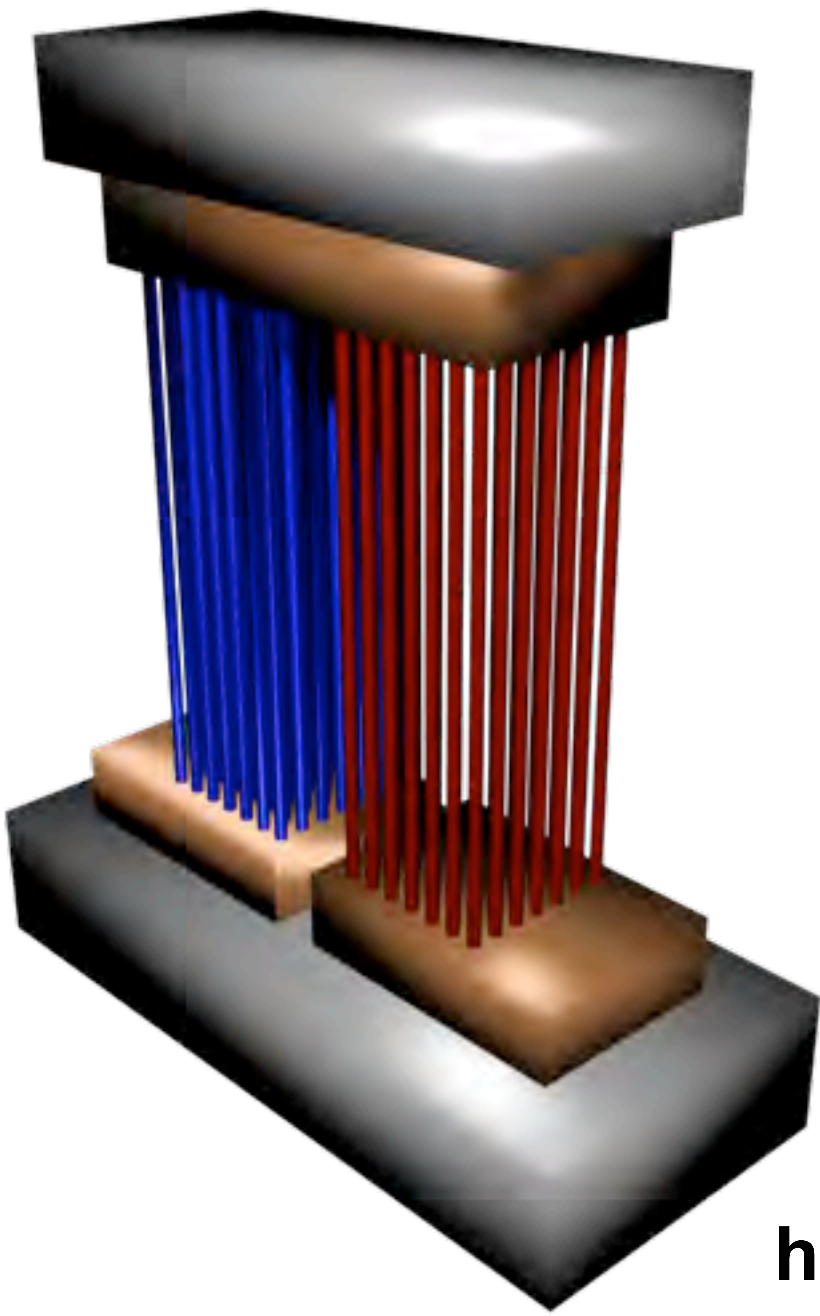
Generate Renewable Energy Efficiently using Nanofabricated Silicon (GREEN Silicon)



D.J. Paul, J.M.R. Weaver, P. Dobson, J. Watling
A. Samarelli and L. Ferre-Llin

University of Glasgow, U.K.

G. Isella, D. Chrastina, S. Cecchi, J. Frigerio, F. Isa

L-NESS, Politecnico de Milano, Como, Italy

J. Stangl, T. Etzelstorfer

University of Linz, Austria

E. Müller & H. von Känel

ETH Zürich, Switzerland

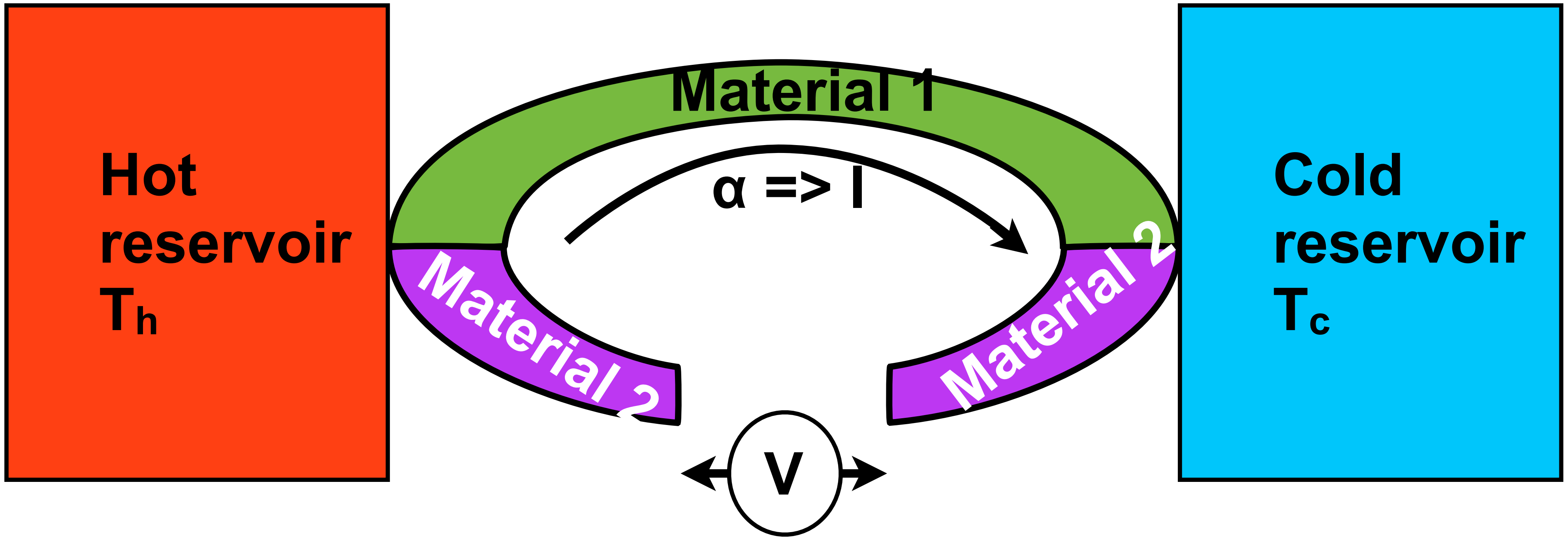
http://www.greensilicon.eu/GREENSilicon/index.html

SEVENTH FRAMEWORK PROGRAMME

GREEN Silicon
Project No. 257750

POLITECNICO MILANO · JKU JOHANNES KEPLER UNIVERSITY LINZ · ETH · University of Glasgow

The Seebeck Effect



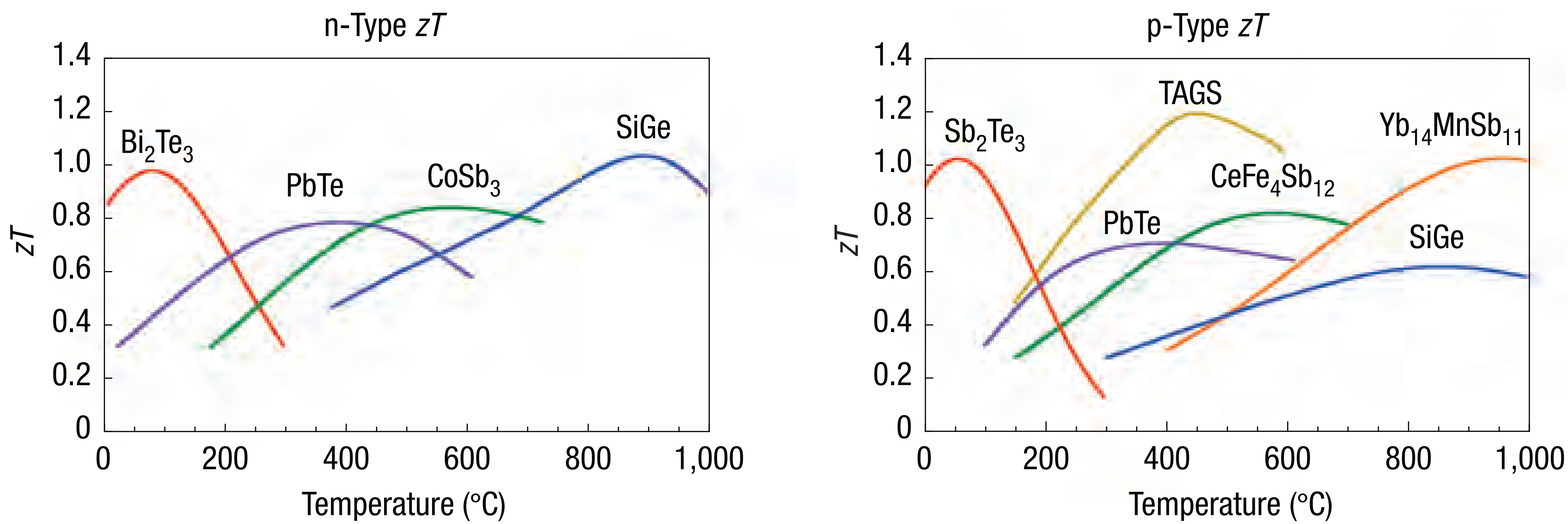
- Open circuit voltage, $V = \alpha (T_h - T_c) = \alpha \Delta T$

Seebeck coefficient, $\alpha = \frac{dV}{dT}$

units: V/K

- Seebeck coefficient = $\frac{1}{q}$ x entropy $\left(\frac{Q}{T}\right)$ transported with charge carrier

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 8th rarest element on earth !!!**
- **Bulk $Si_{1-x}Ge_x$ (x~0.2 to 0.3) used for high temperature satellite applications**

Thermoelectric Power Generating Efficiency

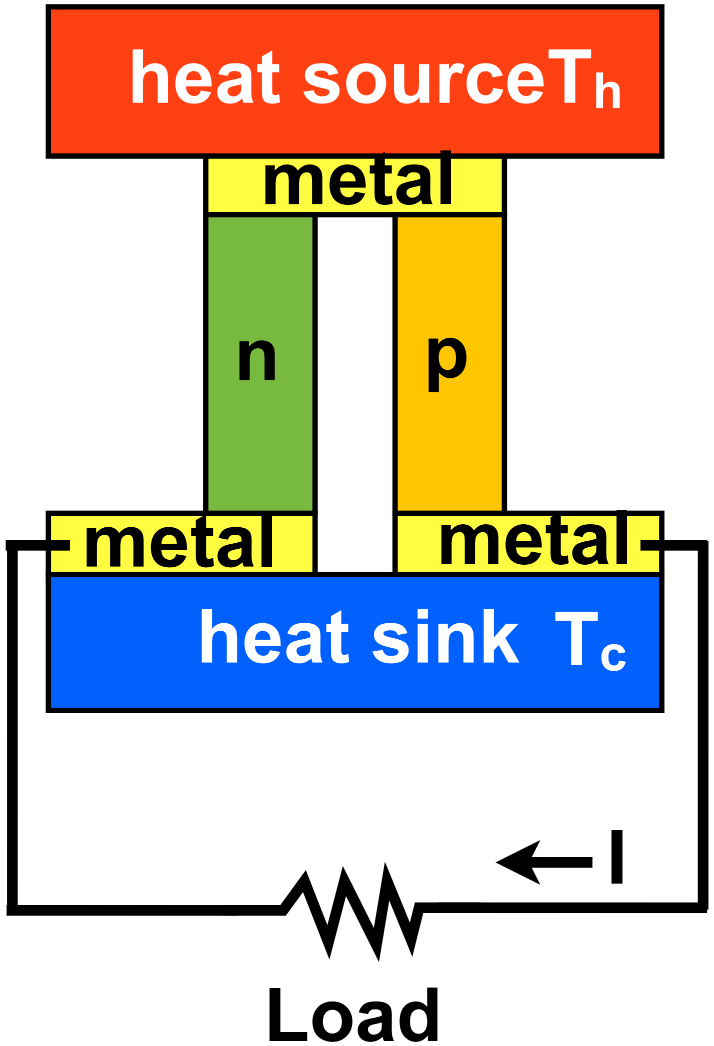
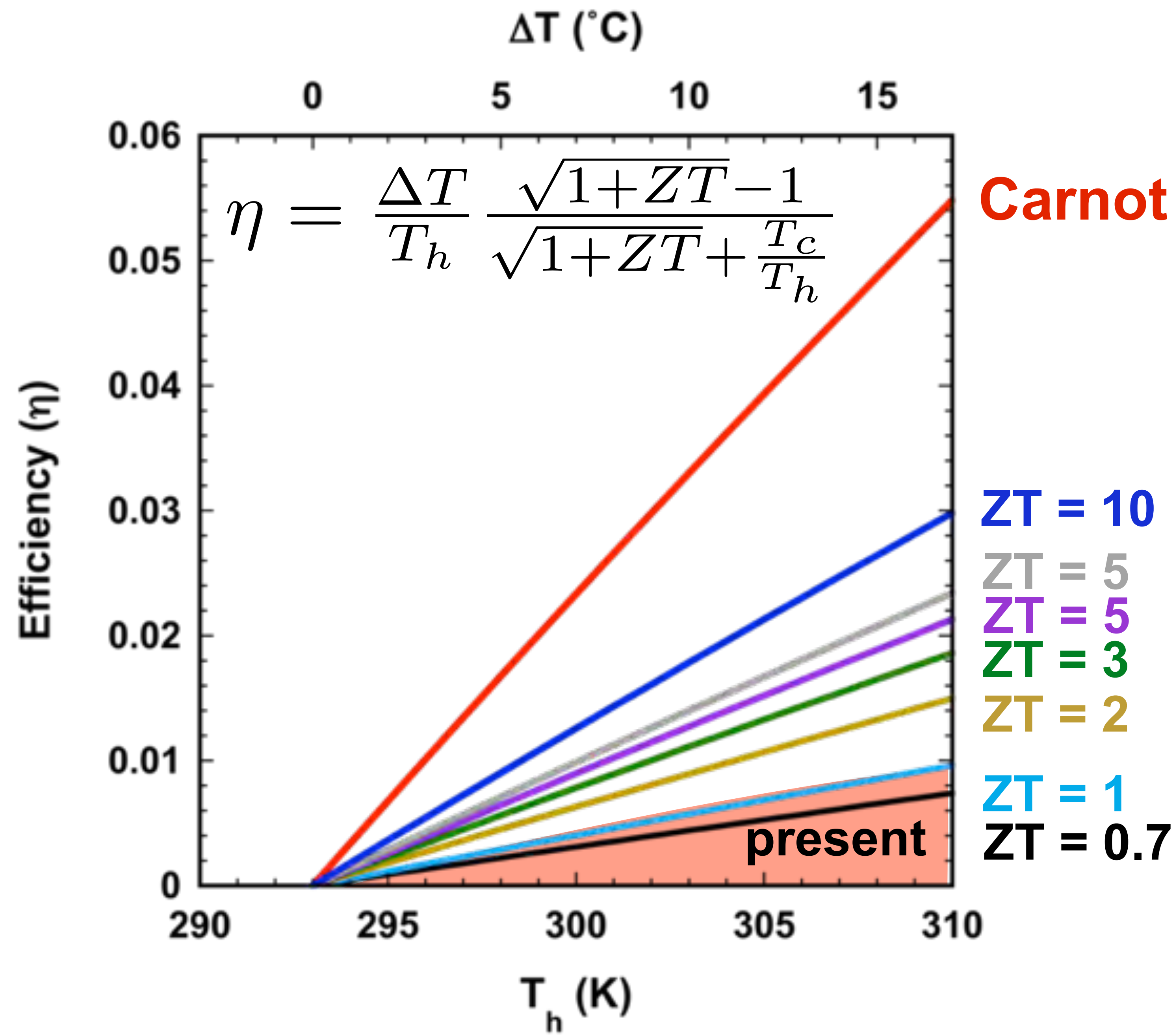


Figure of merit

$$ZT = \frac{\alpha^2 \sigma}{\kappa} T$$

Power factor = $\alpha^2 \sigma$



Impedance matching and maximum power point tracking are key for thermoelectrics

GREEN Silicon: Objectives

Overall Aim: to use nanofabrication with phonon and bandgap engineering to produce cheap, efficient thermoelectric on-chip generators

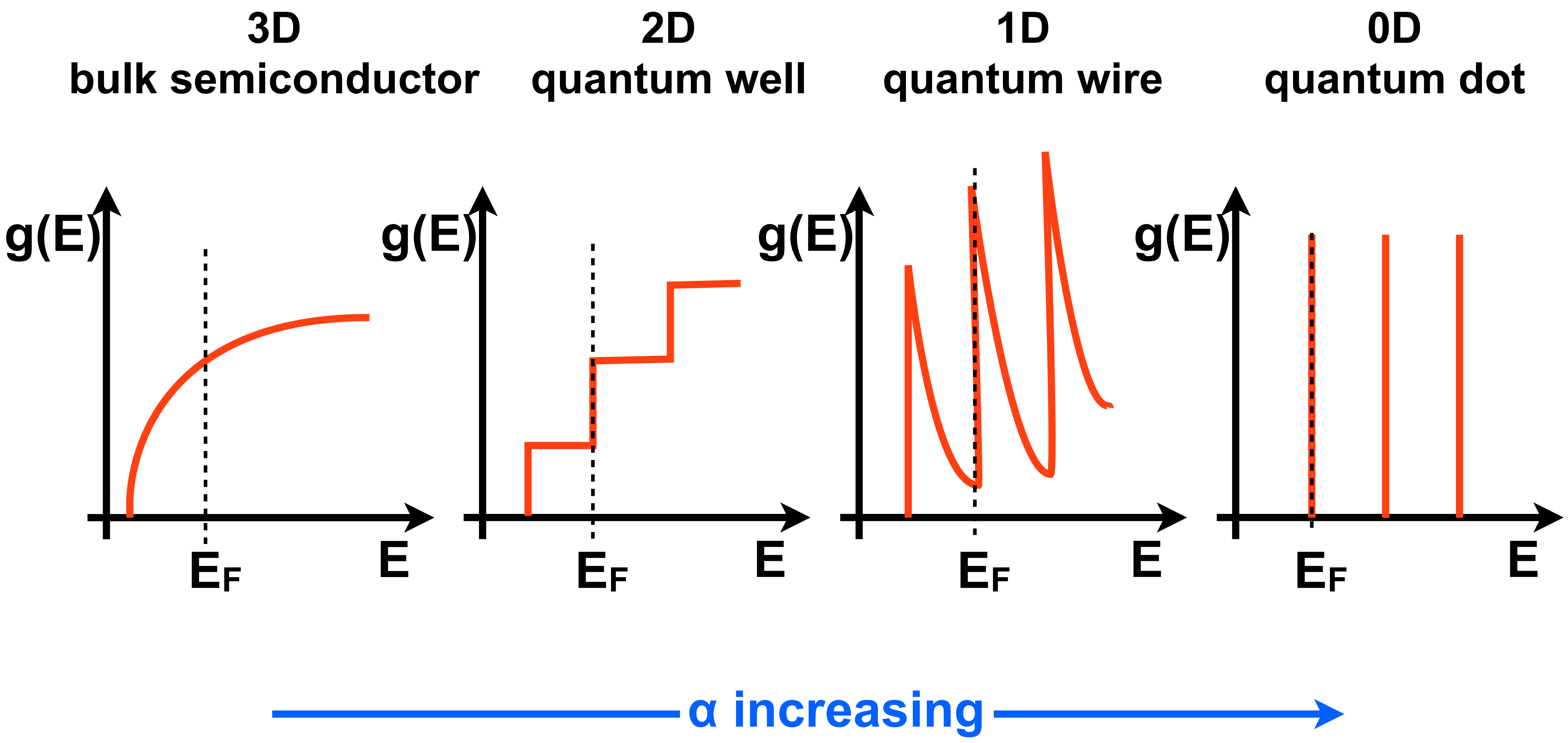
Technology push / application pull:

- Si/SiGe/Ge heterostructures for back-end CMOS process –> on-chip
- Engineer properties using superlattices, 0D quantum dots and 1D nanowires
- Micro- and nano-fabrication technologies for thermoelectric modules
- Combine modelling, growth, fabrication and characterisation to optimise power output

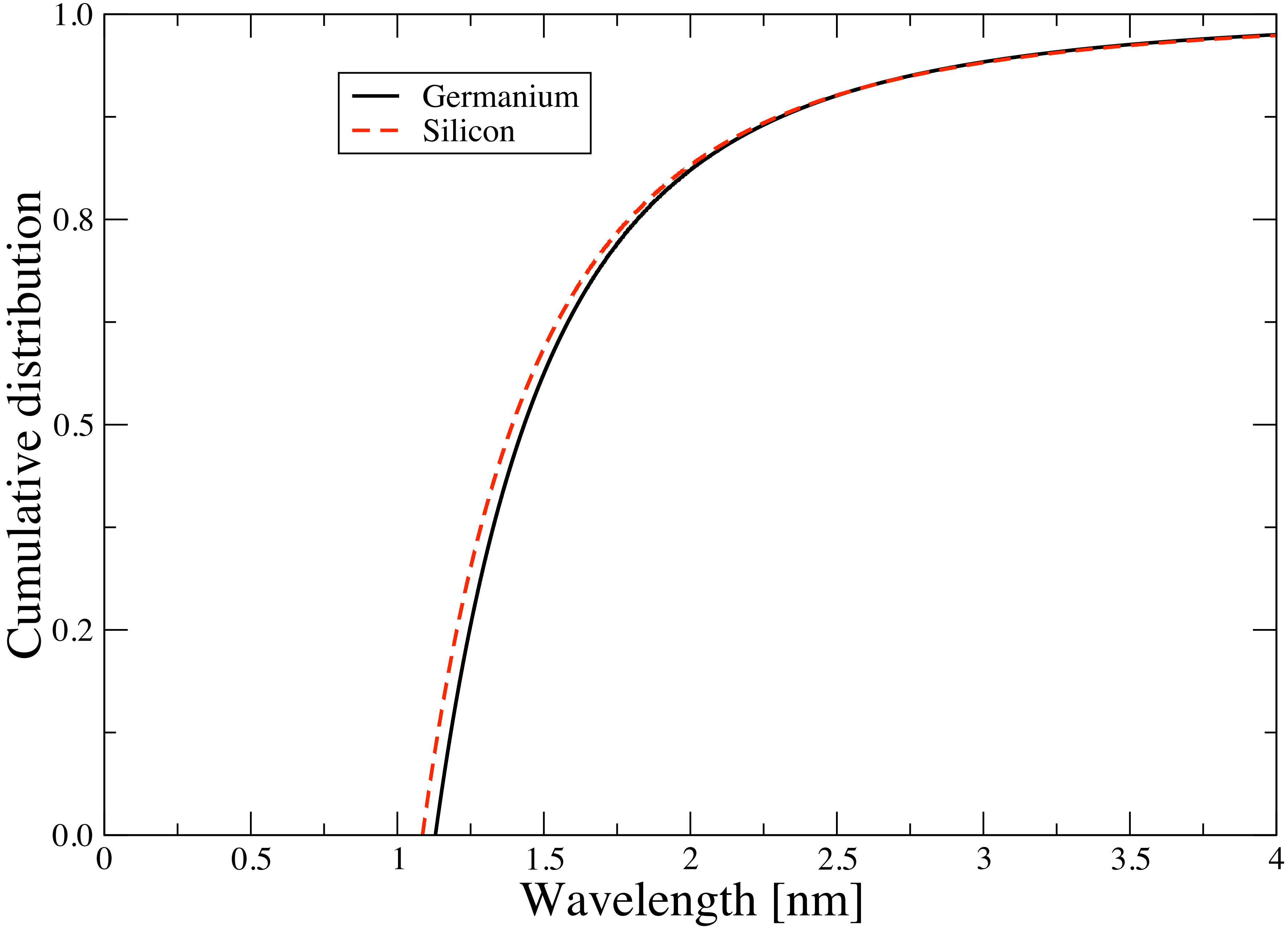
Seebeck Enhancement at Low Dimensions

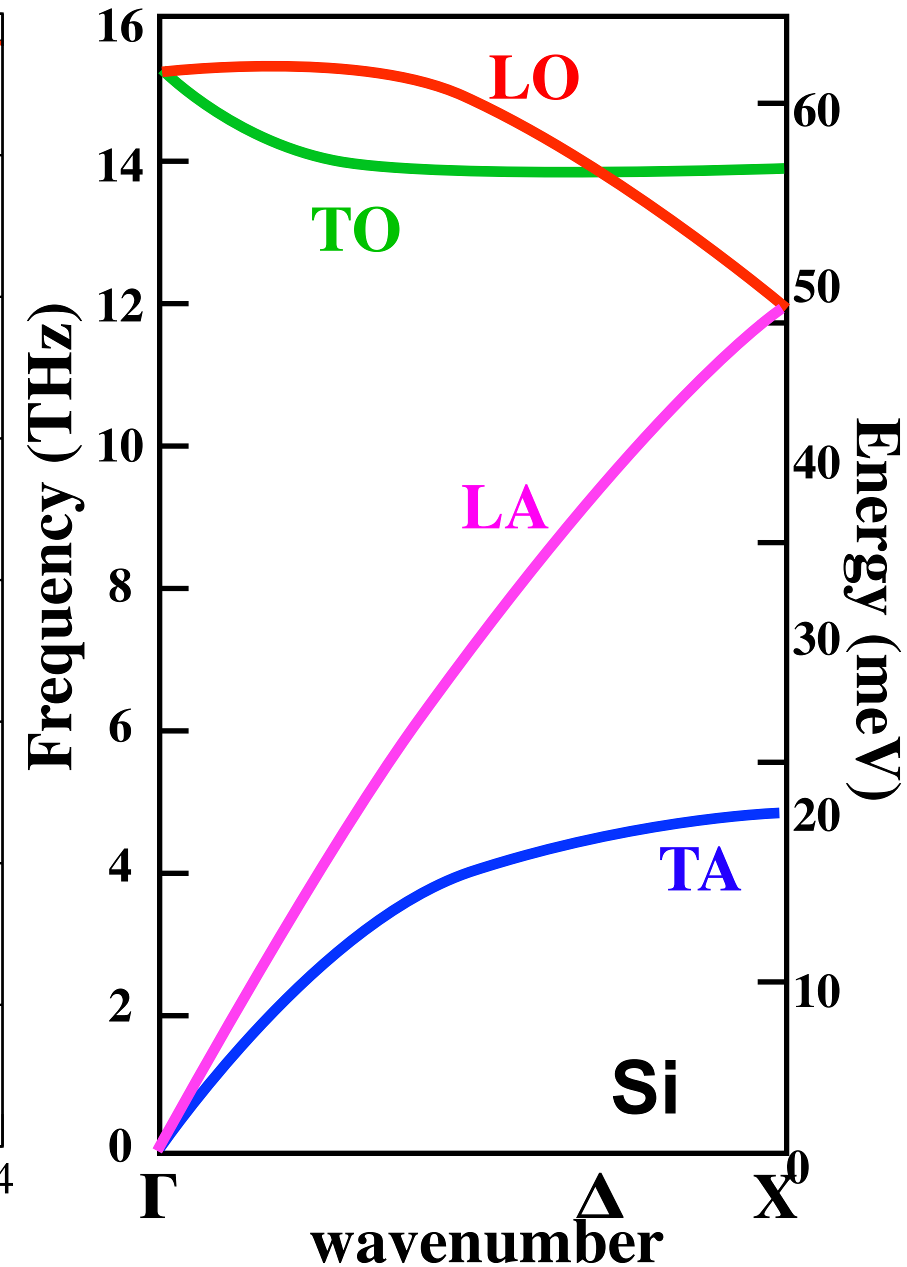
- **Increase α through enhanced DOS:**

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



Phonon Wavelengths that Carry Heat

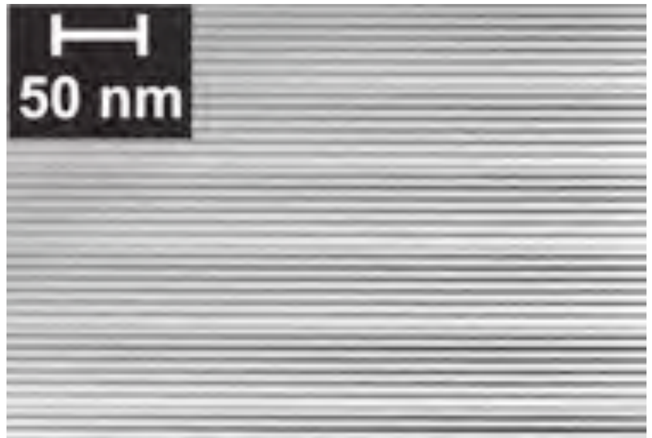




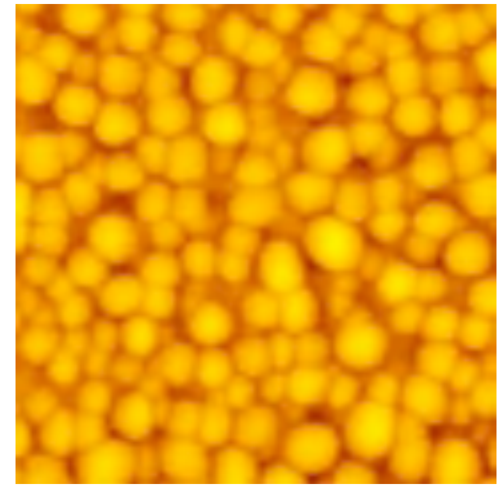
- **Greater than 95% of heat conduction in Si / Ge from acoustic phonons with wavelengths between 1.2 and 3.5 nm**

GREEN Silicon Approach and Vision

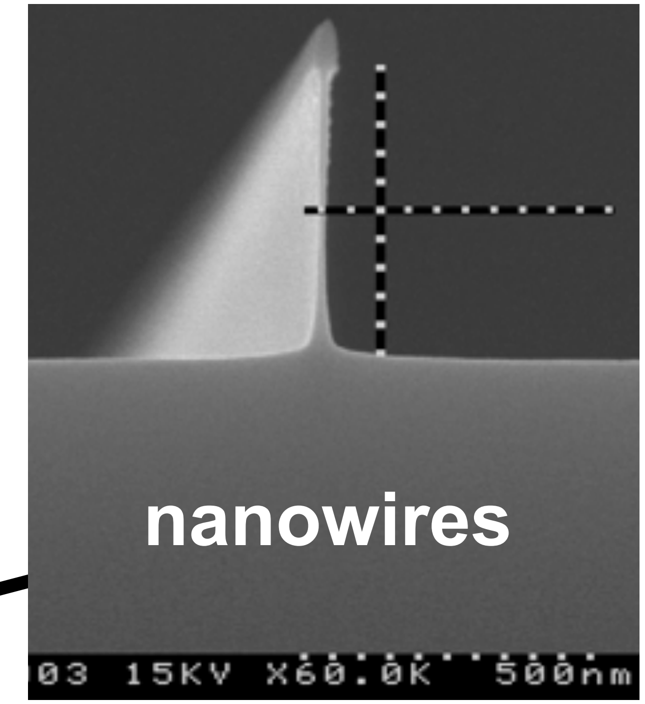
Low dimension technology



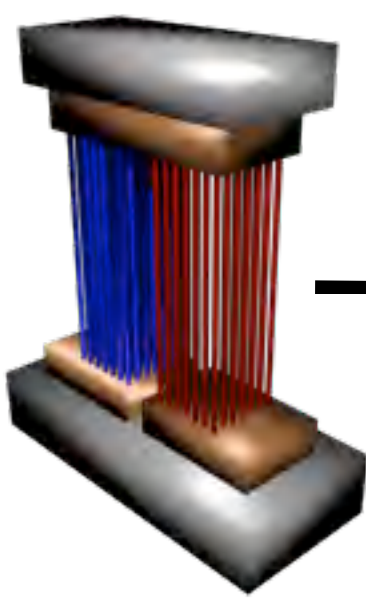
superlattices



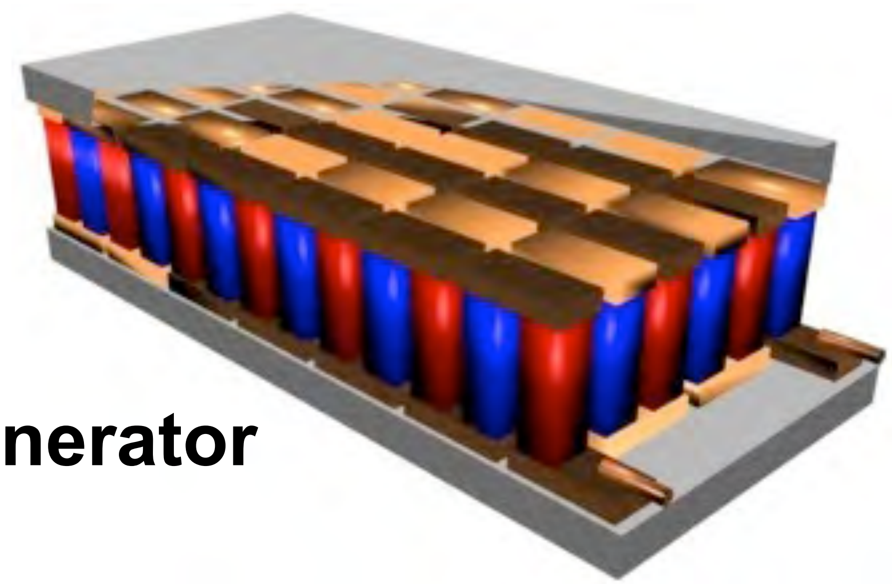
quantum dots



Module



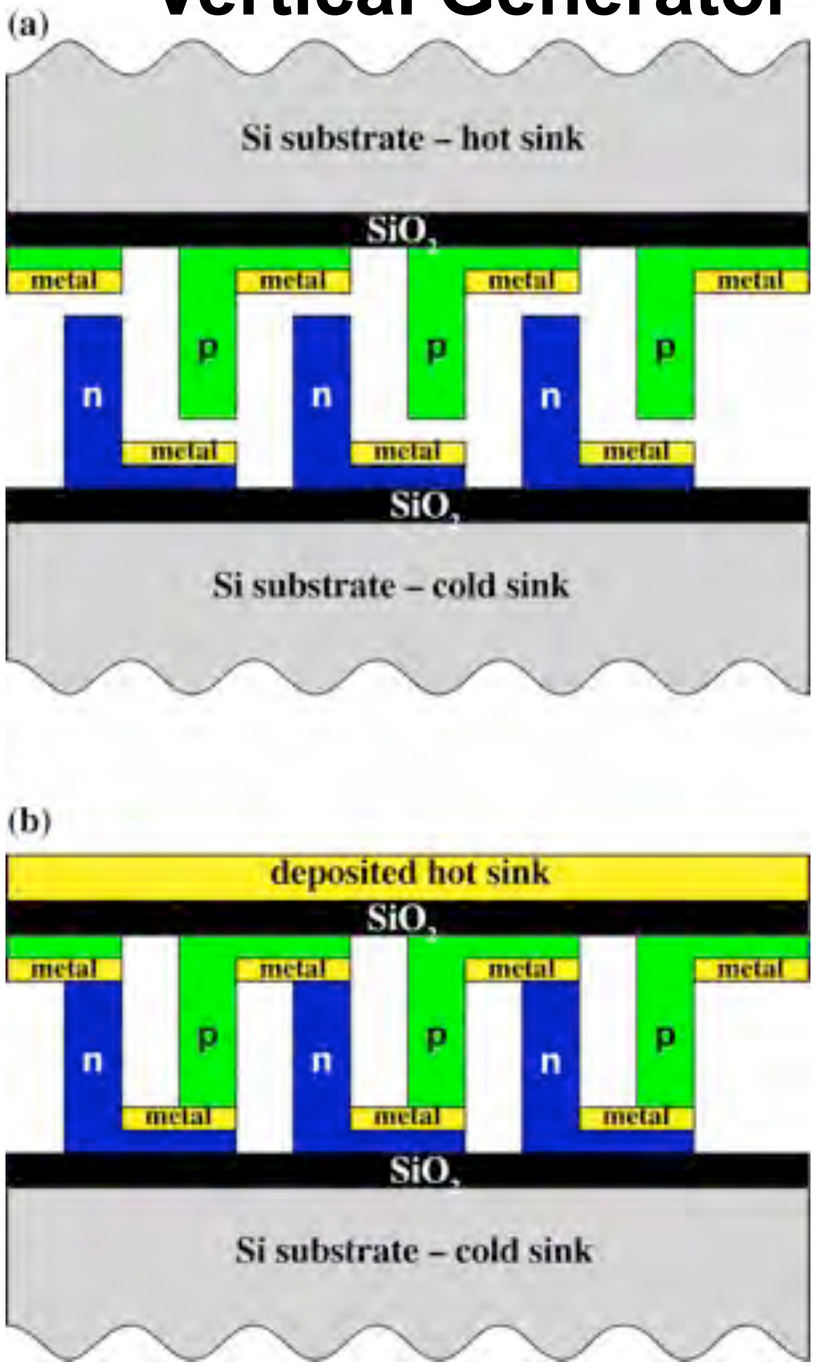
Generator



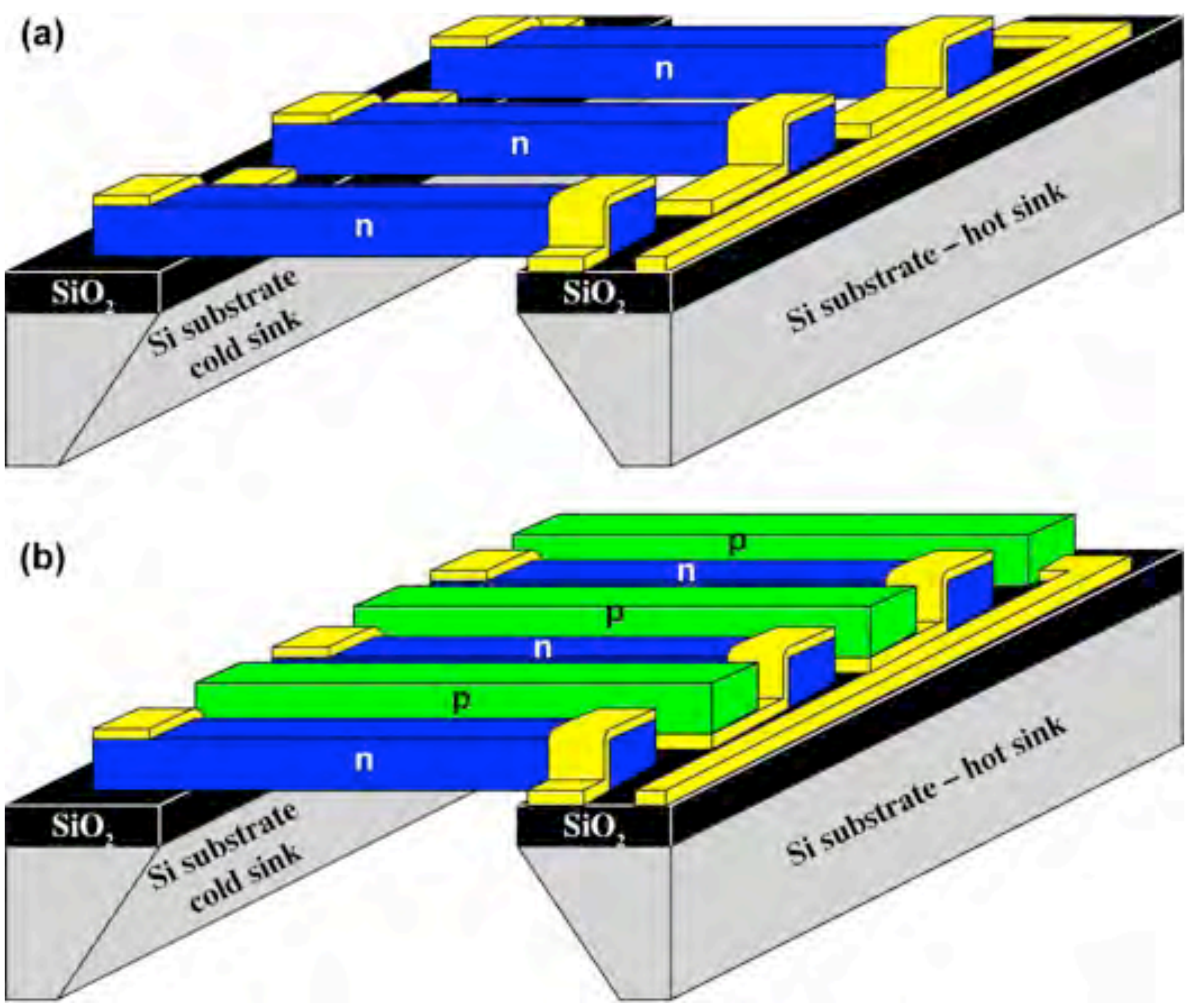
- **Si/SiGe technology –> cheap and back end of line compatible**

Wafer Scale Microfabrication of Generators

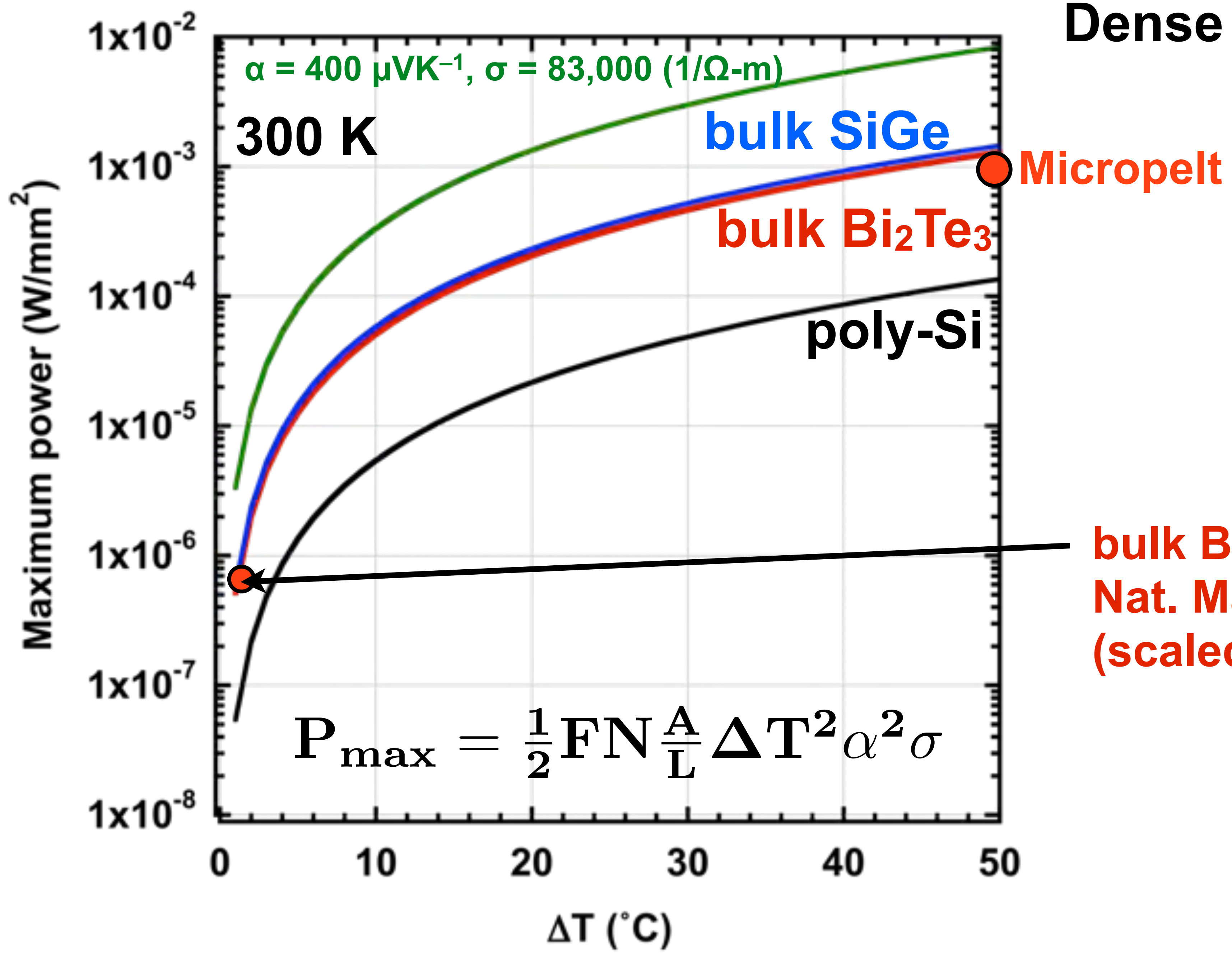
Vertical Generator



Lateral Generator



Maximum Power Estimations: Optimisation



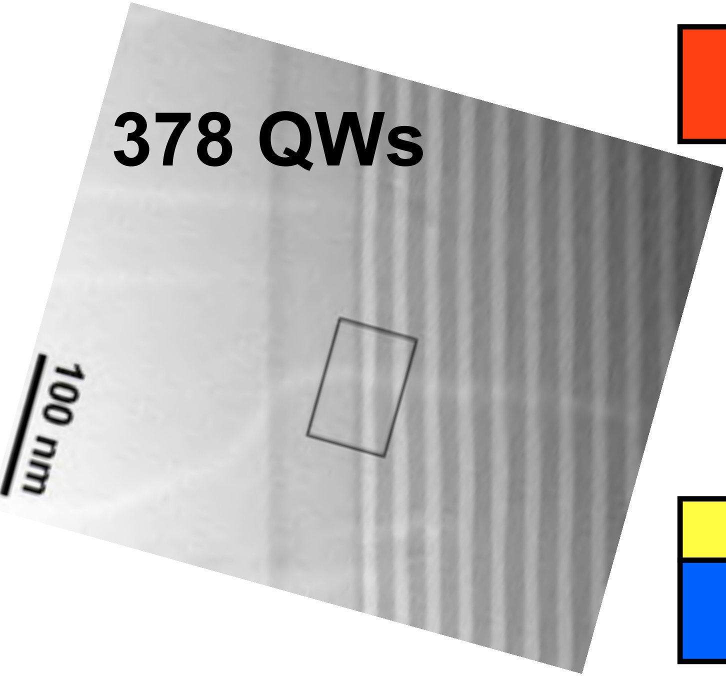
$$P_{max} = \frac{1}{2} F N \frac{A}{L} \Delta T^2 \alpha^2 \sigma$$

Dense microfabricated module

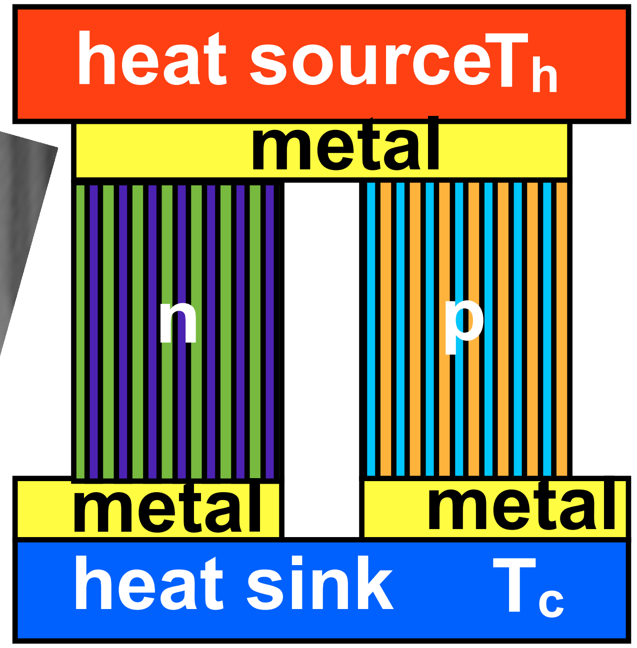
$N = 2500$
$L = 10\ \mu m$
$l_c = 1\ \mu m$
$A = 10 \times 10\ \mu m^2$
$F = 0.2$

N.B. The thermal conductivity must also be considered for ΔT_{max} but not for the maximum power!

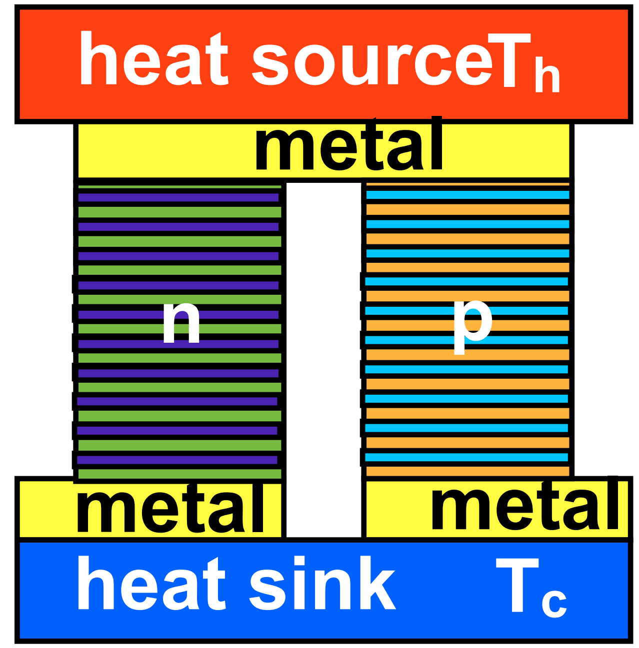
Thermoelectric Low Dimensional Structures

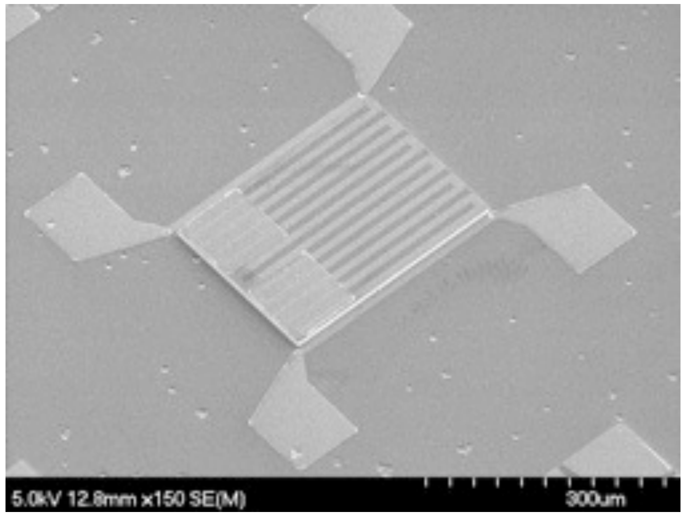


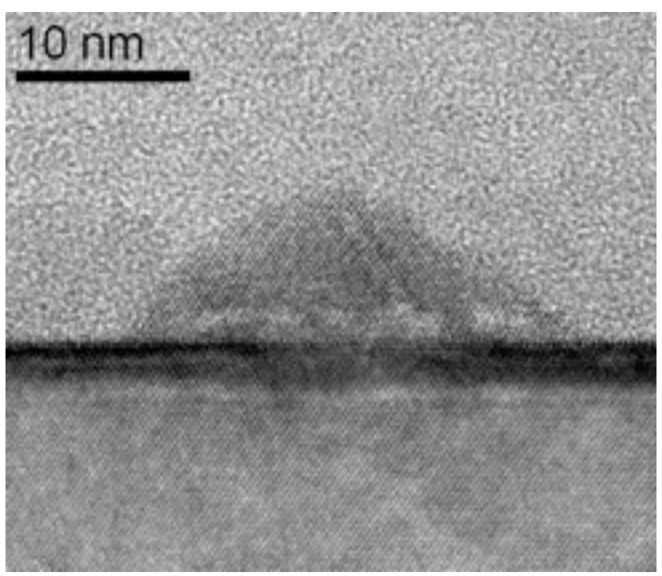
Lateral superlattice



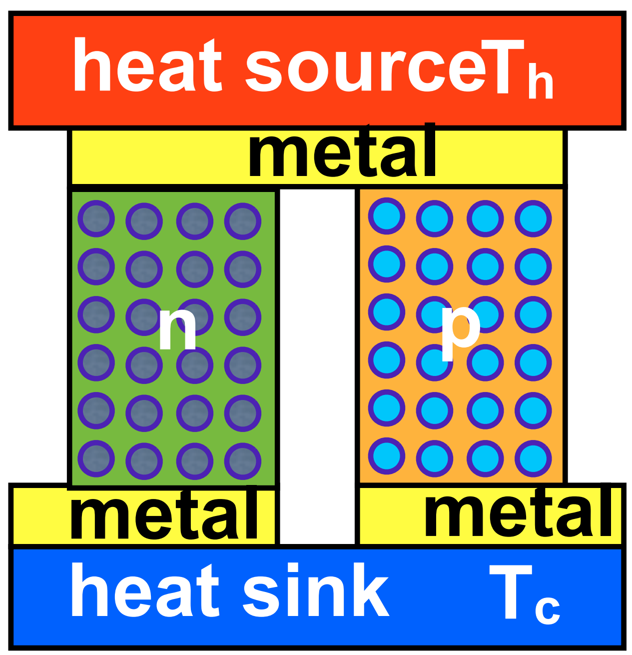
Vertical superlattice



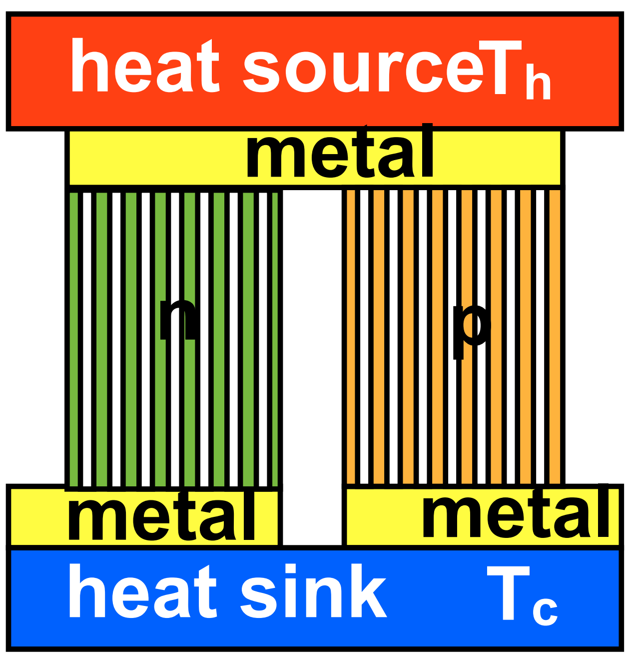


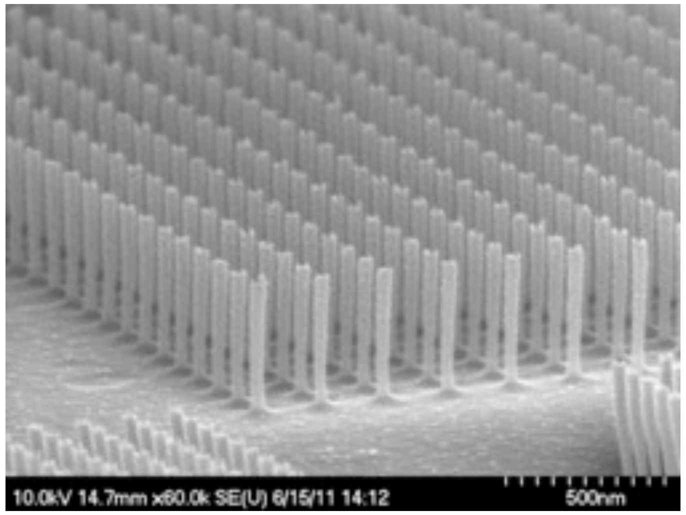


Quantum Dots



Nanowires





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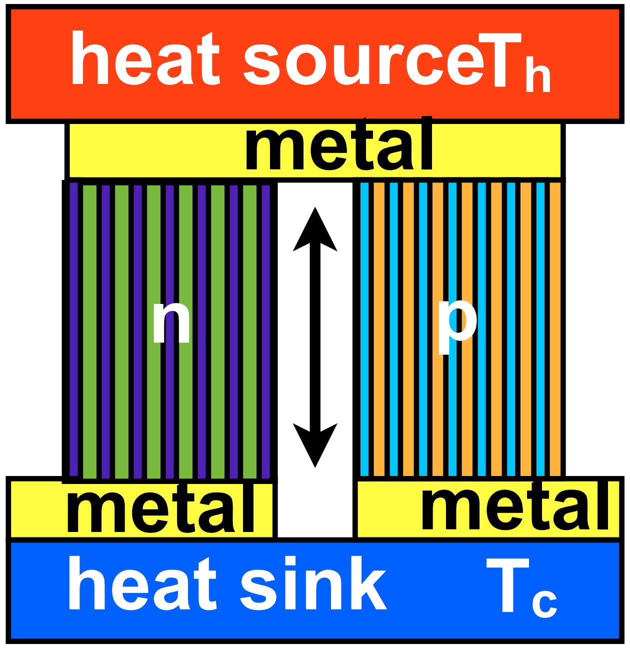
JKU JOHANNES KEPLER UNIVERSITY LINZ
ETH
University of Glasgow

Low Dimensional Structures: 2D Superlattices



- Use of transport along superlattice quantum wells
- Higher α from the higher density of states
- Higher electron mobility in quantum well –> higher σ
- Lower κ_{ph} through additional phonon scattering from heterointerfaces
- Disadvantage: higher κ_{el} with higher σ (but layered structure can reduce this effect)
- Overall Z and ZT should increase

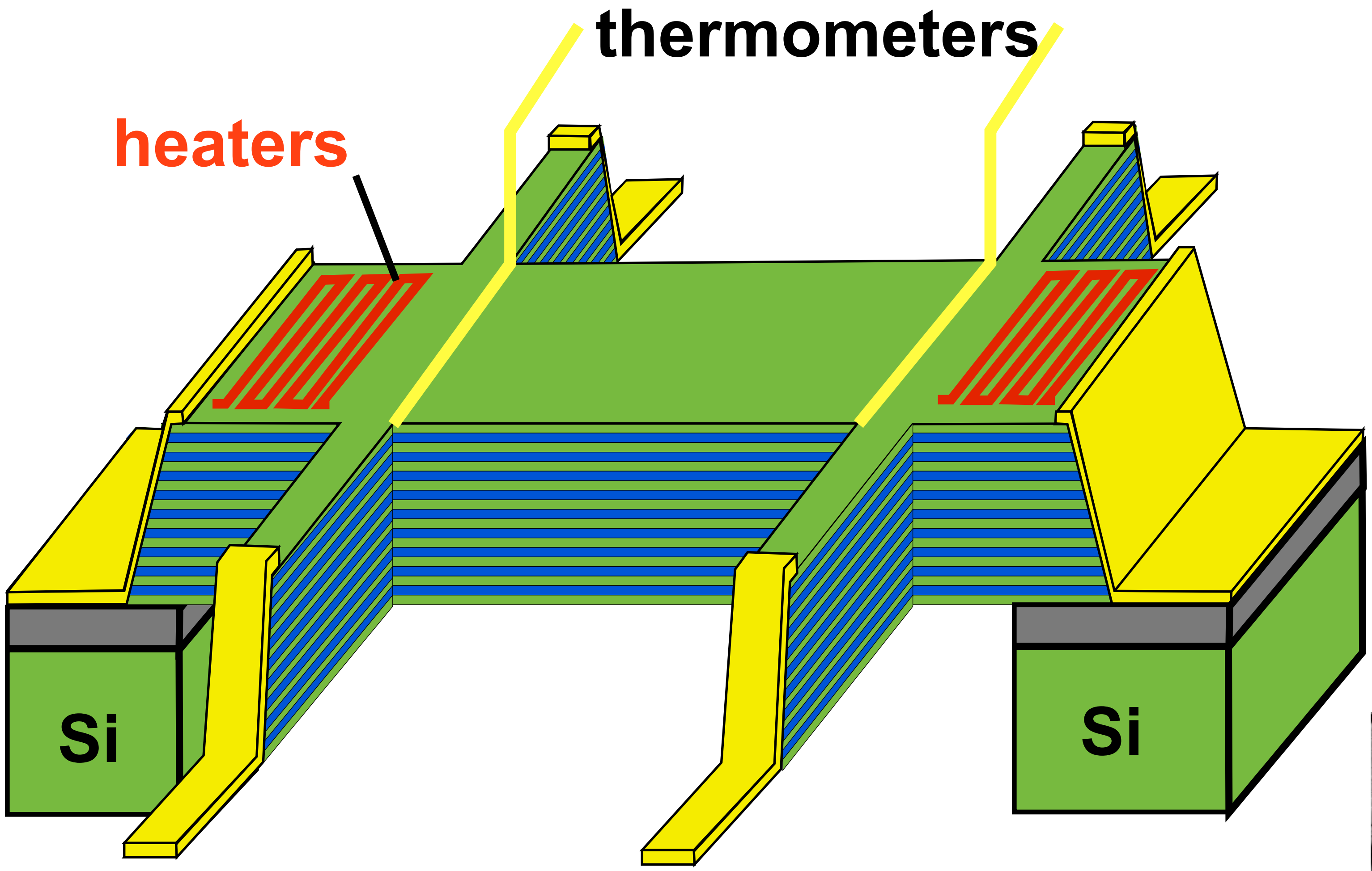
Figure of merit

$$\mathrm{ZT} = \frac{\alpha^2 \sigma}{\kappa} \mathrm{T}$$

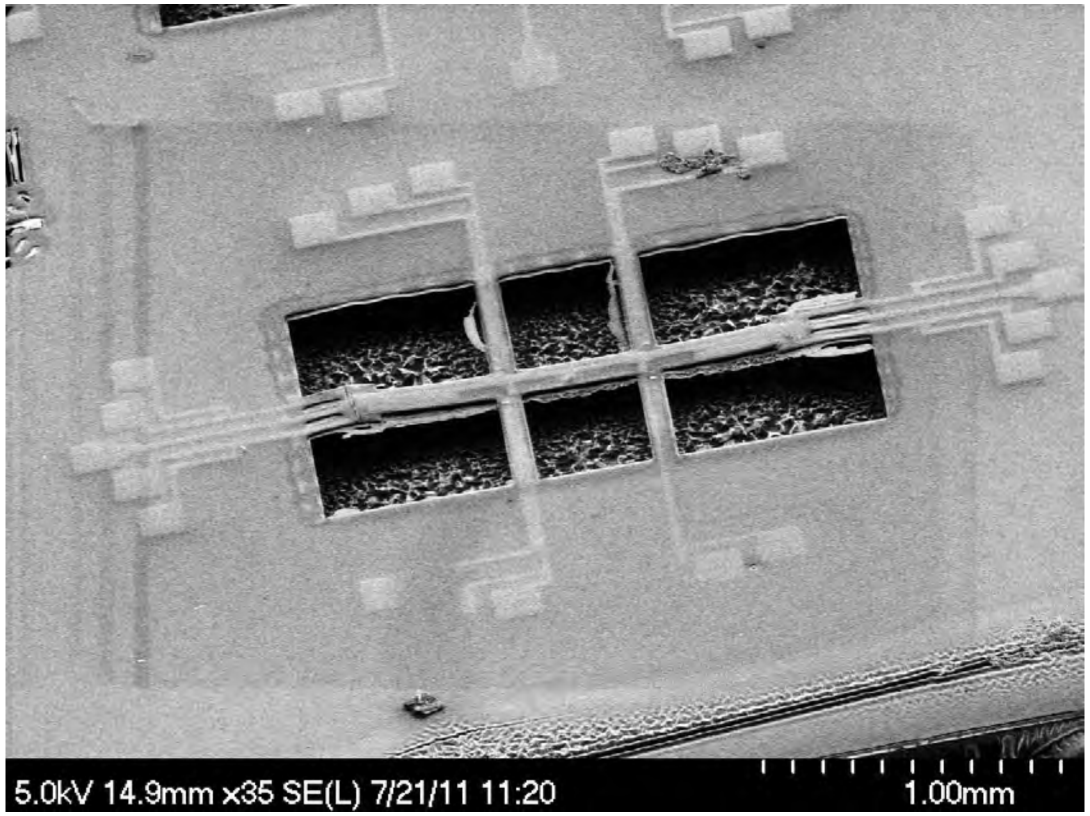
EHC Parker and TE Whall, 1987

L.D. Hicks and M.S. Dresselhaus, Phys. Rev. B 47, 12737 (1993)

Measuring Lateral α, σ, κ and ZT

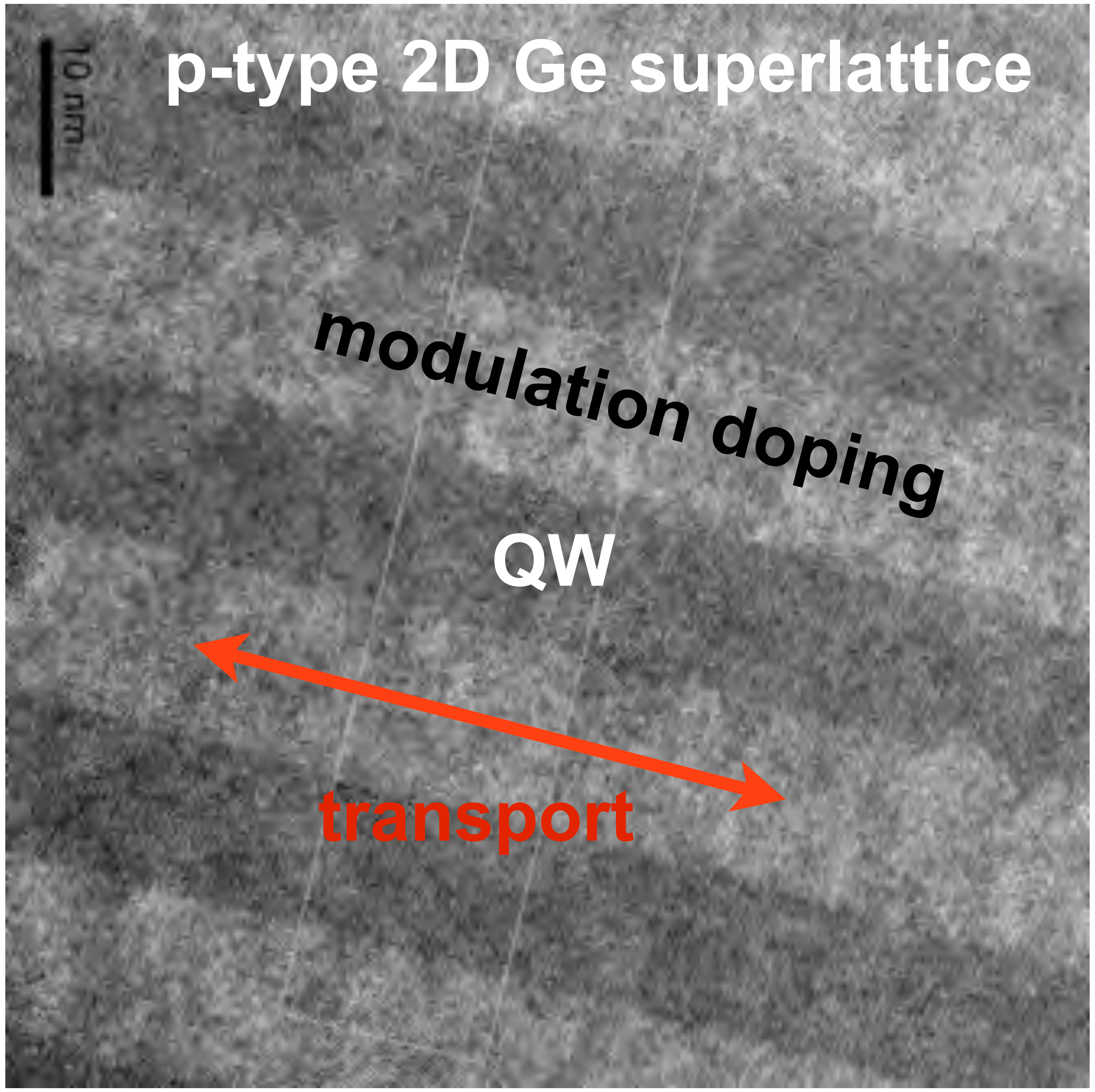


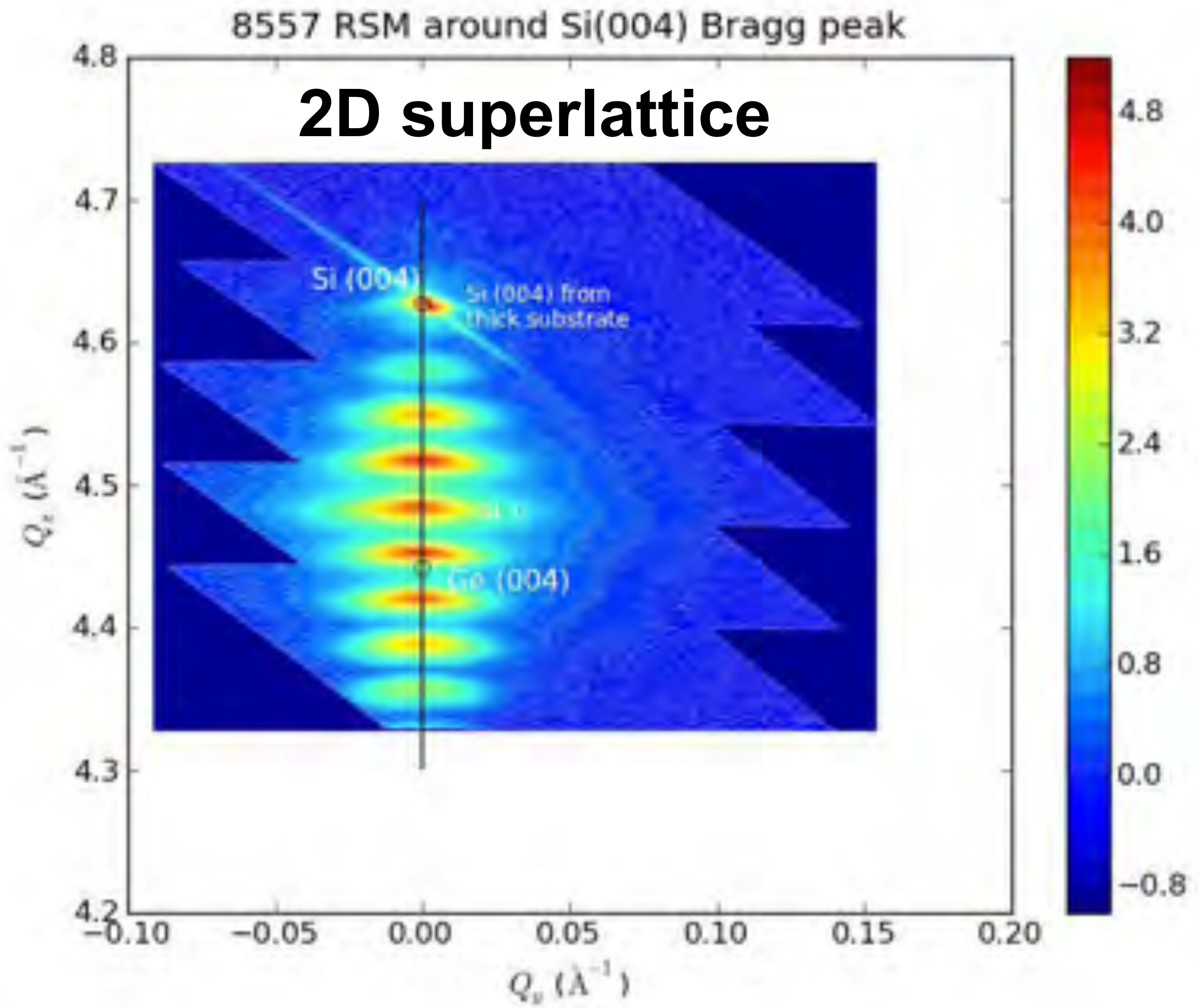
- Hall bar geometry
- Heat transport easier to model



- Accurate electrical measurements easy
- Thermal conductivity most difficult
- Discussions with NPL on EC Metrology Programme

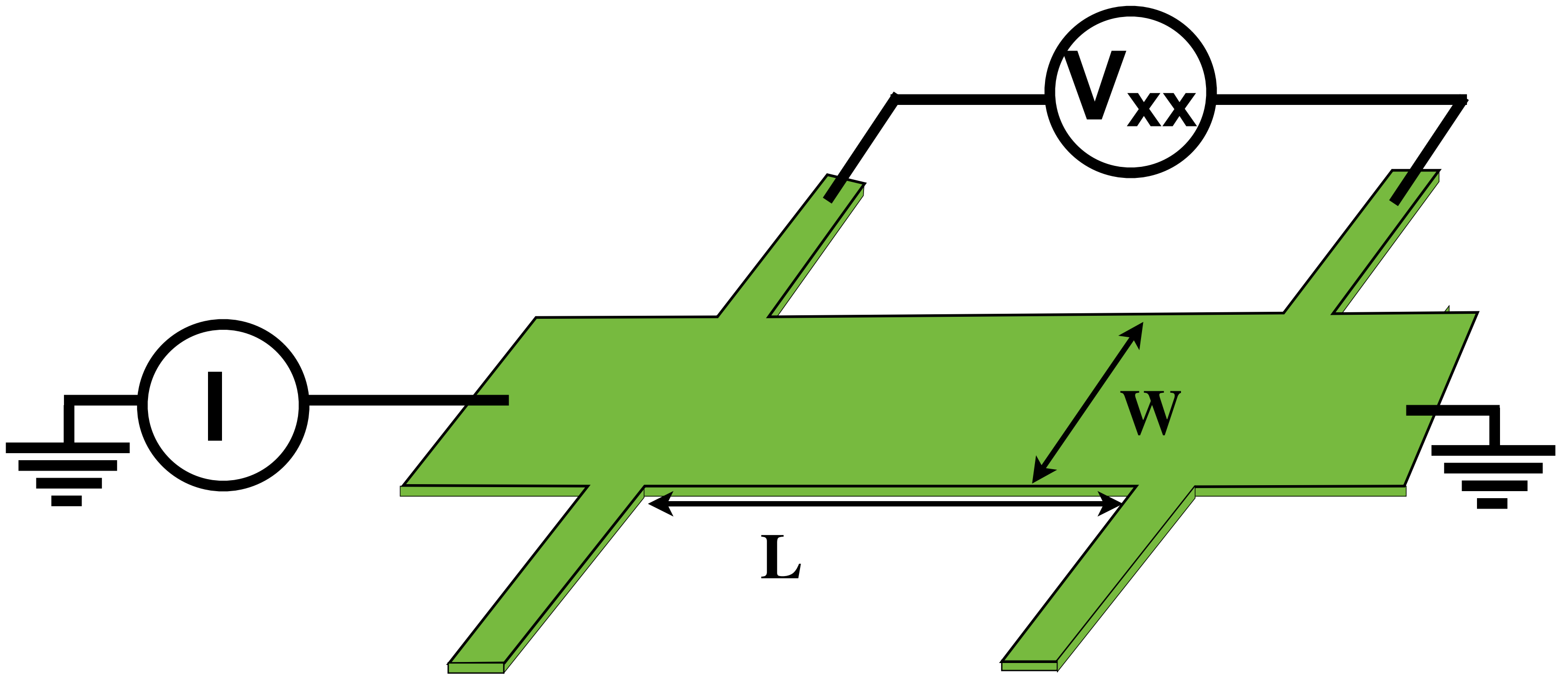
2D p-Ge Modulation Doped Structure 8557

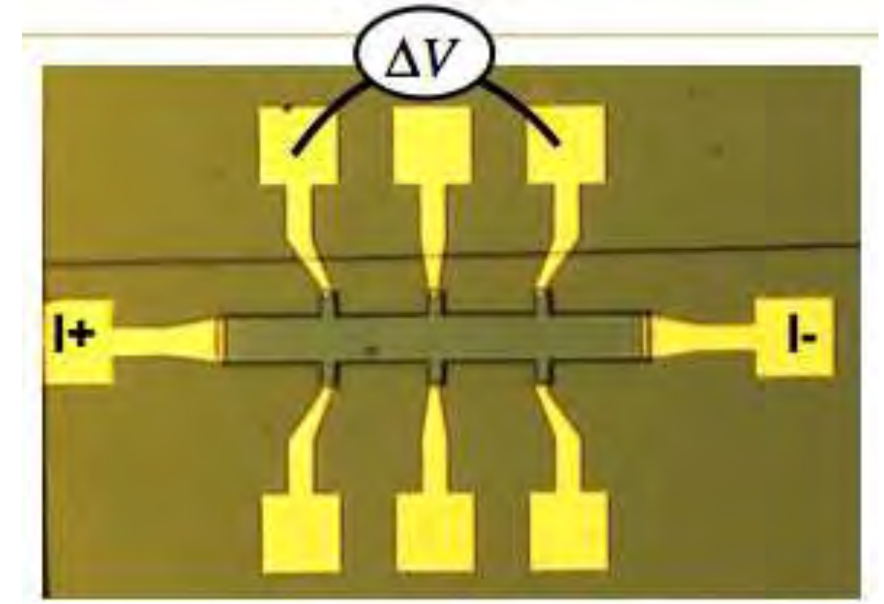




- **TEM & XRD characterisation of 2D modulation-doped superlattice designs**

Electrical Conductivity Measurements p-Ge

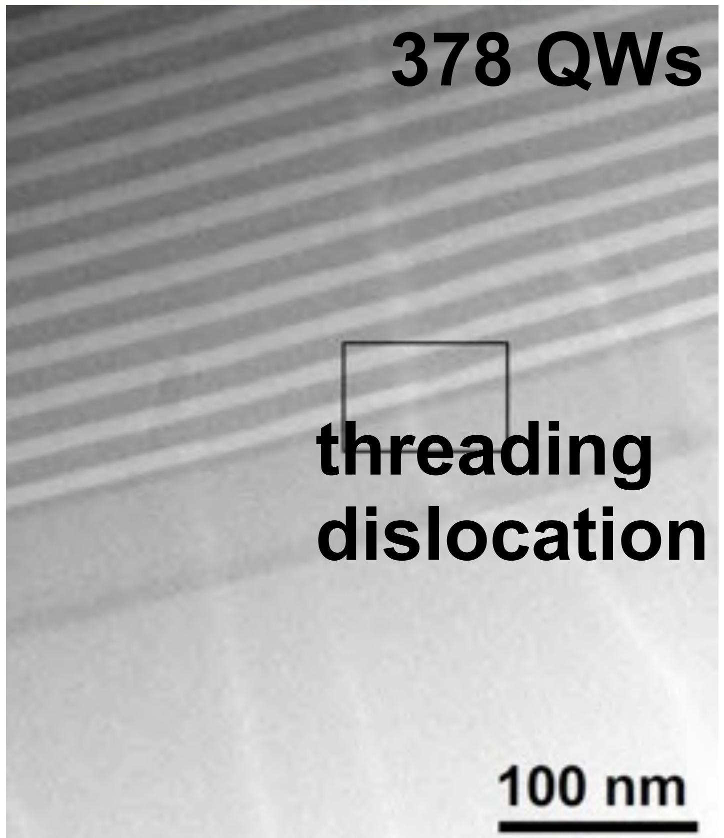




$$\sigma = \frac{IW}{V_{xx}L}$$

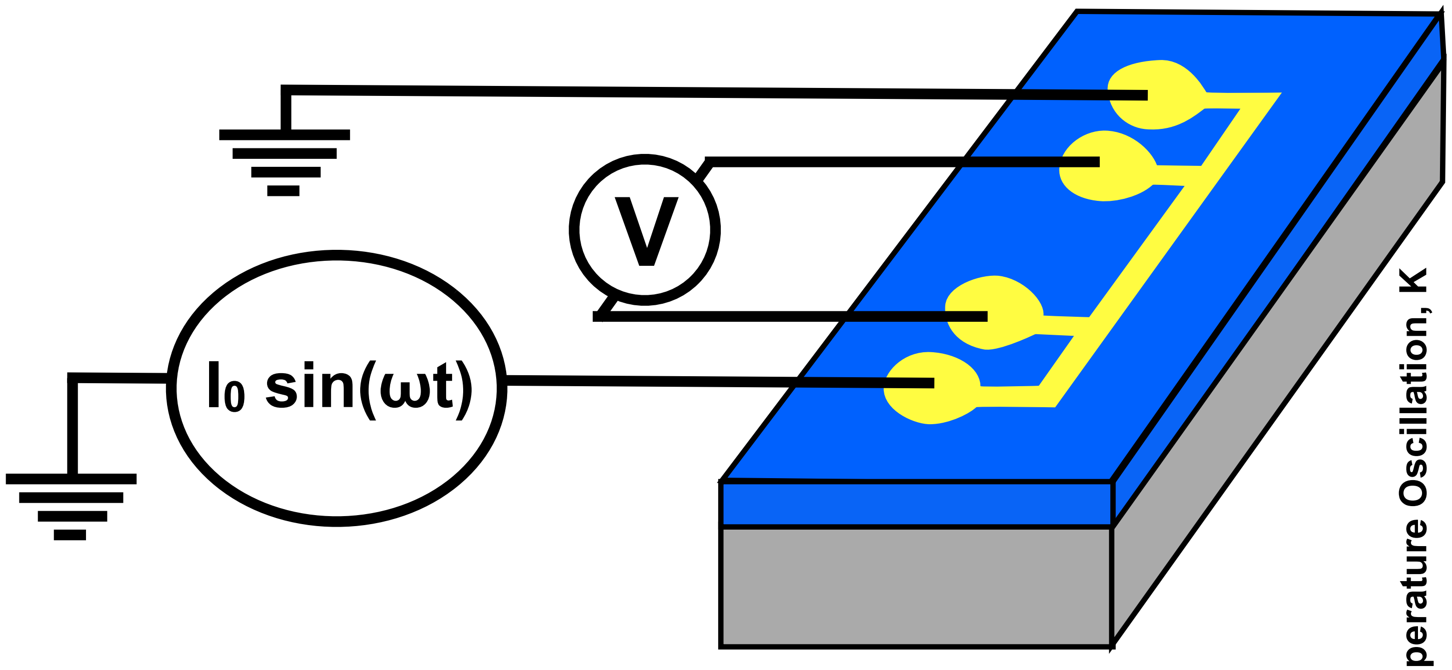
If L > 3W then $\Delta\sigma < 10^{-3}$

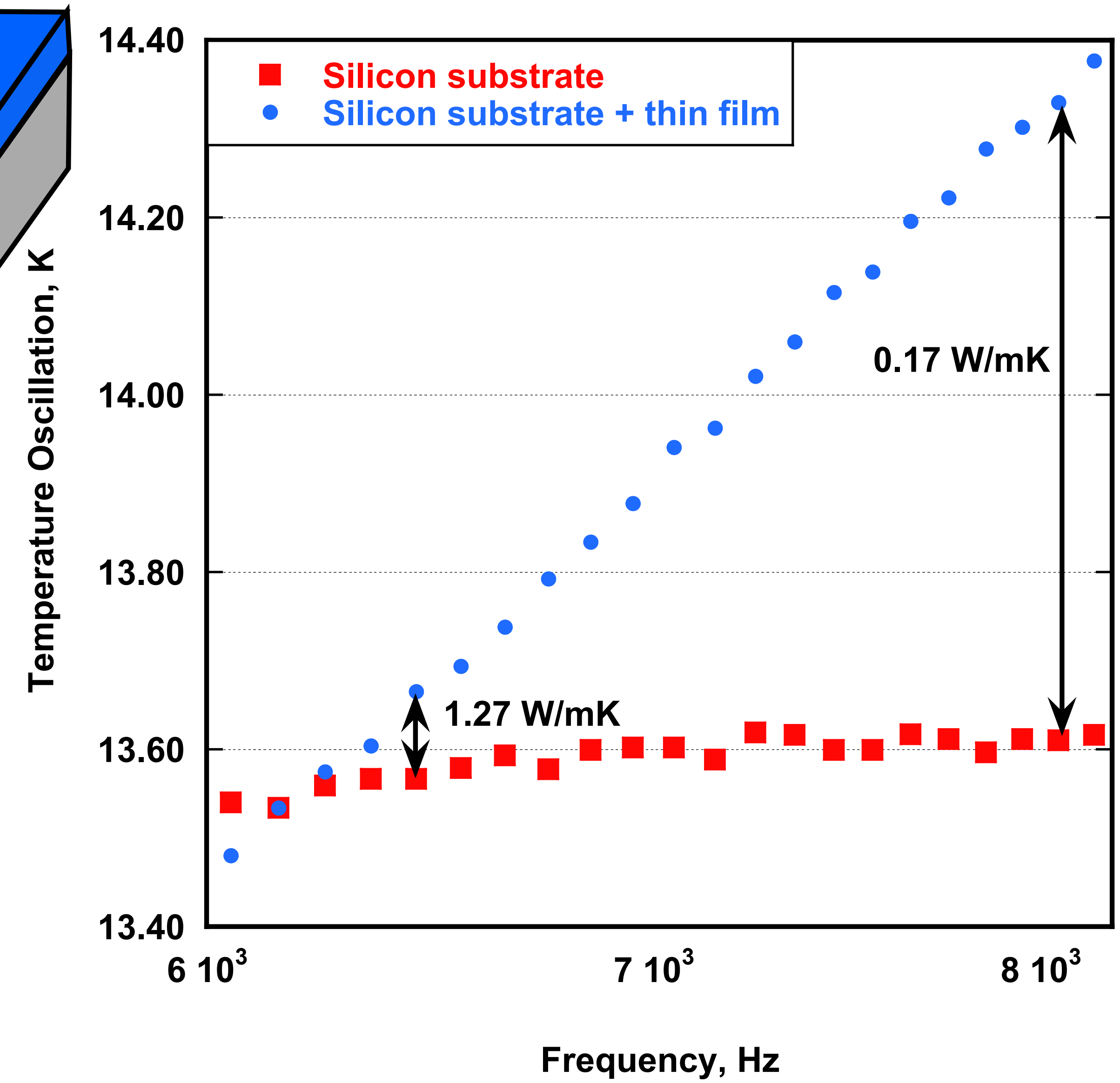
σ = 118,000 ± 15,000 S-m



- **Most measured variations in σ related to non-uniformity of material**

Differential 3ω Thermal Conductivity Measurement



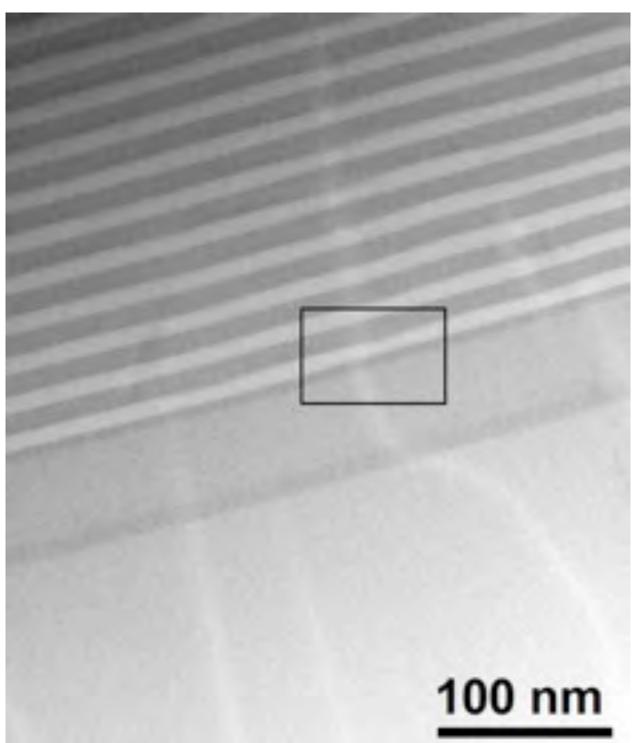


$I \sim \omega$

$T \sim I^2 \sim 2\omega$

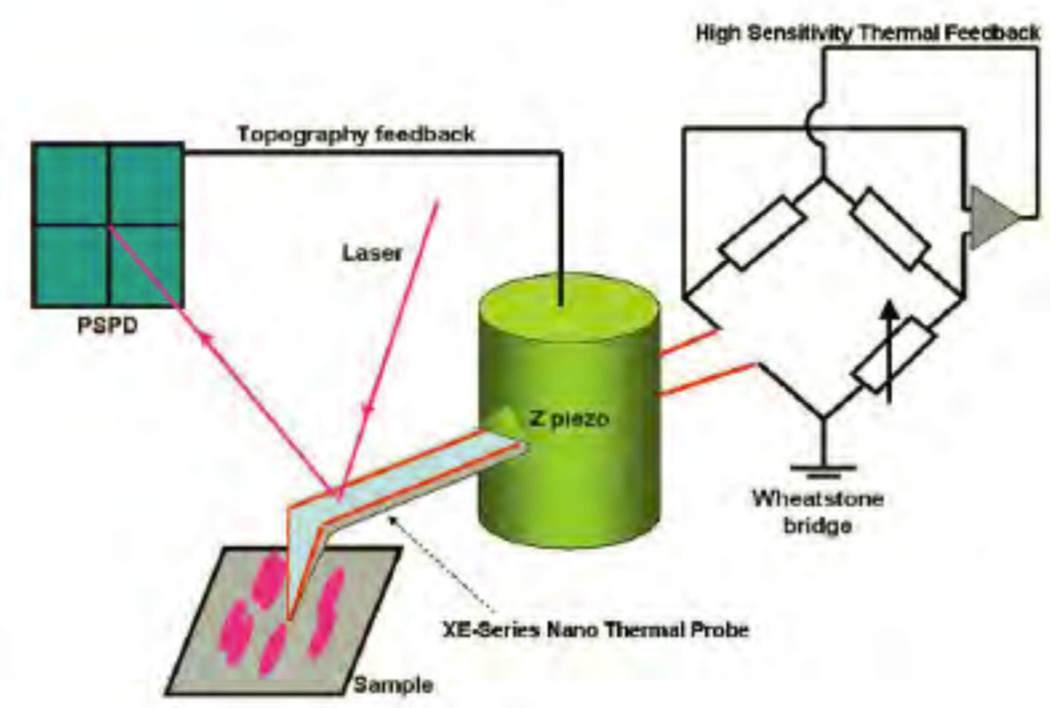
$R \sim T \sim 2\omega$

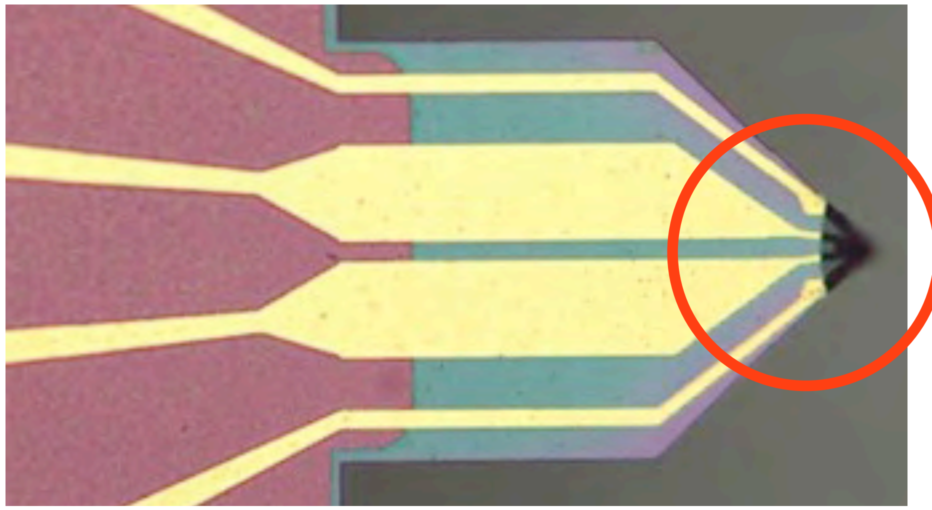
$V = IR \sim 3\omega$

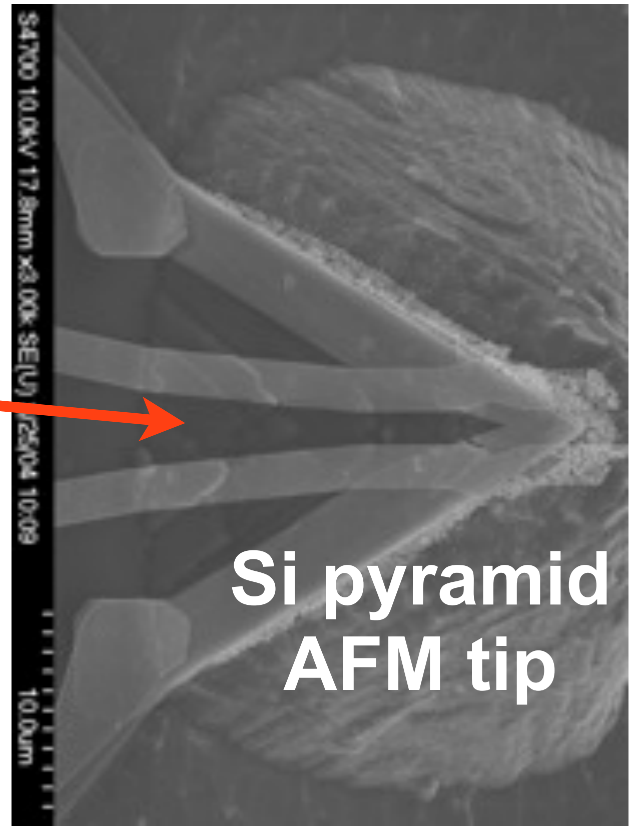


But 3ω technique requires homogenous layers !!!

Thermal Conductivity using Thermal AFM

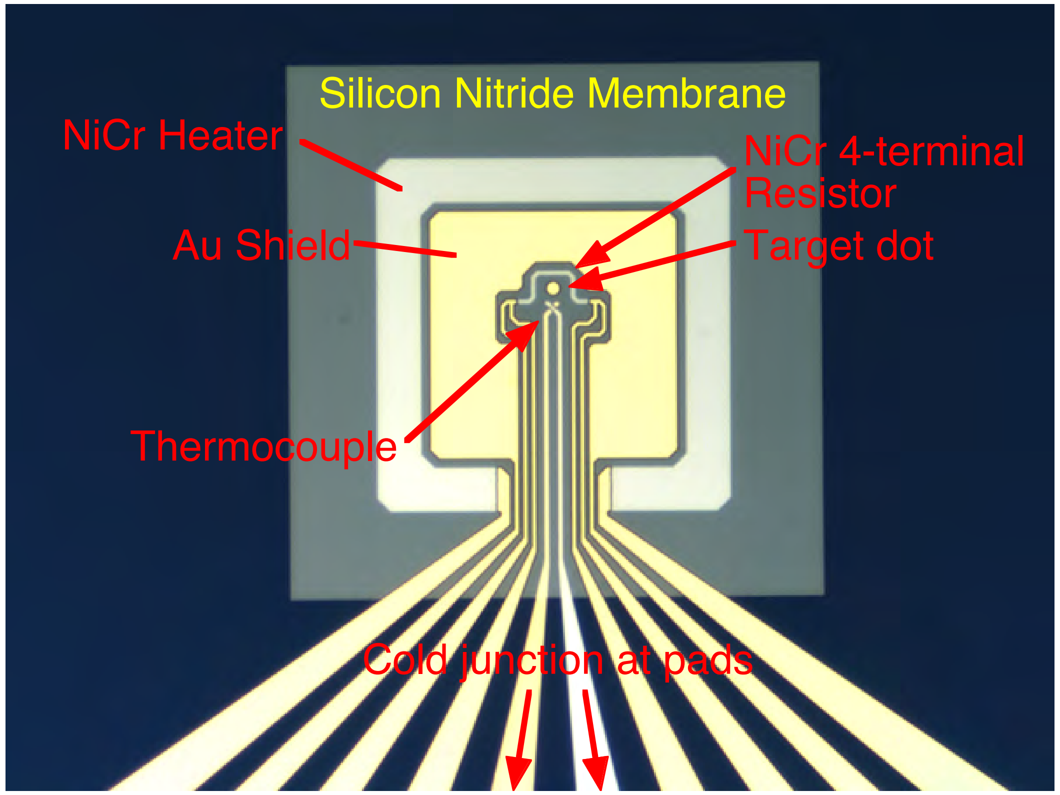


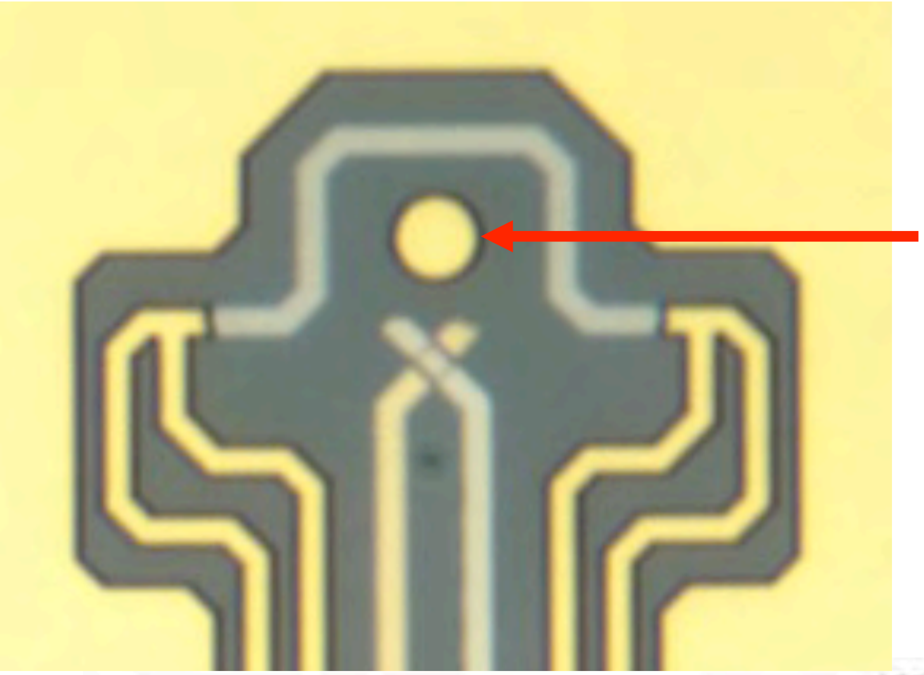




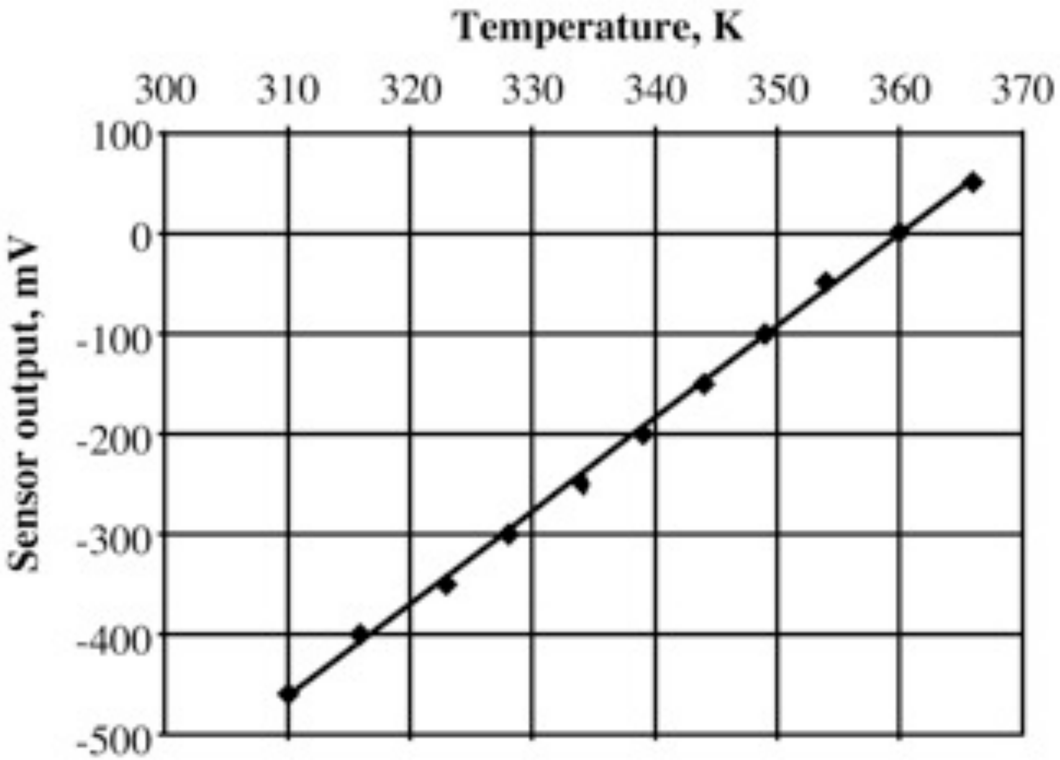
- Spatial resolution < 100 nm (ideal for micro and nano structures)
- Temperature resolution to 0.1 K
- Direct temperature measurements (and 3ω)

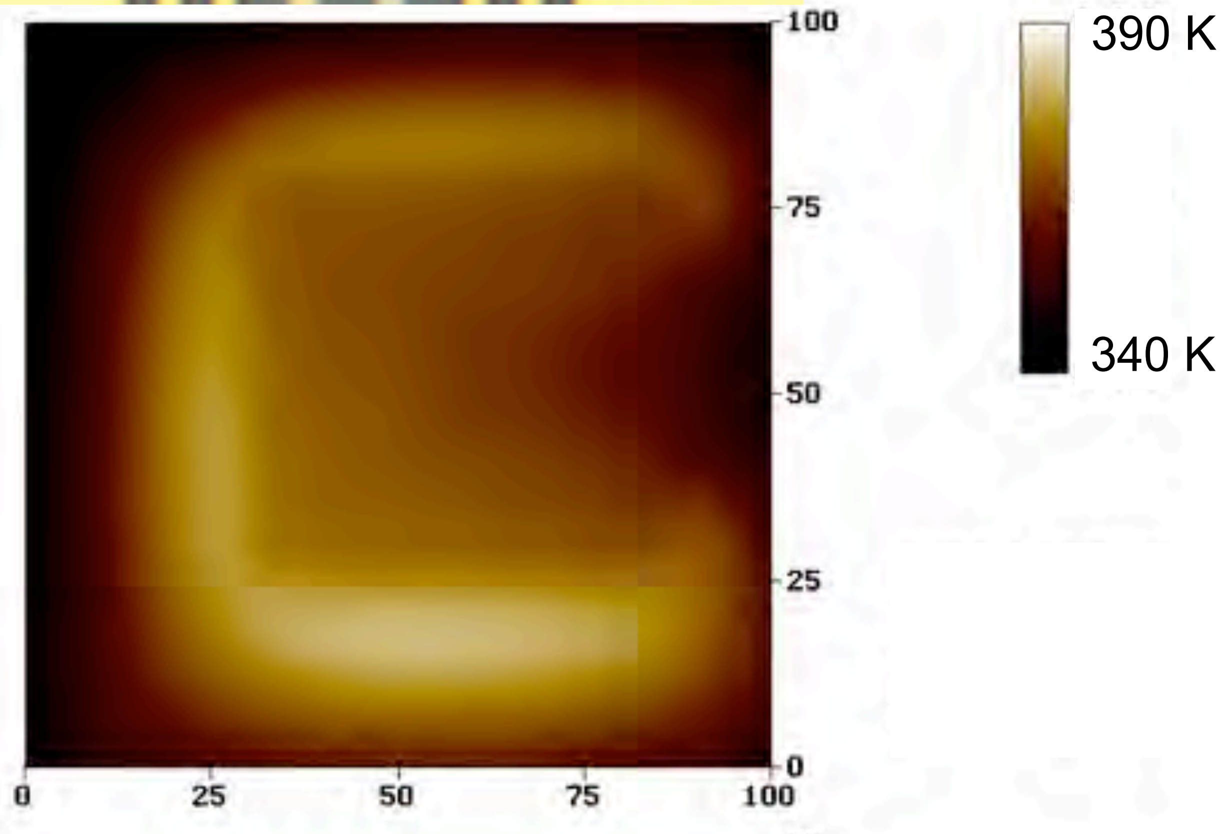
Thermal AFM Calibration





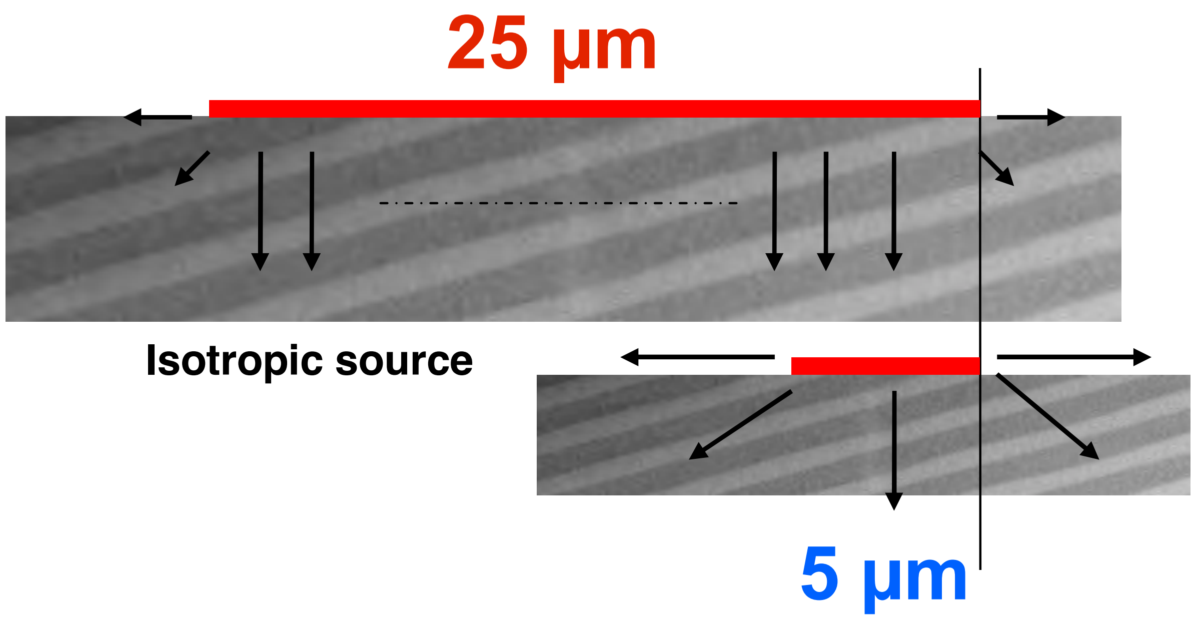
Electrically isolated Au spot: isothermal with resistor



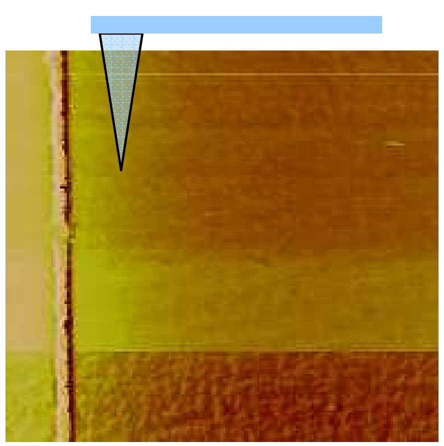


P. S. Dobson, et al., Rev. Sci. Inst. 76, 054901 (2006)

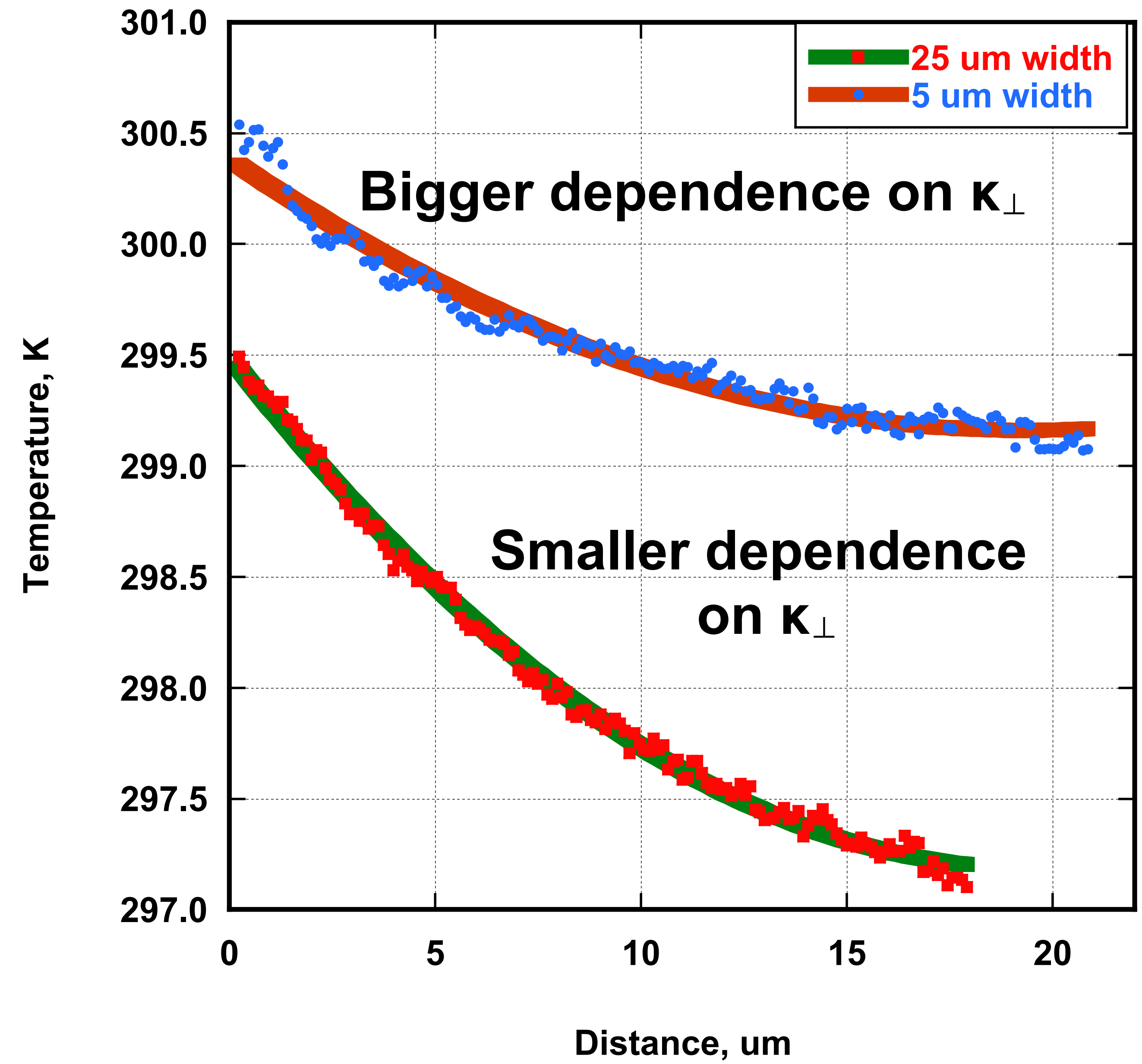
Thermal AFM Measurements p-Ge 8557



Voltage → Temperature vs position

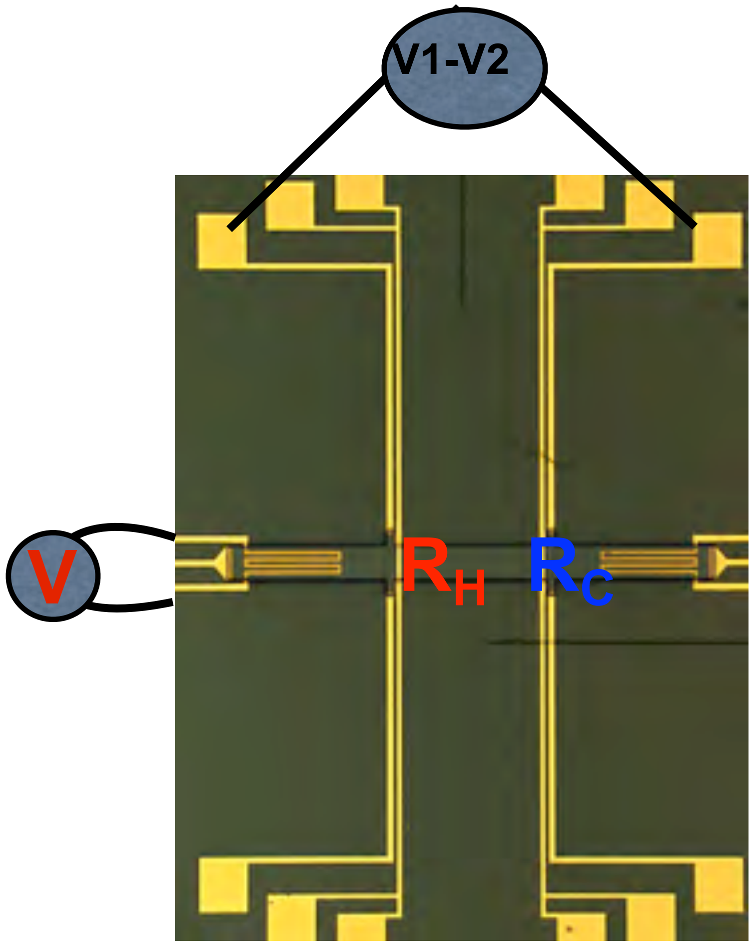


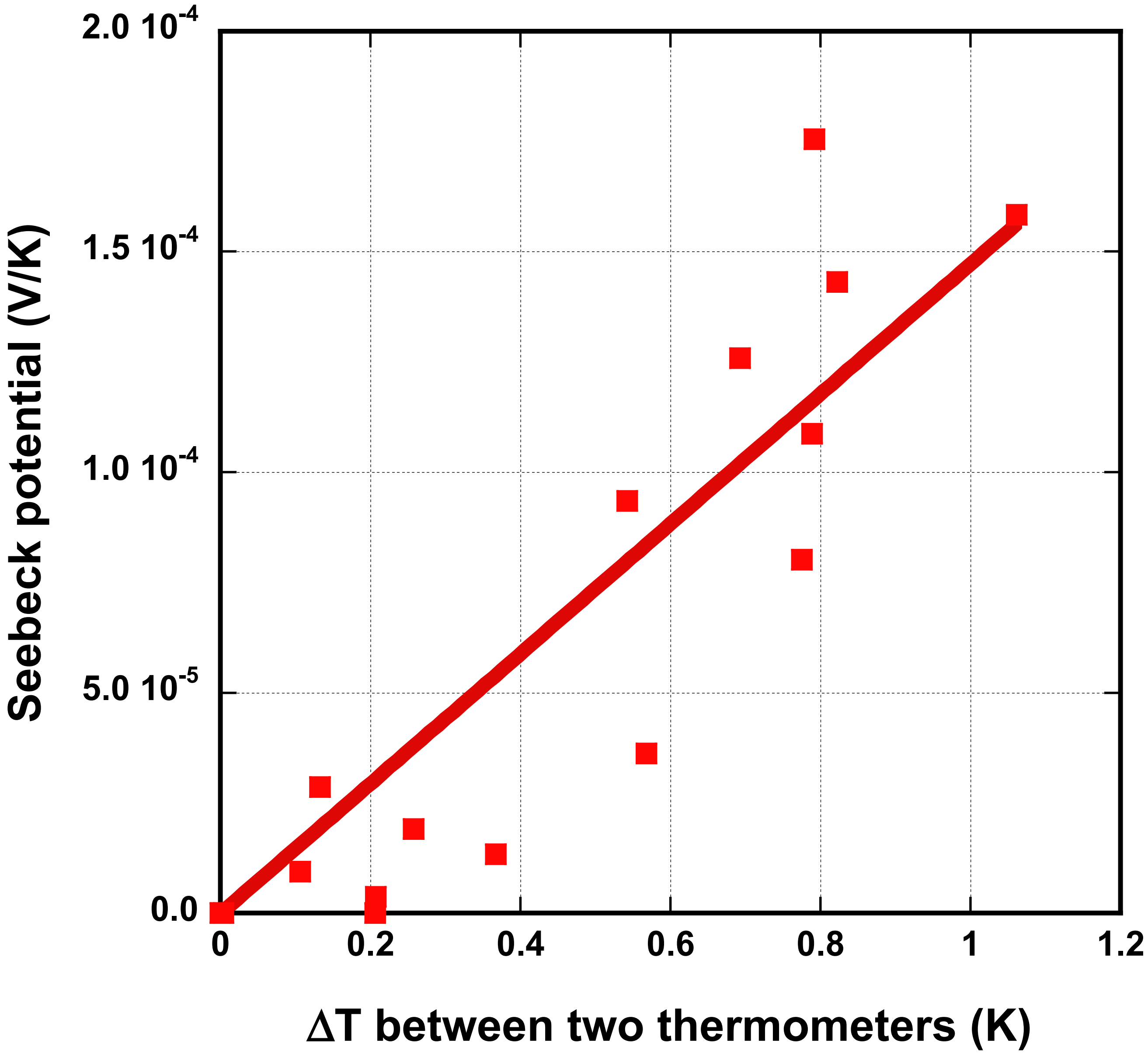
Calibrated thermocouple
+
Johnson noise compensation



κ = 6.36 ± 0.20 W/mK

Seebeck Coefficient Measurements





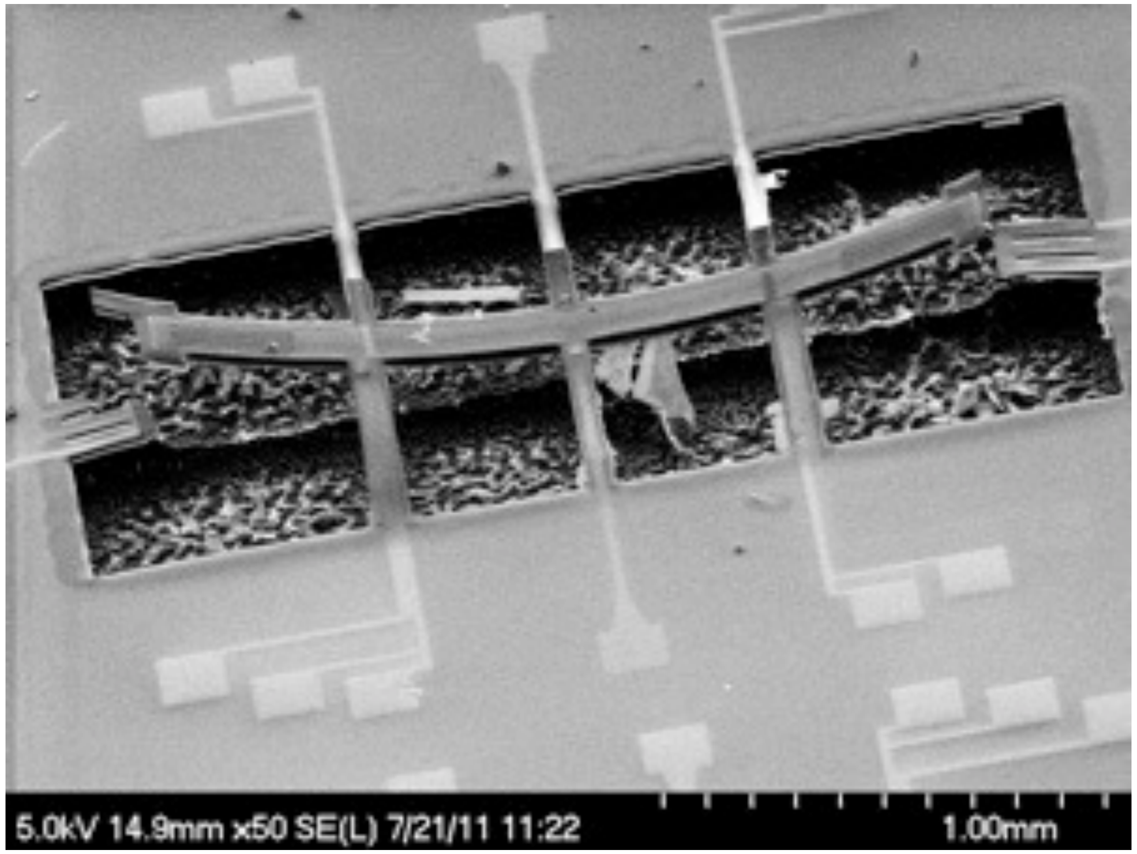
- Apply voltage through one heater
- Measure the ΔV across bar
- Check
- Reverse the voltage
- Reverse the Bar

α = 150 ± 13 μV/K

Strong influence of the substrate: need to remove the substrate for feasible measurements

SiGe Hall Bar with Substrate Removal

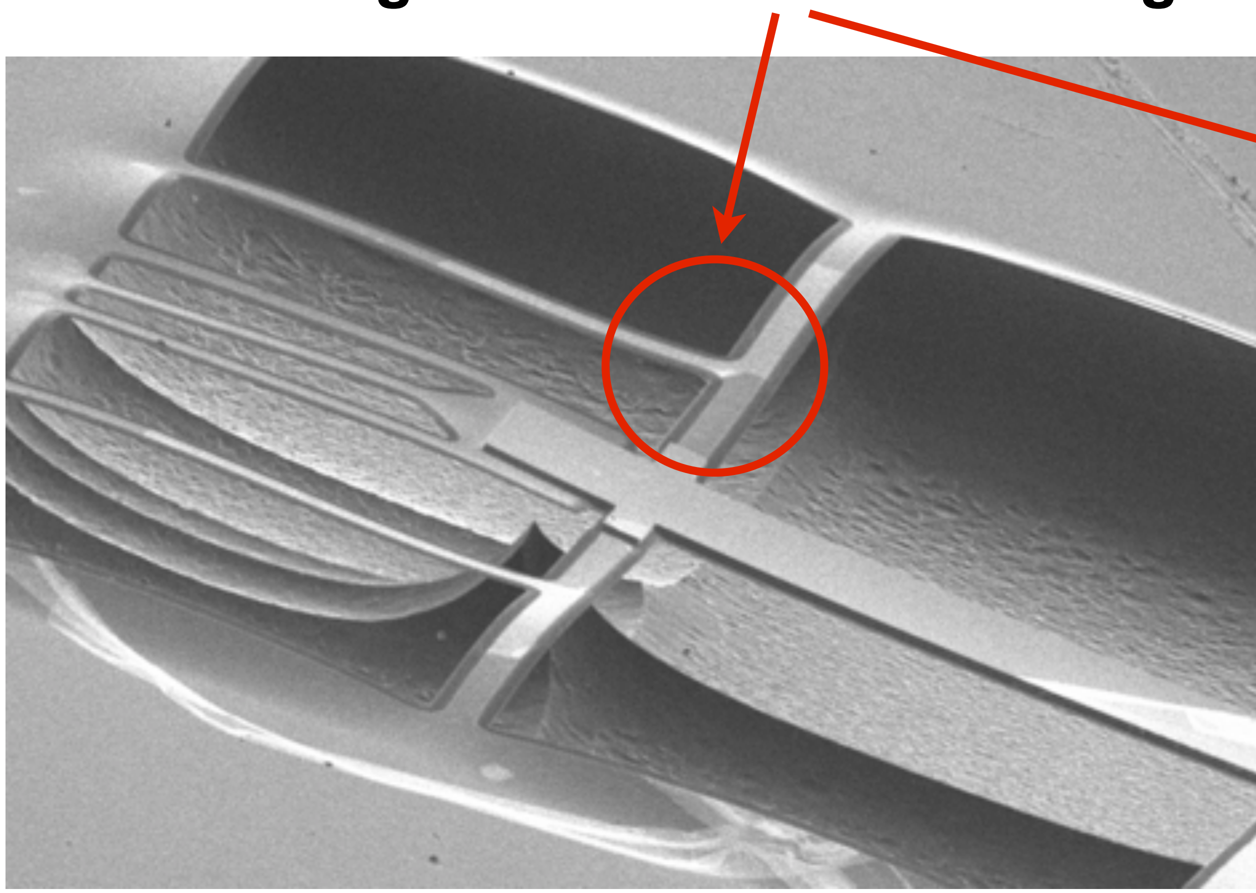
Strain balancing required to make measurements of the thermal conductivity and Seebeck coefficient

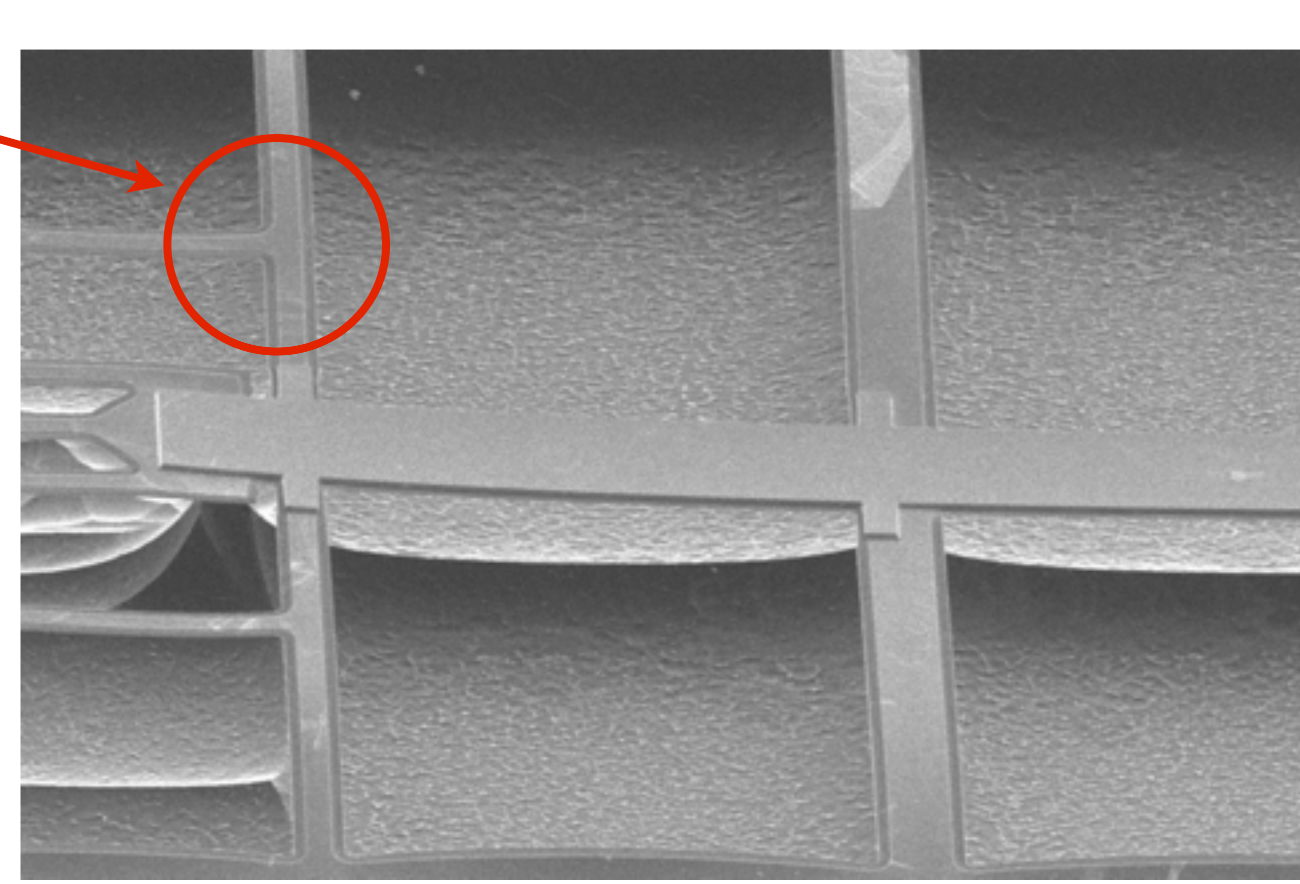


- **Improvements in the material quality**
- **Scaling of the dimension of the Hall Bar (Length and width)**
- **Change in the geometry of the Hall Bar- Silica support structure:**
- **Elimination corners, sharp edges, increase in the number of supports**

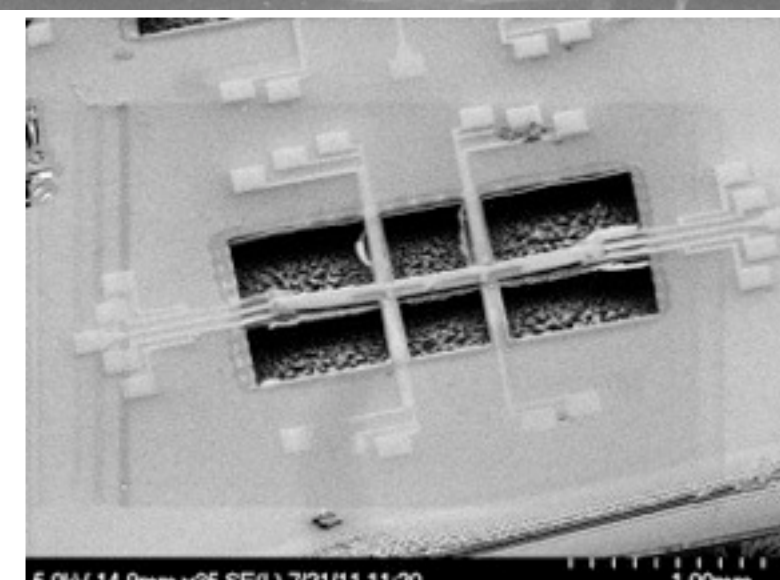
Seebeck Coefficient / Thermopower

- Large Hall Bars (about 1.5 and 2 mm long)
- Adding some mechanical strength to the actual devices.



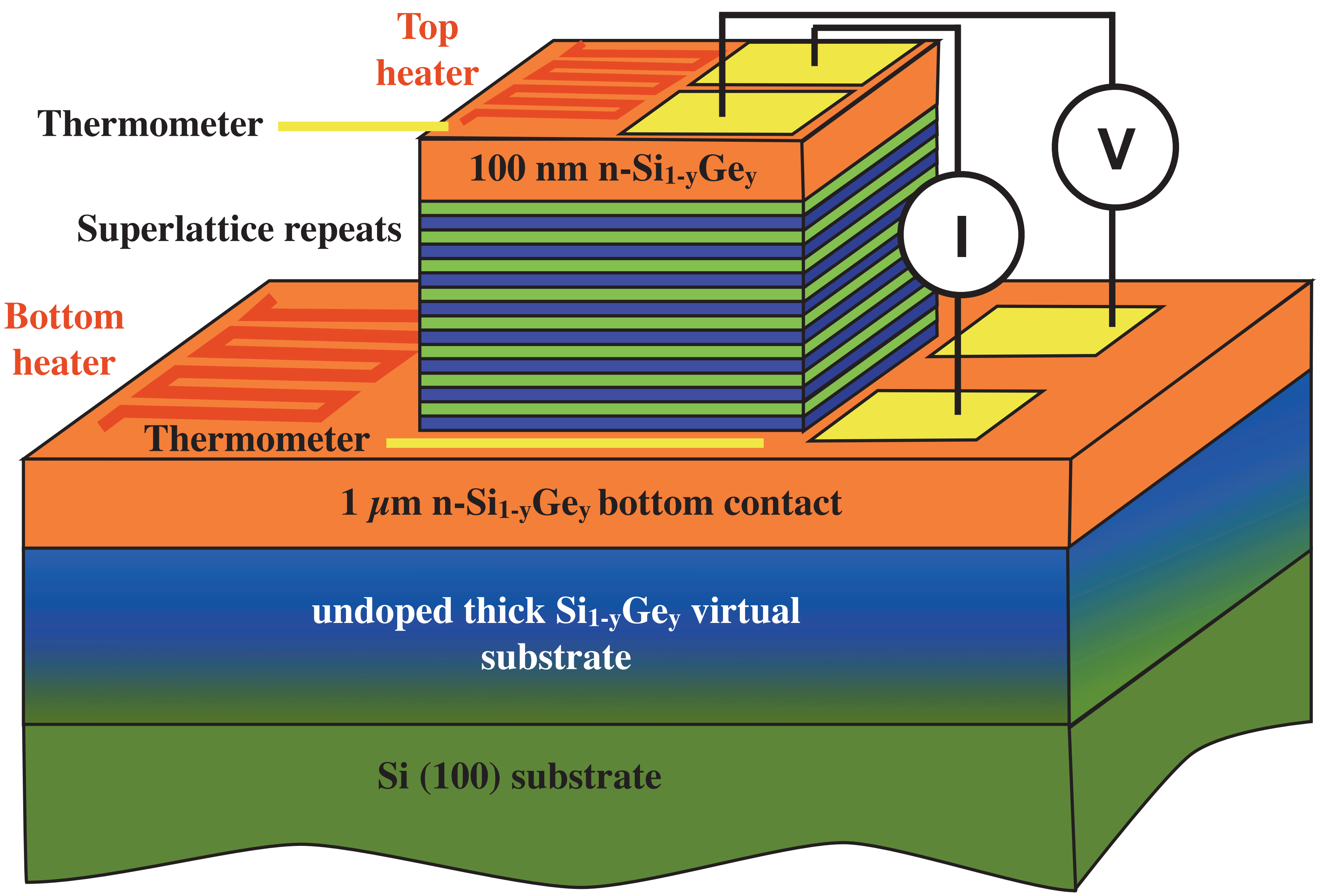


- Patterning new shorter Hall Bars to help the curvature of the membranes.



ZT Measurements of Vertical Devices

ZT Device Schematic Diagram

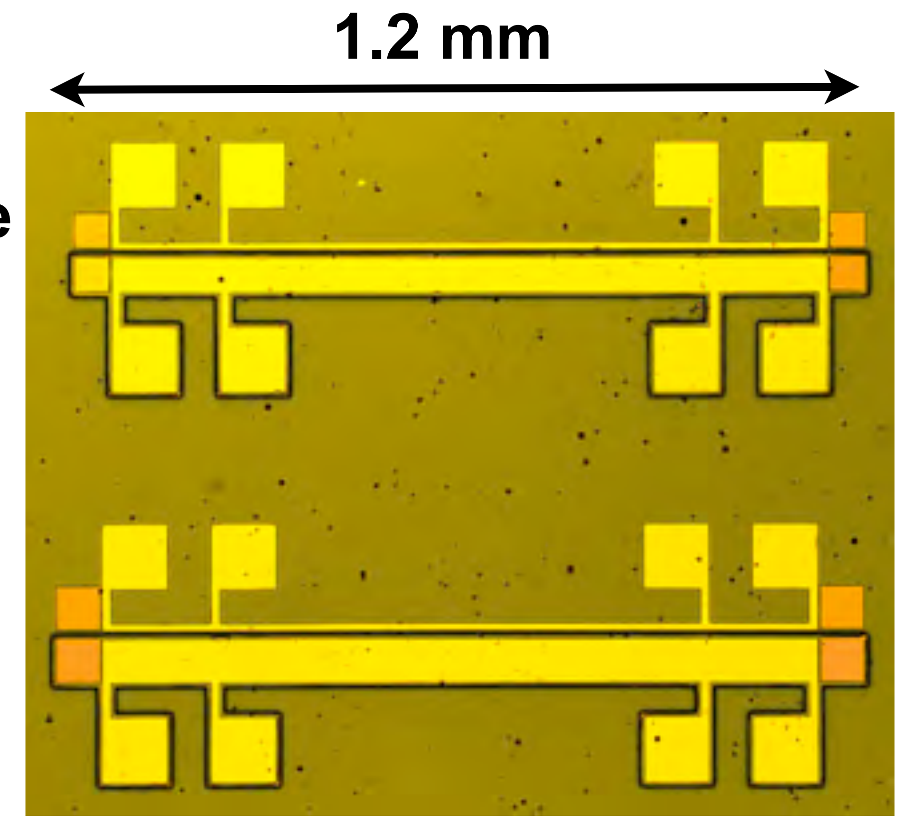


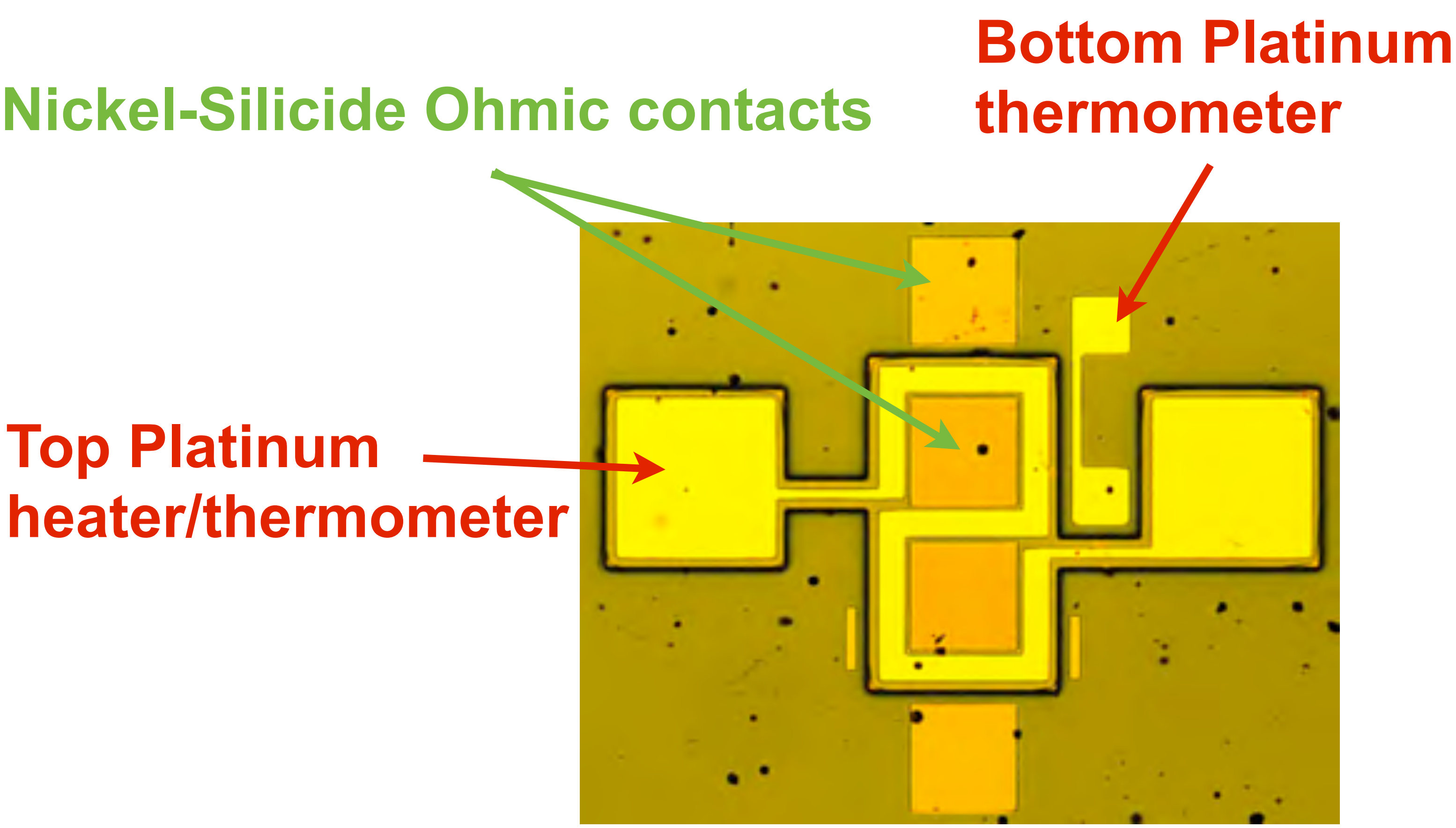
Potential enhancements:

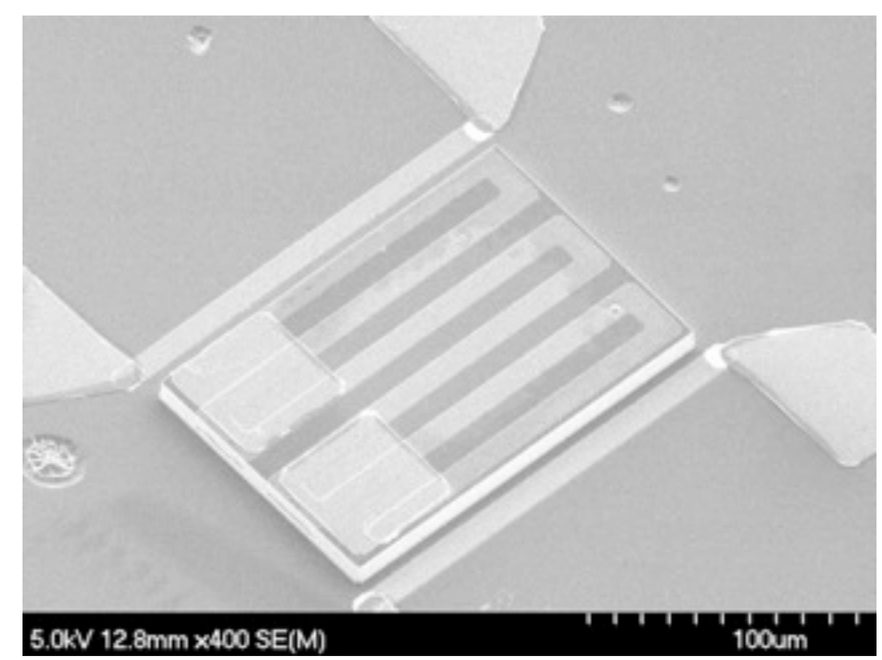
- Seebeck from low dimensions
- Phonon scattering barriers
- Phonon bandgaps / stationary phonons

Vertical devices

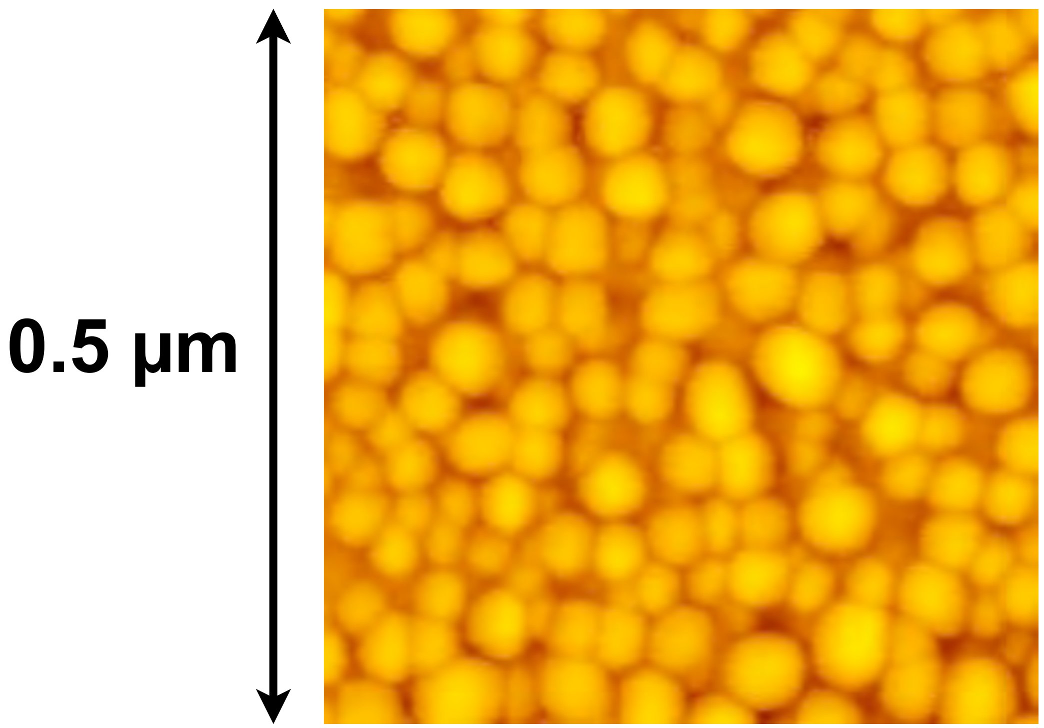
- Different geometries to evaluate vertical properties of the material.
- Heaters used as thermometers to reduce the top surface area of the Mesa -> reduced thermal gradients across in plane surfaces.
- Homogeneous heat flux along out-of-plane direction. Temperature cross calibration using thermal AFM

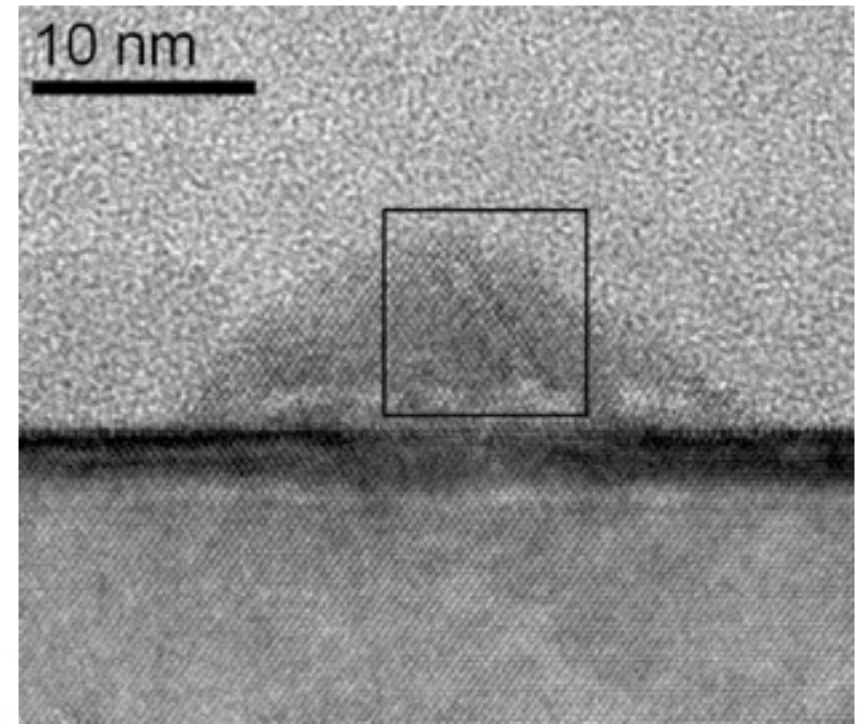


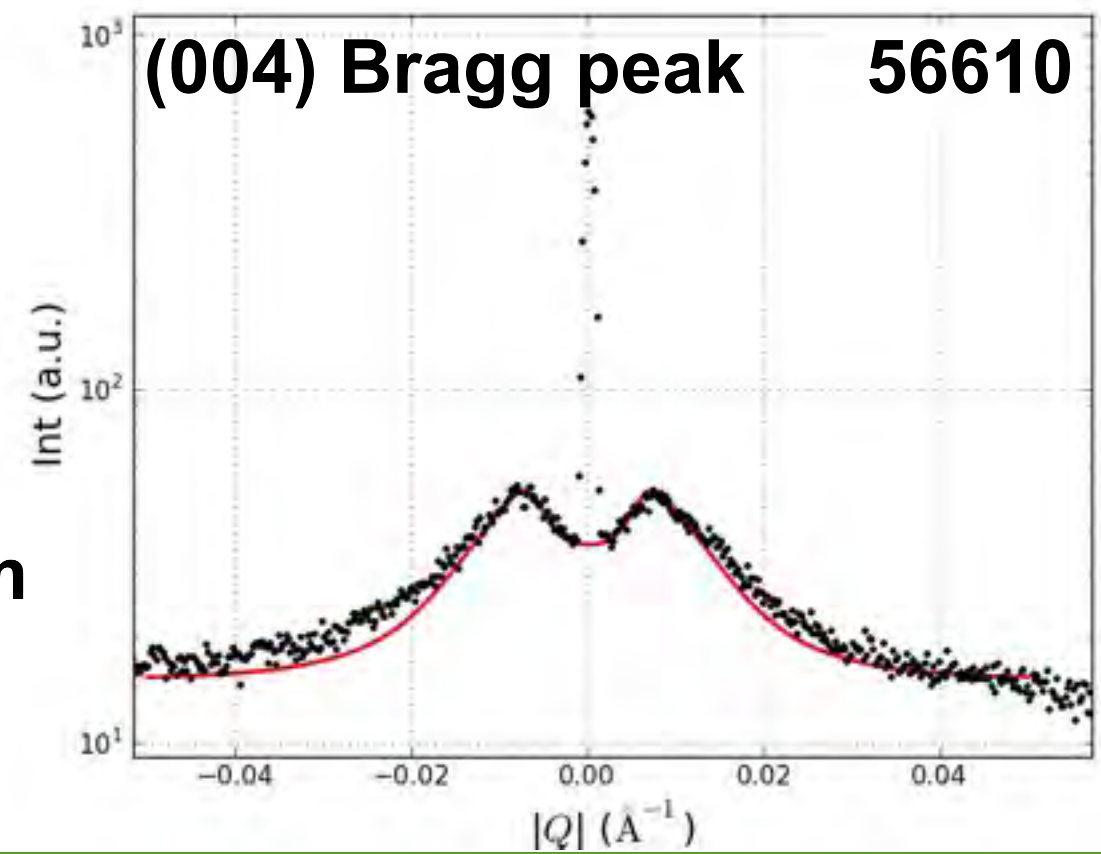




0D Ge Quantum Dots



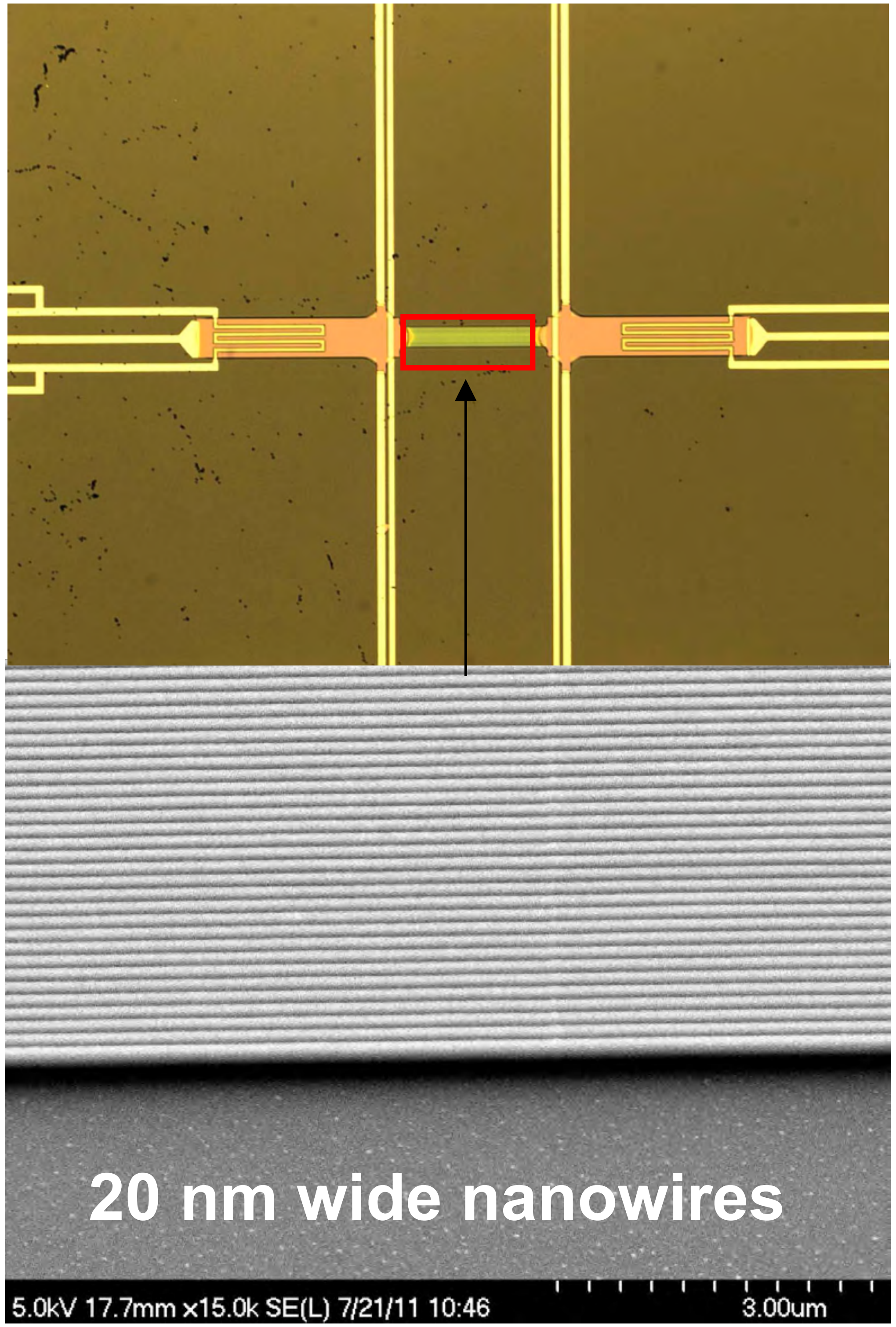




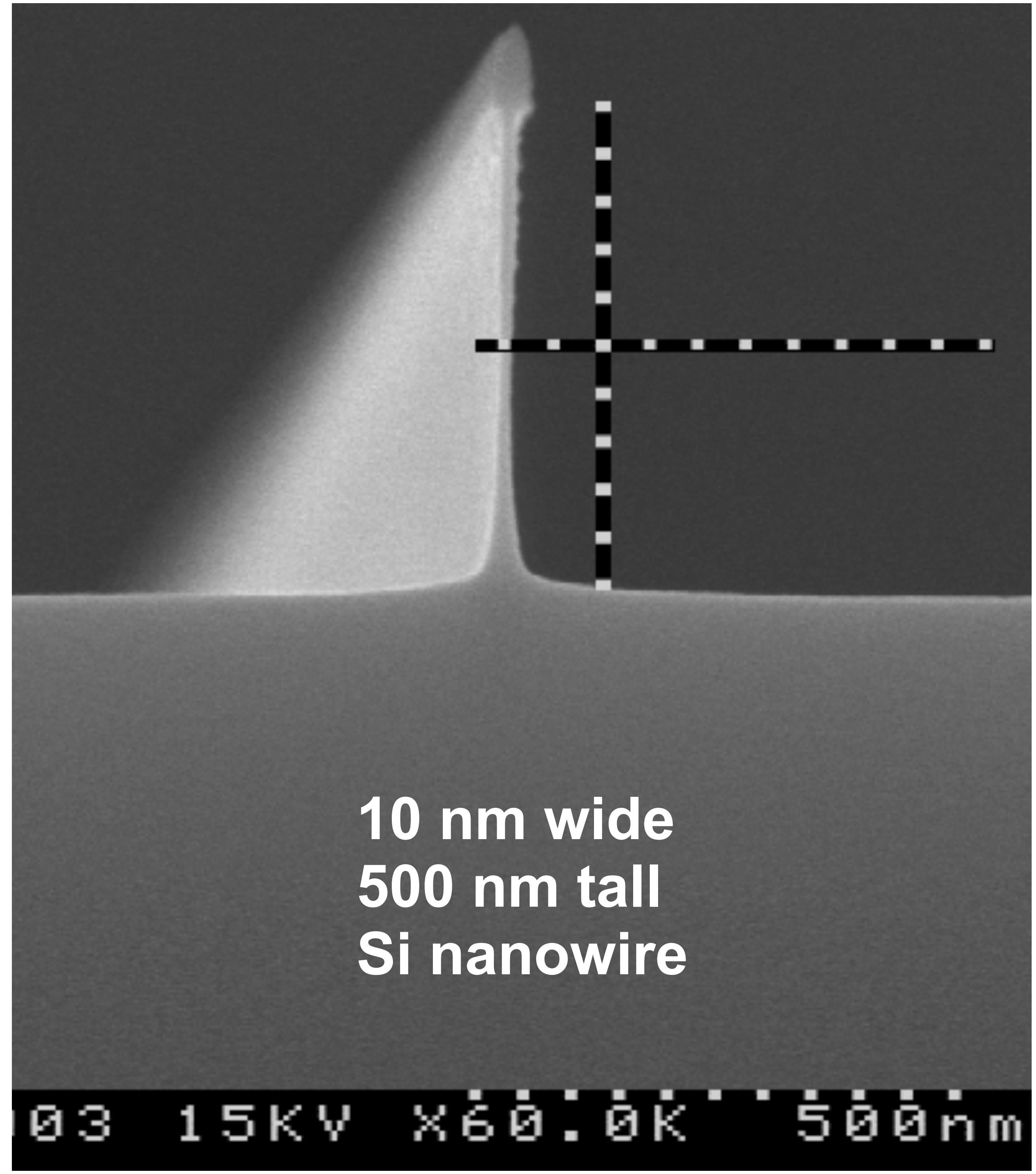
- **Phonon scatterers**
- **XRD mean dot size 8 ± 5 nm**
- **XRD mean dot spacing 14 ± 14 nm**
- **i.e. uncorrelated dots**

1D Si Nanowires

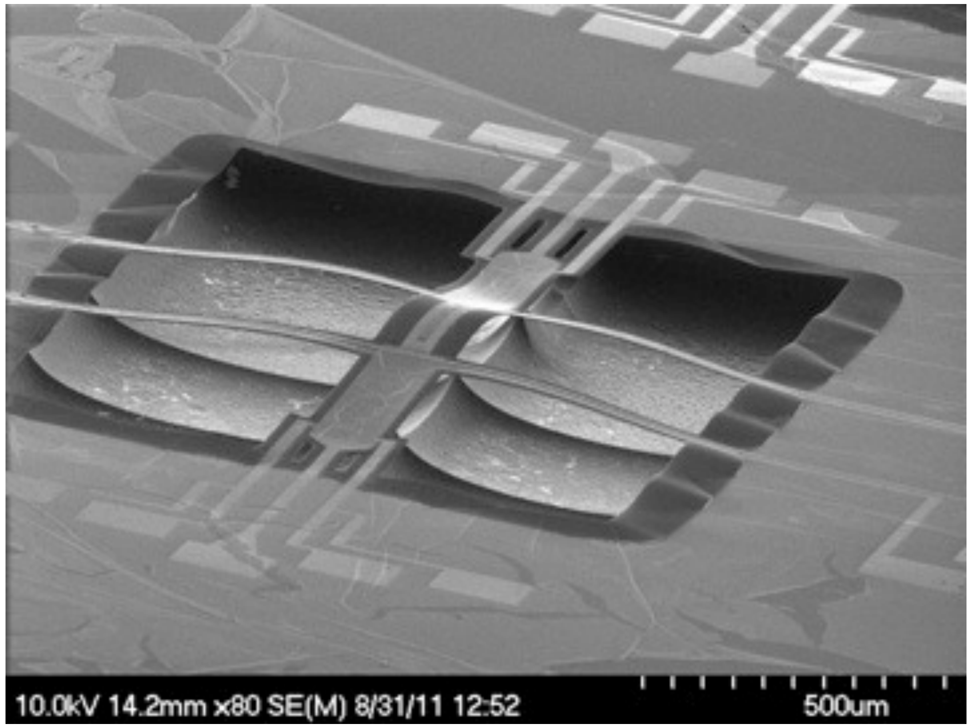
Lateral Nanowires

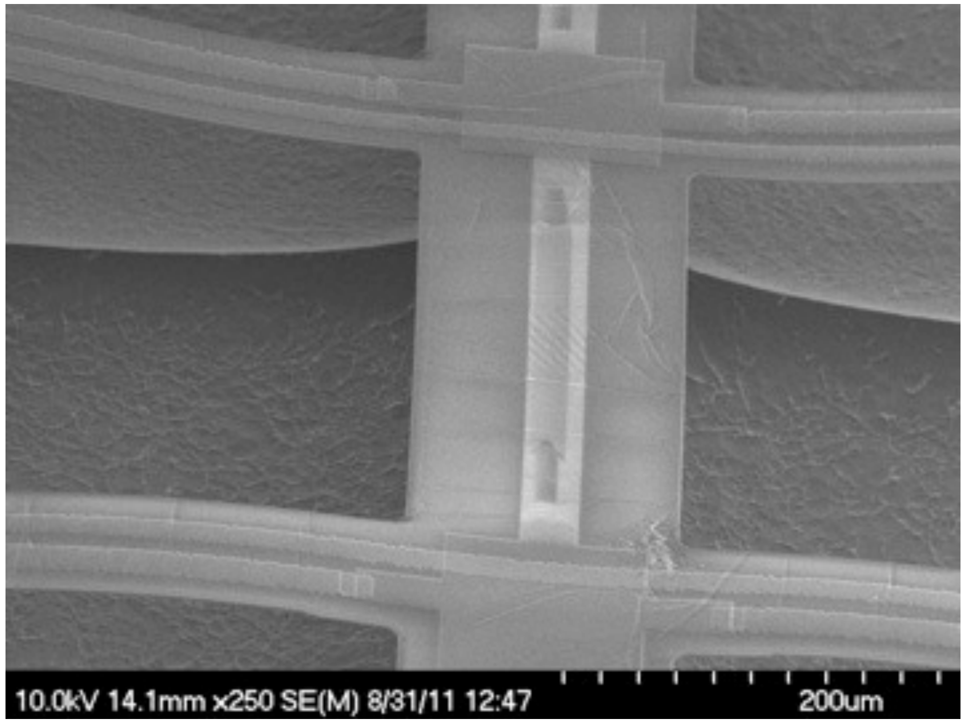


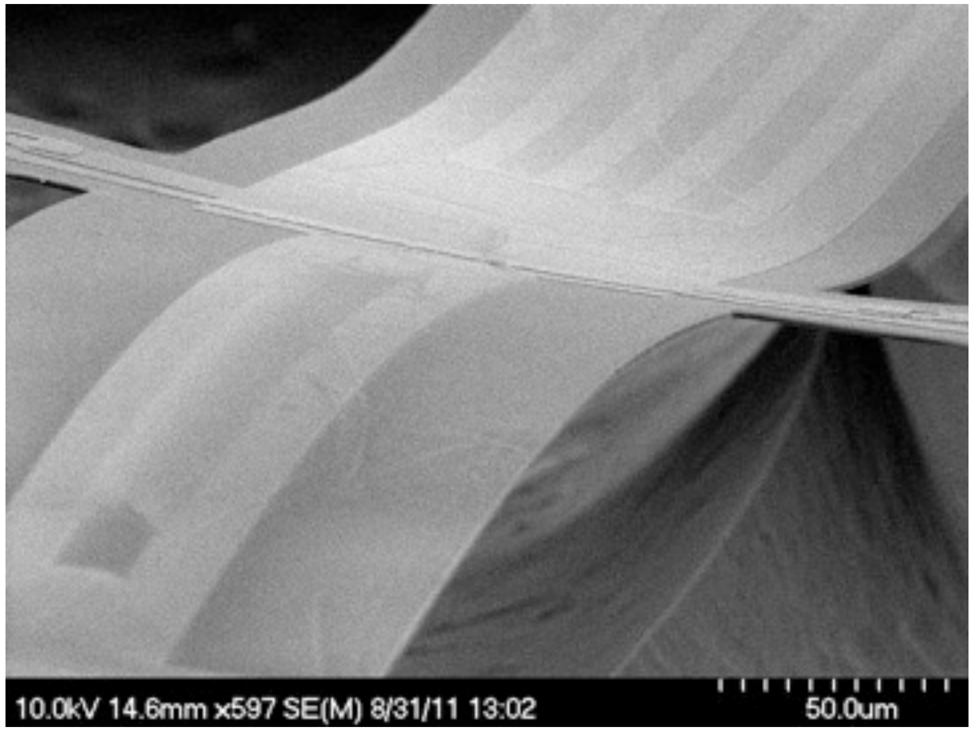
Vertical Nanowires

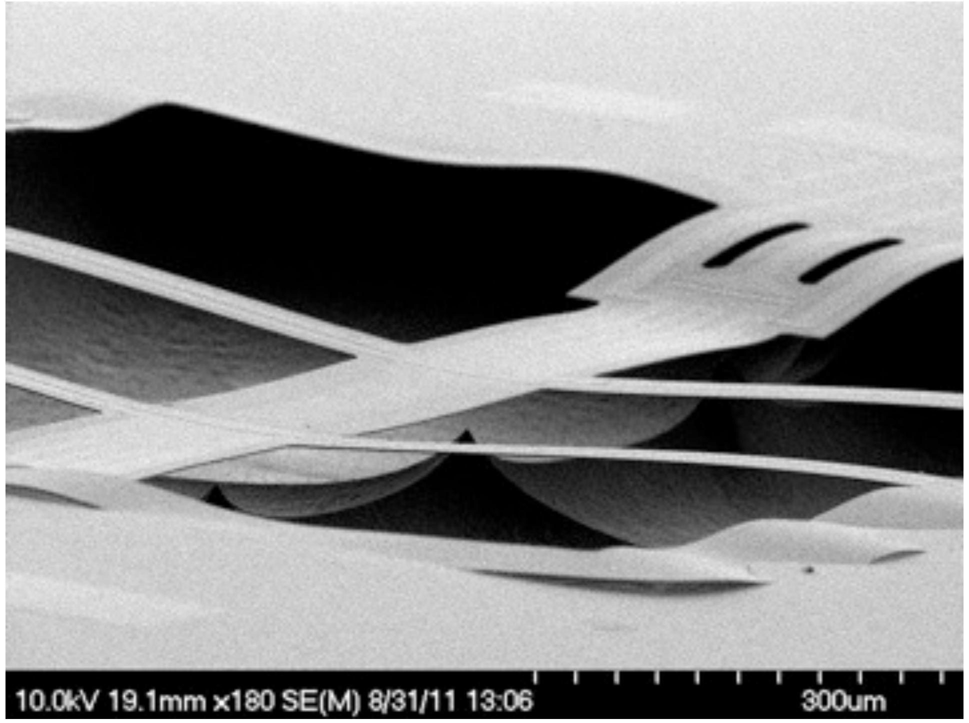


100 x 20 nm Wide Si Nanowires in Suspended Hall Bar









Proof of concept: The structure are feasible → Technology

SEVENTH FRAMEWORK PROGRAMME

GREEN Silicon
Project No. 257750

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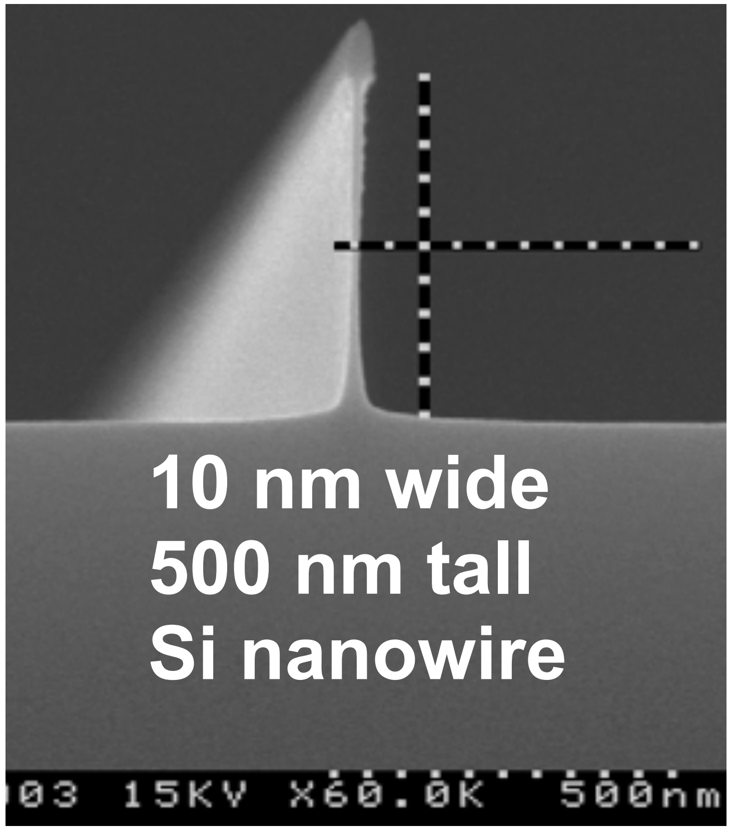
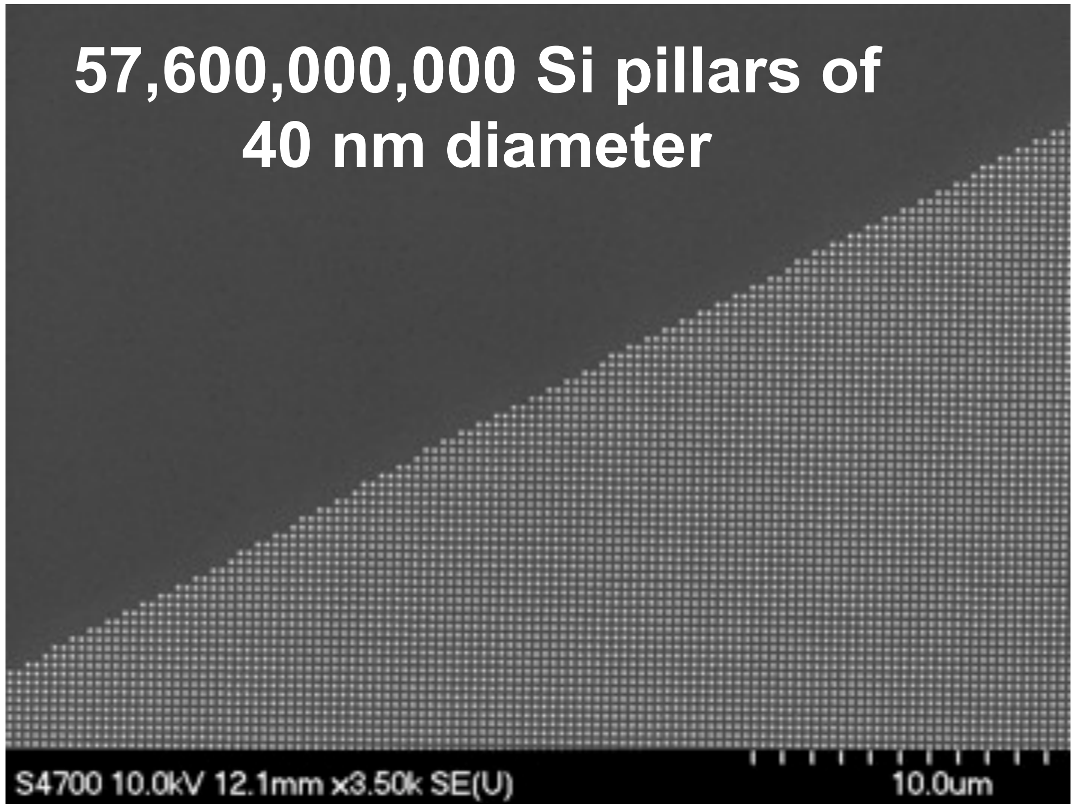
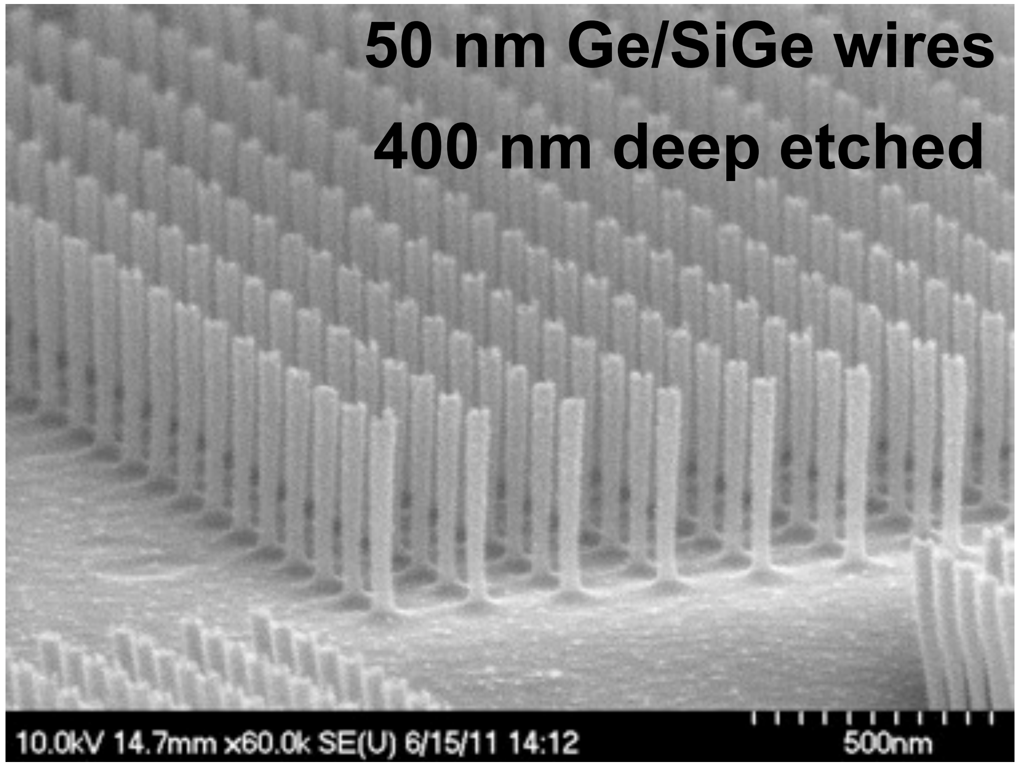
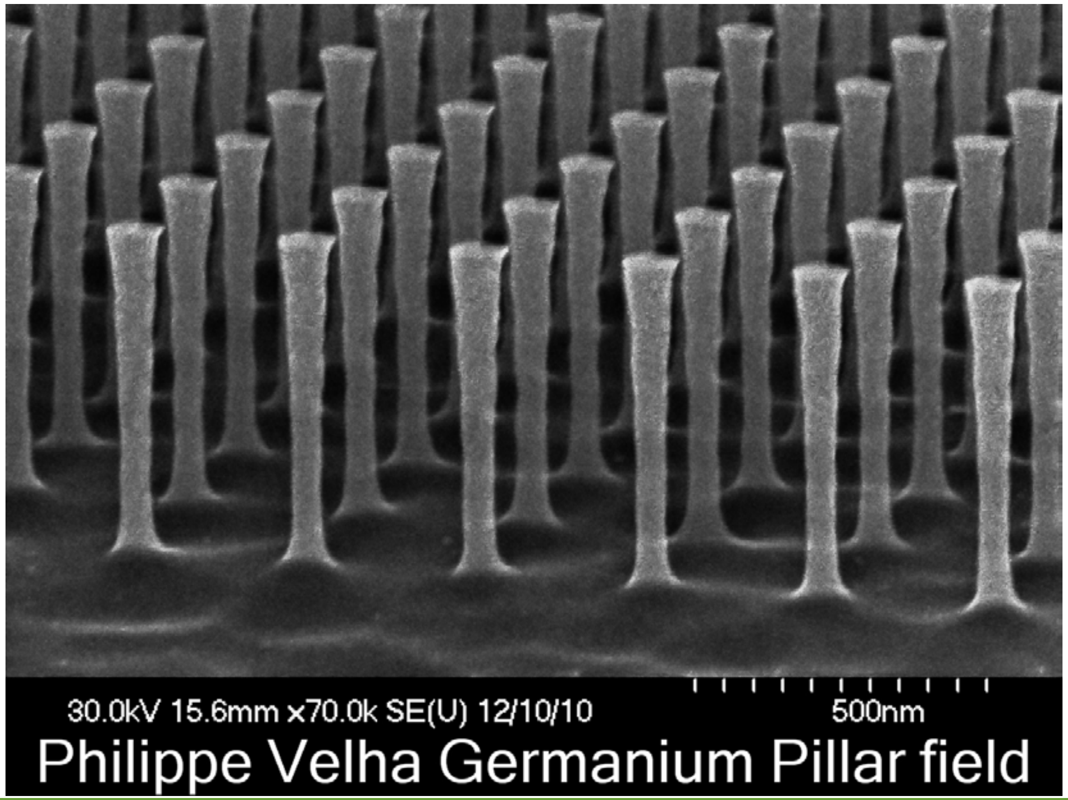
Si Nanowires: Practical 1D enhancements?









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Summary

- Si/SiGe heterostructures for engineered electron & phonon transport towards enhanced thermoelectrics
- Accurate thermal measurements difficult –> standards?
- Many thermal measurement techniques inaccurate
- http://www.greensilicon.eu/GREENSilicon/index.html

Douglas.Paul@glasgow.ac.uk
http://www.jwnc.gla.ac.uk/
Tel:- +44 141 330 5219