
Ge MIR Plasmonics



Si SETs & Electrometers

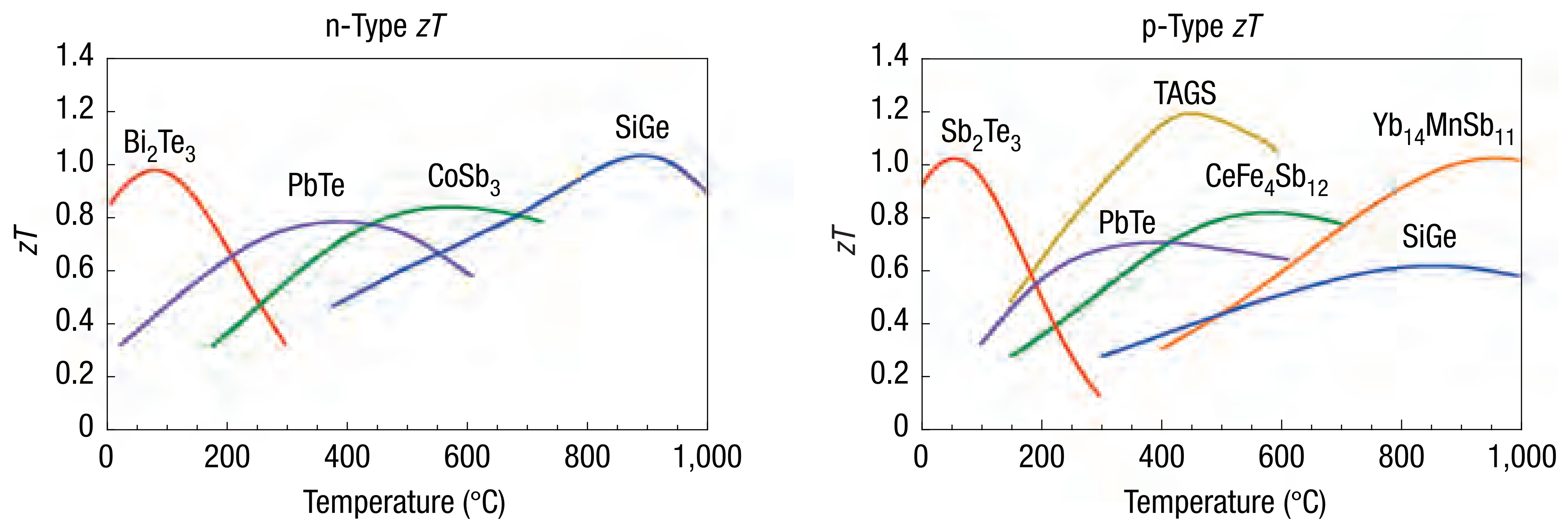


Ge SPADs & Si Quantum Photonics



SiGe Thermoelectrics

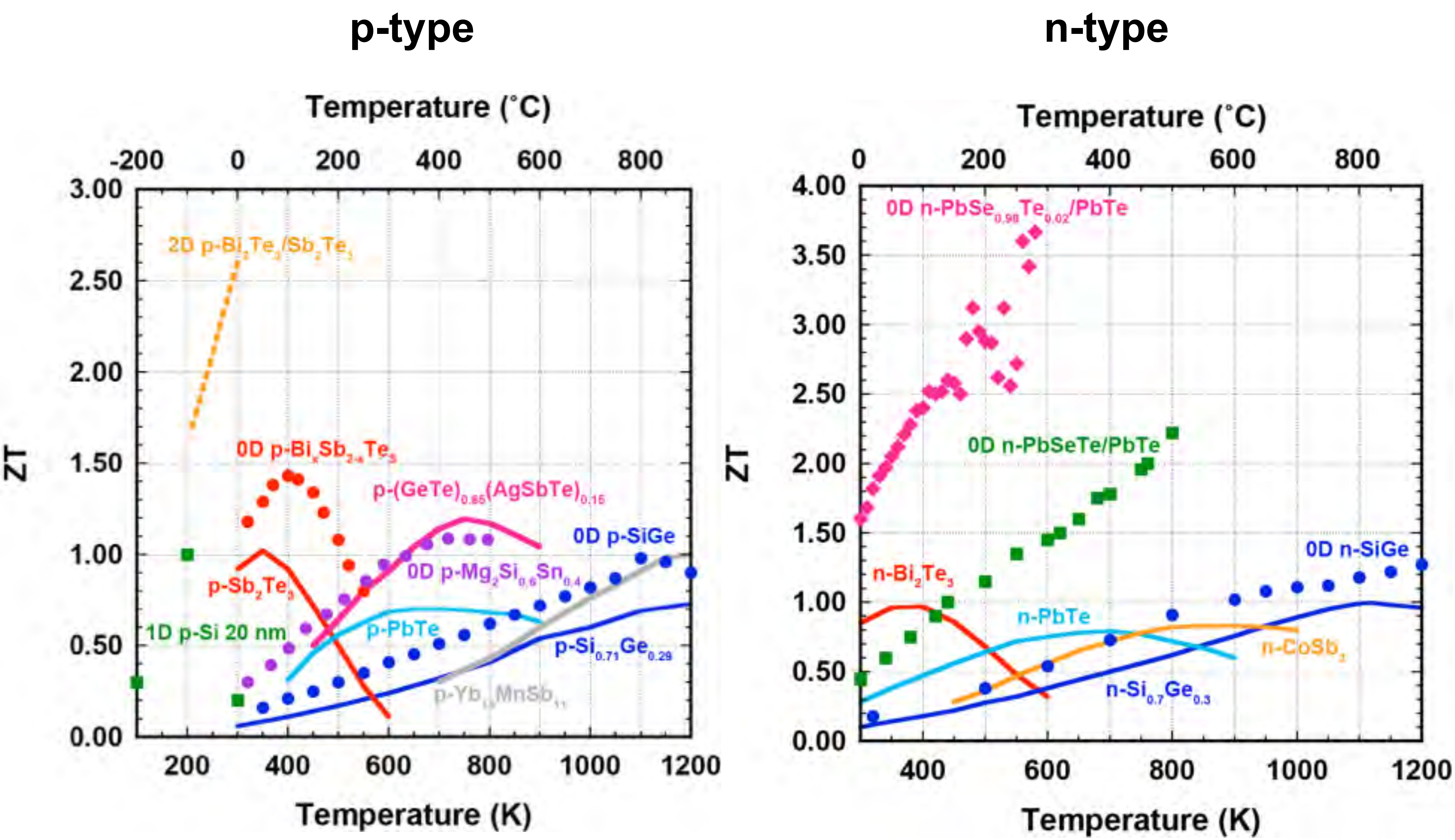
Bulk Thermoelectric Materials Performance



Nature Materials 7, 105 (2008)

- **Bulk n-Bi_2Te_3 and p-Sb_2Te_3 used in most commercial thermoelectrics & Peltier coolers**
- **But tellurium is 9th rarest element on earth !!!**
- **Bulk $Si_{1-x}Ge_x$ (x~0.2 to 0.3) used for high temperature satellite applications**

ZT versus Temperature

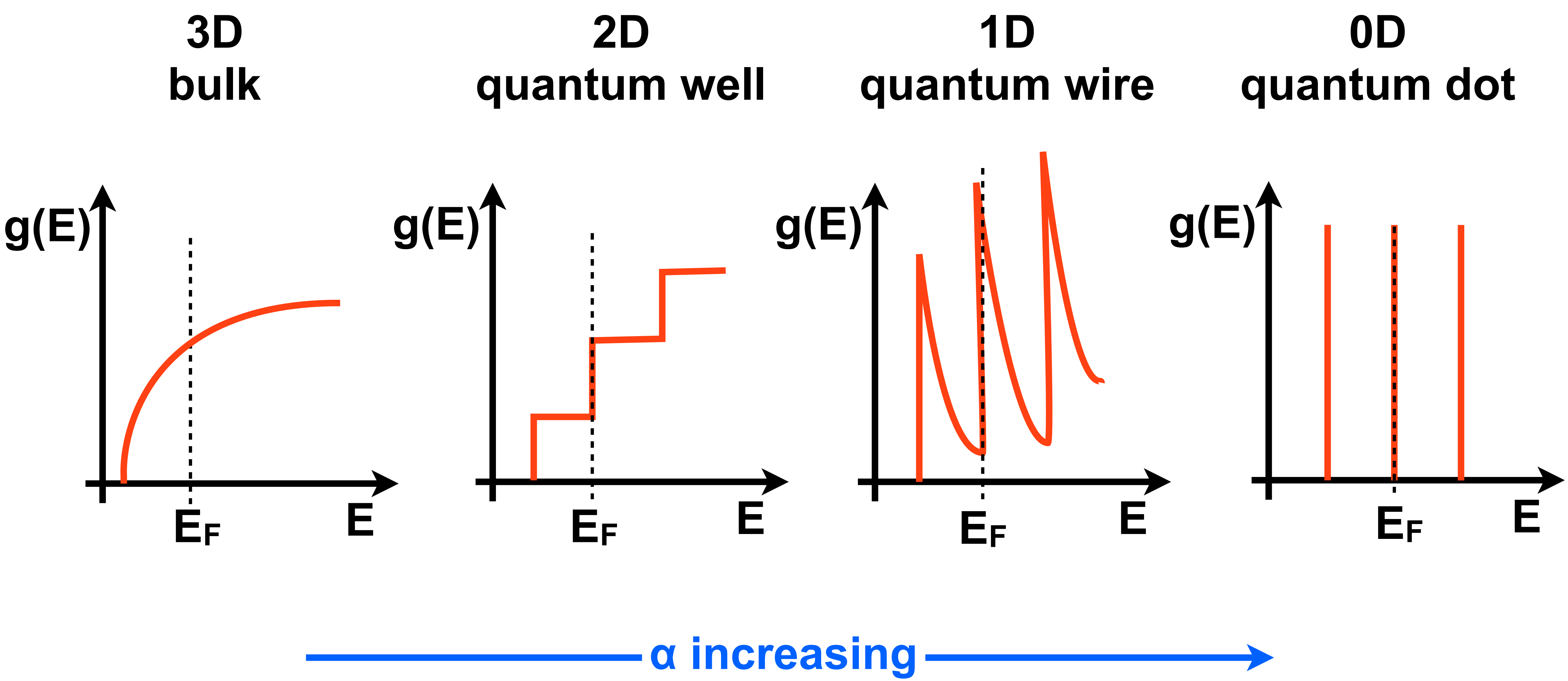


- **Nanostructures can improve Seebeck coefficient and/or decrease thermal conductivity**

Seebeck Enhancement at Low Dimensions

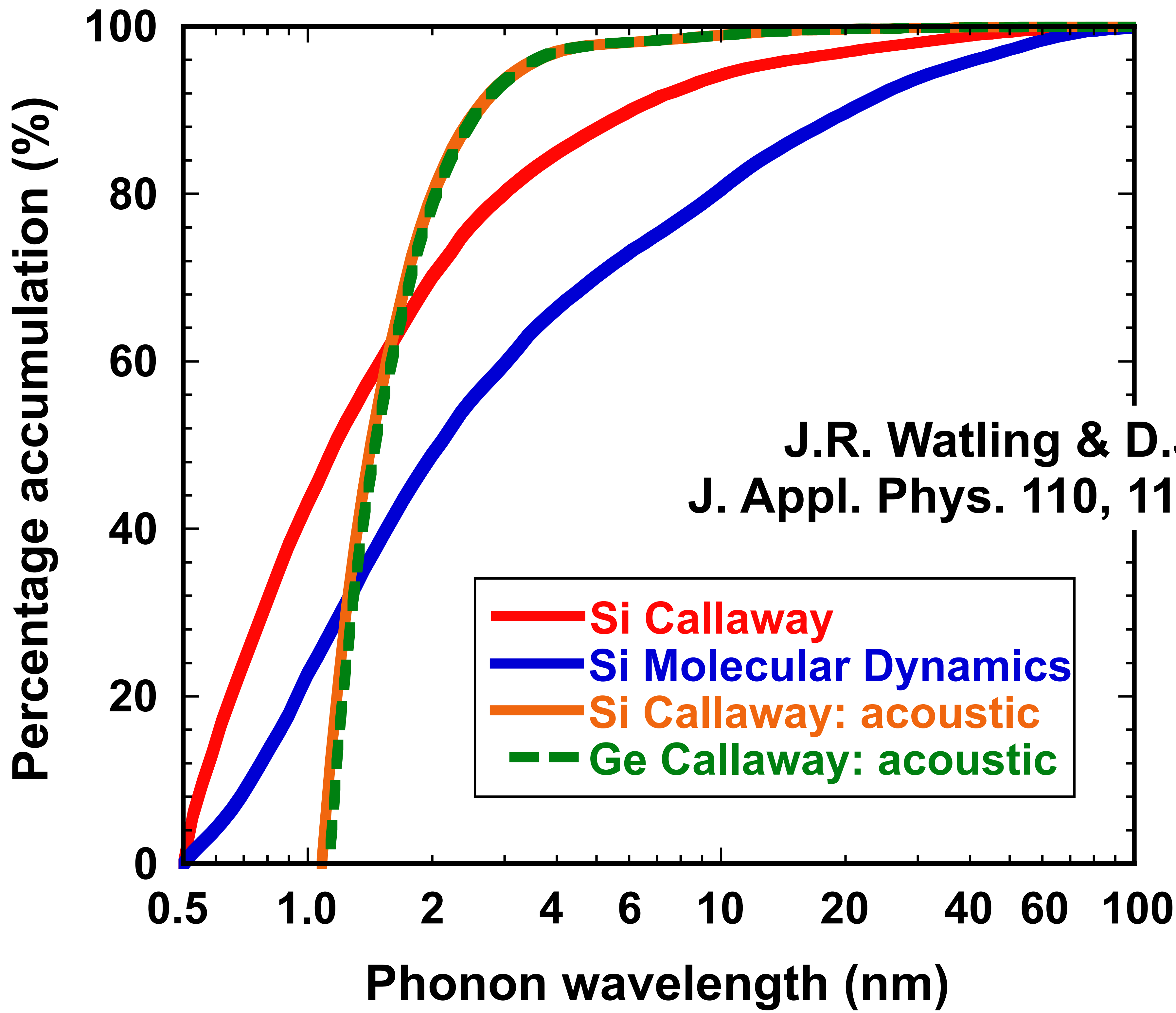
- **Increase α through enhanced DOS:**

$$\alpha = -\frac{\pi^2}{3q}k_B^2 T \left[\frac{d\ln(\mu(E)g(E))}{dE}\right]_{E=E_F}$$



M. Cutler & N.F. Mott, Phys. Rev. 181, 1336 (1969)

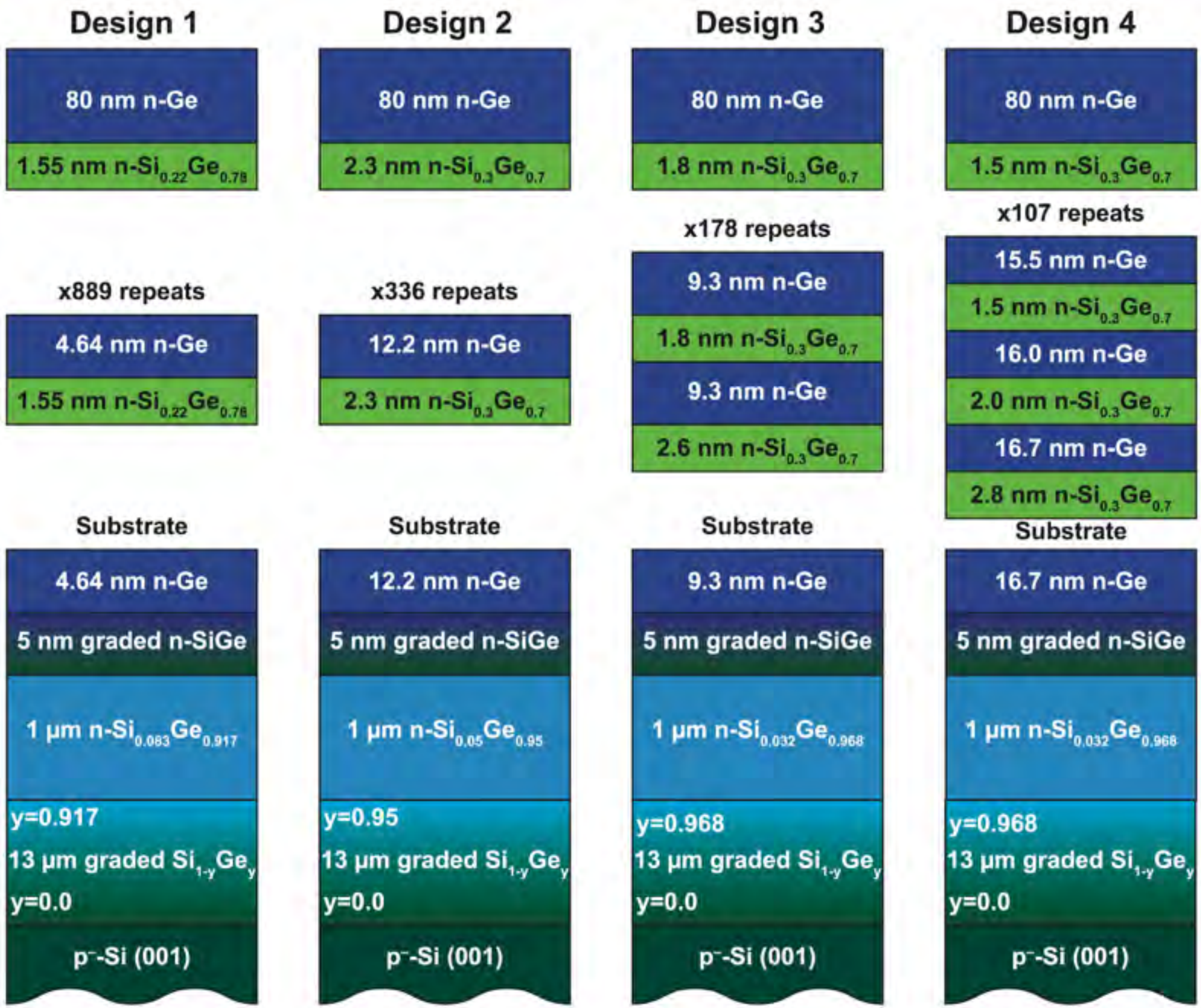
Acoustic Phonon Wavelengths



J.R. Watling & D.J. Paul,
J. Appl. Phys. 110, 114508 (2013)

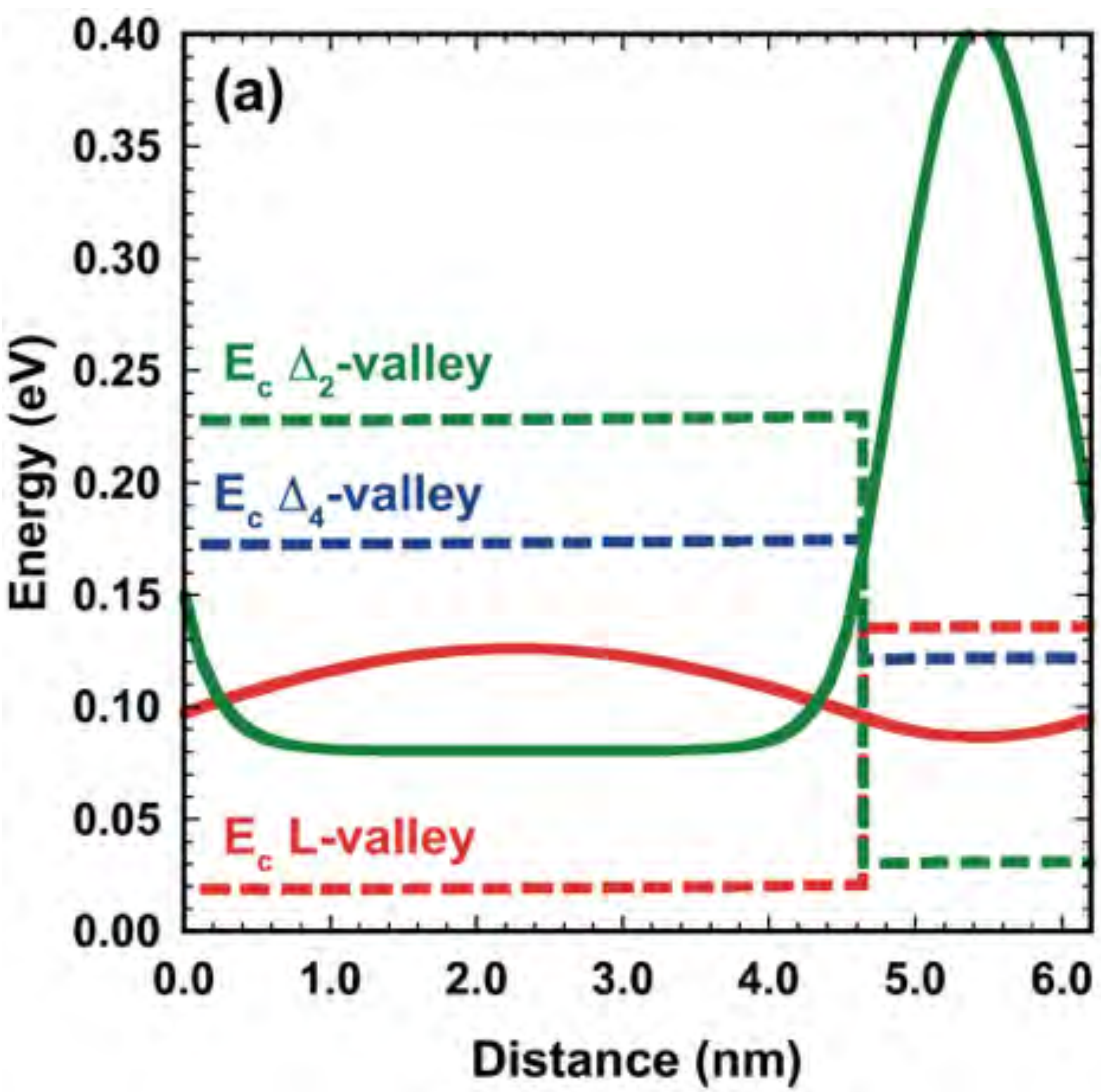
- Key wavelengths for scattering phonons 1.2 to 4 nm

Superlattice Designs: 4.5 µm Thick

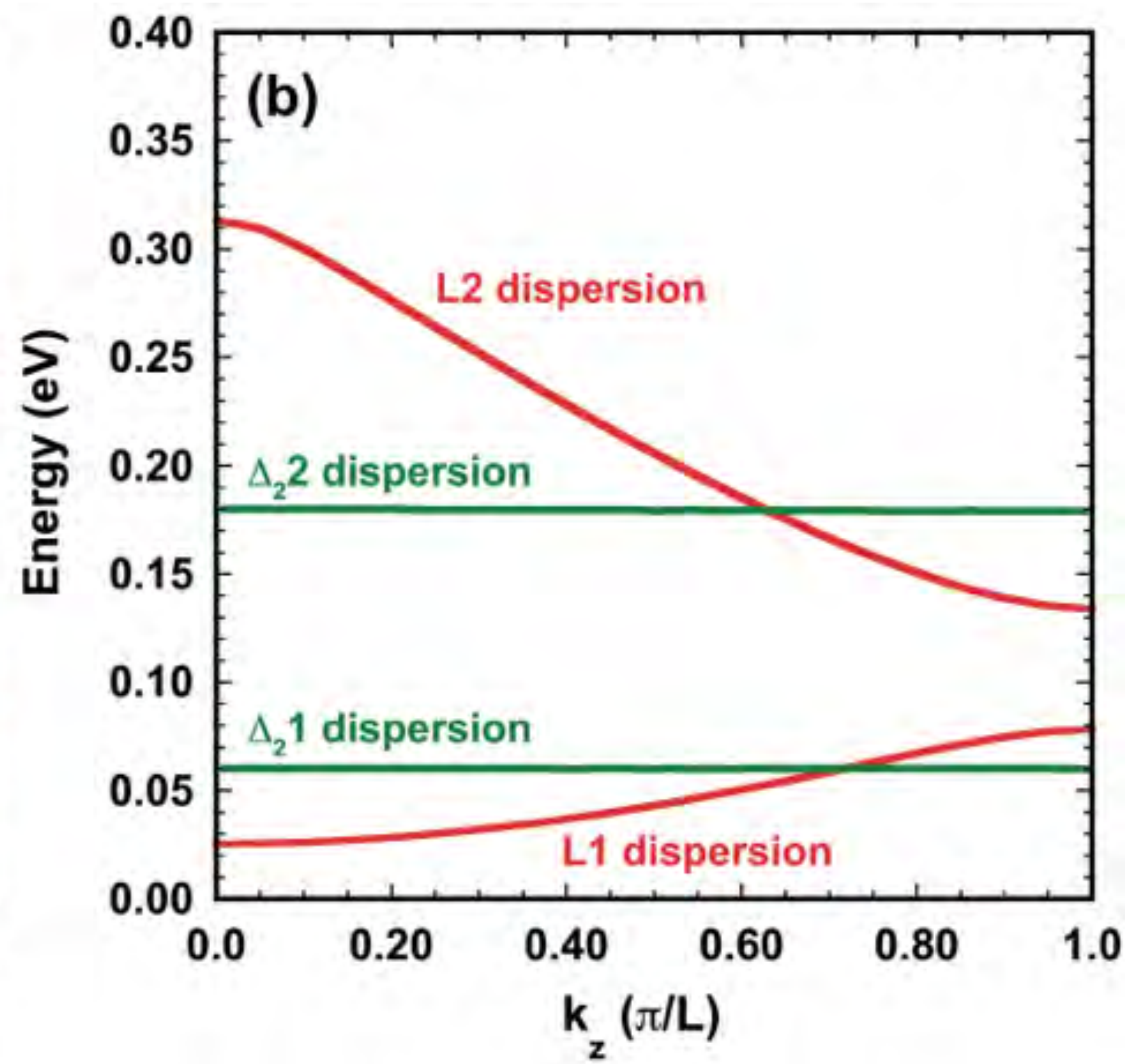


Narrow QW Superlattice Minibands

Conduction bands



Miniband dispersions



- **Only L-valley electrons form minibands**

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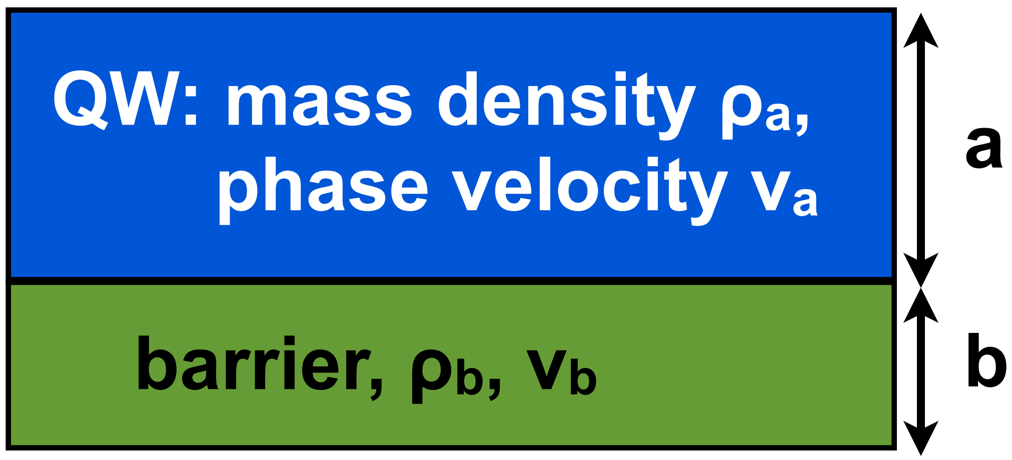
Rytov 1D Continuum Model for Layered Materials

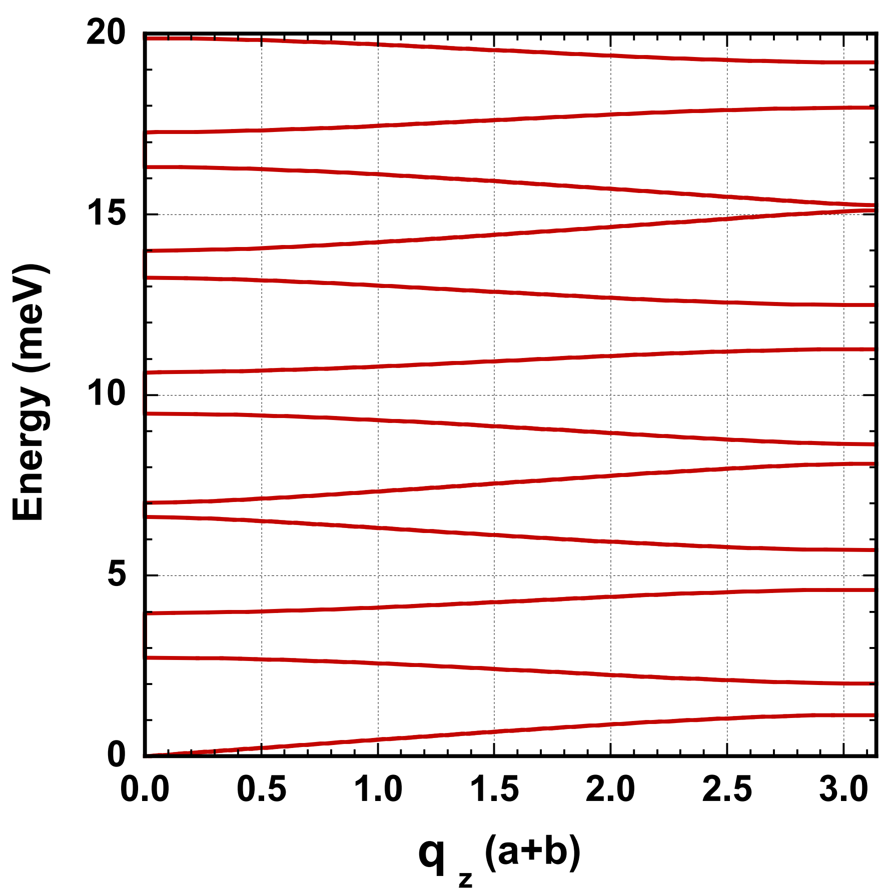
Superlattice N $\rightarrow \infty$



Acoustic mismatch: $$\eta = \frac{\rho_b v_b}{\rho_a v_a}$$

Superlattice zone boundaries: $$q_z = \frac{n\pi}{a+b}$$

$$\cos q_z(a+b) = \cos q_a a \cos q_b b - \left[\frac{1+\eta^2}{2\eta}\right] \sin q_a a \sin q_b b$$



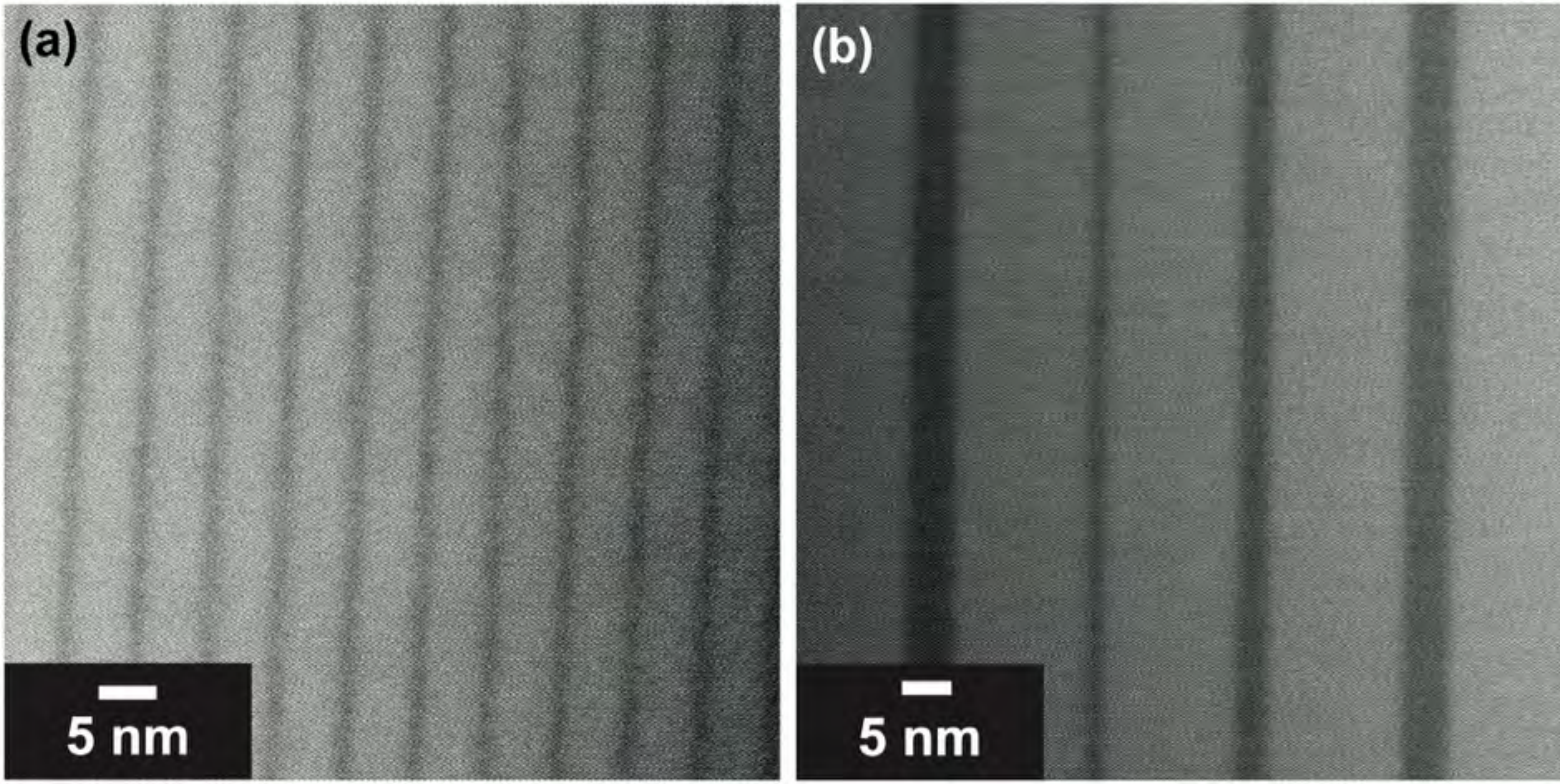
[001]

acoustic phonon bandgap

S.V. Rytov, Sov. Phys. Acoustics 2, 67 (1956)

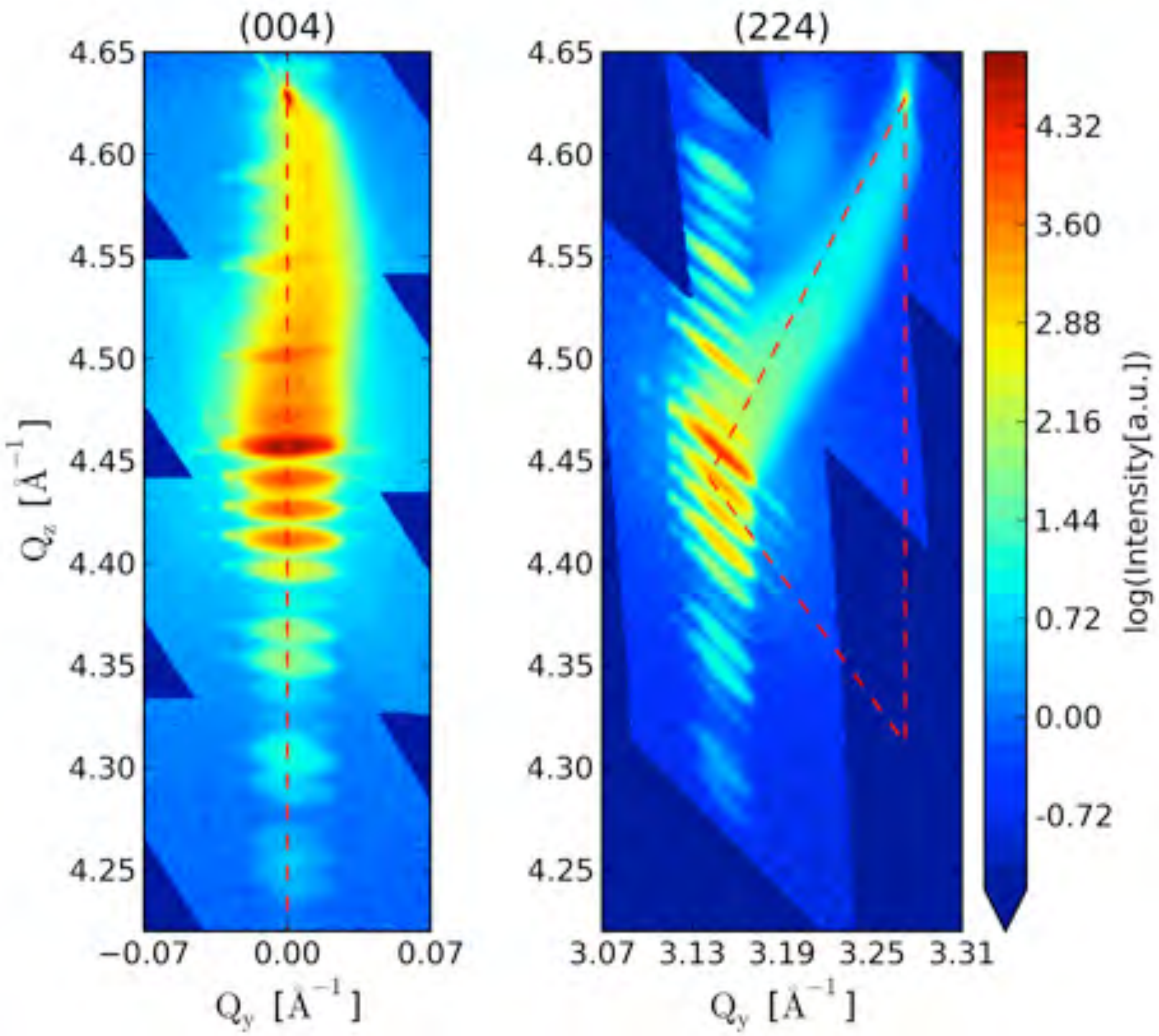
TEM of Single Barrier & 3 Barrier Material

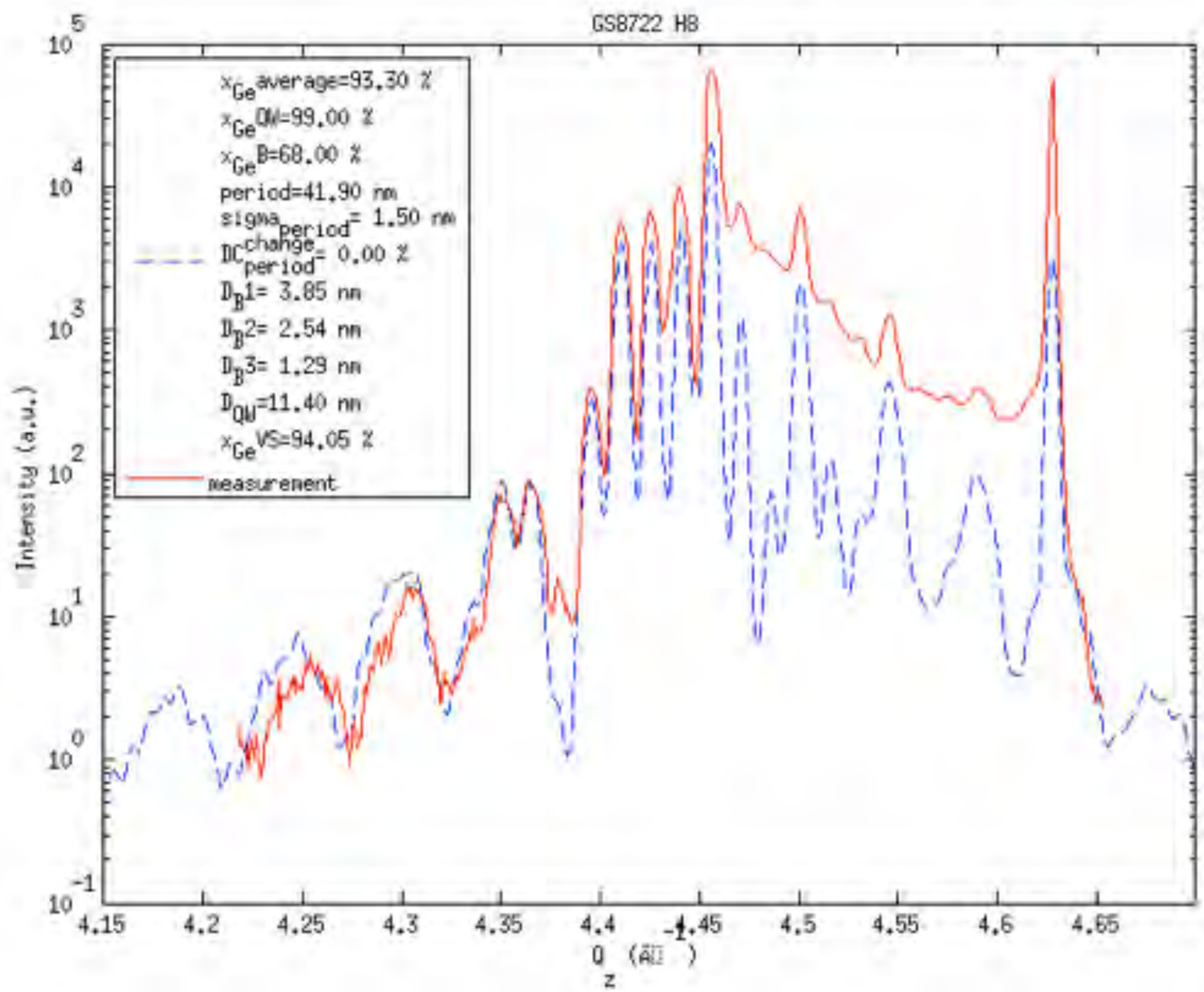
Single barrier | **Three barriers**



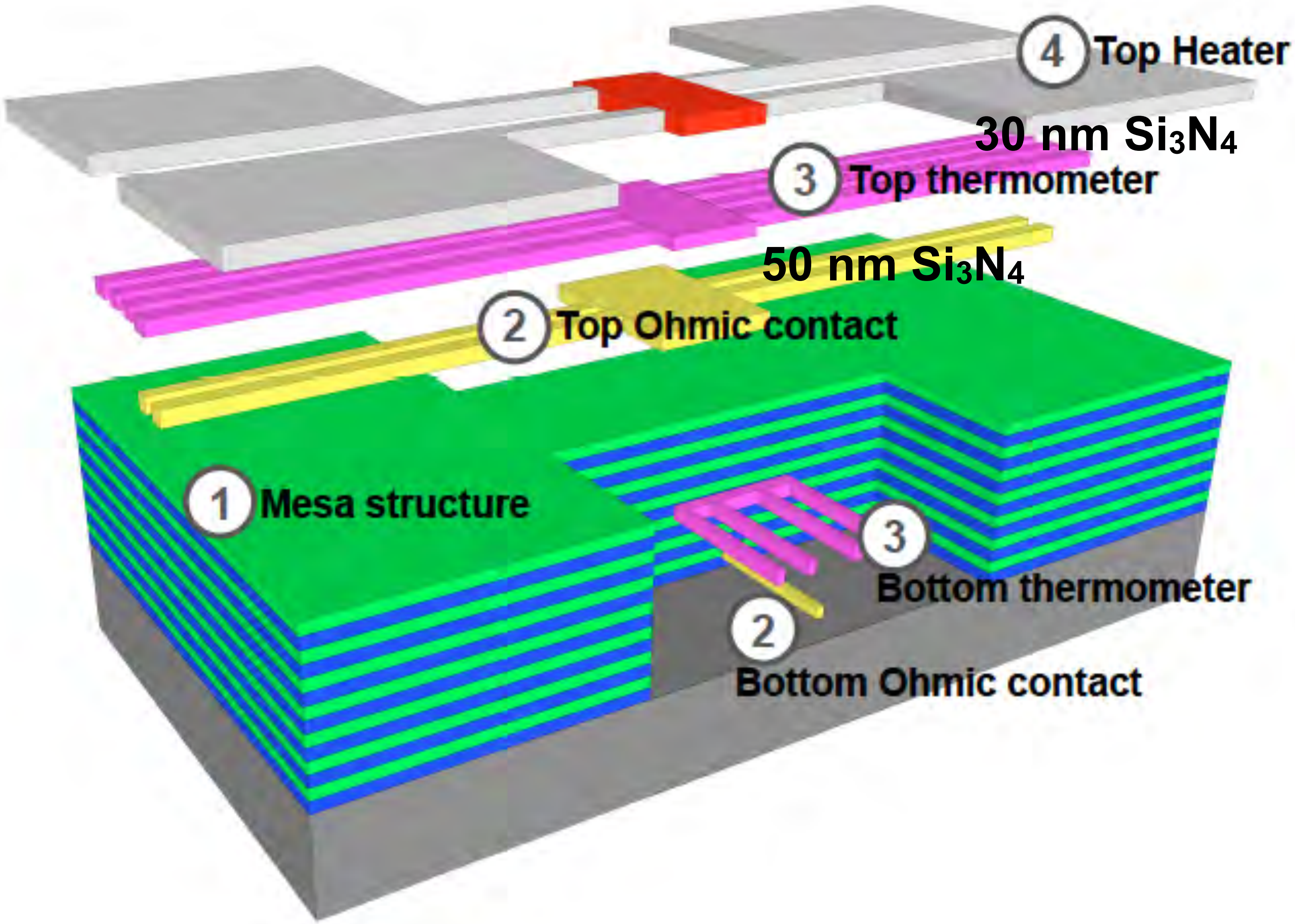
n-type vertical Design 6 (8722)

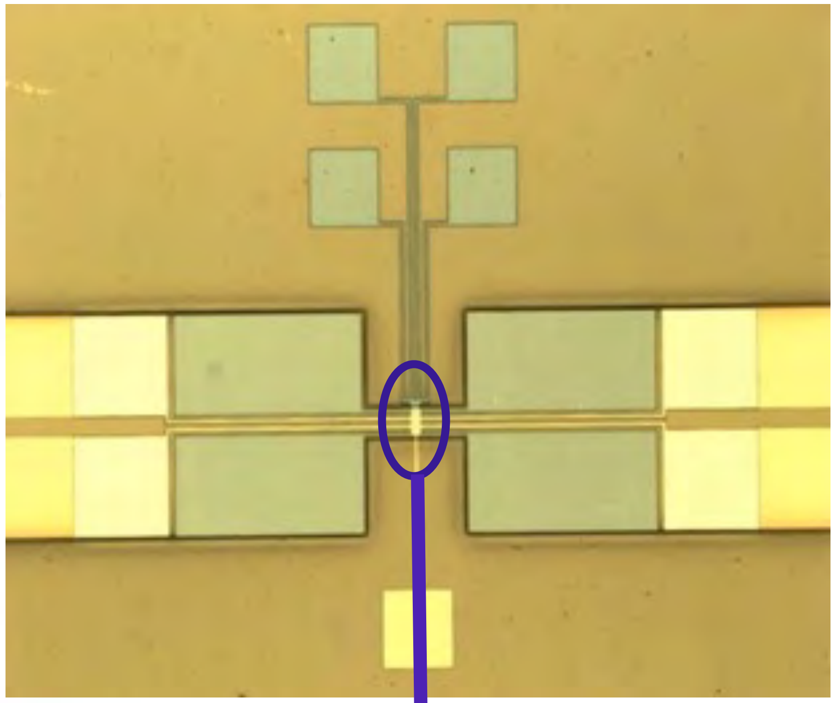
3 barriers with wide Ge QWs

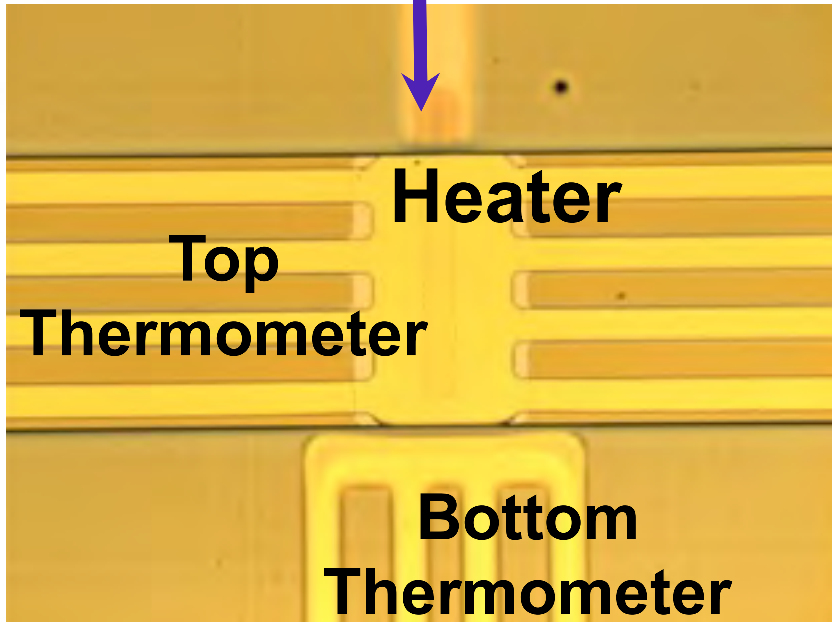




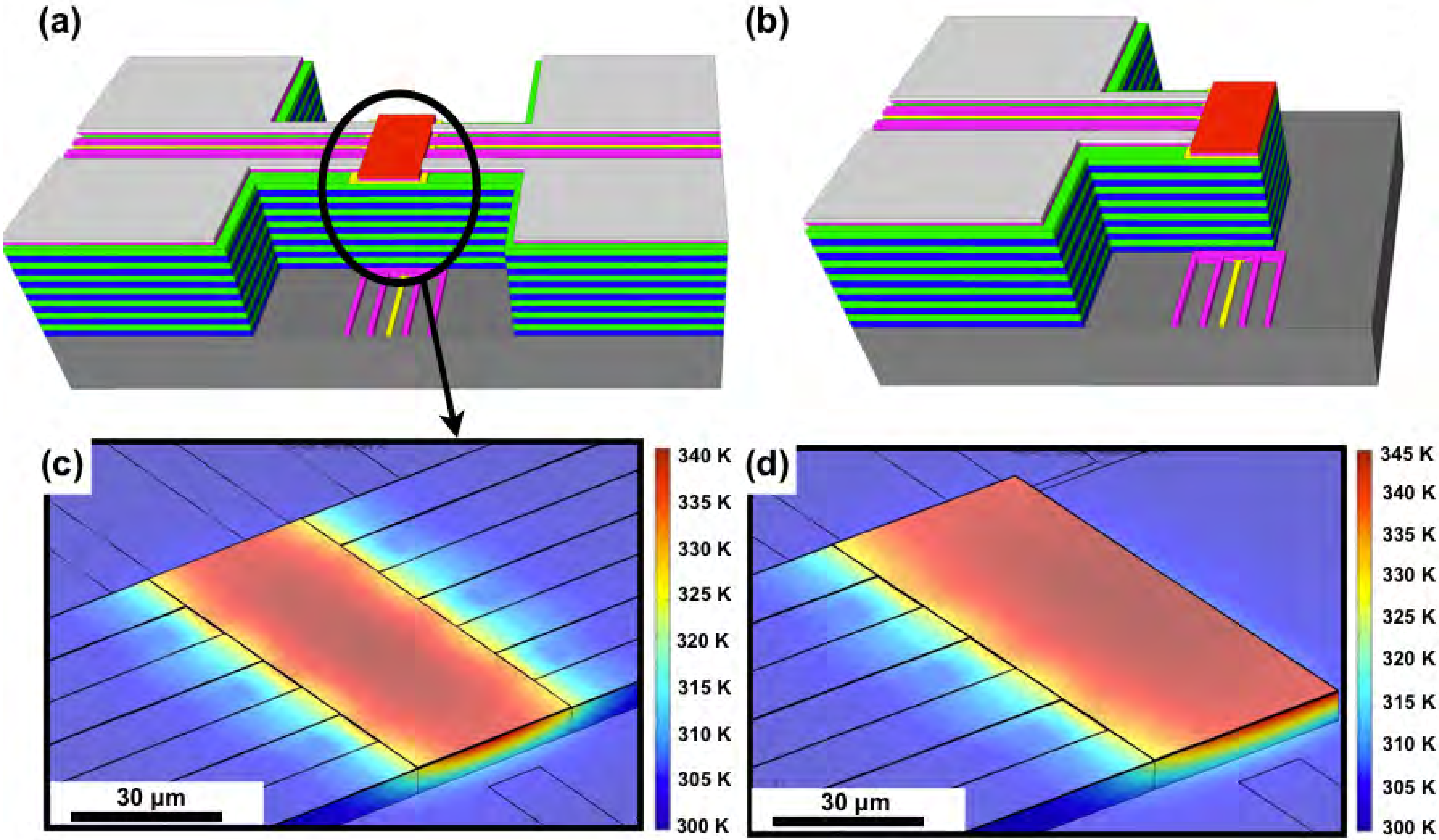
Vertical structure characterisation device



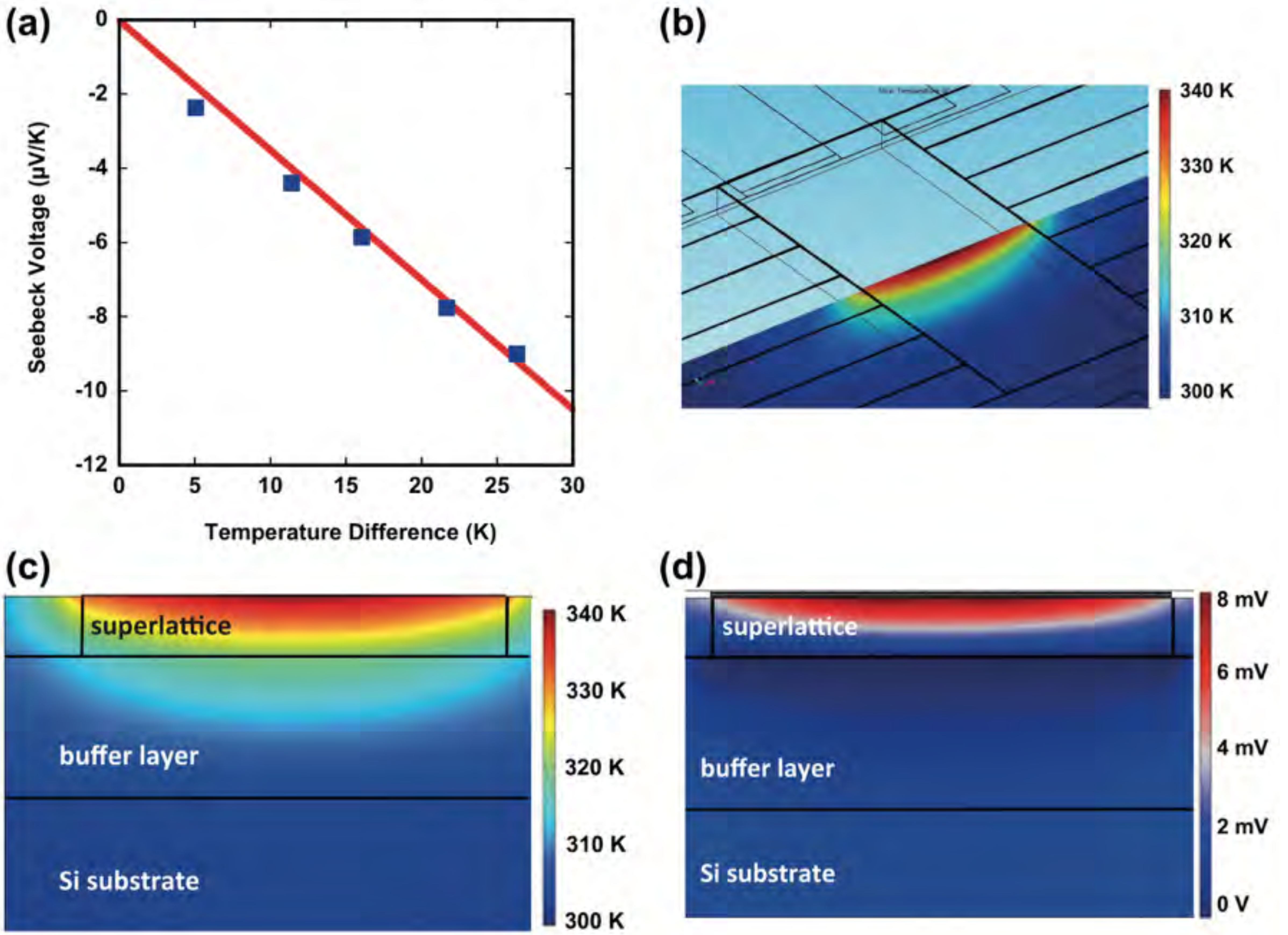




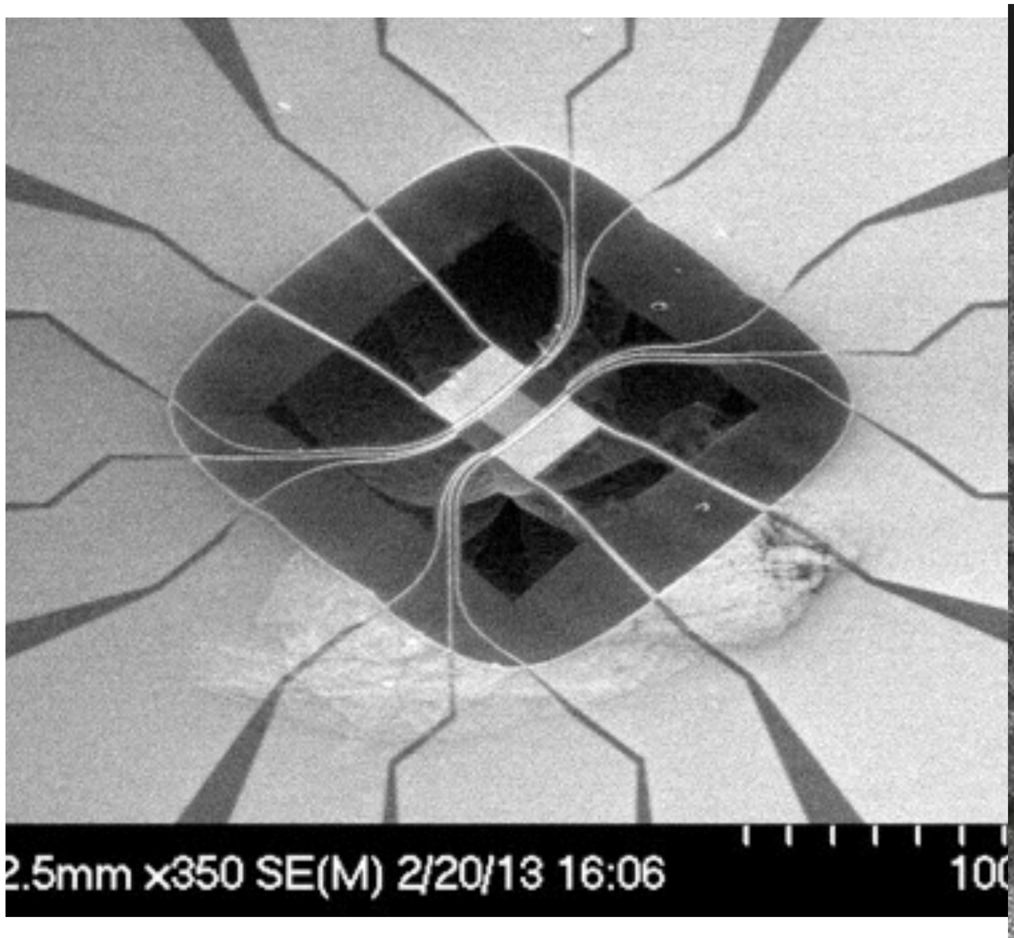
Comsol Thermal Parasitic Modelling

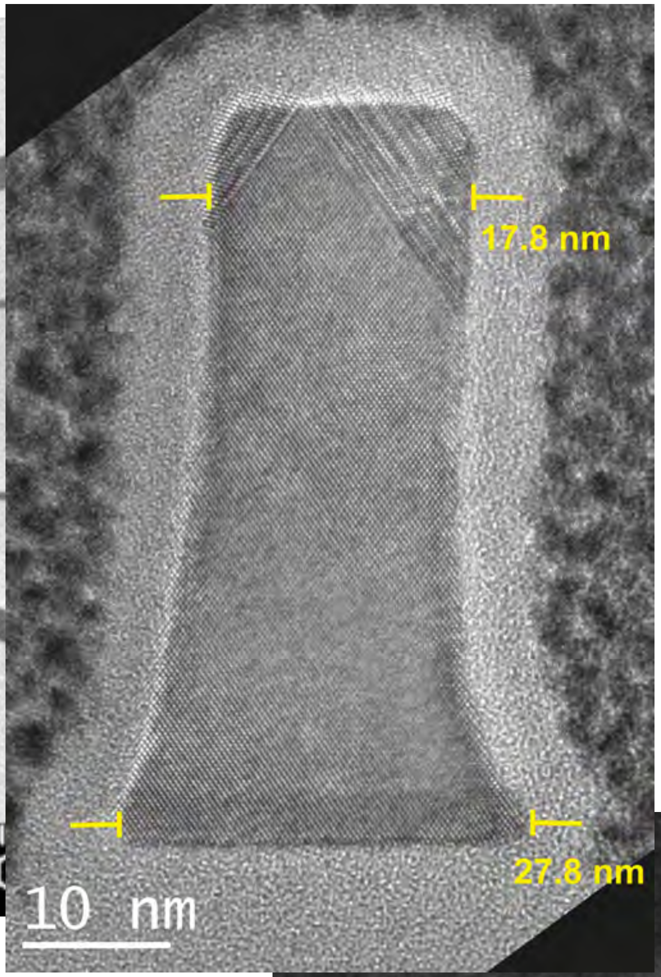


Cosmol Thermal Modelling



45 nm Wide n-Silicon Nanowires

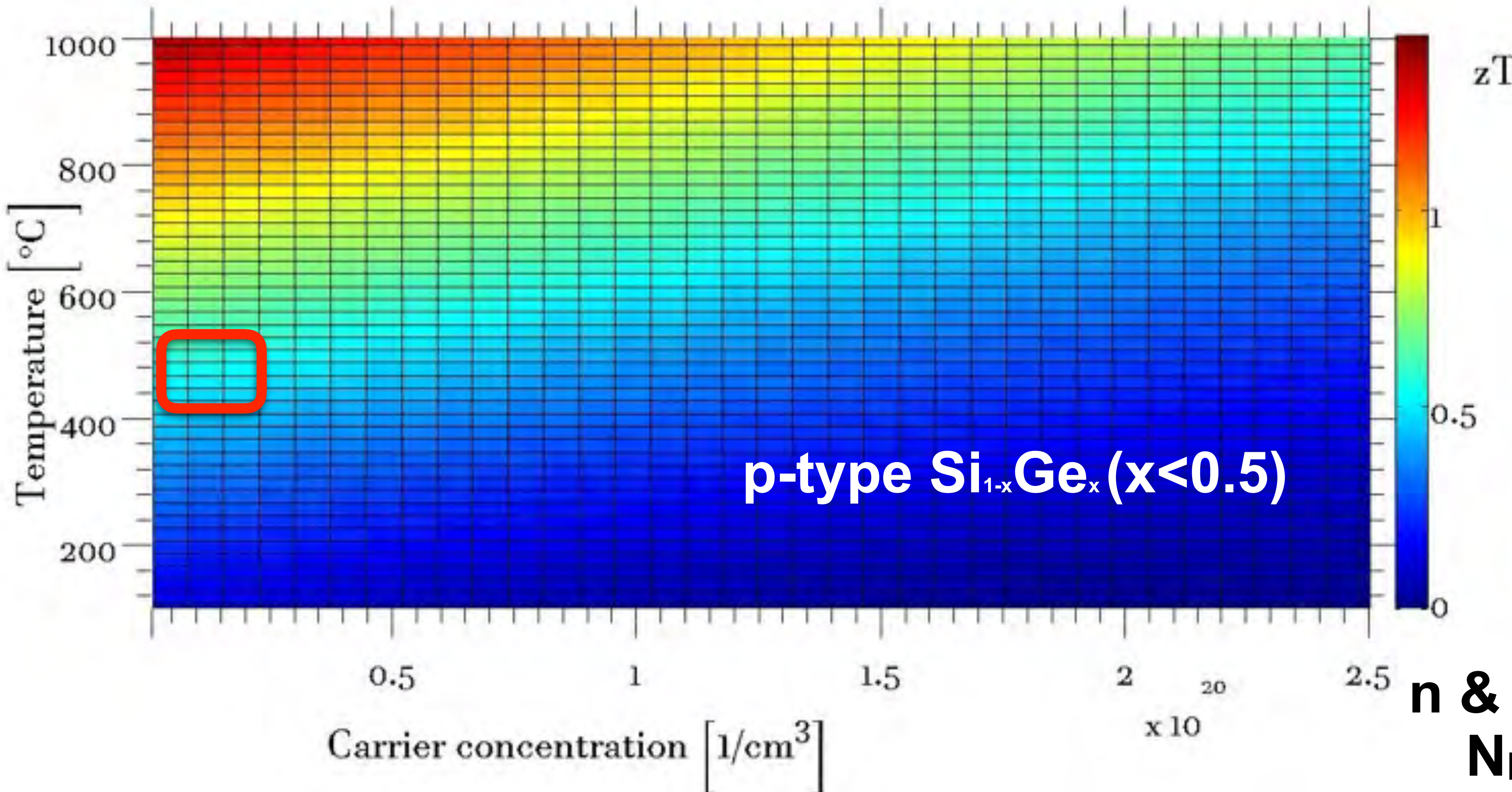




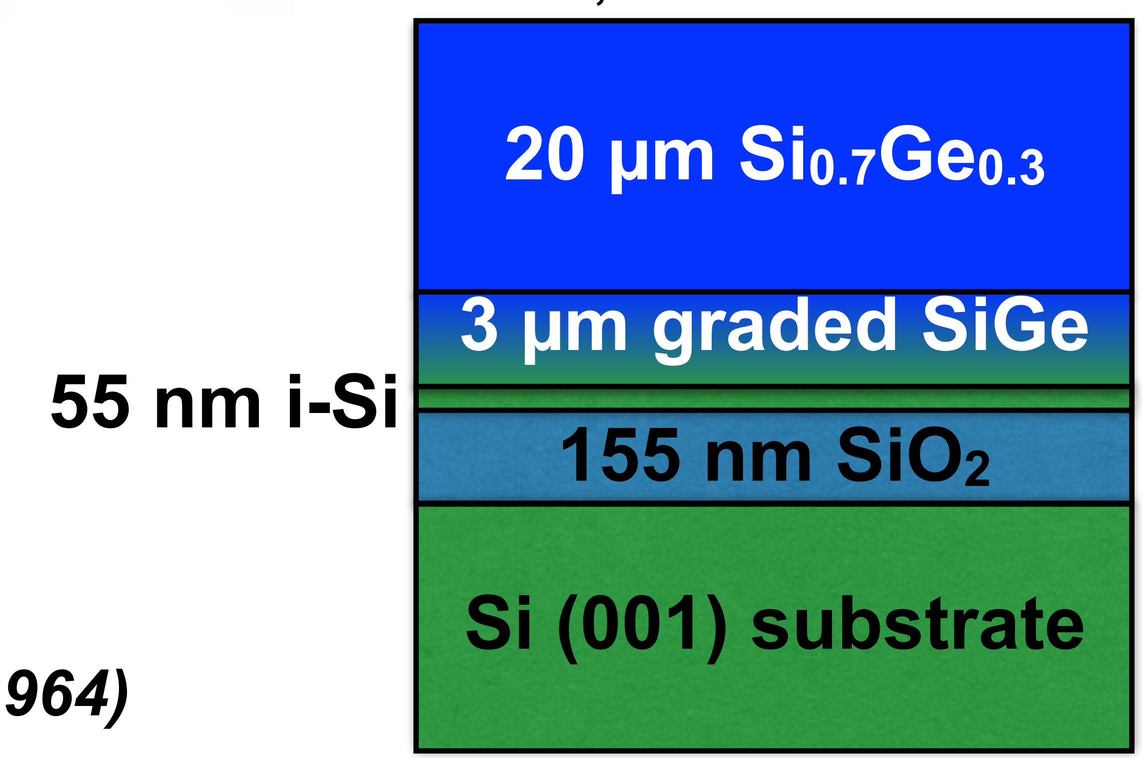
- σ = 20,300 S/m 4 terminal
- κ = 7.78 W/mK
- α = –271 μV/K
- ZT = 0.057

- ZT enhanced by x117
- $\alpha^2\sigma$ = 1.49 mW $m^{-1}K^{-2}$
- What enhancements with SiGe ?

Bulk SiGe Material Design



n & p-doped wafers
$N_{D,A} = 10^{19}$ cm^{-3}

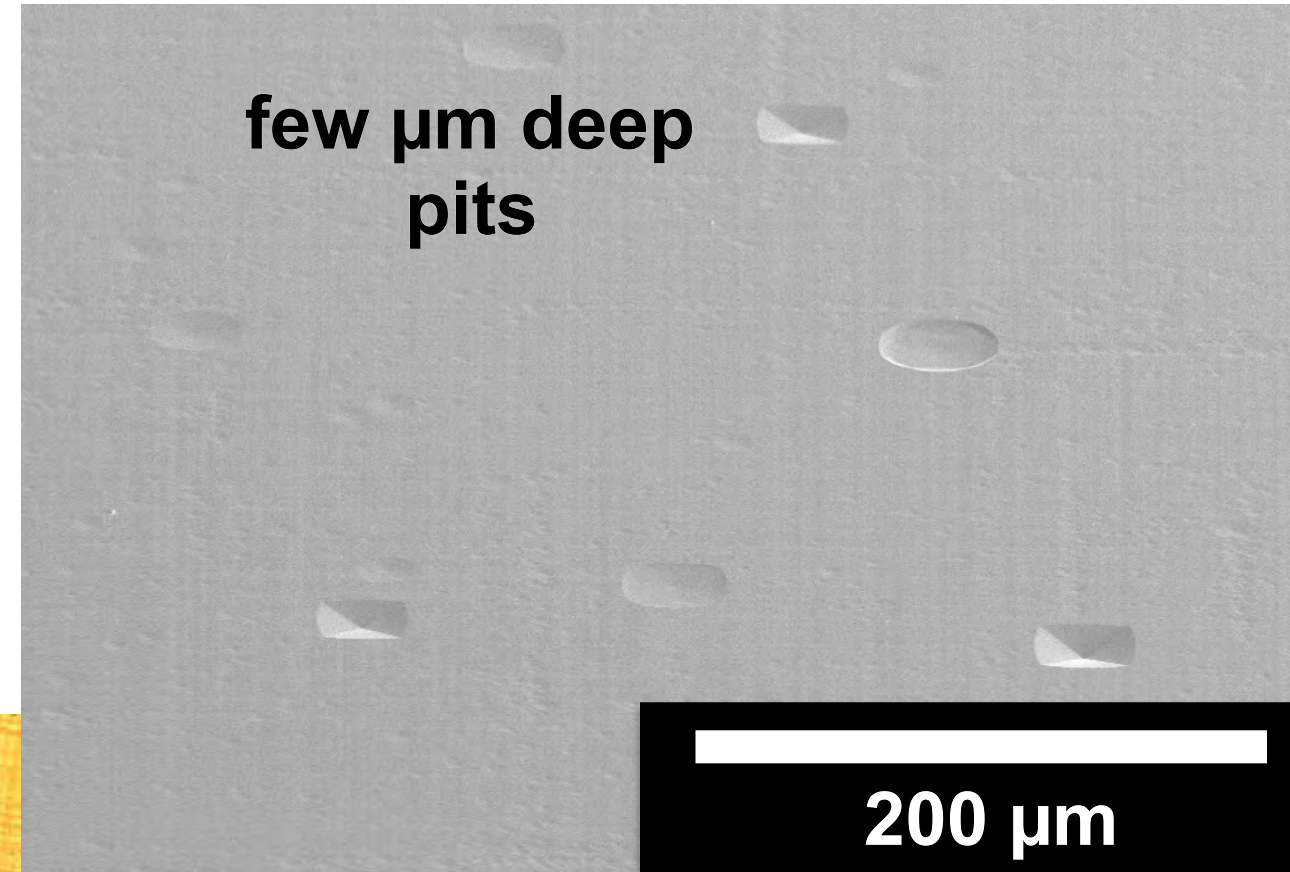


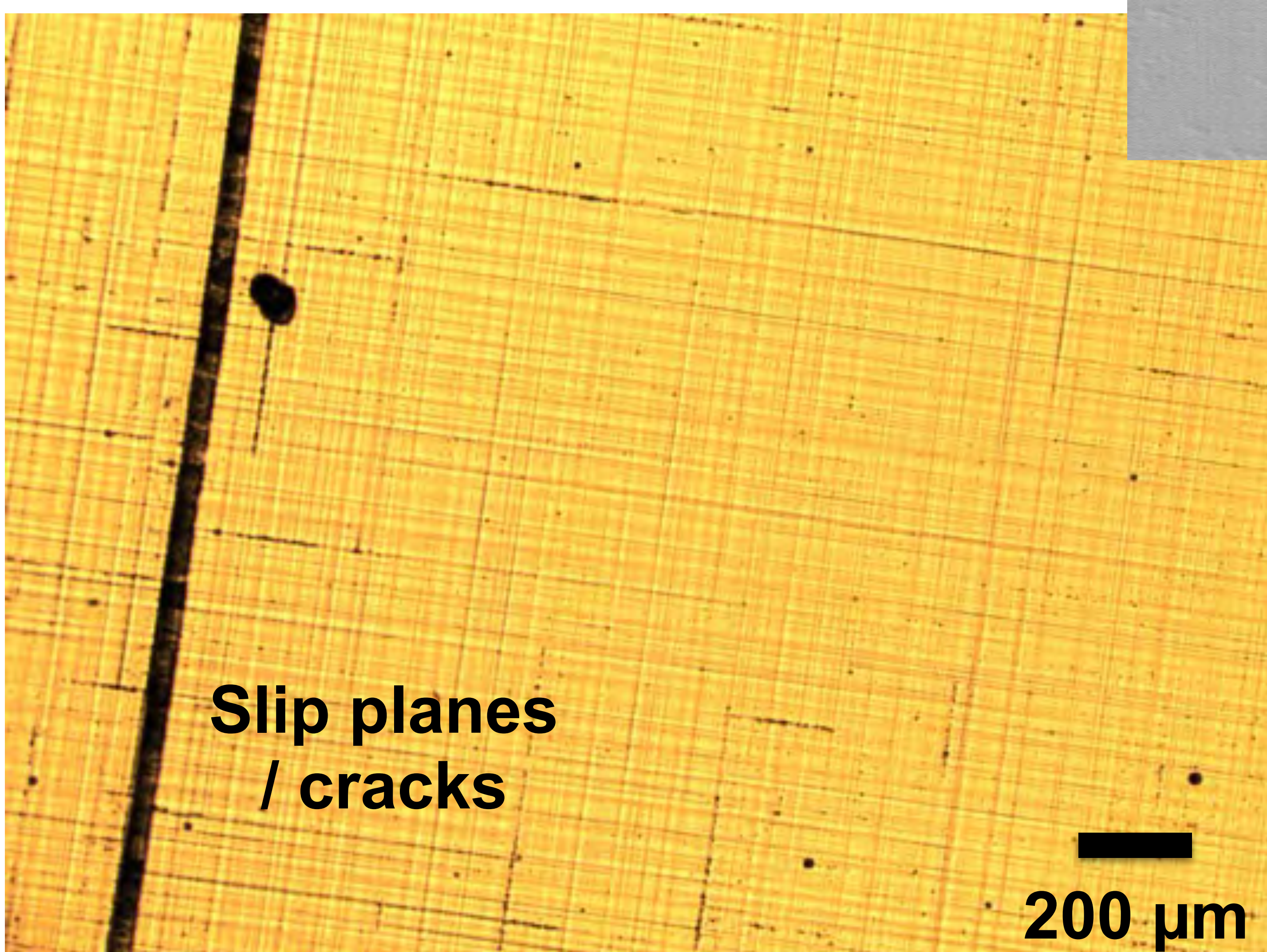
J.P. Dismukes et al., J. Appl. Phys., 35, 2899 (1964)

LPCVD SiGe Wafer Growth

ASM 2000E LPCVD system

200 mm SOITEC 55 nm Si, 155 nm box substrates





n & p-doped wafers
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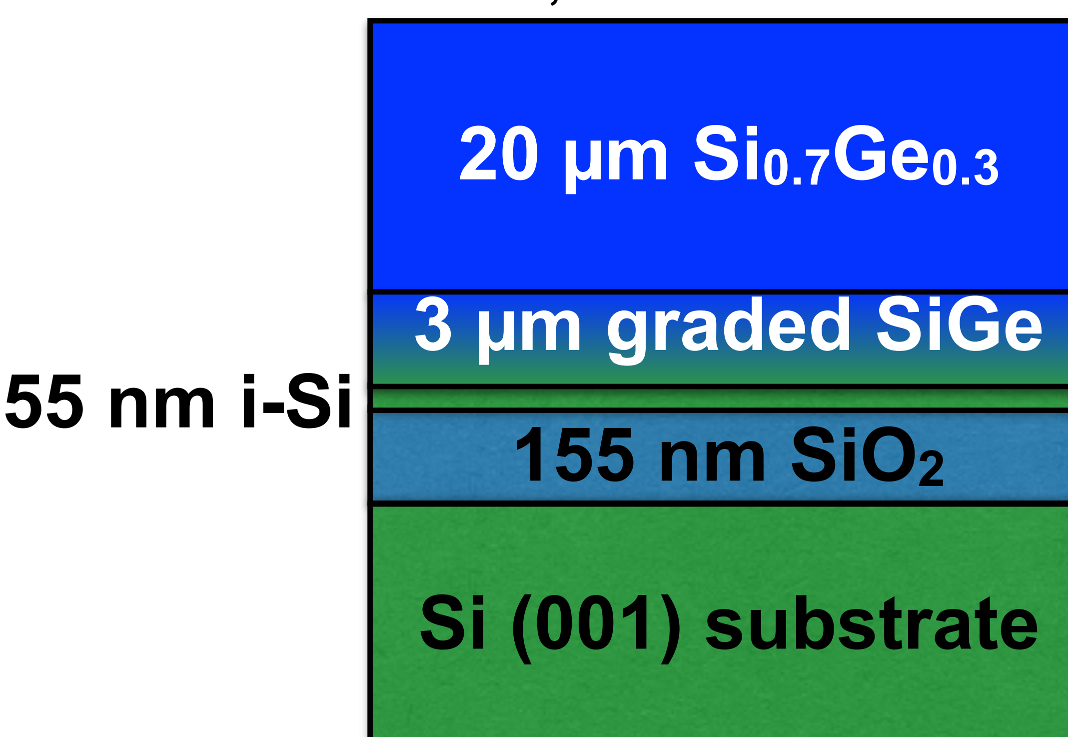
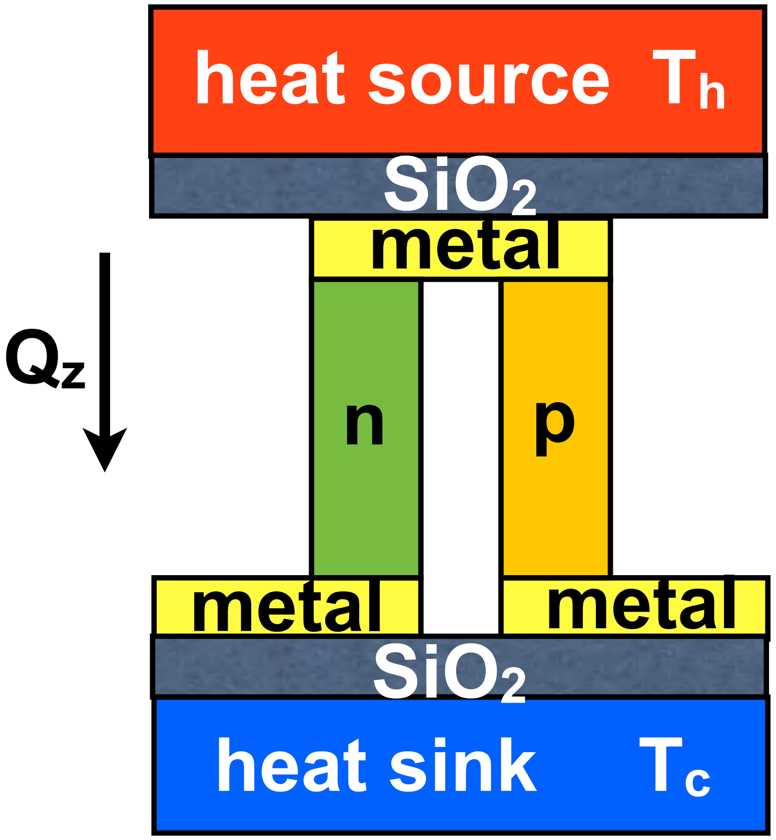


Module Design: Heat Flow, Q



- **Fourier's law of heat conduction**

$$\mathbf{Q} = -\kappa \nabla \mathbf{T}$$

- **Assume 1D heat flow**

$$\mathbf{Q_z} = -\kappa(\mathbf{T}) \frac{\mathbf{dT}}{\mathbf{dx}}$$

Fourier heat conduction **Peltier effect**

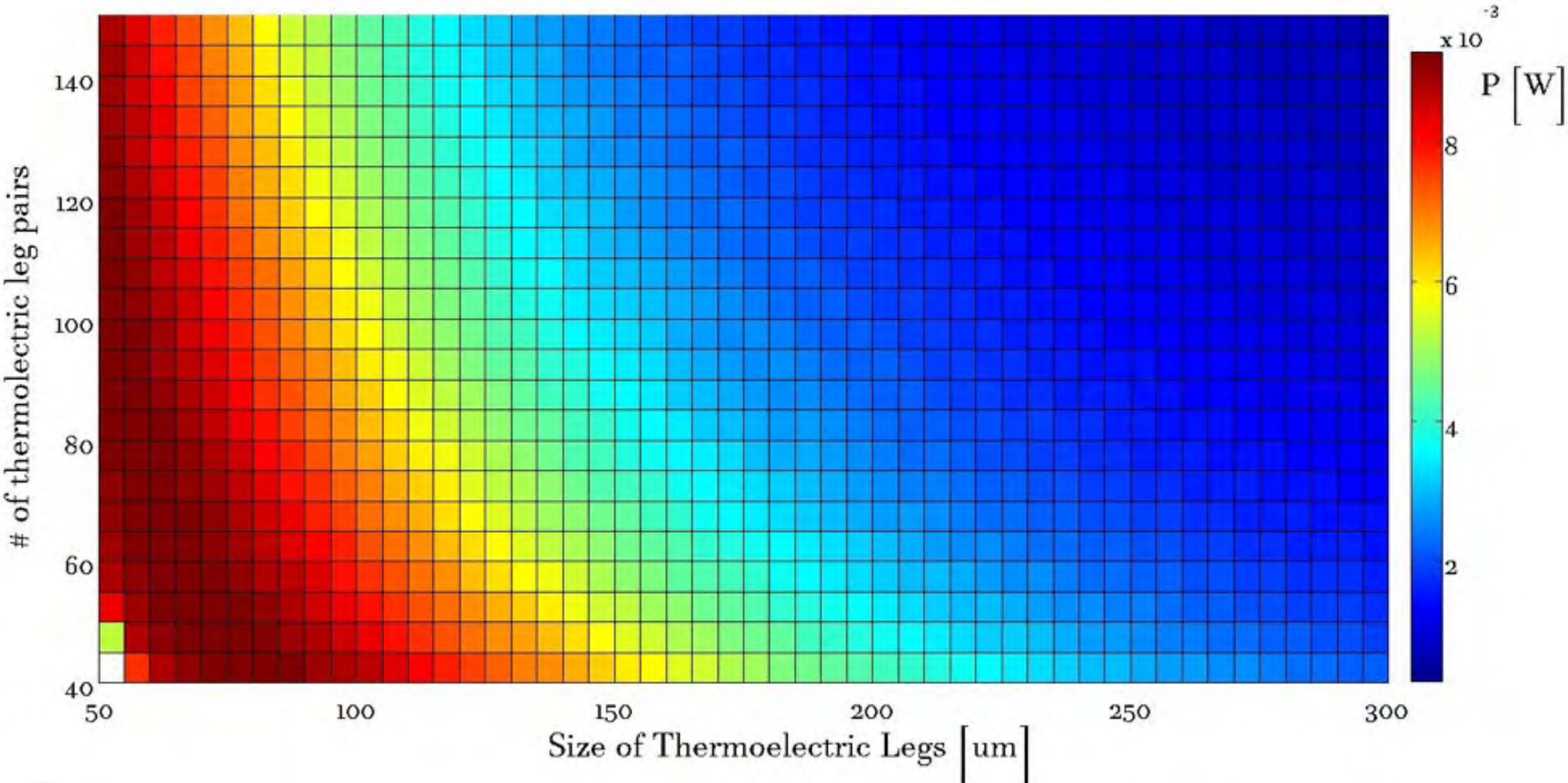
$$\mathbf{Q_z A_{chip}} = -\kappa_{\mathbf{SiGe}}(\mathbf{T}) \mathbf{N_{legs} A_{legs}} \frac{\mathbf{T_H - T_C}}{\mathbf{L}} + \mathbf{N_{leg}} \alpha(\mathbf{T}) \mathbf{I T_H}$$

$$-\mathbf{R_{int}}(\mathbf{T})\mathbf{I}^2 + \kappa_{\mathbf{air}} \mathbf{A_{air}} \frac{\mathbf{T_H - T_C}}{\mathbf{L}} + \mathbf{h_C A_{air}}(\mathbf{T_H - T_C})$$

Joule heating **thermal conduction through air** **thermal convection through air**

Simulation of Performance @ T_H = 500 ˚C

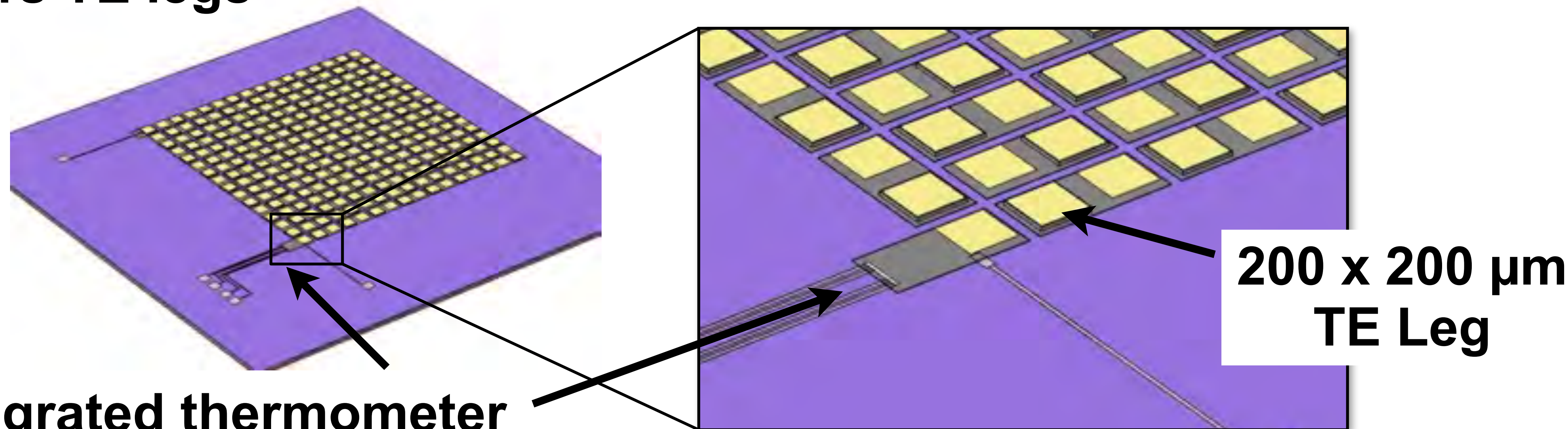
- Input heat, $Q_z = 5\ W/cm^2$
- Operating temperature, T_H = 500 ˚C

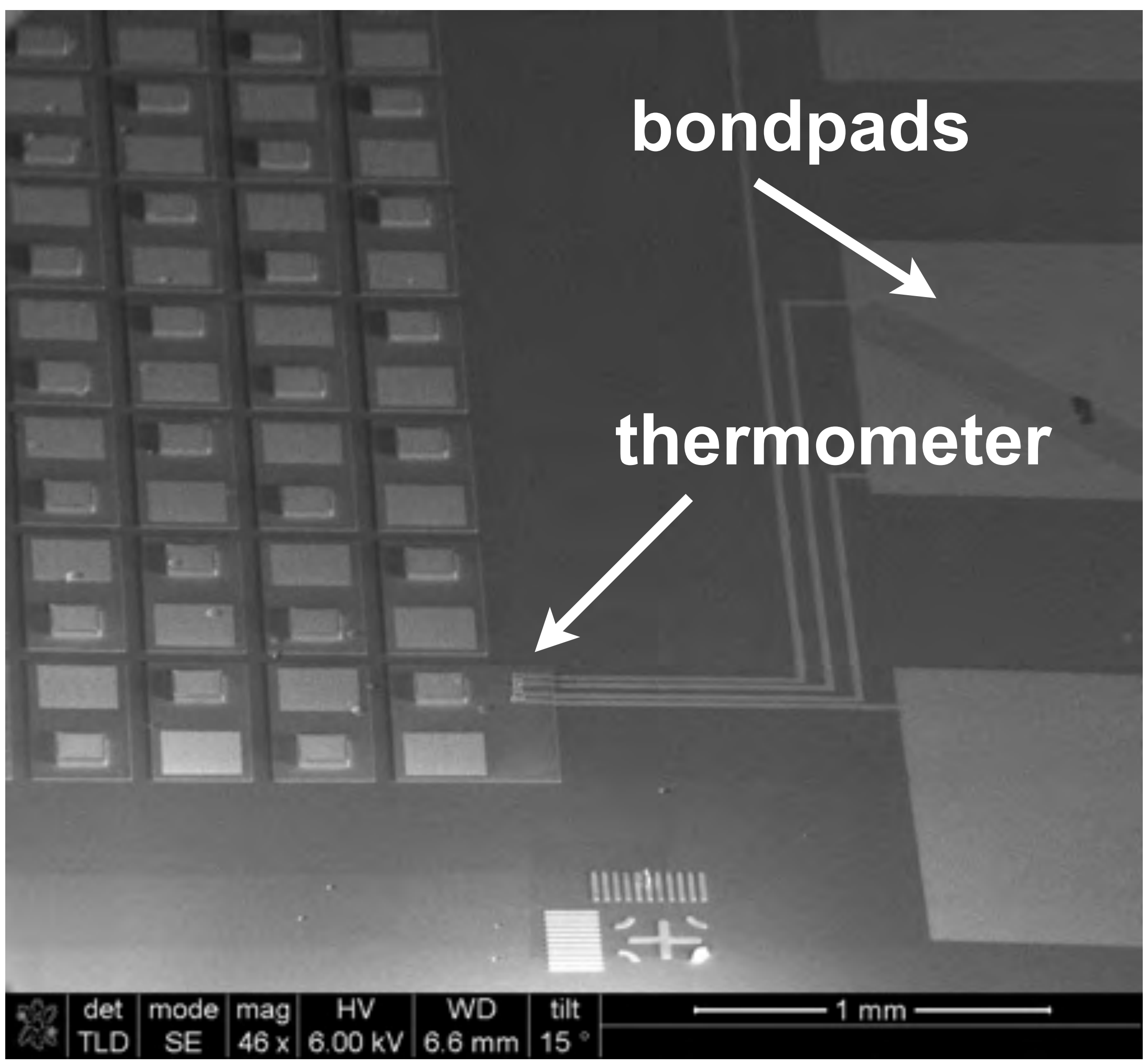


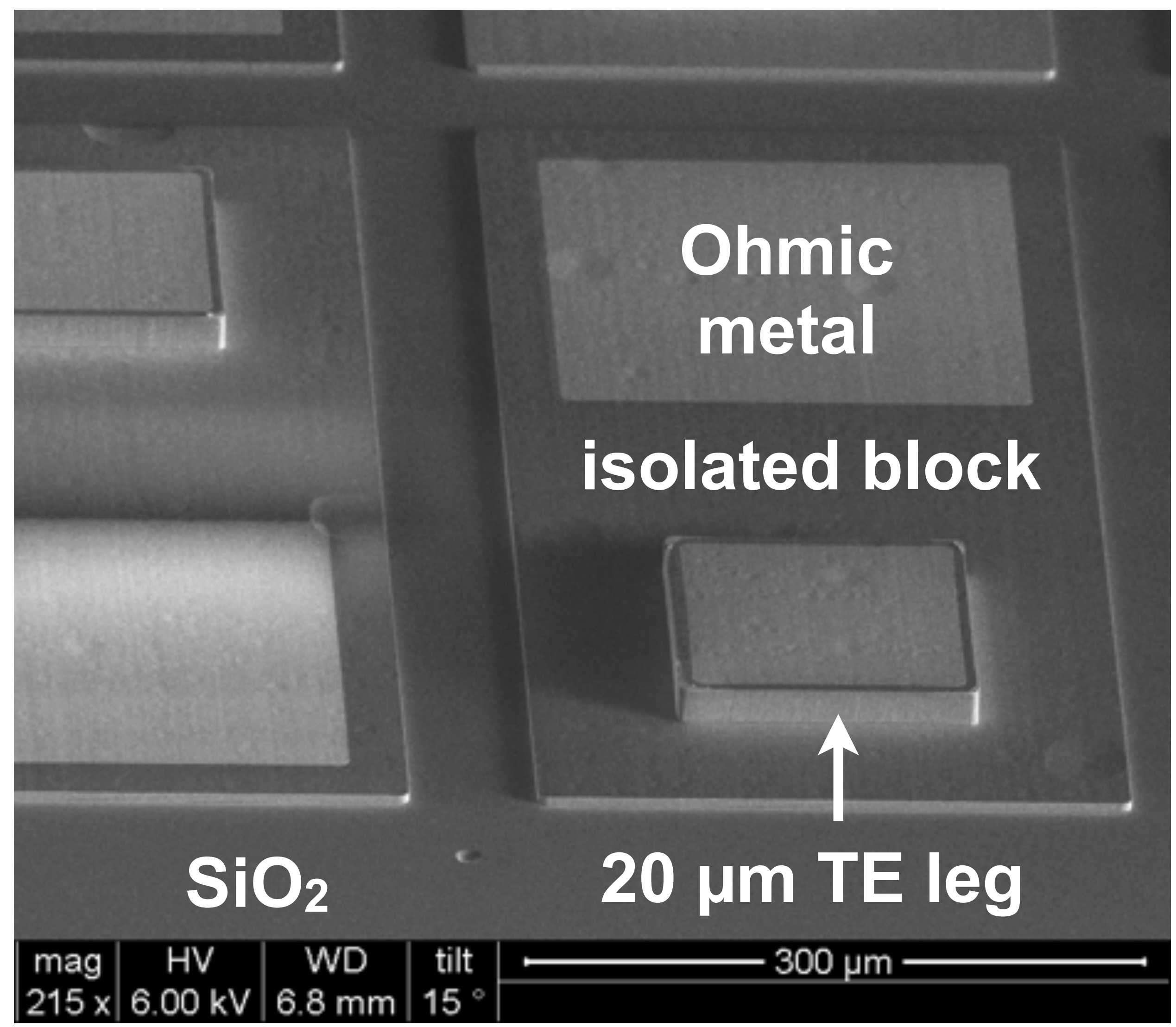
- Shorter legs better for high P but need to consider κ to maintain ΔT

Microfabricated Legs & Thermometers

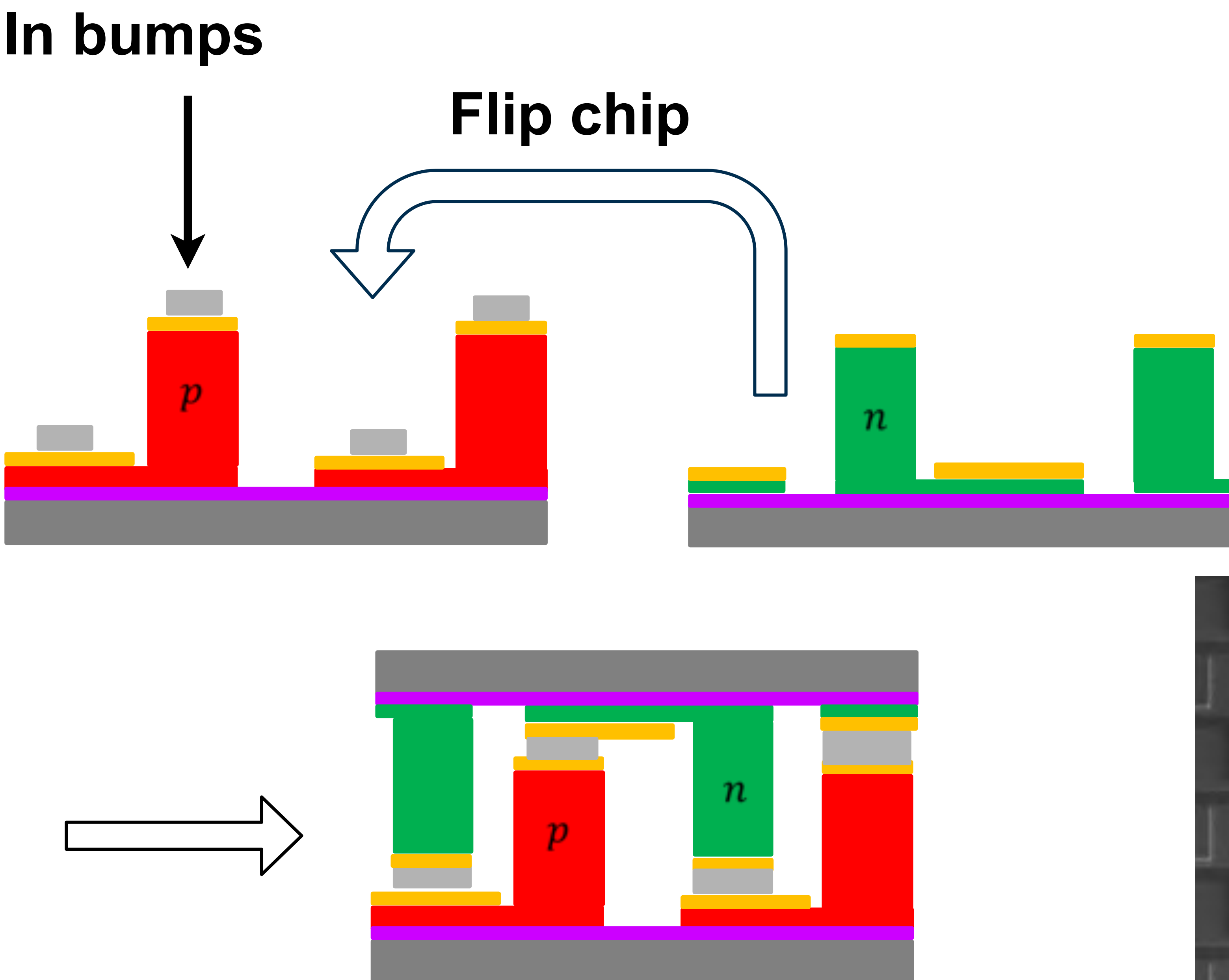
68 pairs TE legs

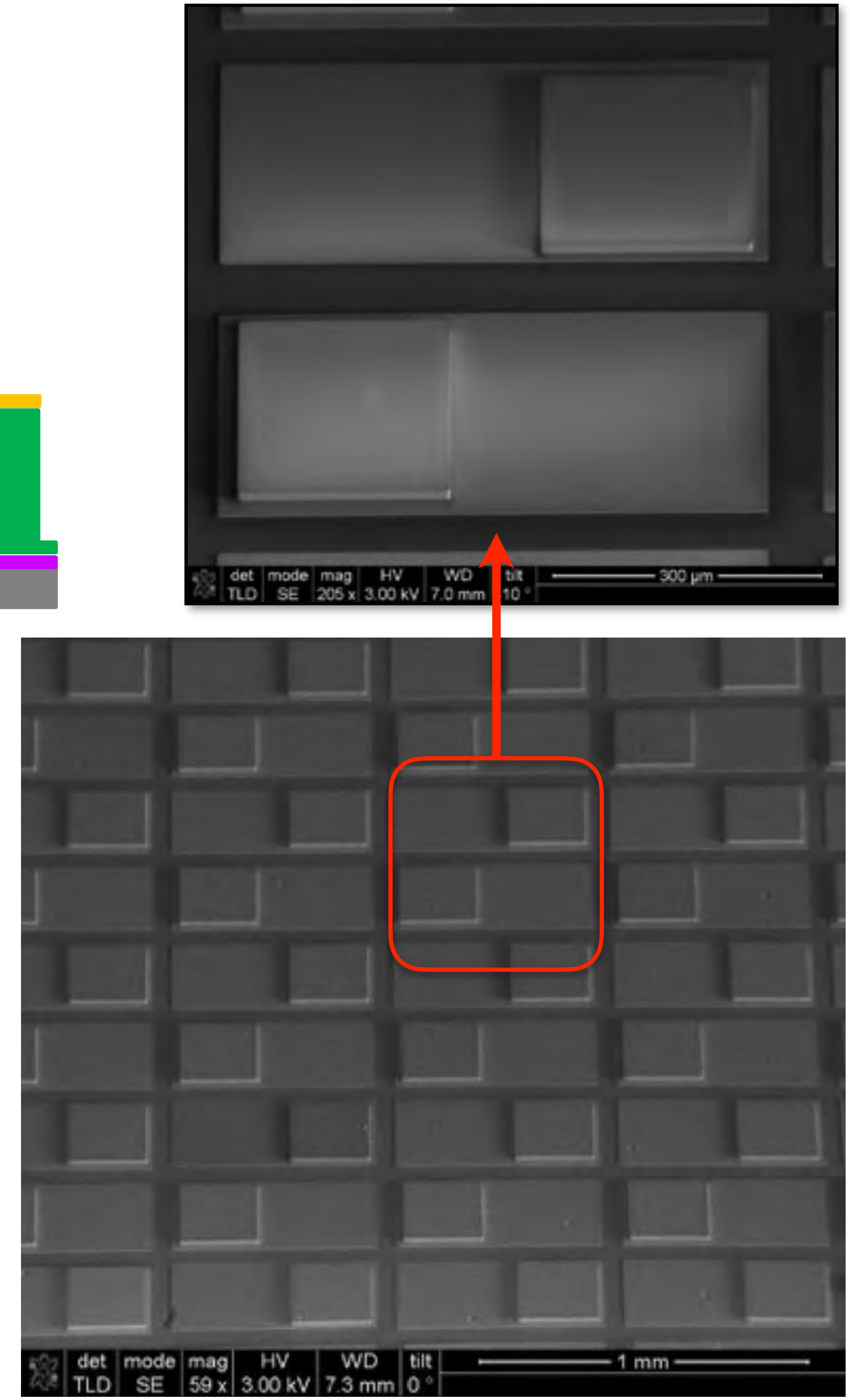






Flip-Chip Bonding





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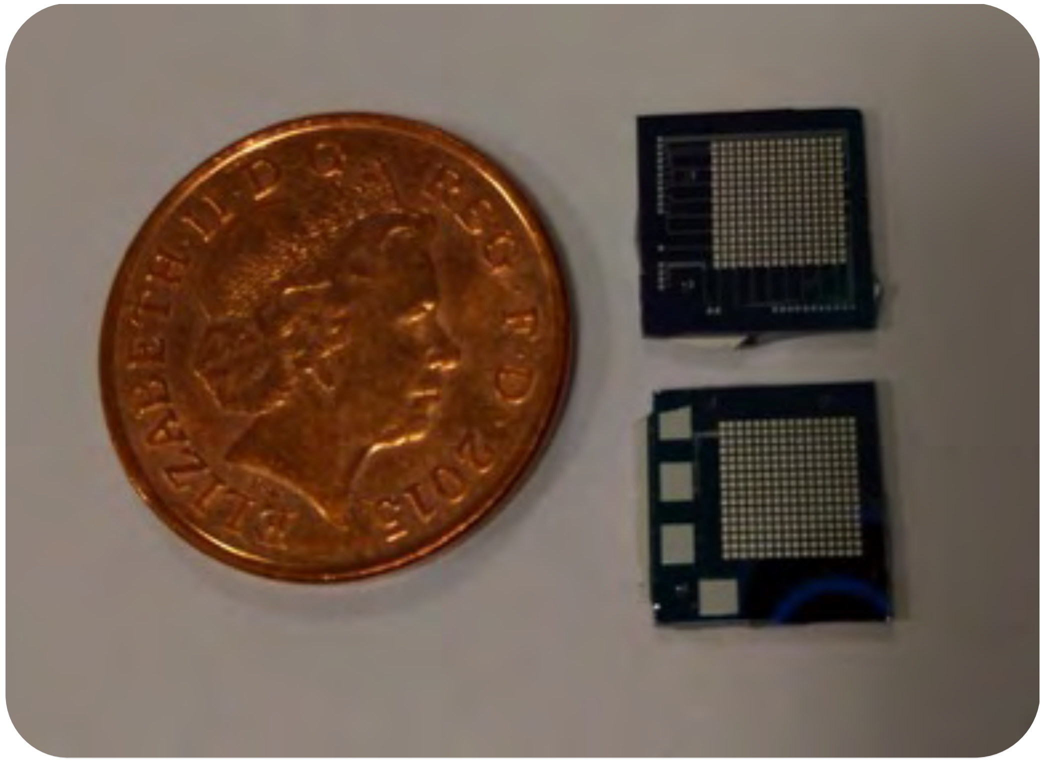
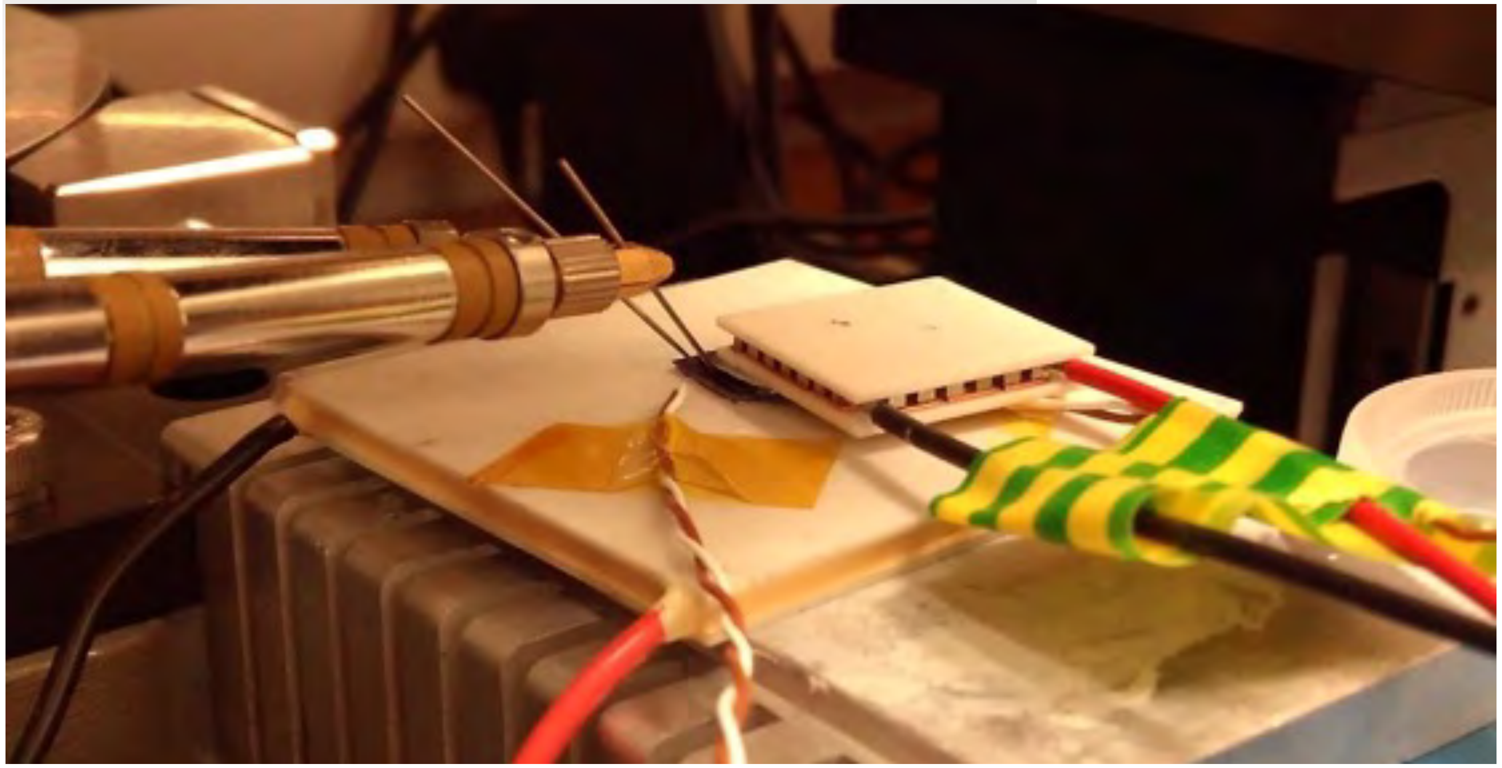
Final Module & Test





Heater & 2 Peltiers used to drive heat through module

Microfabricated thermometers measure ΔT

Issues and Future Work

- Material cracks limit yield & ∴ legs: requires better epitaxy (limited area epitaxy?)
- In bumps limit T_H & dominate leg R
- High temperature bumps & flip-chip bonding in development
- Present silicides limited to ≤ 400 ˚C: new high T silicides e.g. $TiSi_2$ or WSi_2 stable to > 700 ˚C
- Ohmic to bumps requires better diffusion barrier => TiN

Summary

- Si/SiGe heterostructures for engineered electron & phonon transport towards enhanced thermoelectrics
- New test structures for α and κ developed
- ZT and power factor enhanced over bulk Si, Ge and SiGe values
- Prototype modules delivered: optimisation required
- http://www.greensilicon.eu/GREENSilicon/index.html

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