Thermoelectric Energy Harvesting: Micro and Nanoscale

Prof Douglas Paul

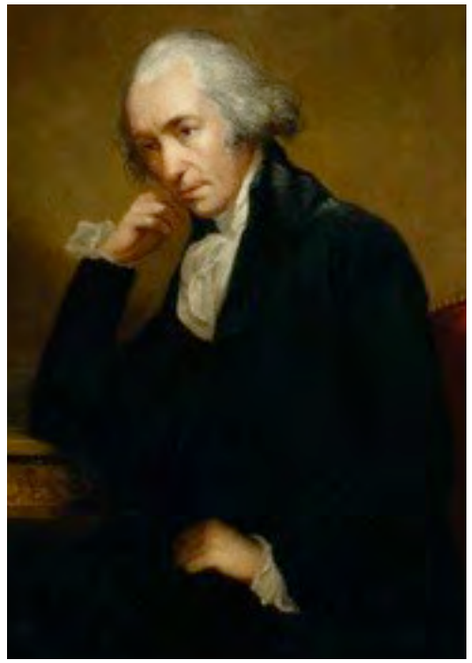
Director, James Watt Nanofabrication Centre

EPSRC III-V National Facility

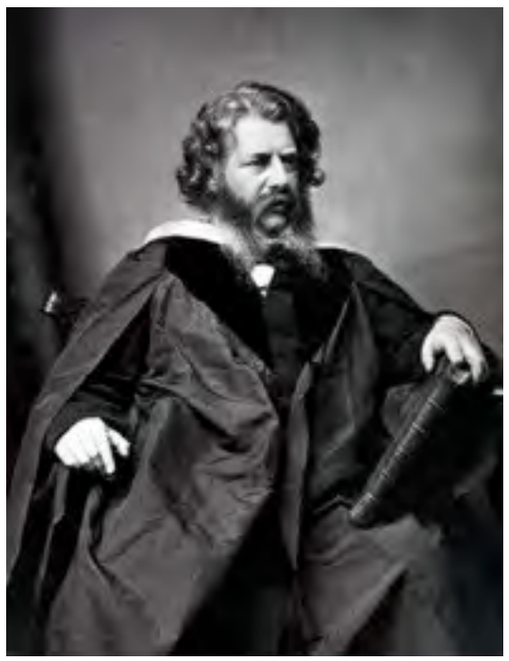
Douglas.Paul@glasgow.ac.uk

Famous Glasgow Scholars in Energy

William Thomson
(Lord Kelvin)



James Watt



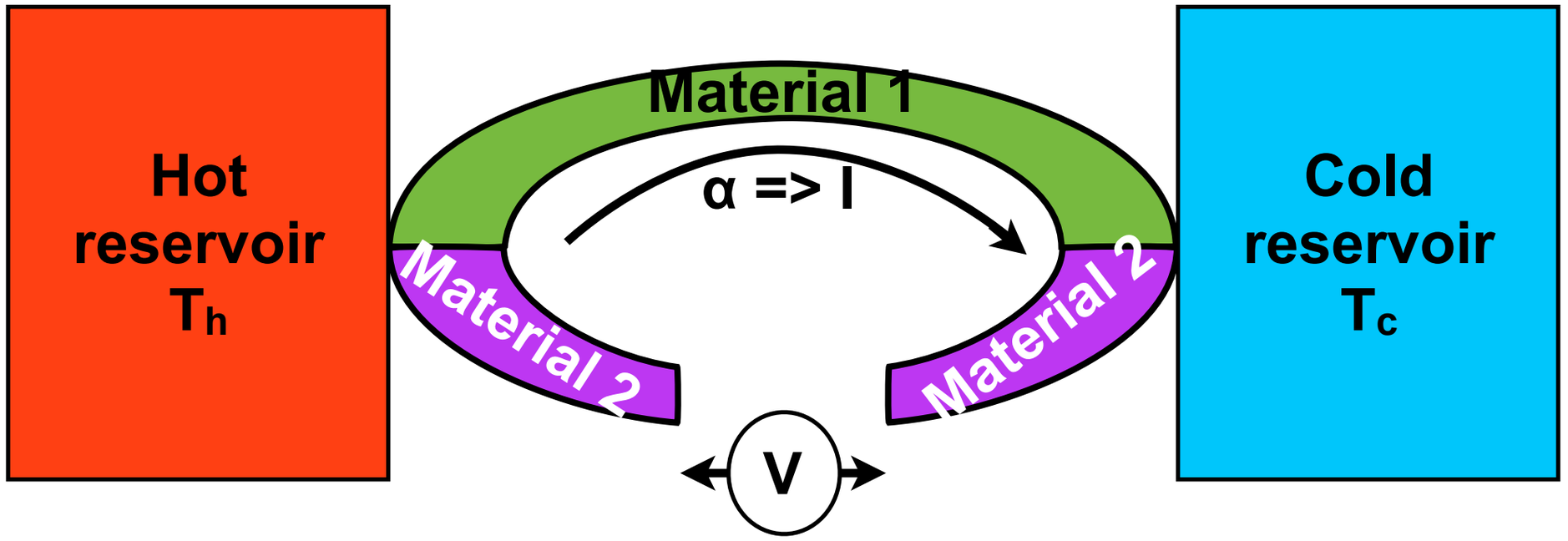
William John
Macquorn Rankine

Joseph Black

Rev Robert Stirling

Rev John Kerr

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**

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Thermoelectric Power Generating Efficiency

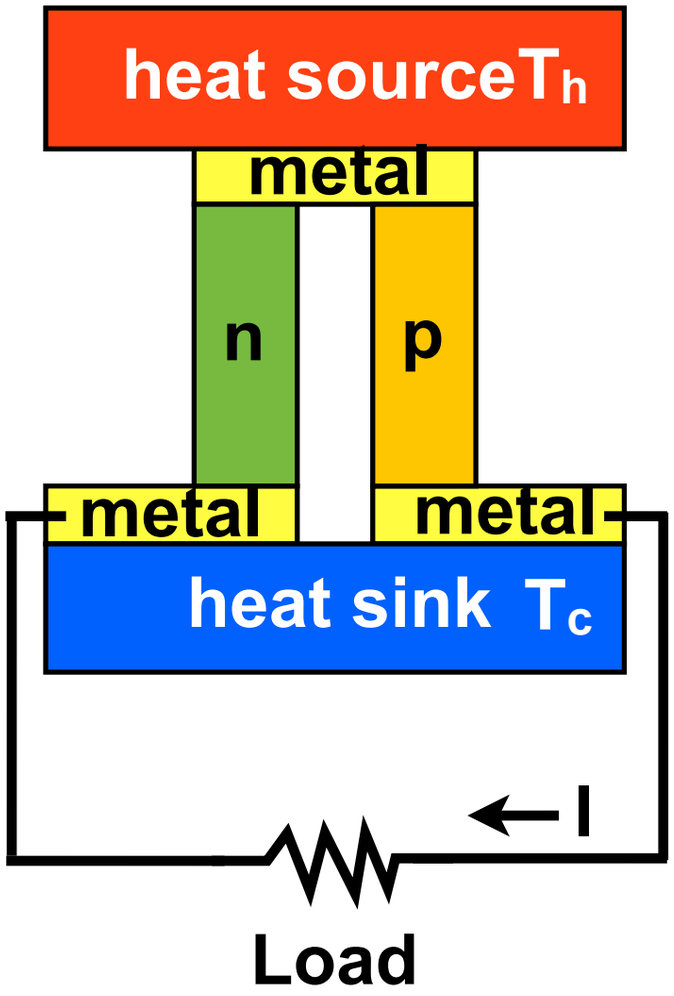
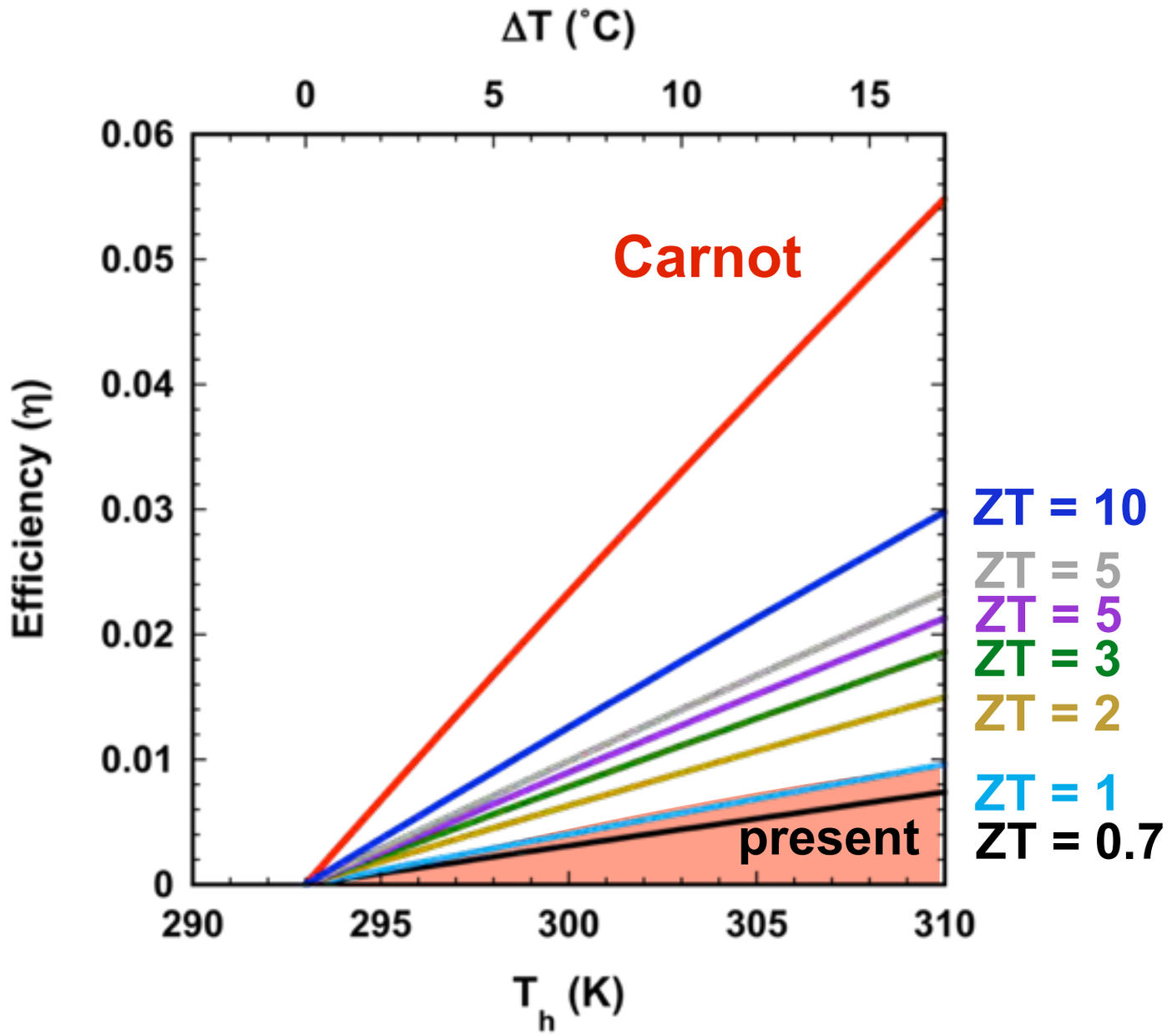


Figure of merit

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

$$\eta = \frac{\Delta T}{T_h} \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_c}{T_h}}$$



Power factor = $\alpha^2\sigma$

Impedance matching and maximum power point tracking are key for thermoelectrics

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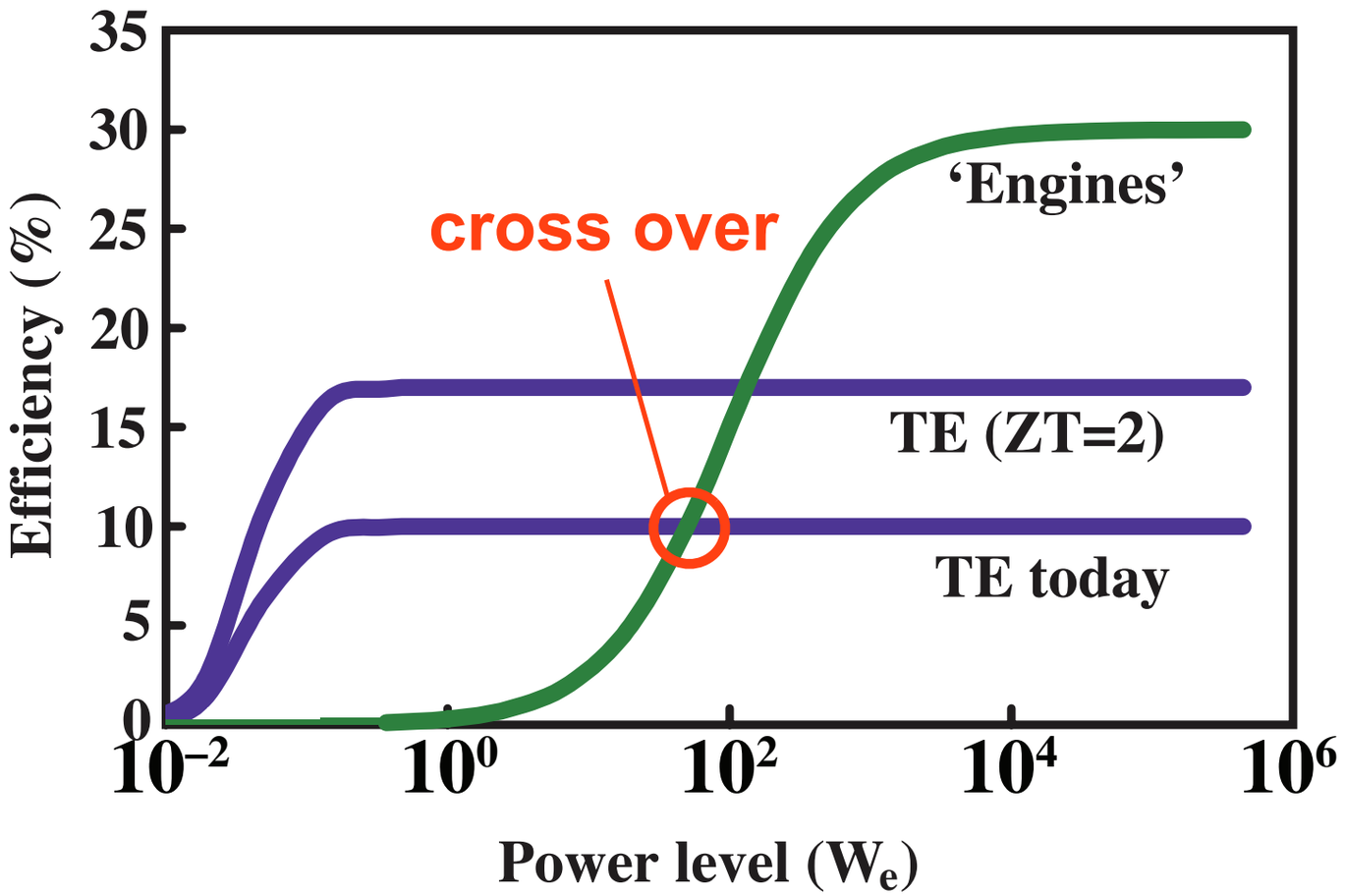
Power Generation From Macro to Micro

Illustrative schematic diagram



At large scale, thermodynamic engines more efficient than TE

ZT average for both n and p over all temperature range

Diagram assumes high ΔT

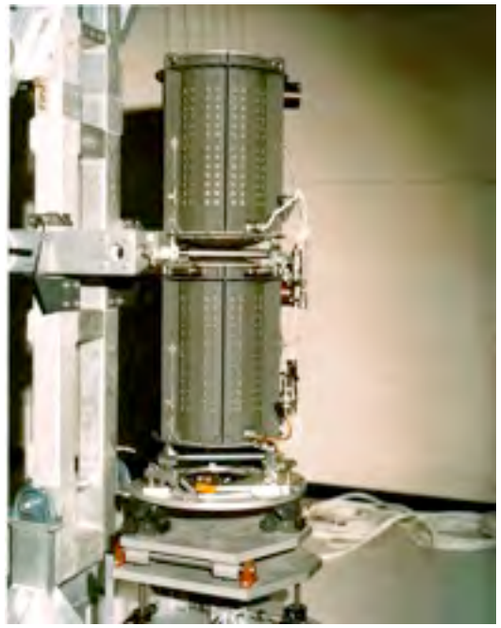
- **At the mm and μm scale with powers << 1W, thermoelectrics are more efficient than thermodynamic engines (Reynolds no. etc..)**

C.B. Vining, Nature Mat. 8, 83 (2009)

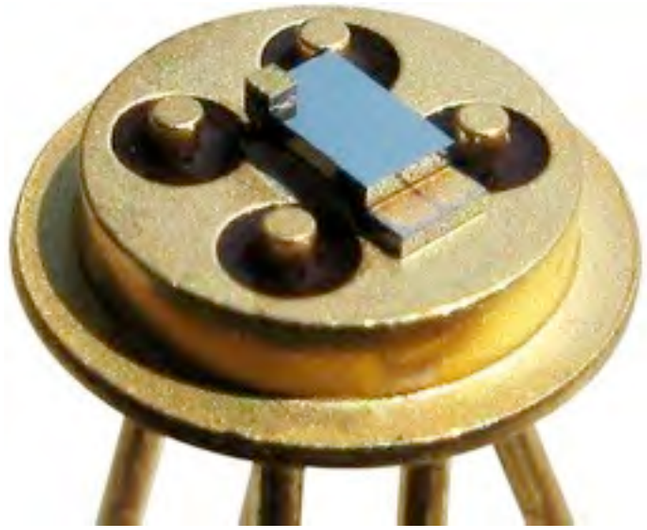
Thermoelectric Applications

Cars: replace alternator

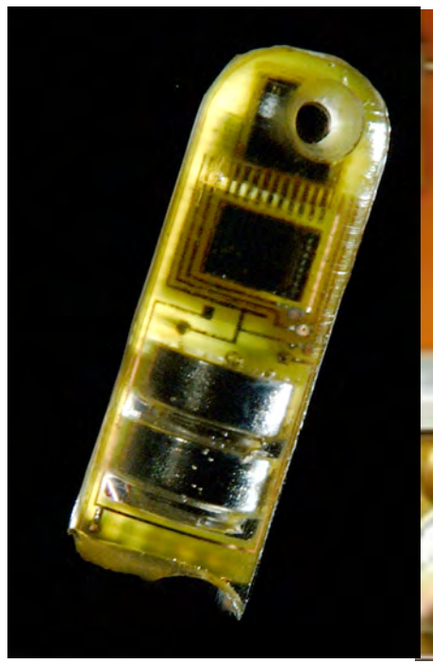
NASA Voyager I & II

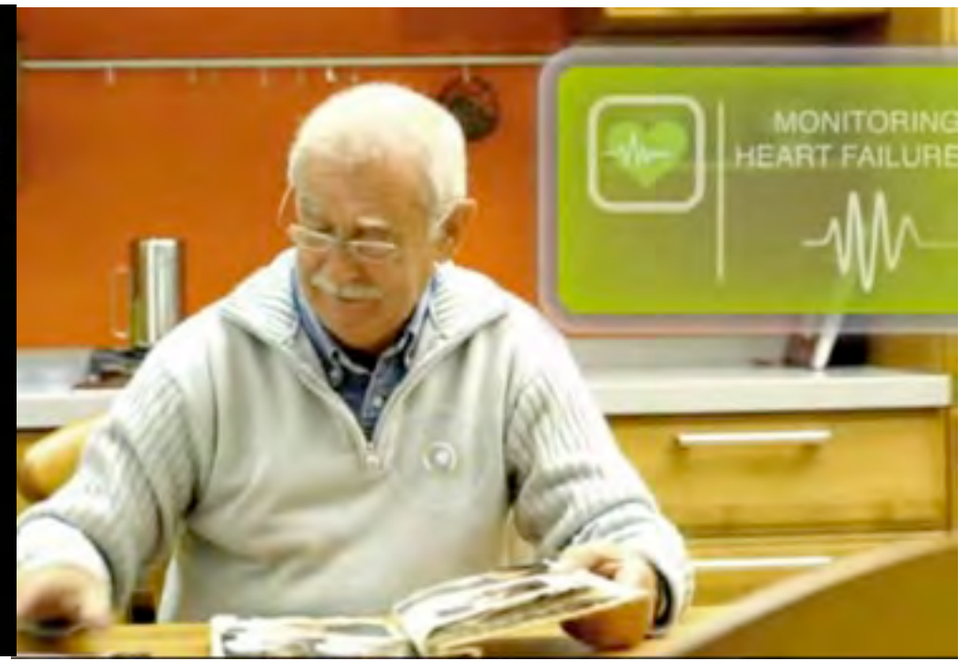


Peltier cooler: telecoms lasers



Temperature control for CO_2 sequestration





Powering autonomous sensors: ECG, blood pressure, etc.

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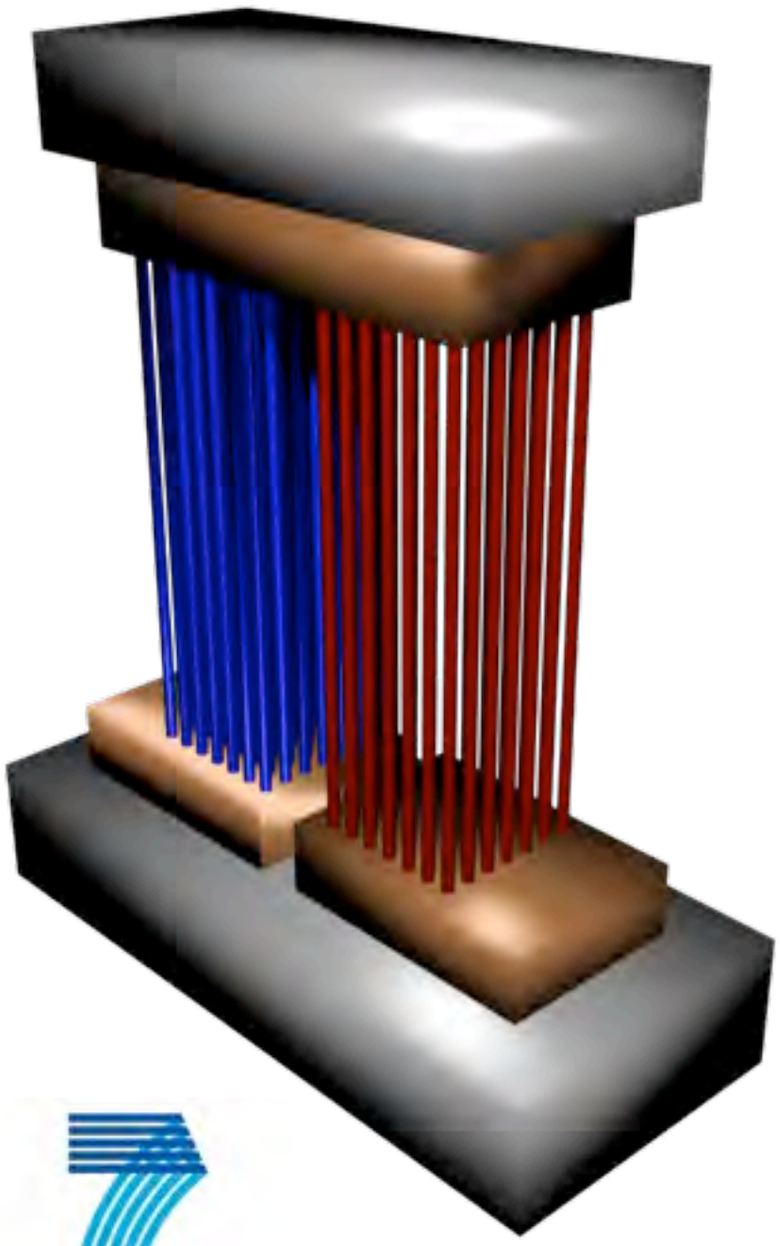
GREEN Silicon

Generate Renewable Energy Efficiently using Nanofabricated Silicon (GREEN Silicon)



D.J. Paul, J.M.R. Weaver, P. Dobson & J. Watling

University of Glasgow, U.K.

G. Isella, D. Chrastina & H. von Känel

L-NESS, Politecnico de Milano, Como, Italy

J. Stangl, T. Fromherz & G. Bauer

University of Linz, Austria

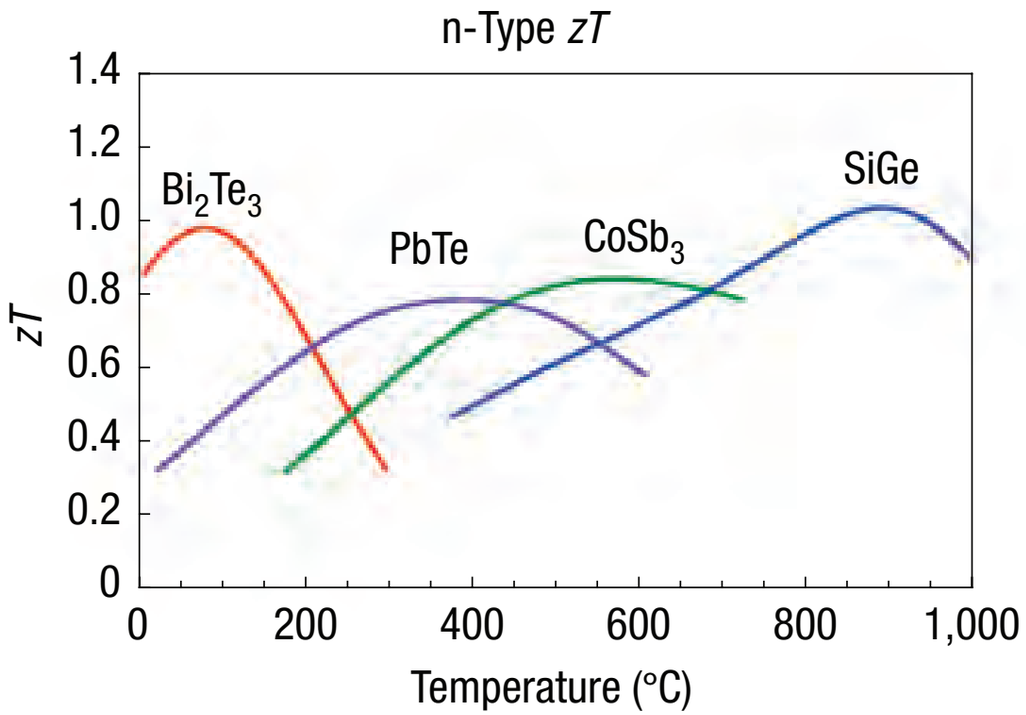
E. Müller

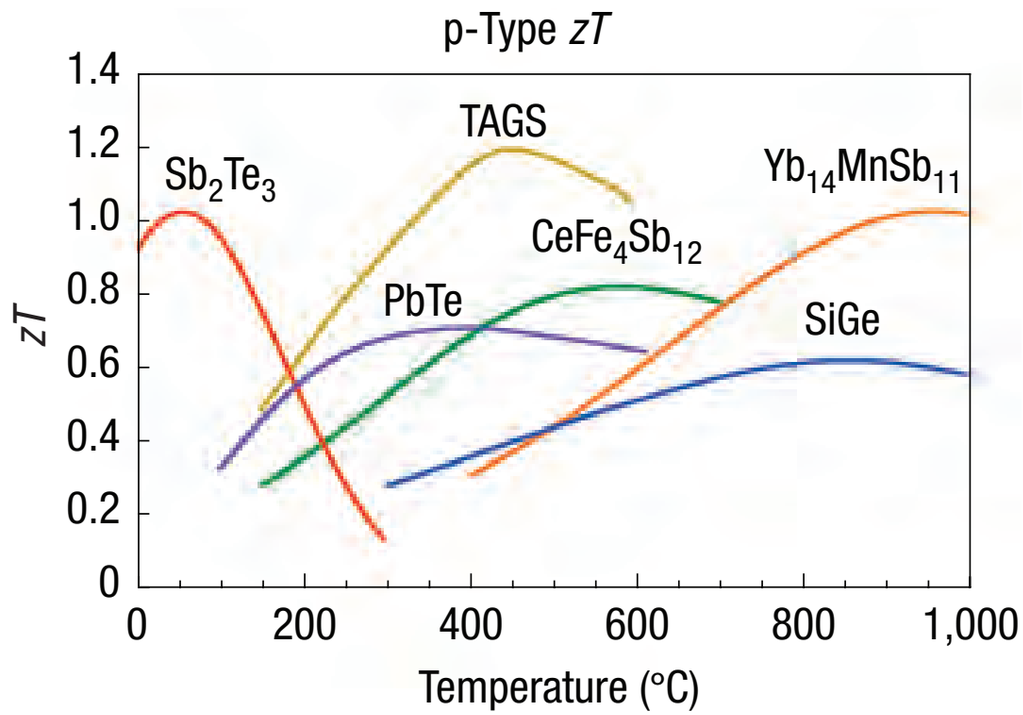
ETH Zürich, Switzerland

SEVENTH FRAMEWORK PROGRAMME

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

Bulk Thermoelectric Materials Performance





Nature Materials 7, 105 (2008)

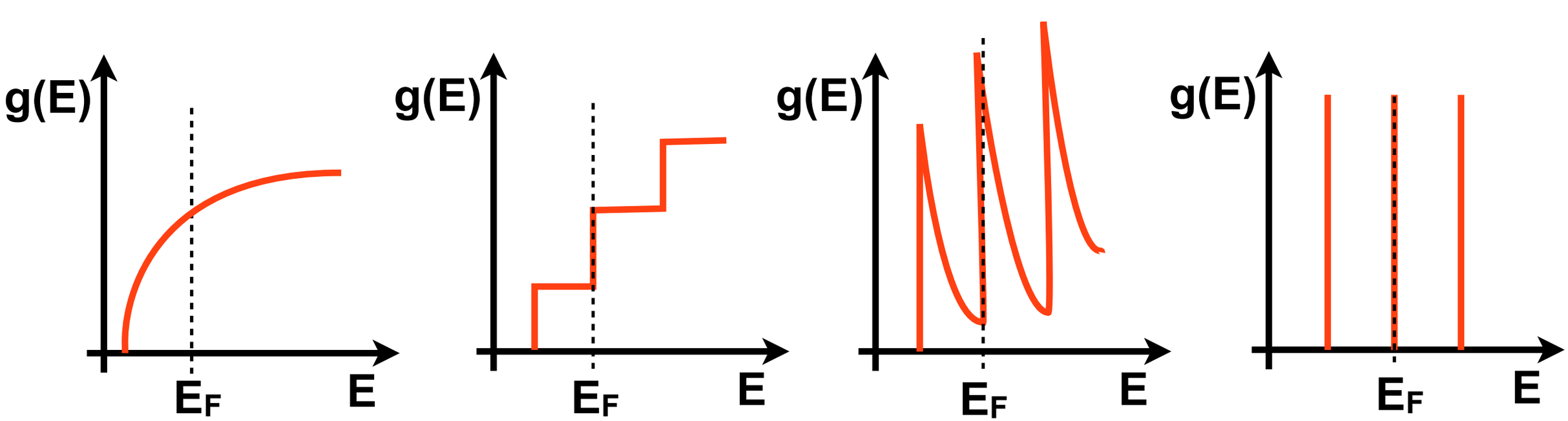
- **Bulk n-Bi_2Te_3 and p-Sb_2Te_3 used in most commercial thermoelectrics & Peltier coolers**
- **But tellurium is 8th rarest element on earth !!!**
- **Bulk $Si_{1-x}Ge_x$ (x~0.2 to 0.3) used for high temperature satellite applications**

Seebeck Enhancement at Low Dimensions

- **Increase α through enhanced DOS:**

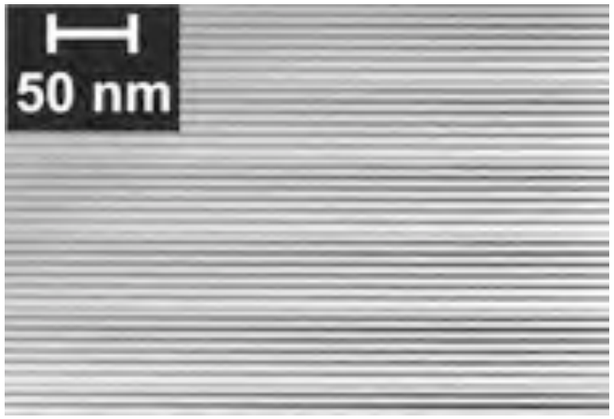
$$\alpha = -\frac{\pi^2}{3q} k_B^2 T \left[\frac{d \ln(\mu(E) g(E))}{dE} \right]_{E=E_F}$$

3D bulk	2D quantum well	1D quantum wire	0D quantum dot

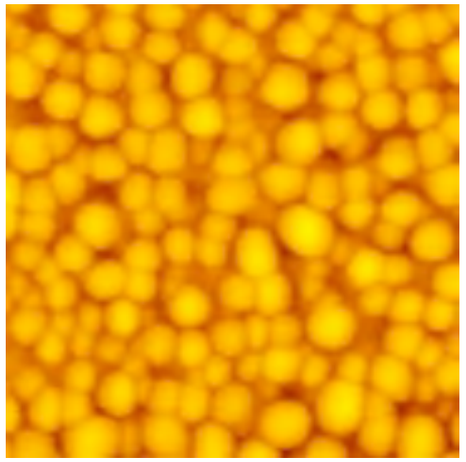


GREEN Silicon Approach

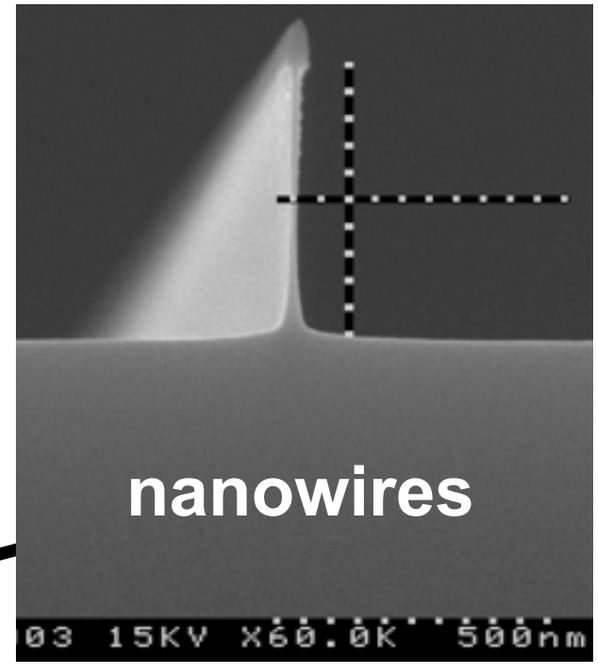
Low dimension technology



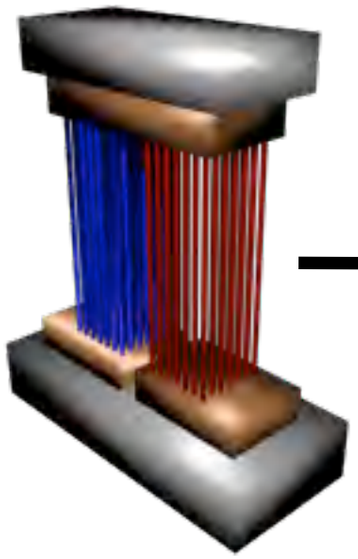
superlattices

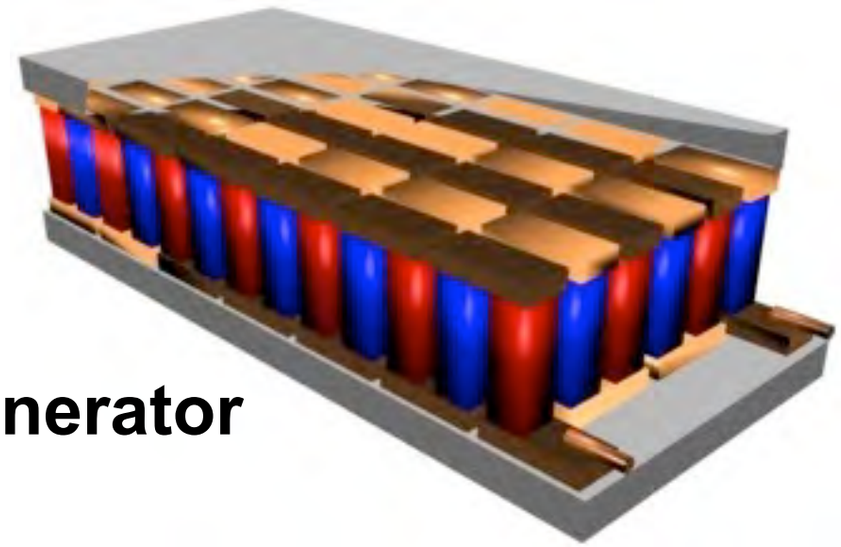


quantum dots



Module





Generator

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

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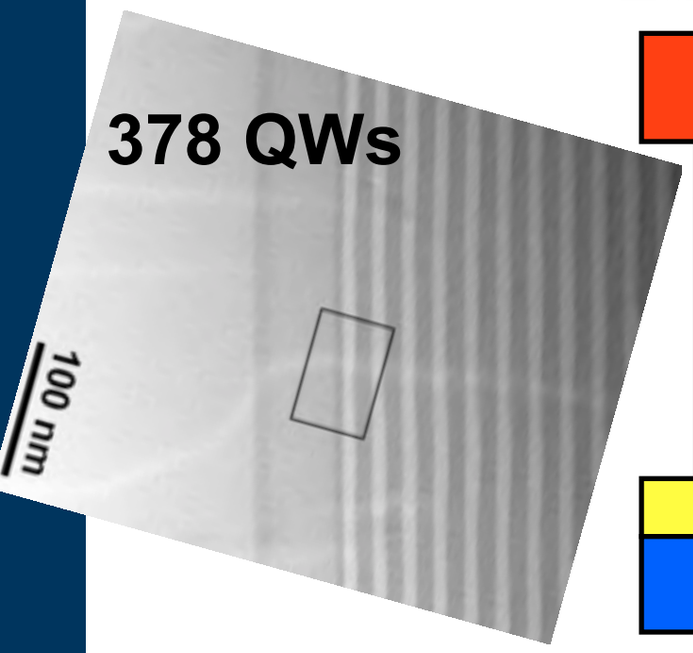
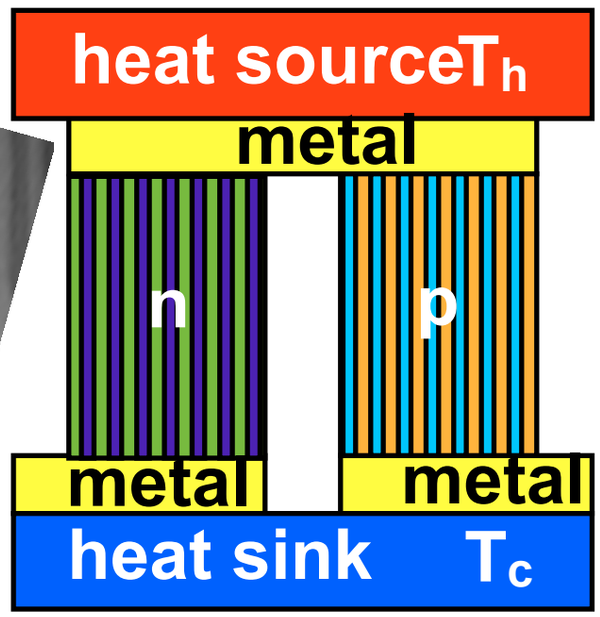
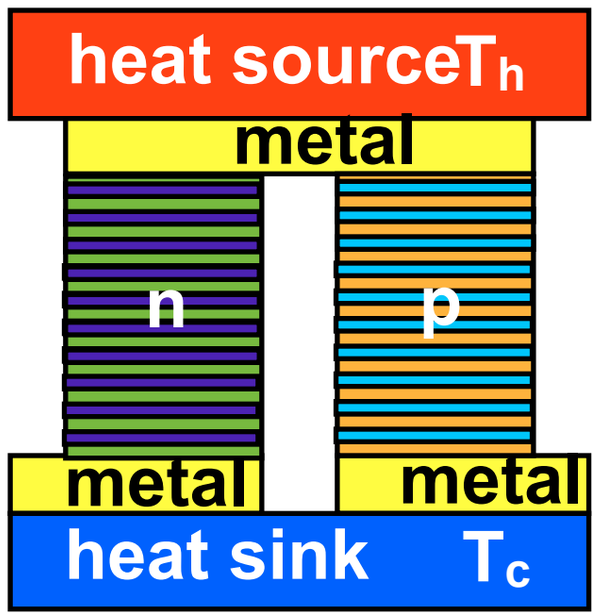
Thermoelectric Low Dimensional Structures

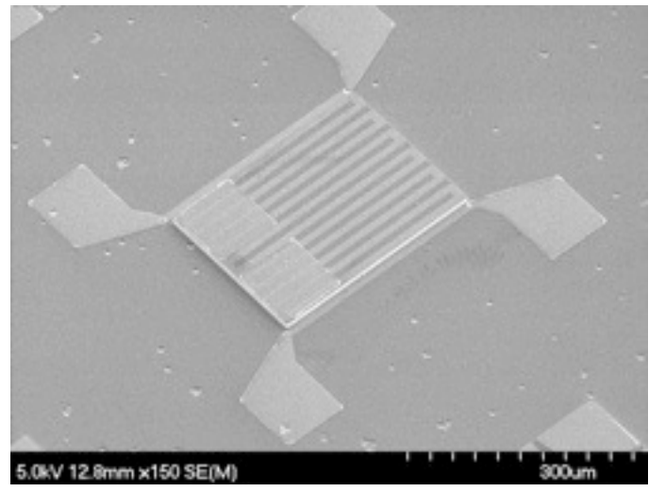
Lateral superlattice



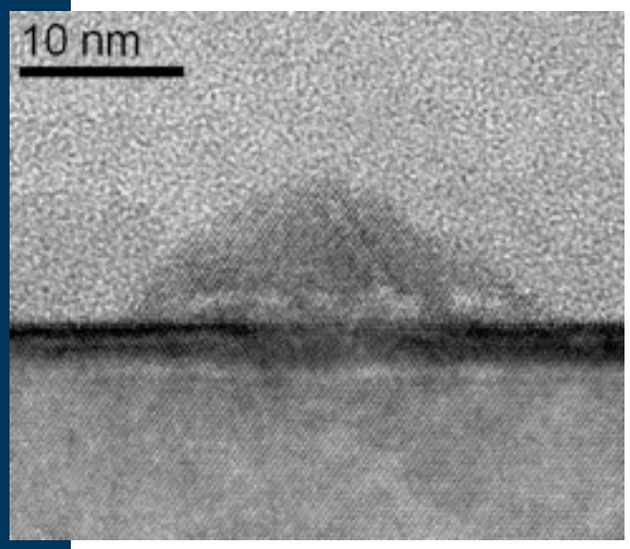


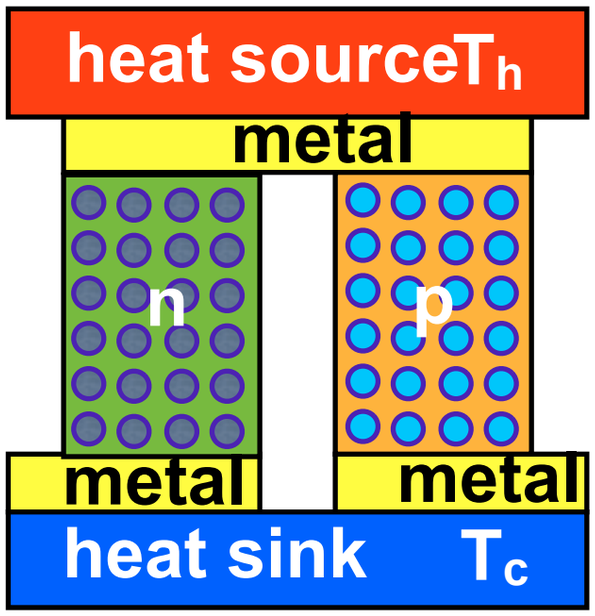
Vertical superlattice



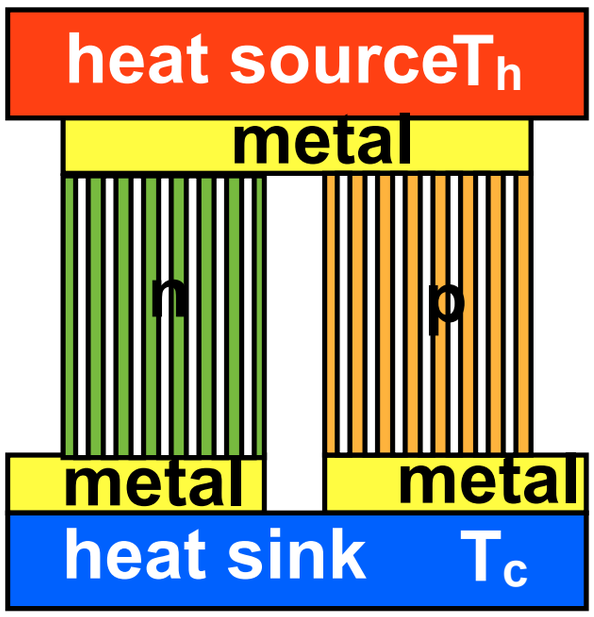


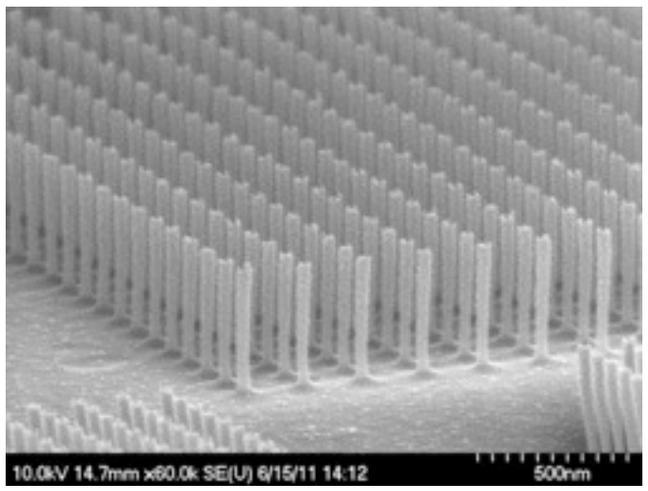
Quantum Dots



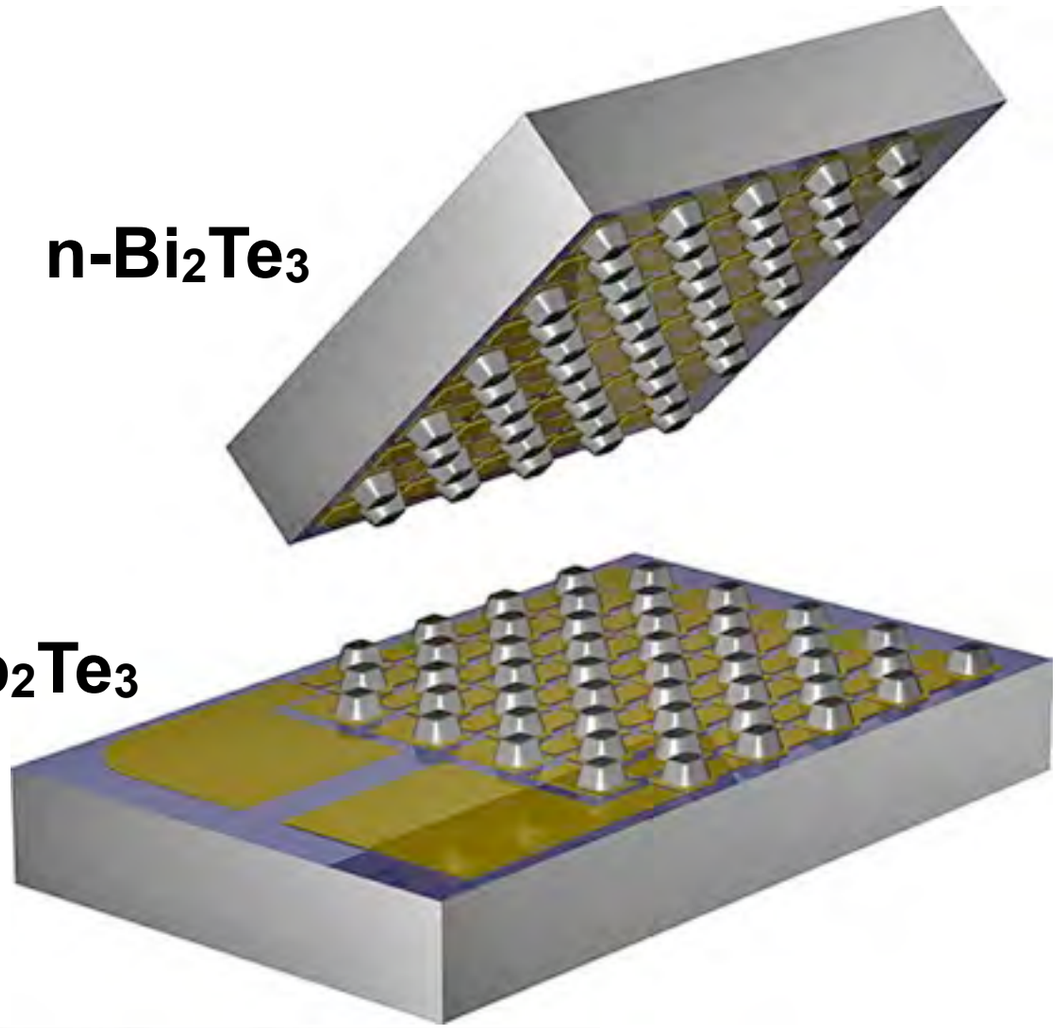


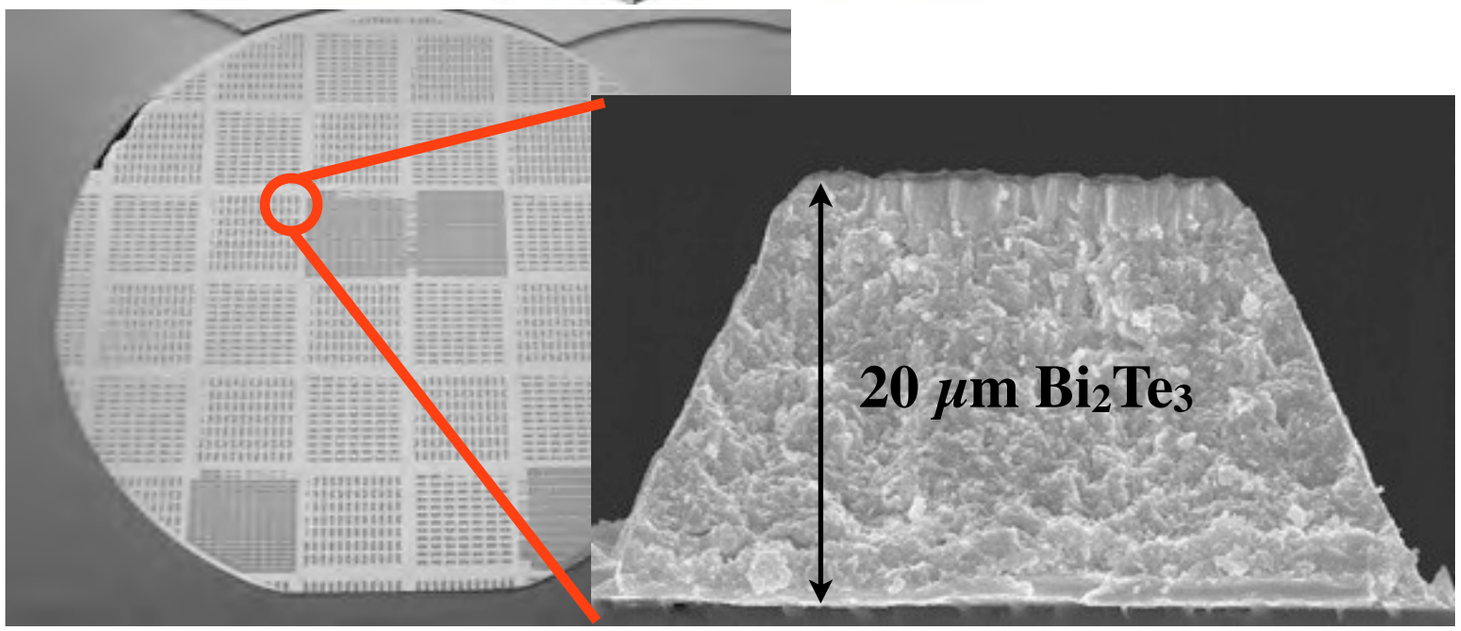
Nanowires



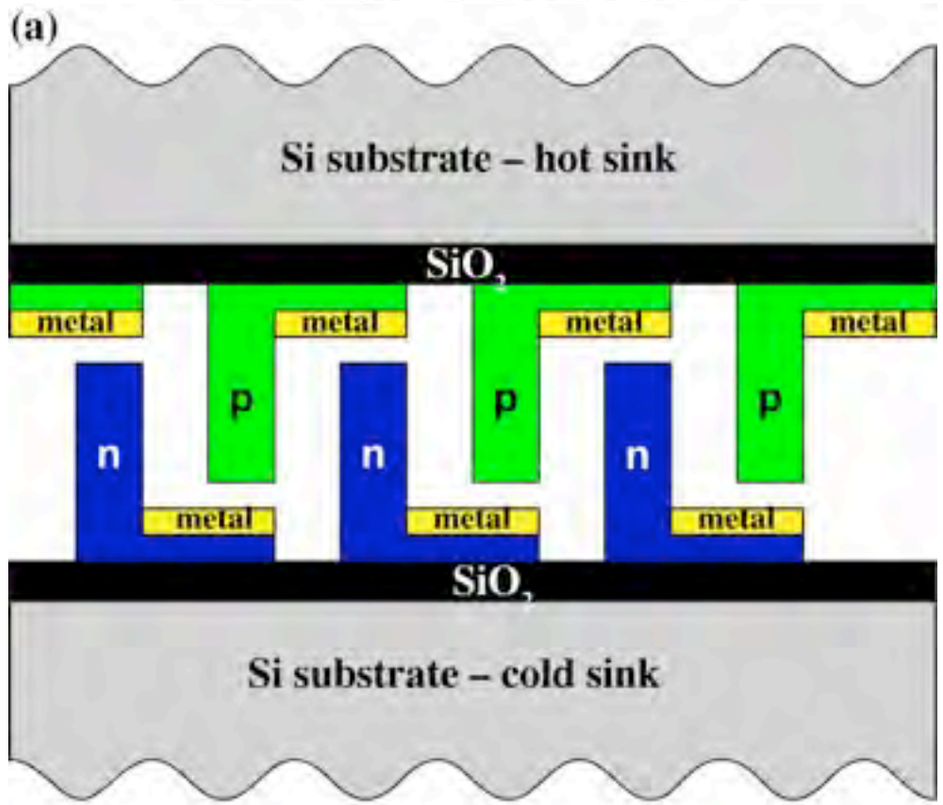


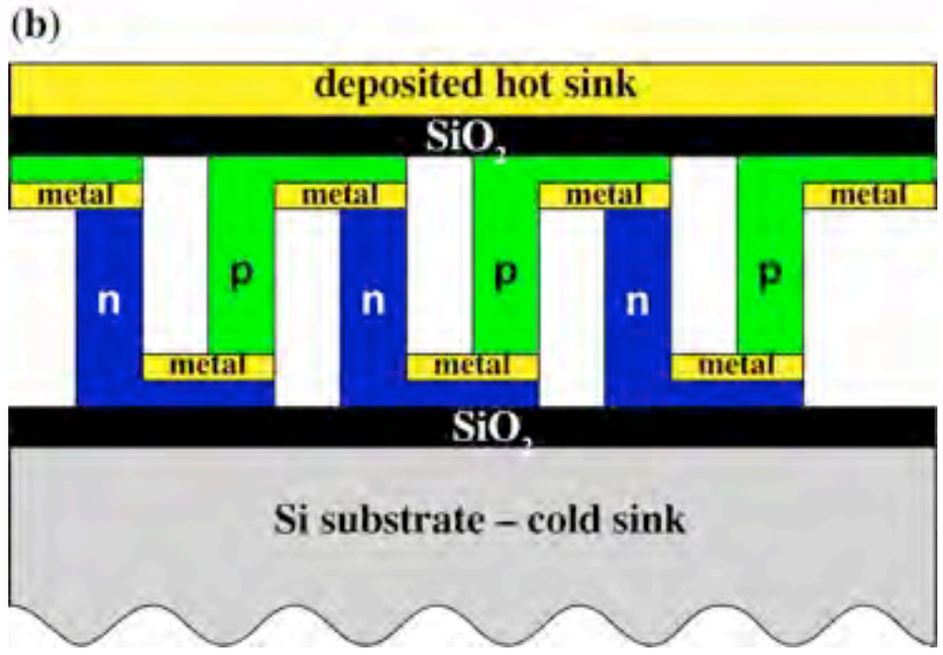
Wafer Scale Microfabrication of Generators





Vertical Generator





http://www.micropelt.com/

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James Watt Nanofabrication Centre @Glasgow

Vistec VB6 & EBPG5

E-beam lithography

Süss MA6 optical lith

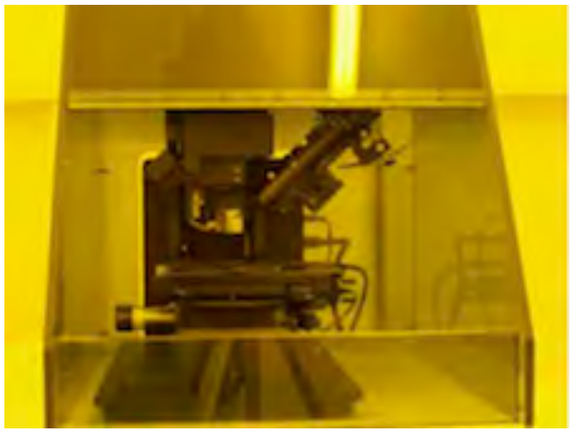
- 750 m^2 cleanroom - pseudo-industrial operation
- £54M funding: 17 technicians + 4 PhD technologists
- EPSRC III-V National Facility (and Electronics Design Centre)
- Processes include: MMICs, III-V, Si/SiGe/Ge, integrated photonics, metamaterials, MEMS (microfluidics)
- Commercial access through Kelvin NanoTechnology
- http://www.jwnc.gla.ac.uk

10 RIE / PECVD

5 Metal dep tools

4 SEMs: Hitachi S4700

Veeco: AFMs



Electron Beam Lithography Capability

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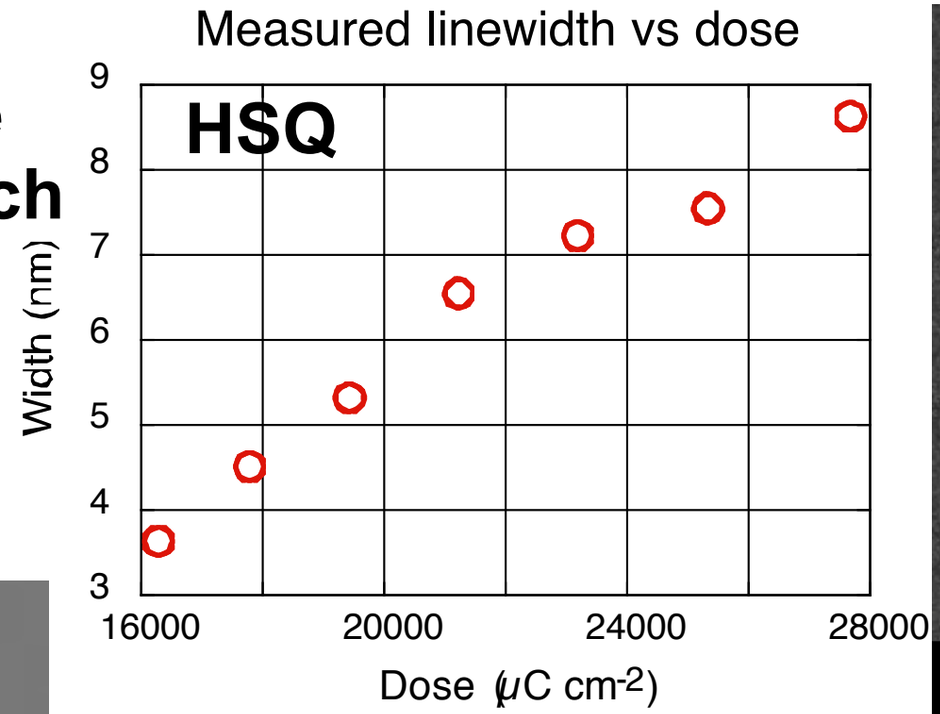
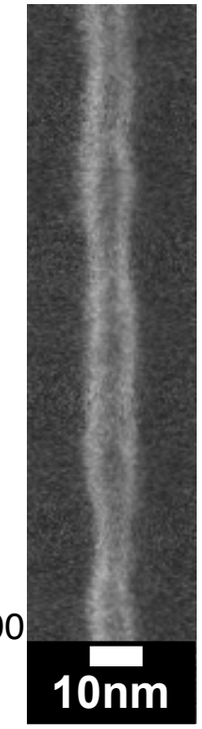
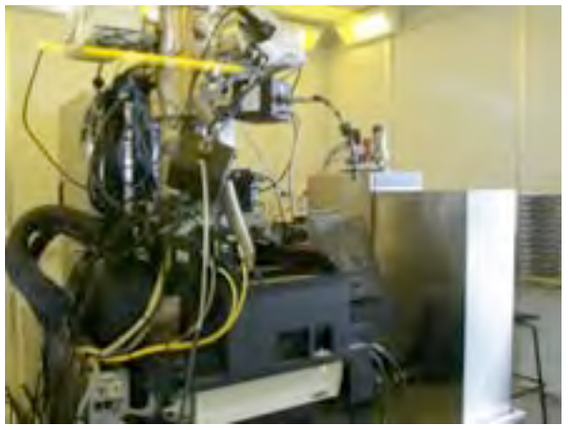
30 years experience of e-beam lithography

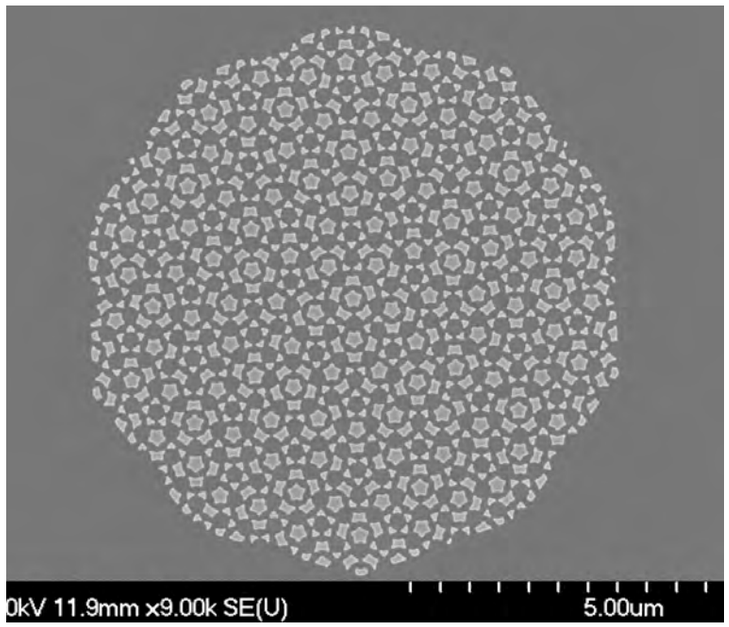
Sub-5 nm single-line lithography for research







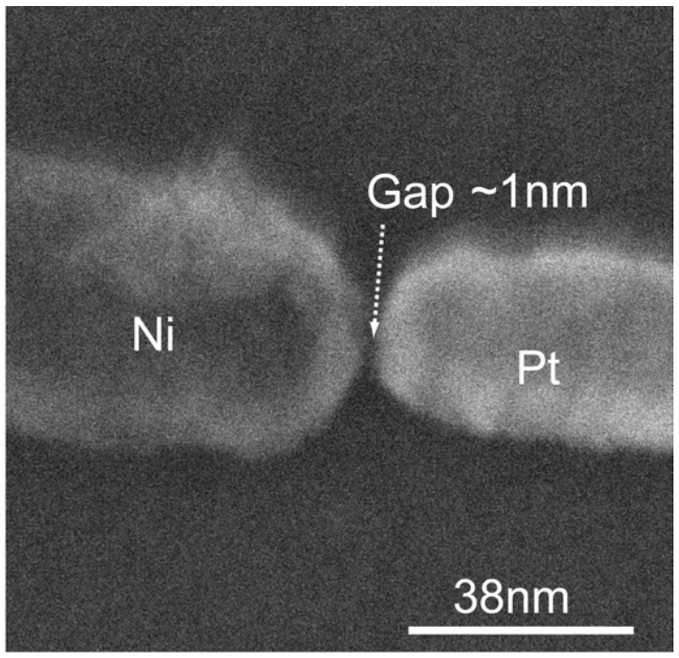
Vistec VB6



Penrose tile: layer-to-layer alignment 0.46 nm rms

Vistec EBPG5

Alignment allows 1 nm gaps between different layers



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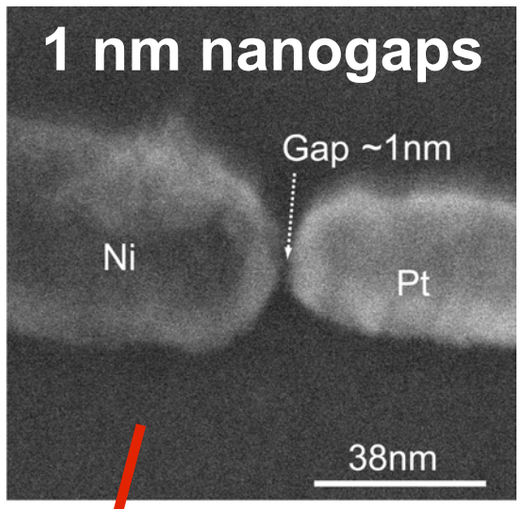
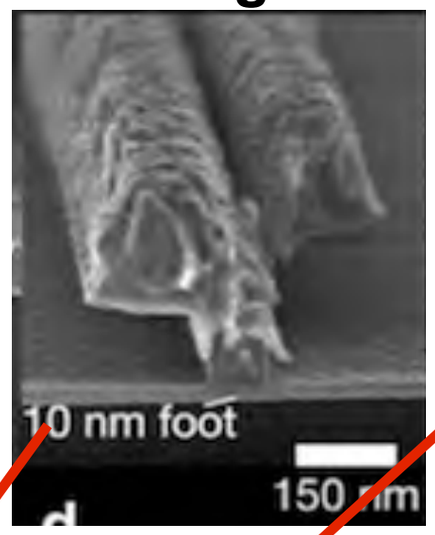
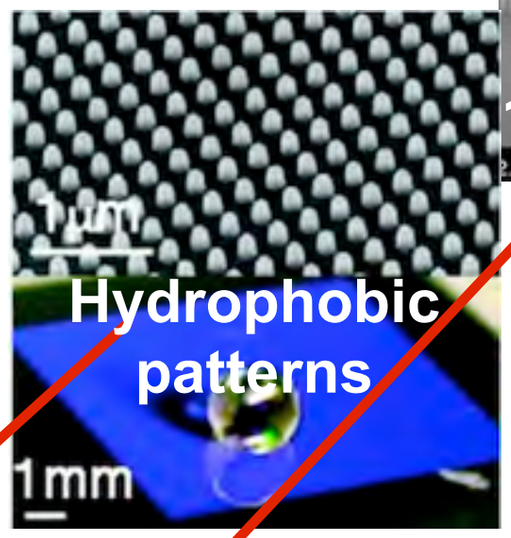
Micro and Nanotechnology from Glasgow

1 nm nanogaps



Nanoelectronics: 10 nm T-gate HEMT

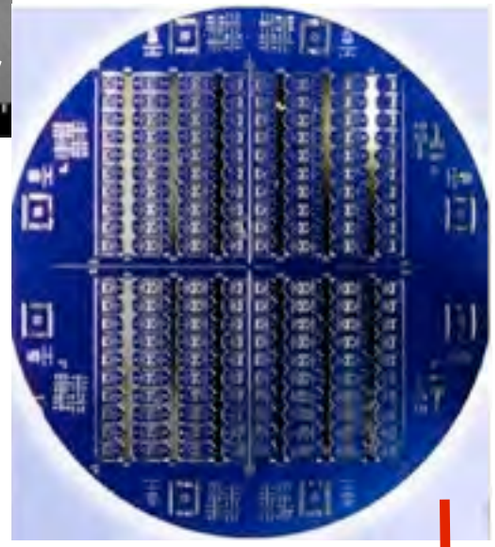




Optoelectronics: 1.55μm DFB laser

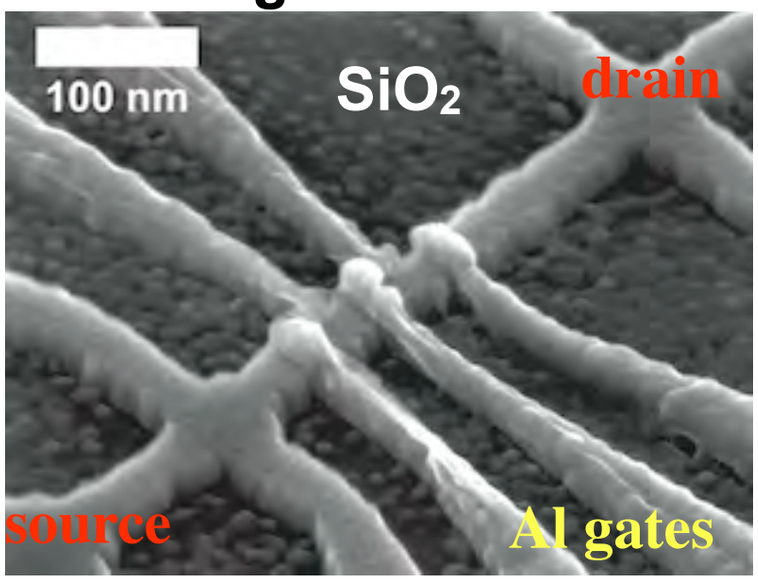
Healthcare: STEM cell interrogation

Manufacture: AFM probes

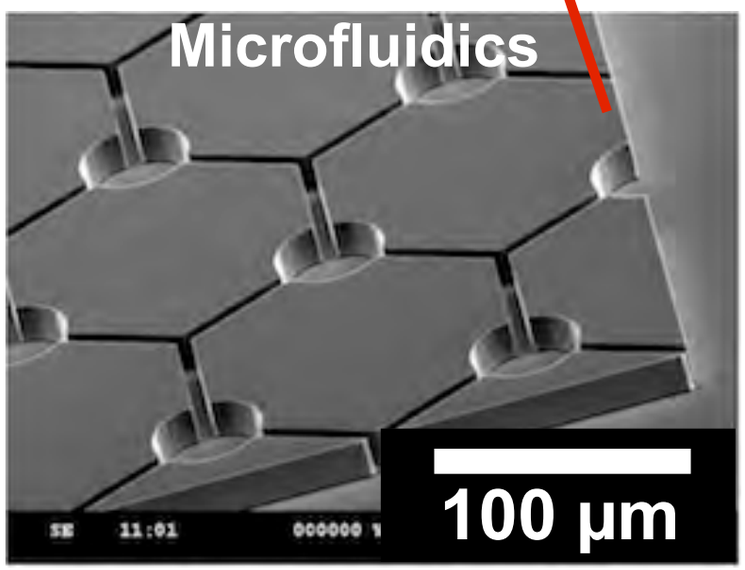


10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} metres

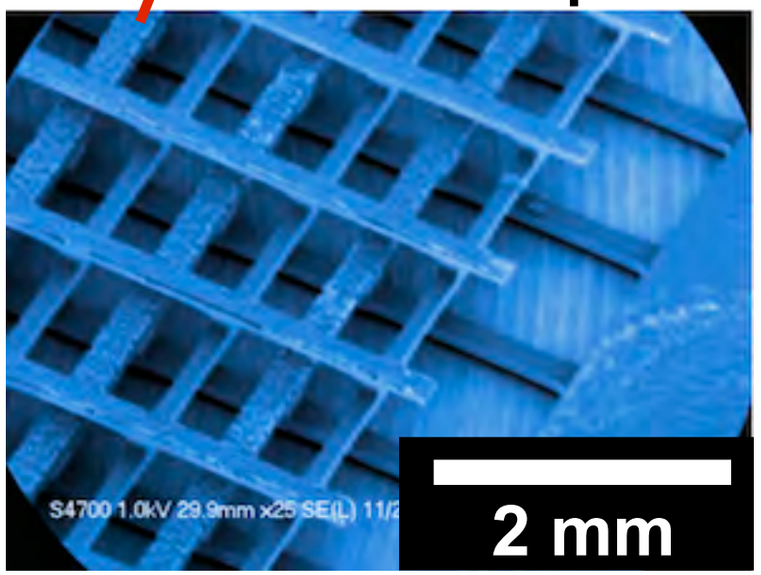
Sensing: Si nanowires



Environment: Microfluidics



MEMS: THz optics



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Over 250 Industrial Partners & Customers

KELVIN NANOTECHNOLOGY

Wireless bioDevices

Intellemetrics

intense

JRC Semiconductor Research Corporation

numonyx

DMD Diamond Microwave Devices Limited

e2v

Raytheon Systems Limited

BAE SYSTEMS

GSS Gas Sensing Solutions

Micron

M SQUARED

Unilever

SELEX GALILEO

elementsix

QinetiQ

IBM

National Semiconductor

AsahiKASEI

and

GWENT GROUP Advanced Material Systems

syrris

oclaro

TeraView

toumaz

FIAT

CRF

CENTRO RICERCHE FIAT

gsk

Honeywell

GlaxoSmithKline

DOOSAN

Kodak

Doosan Babcock

Genetix

freescale semiconductor

COHERENT

epigem

LOGITECH Materials Technologists & Engineers

University of Glasgow

Who do we make devices for?

UNIVERSITY OF CAMBRIDGE

UNIVERSITY OF OXFORD

Imperial College London

The University of Nottingham

WARWICK

POLITECNICO DI MILANO

Berkeley UNIVERSITY OF CALIFORNIA

STANFORD UNIVERSITY

Nano Research Lab

Nanoelectronics Research Lab UC Santa Barbara

UAM

UNIVERSITY OF TORONTO

NRF UCLA Nanoelectronics Research Facility

Vrije Universiteit Brussel

The University Of Sheffield.

dmu.ac.uk DE MONTFORT UNIVERSITY LEICESTER

UNIVERSITY OF BATH

POLITÉCNICA "Ingeniamos el futuro"

JOHANNES KEPLER UNIVERSITÄT LINZ | JKU

University of Strathclyde Glasgow

UNIVERSITY OF Southampton

UNIVERSITY OF SURREY

Queen's University Belfast

TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

PRIFYSGOL ABERYSTWYTH UNIVERSITY

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

Universitat de les Illes Balears

HERIOT WATT UNIVERSITY

University of St Andrews

INSTITUT d'OPTIQUE GRADUATE SCHOOL

Universität Konstanz

VNiVERSiDAD D SALAMANCA

California NanoSystems Institute

UNIVERSITY OF ABERDEEN

University of BRISTOL

imec

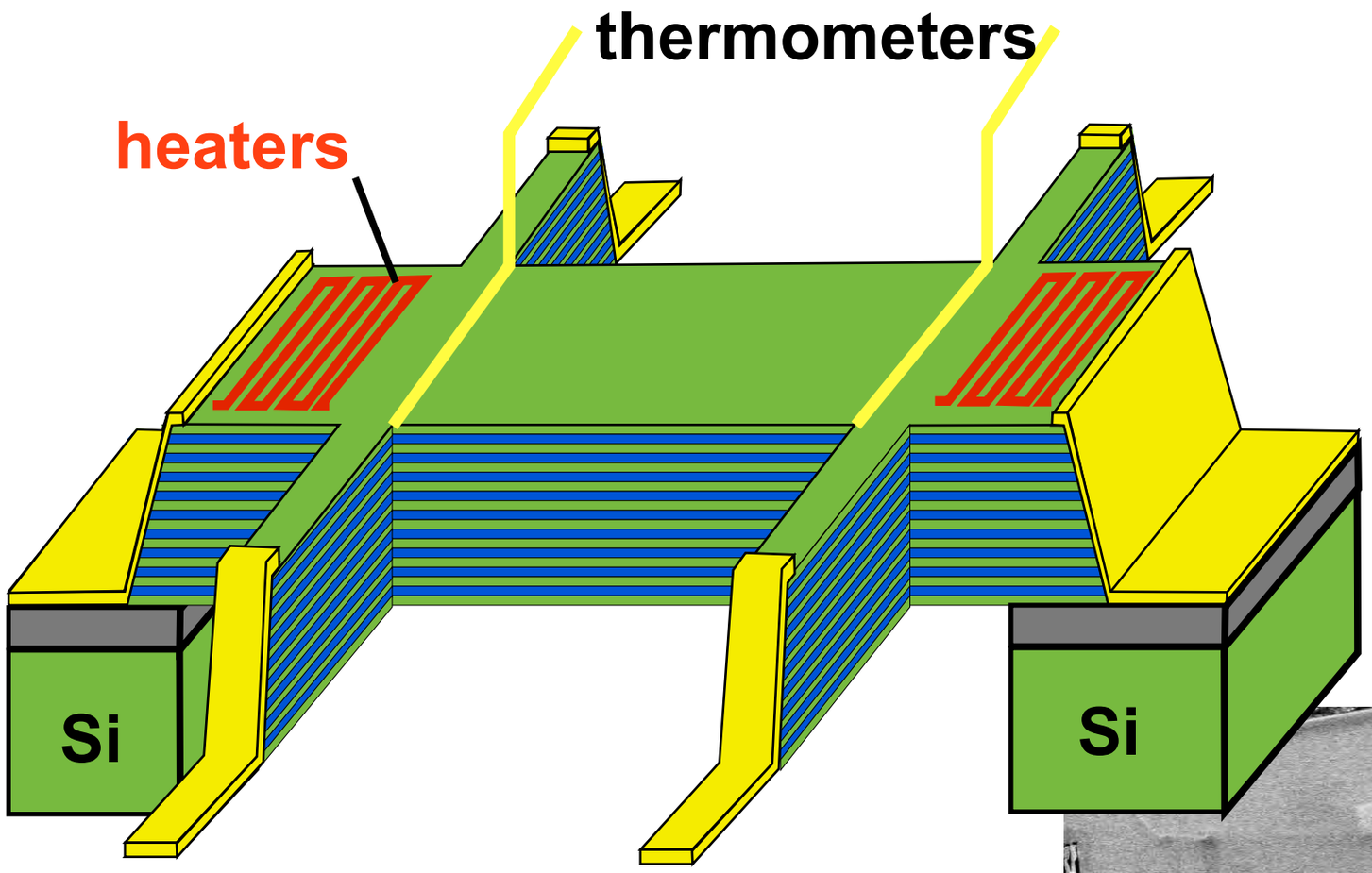
Università degli Studi di Pavia

UCL

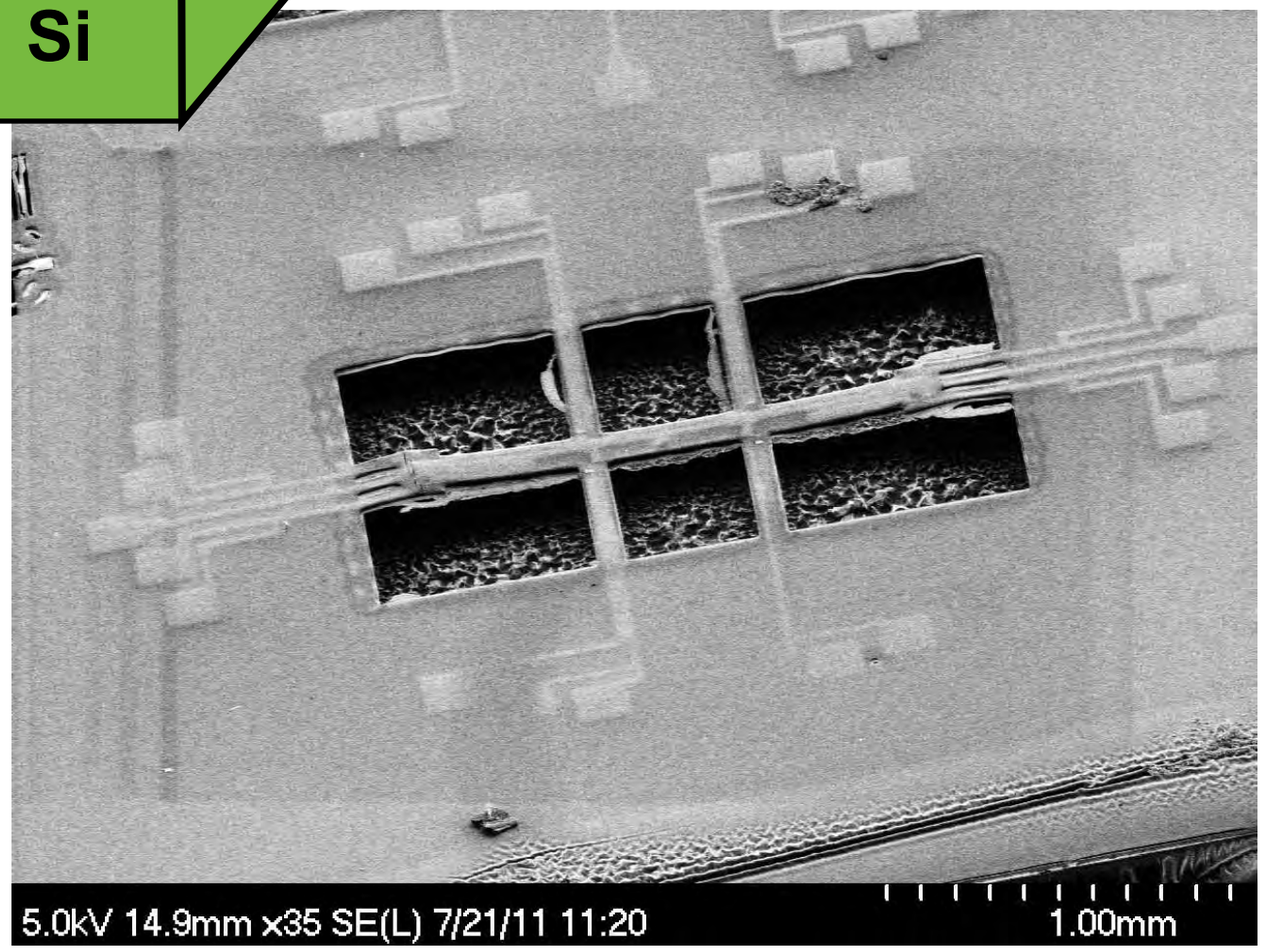
ROMA TRE UNIVERSITÀ DEGLI STUDI

UNIVERSITÉ PARIS-SUD 11

Measuring Lateral α, σ, κ and ZT



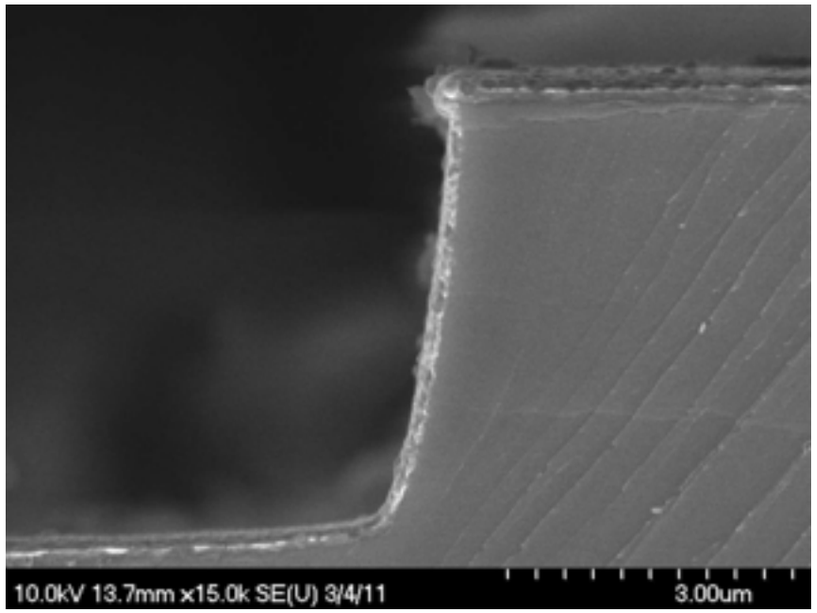
- Hall bar geometry
- Heat transport easier to model

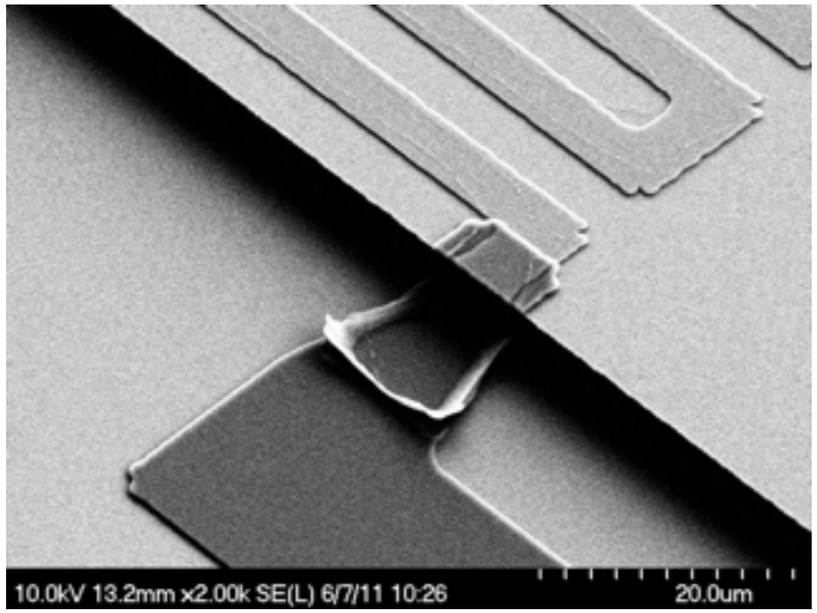


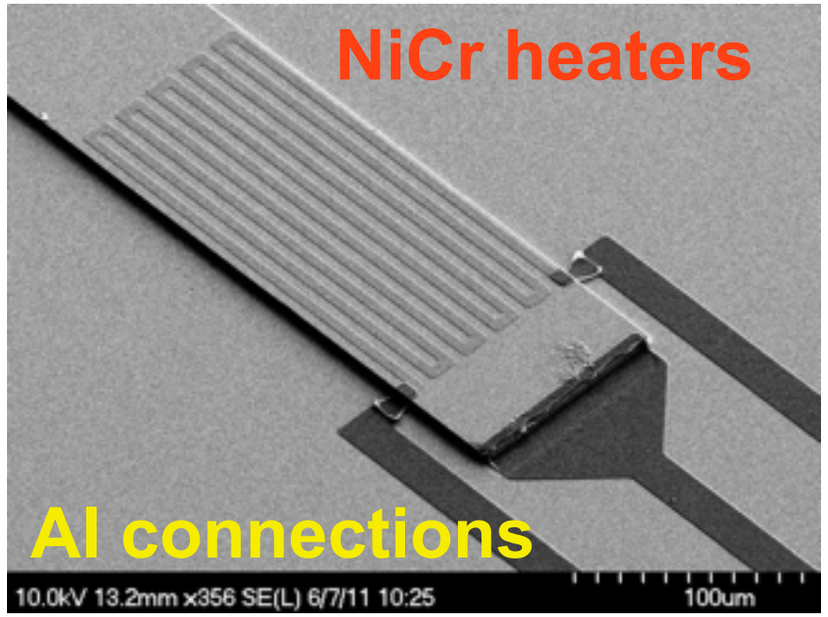
- Accurate electrical measurements easy
- Thermal conductivity most difficult

Fabrication Issues

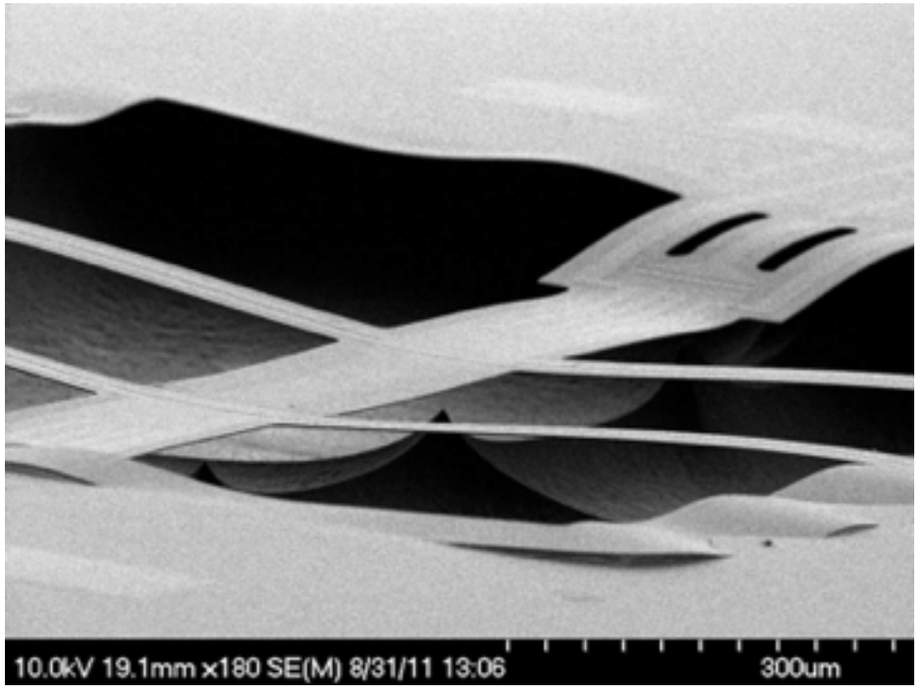
Metal running over 5 to 12 μm steps



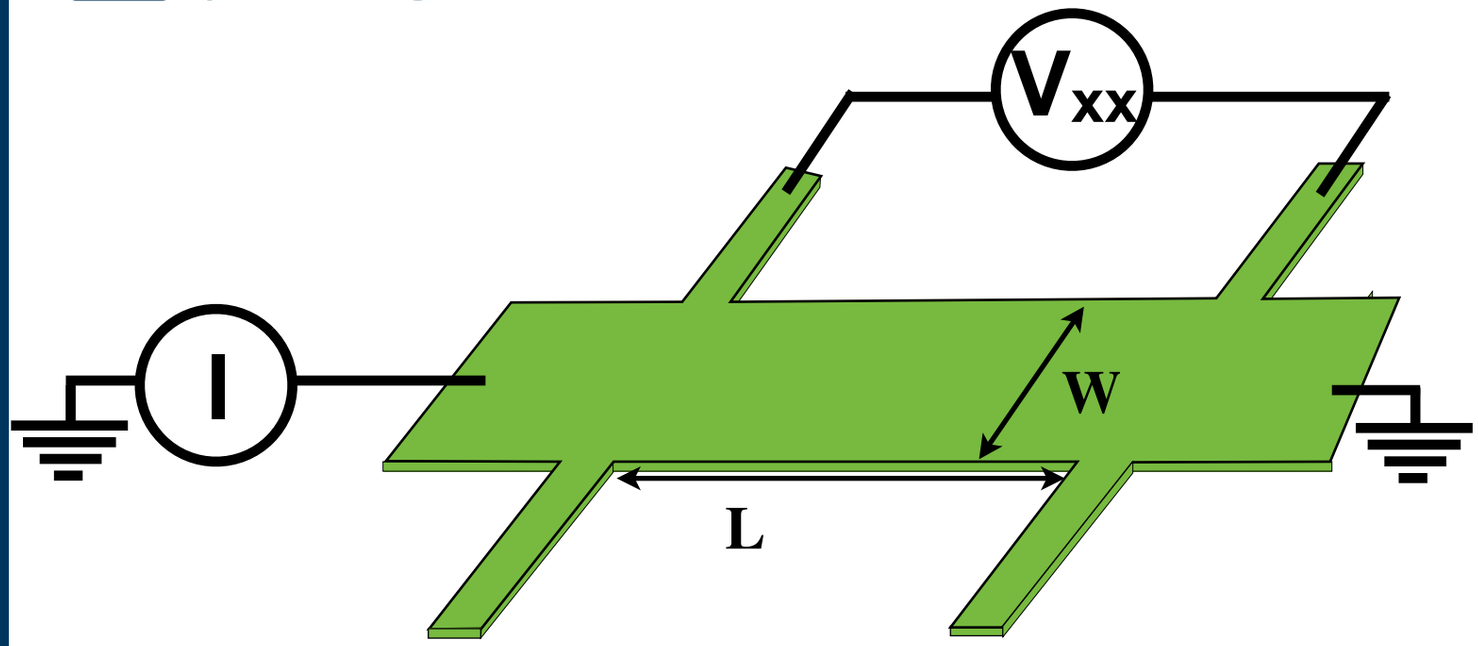


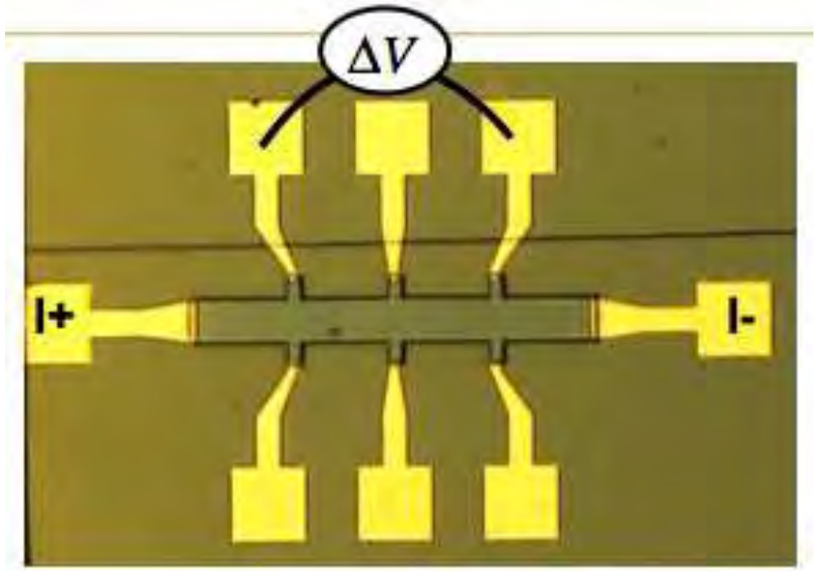


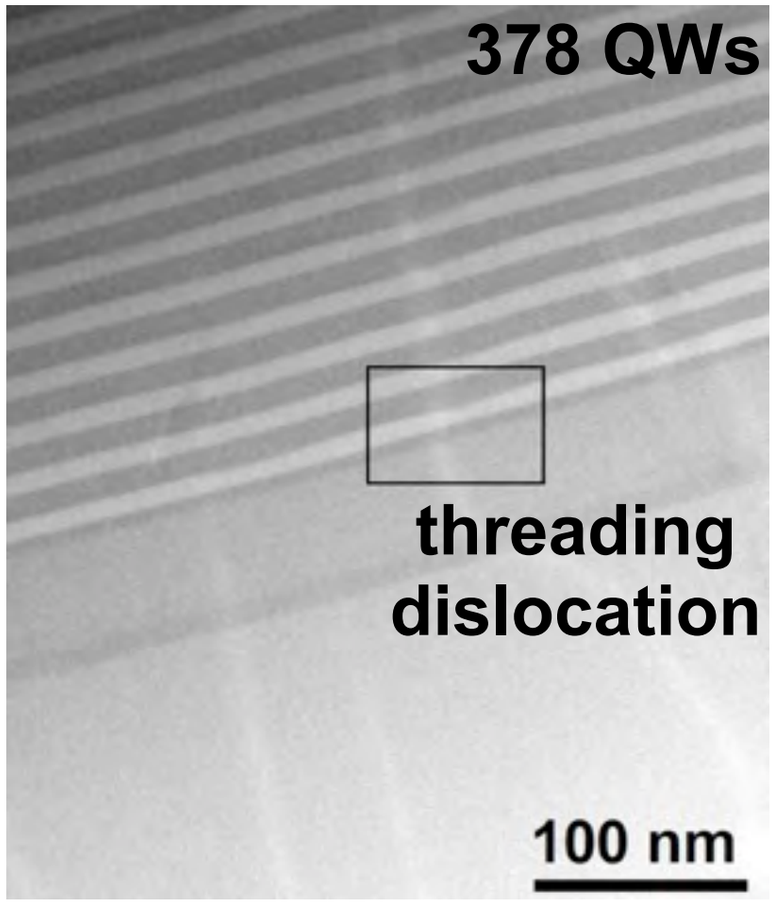
Removing substrates to prevent parallel thermal transport



Electrical Conductivity Measurements







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

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

σ = 118,500 ± 3,500 S-m

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

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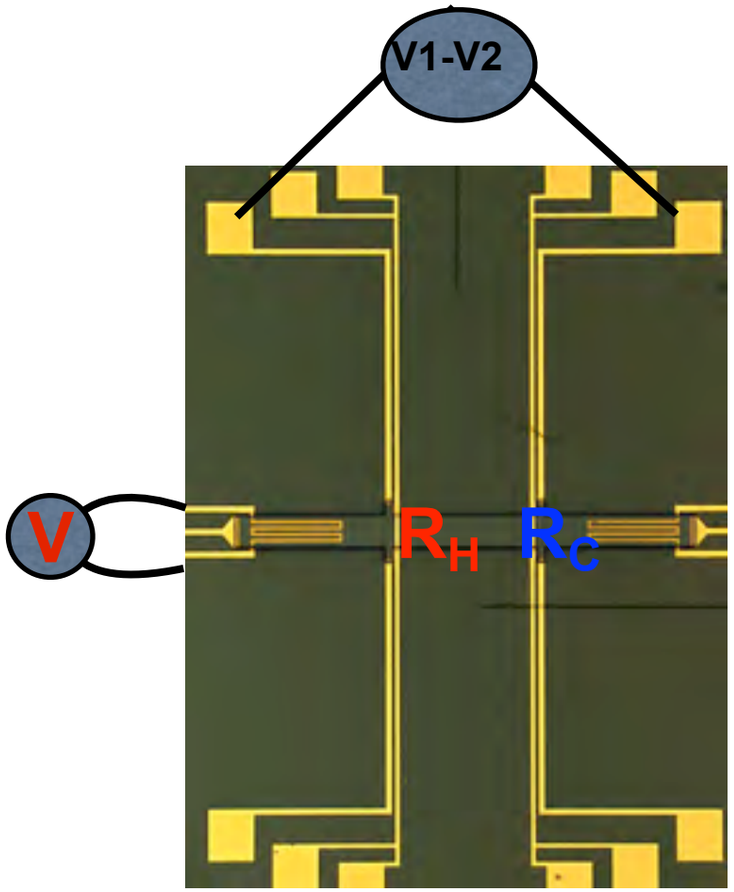
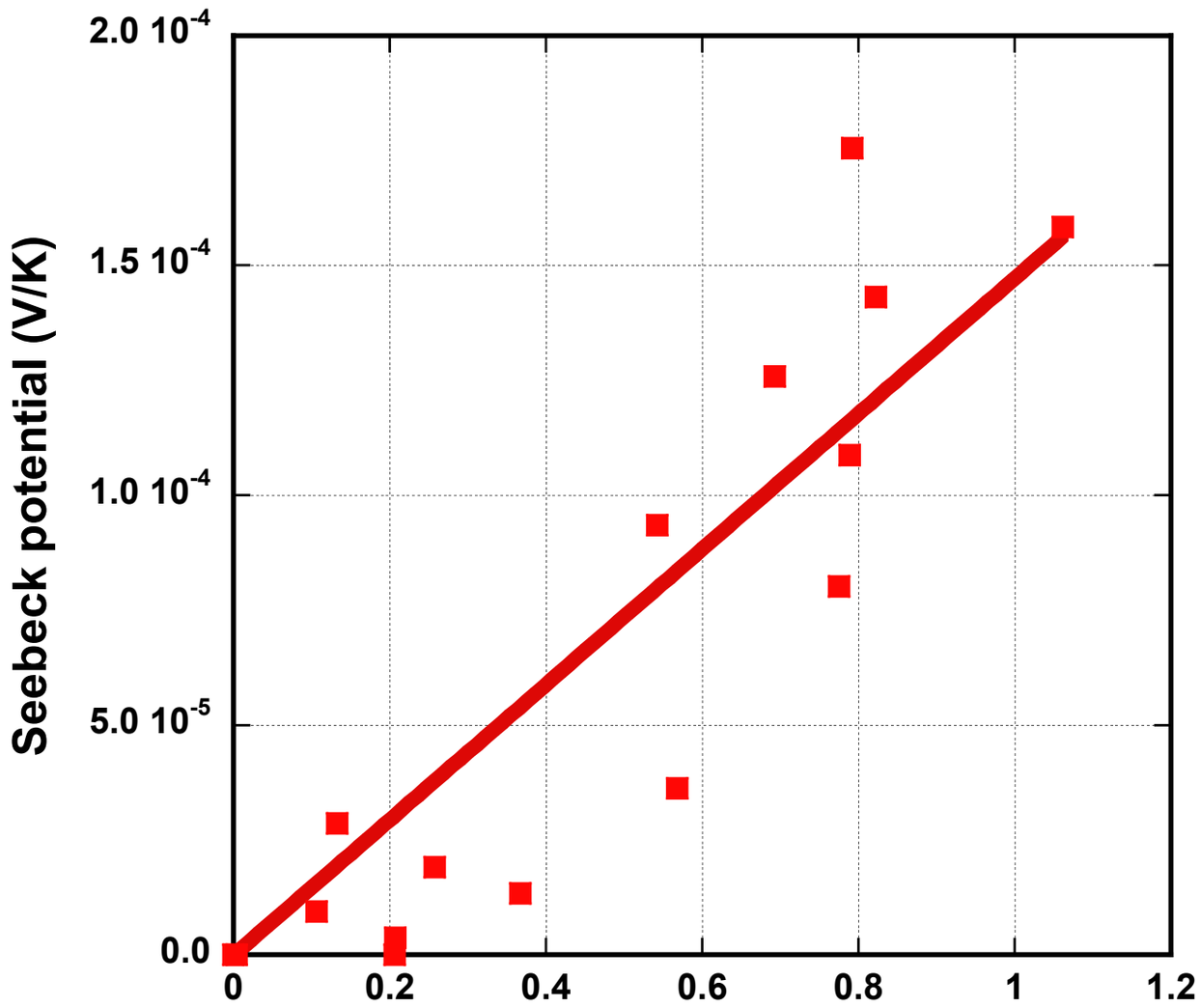
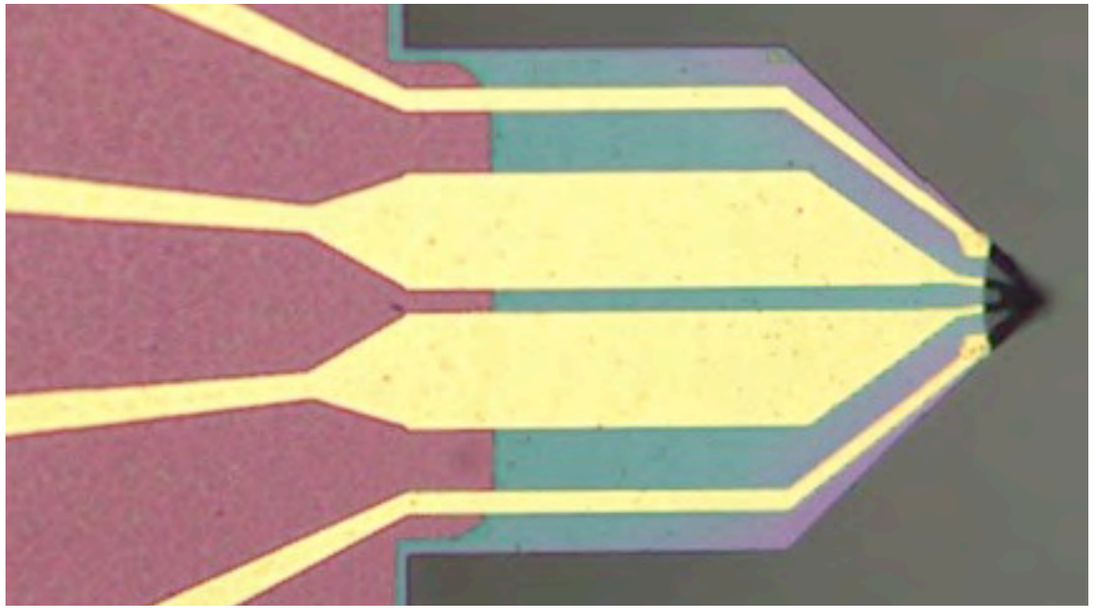
Seebeck coefficient measurements

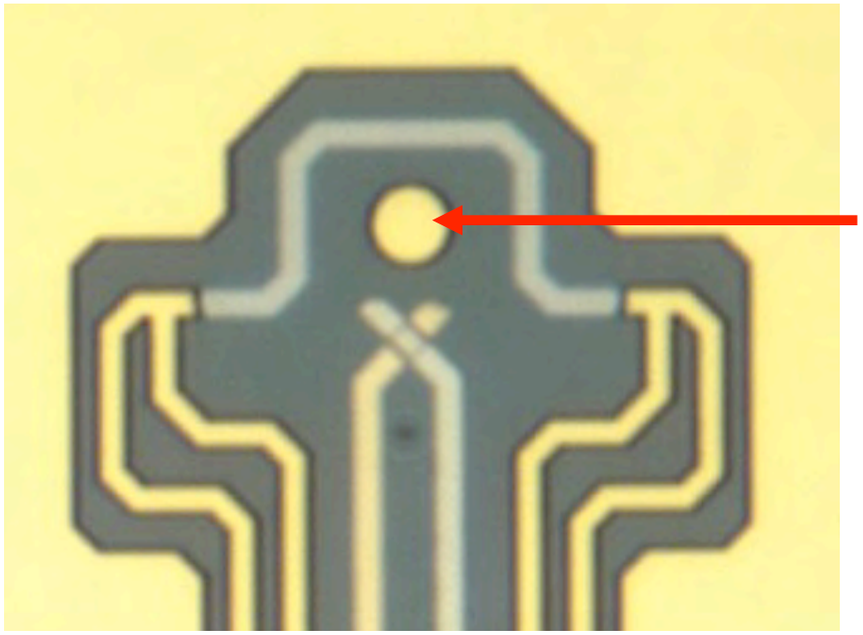




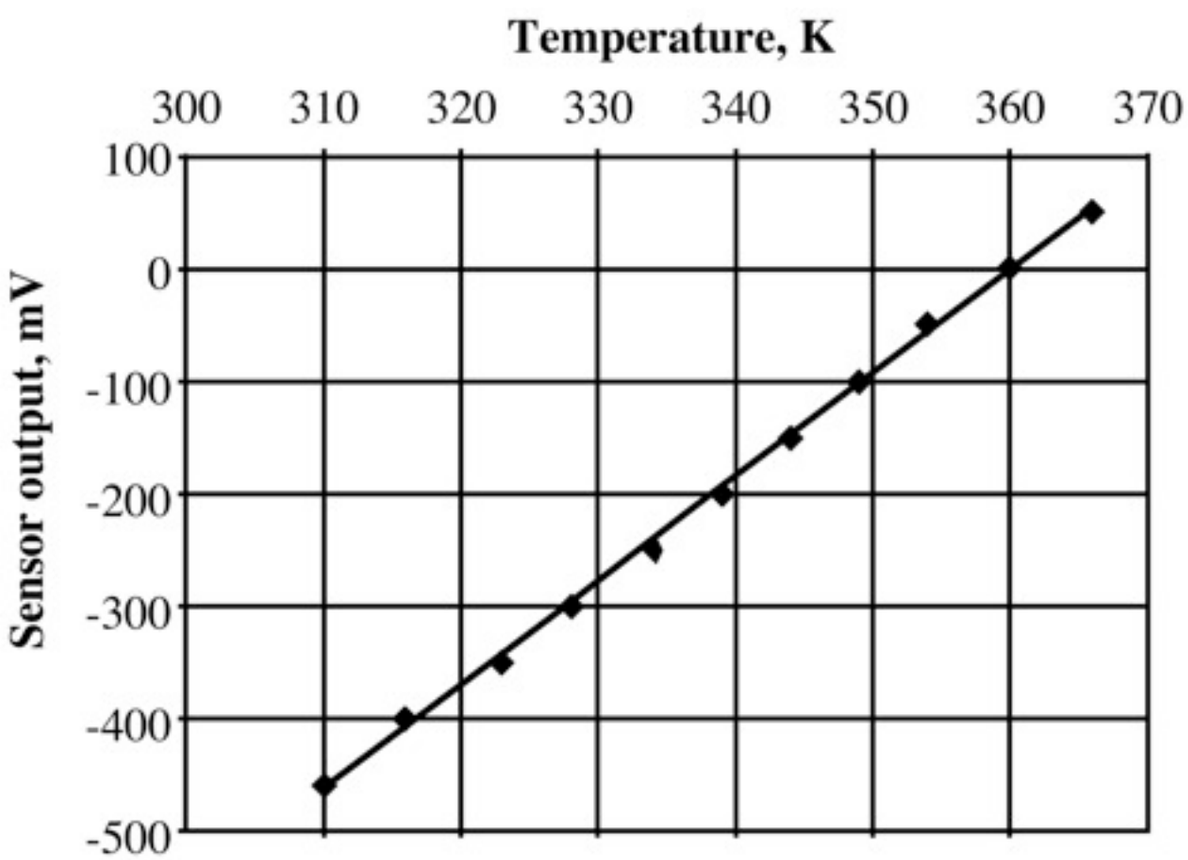
α = 150 ± 13 μV/K

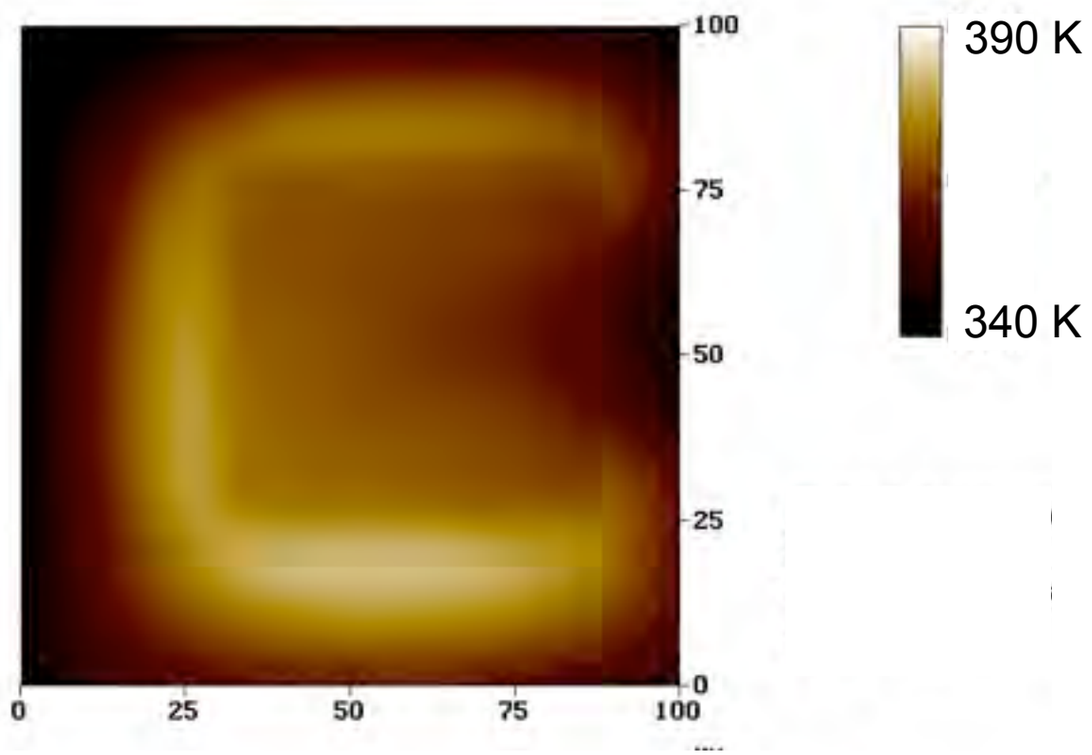
Scanning Thermal Microscopy





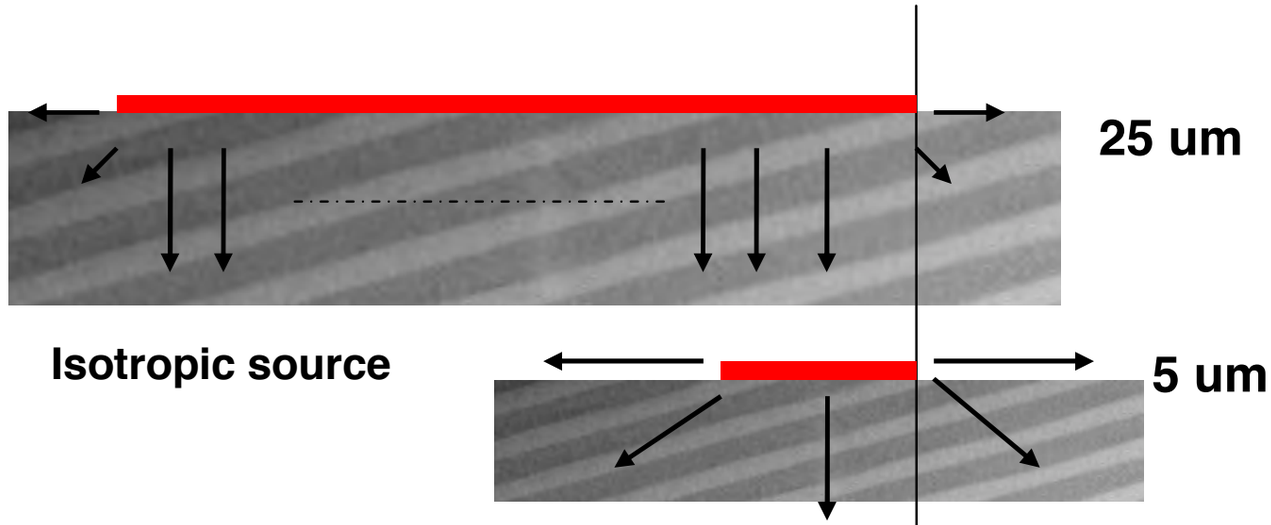
Electrically isolated Au spot: isothermal with resistor





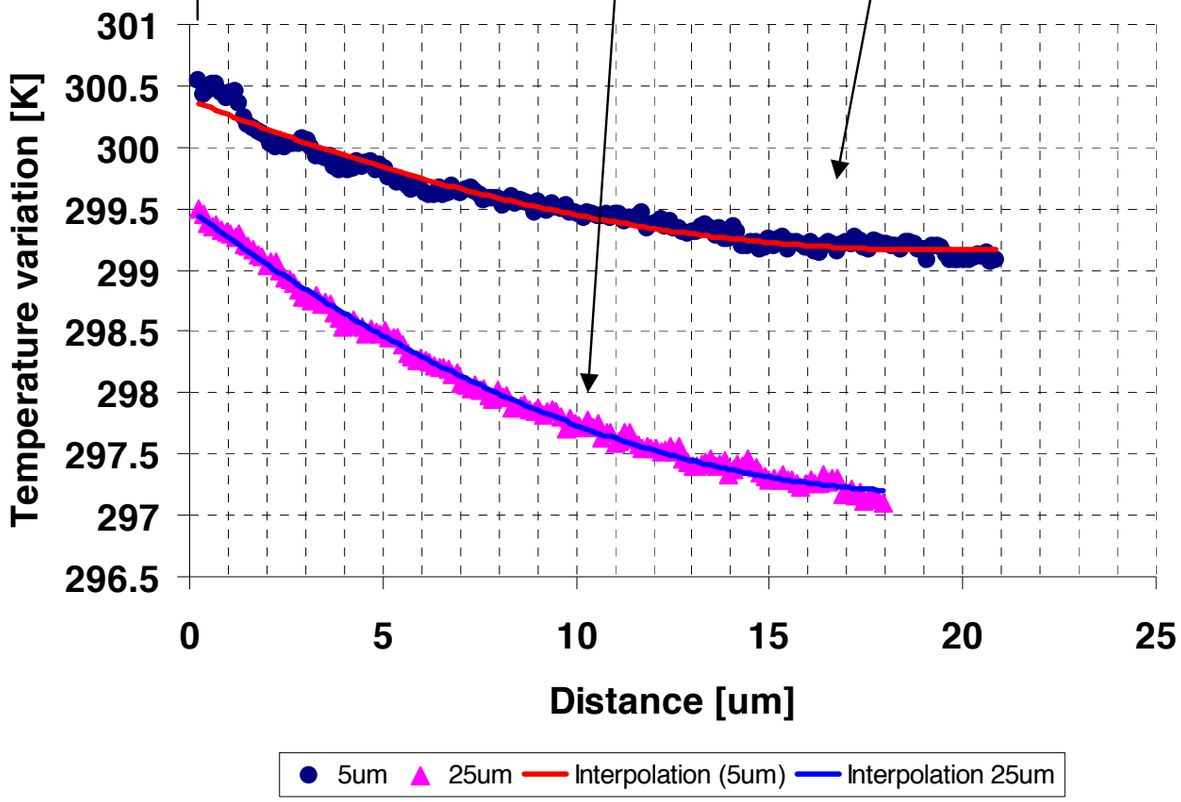
P. S. Dobson, et al., Rev. Sci. Inst. 76, 054901 (2006)

Thermal AFM Measurements 8557

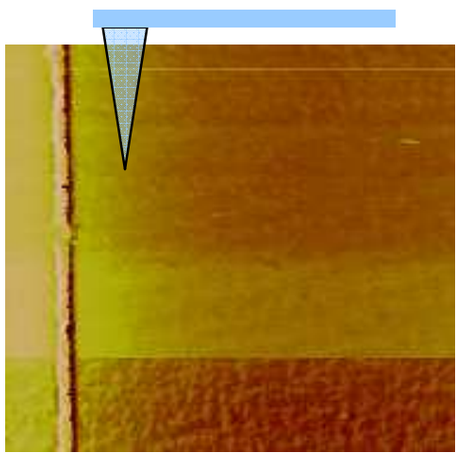


Bigger dependence of the cross plane thermal conductivity

Smaller gradient in the horizontal direction



Voltage → Temperature vs position



Calibrated thermocouple

+

Johnson noise compensation

κ = 6.36 ± 1.02 W/mK

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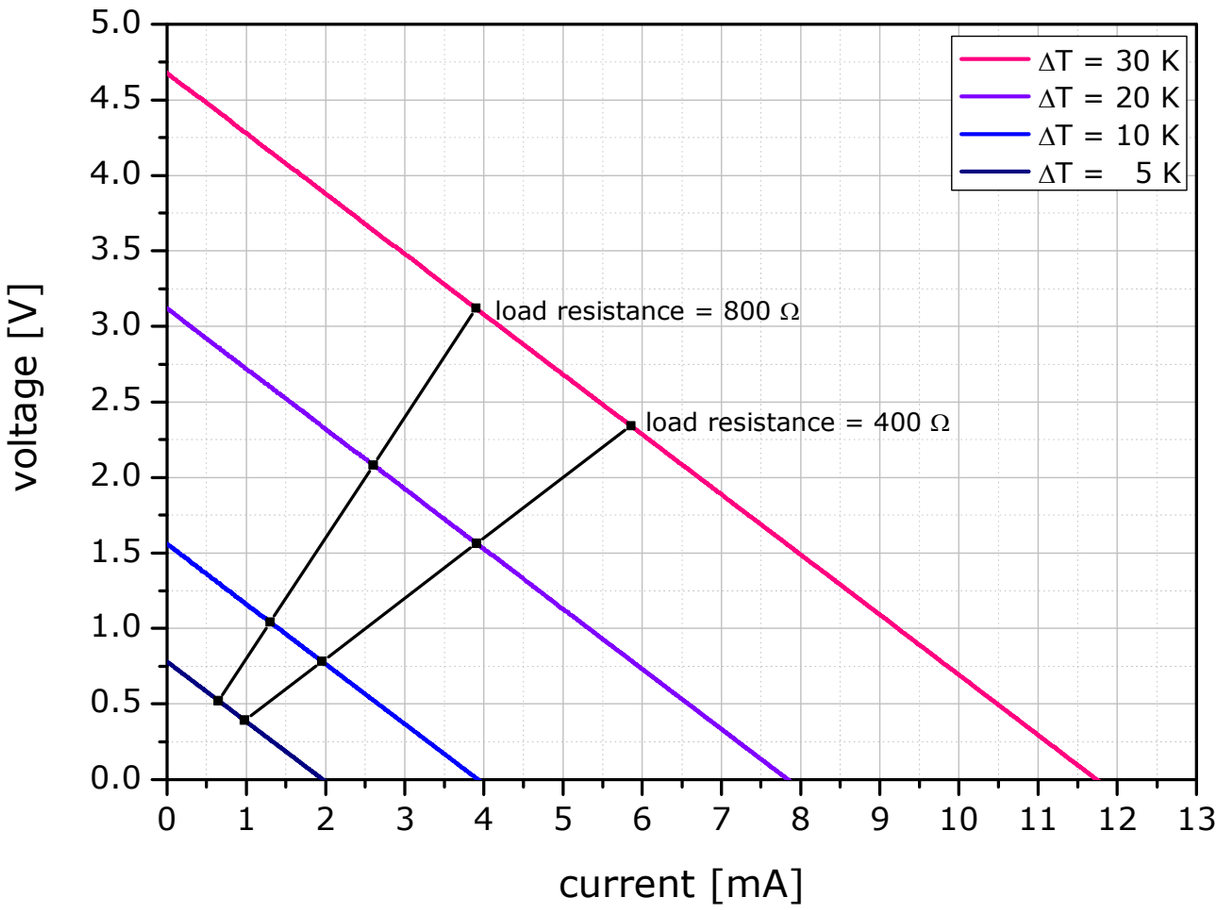
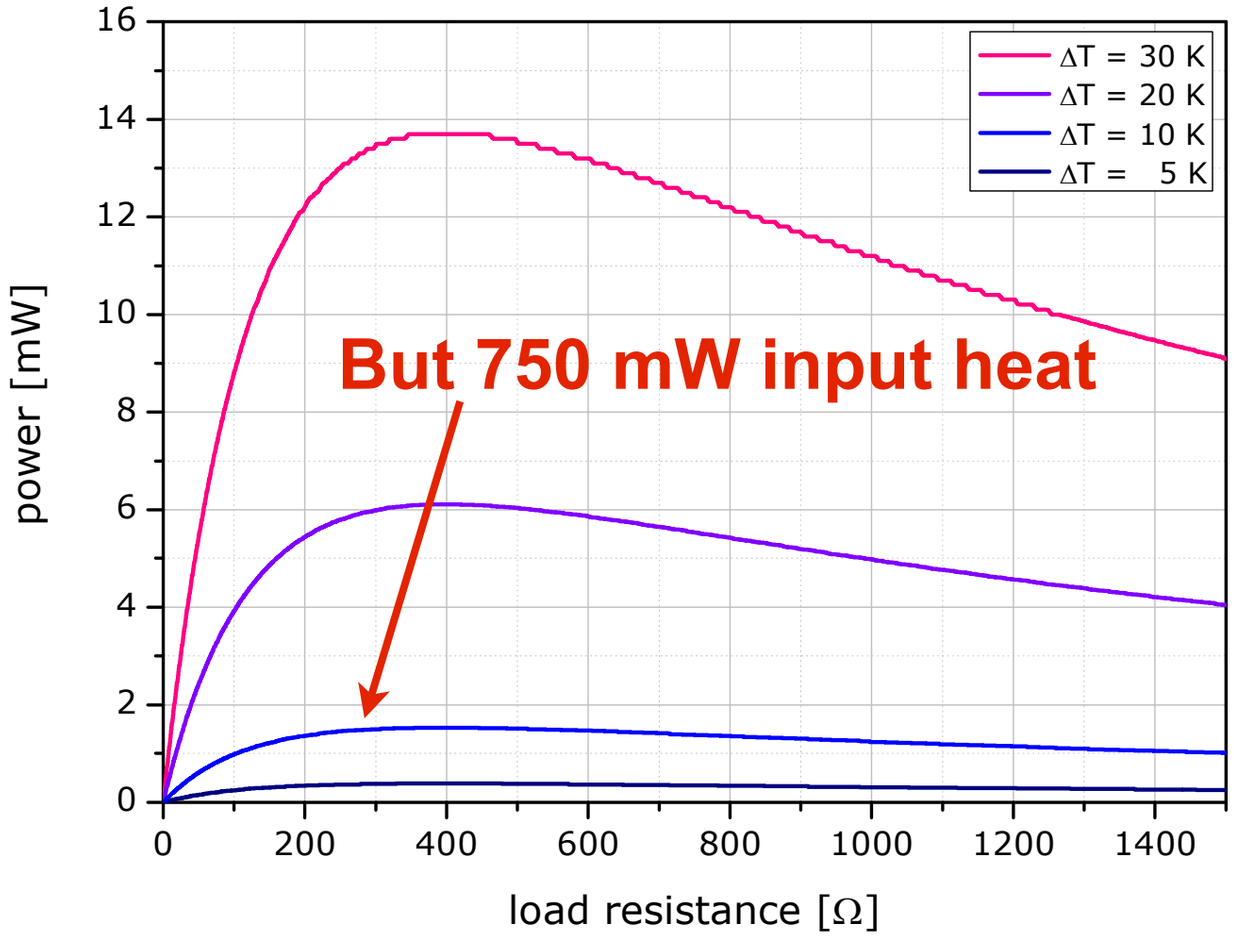
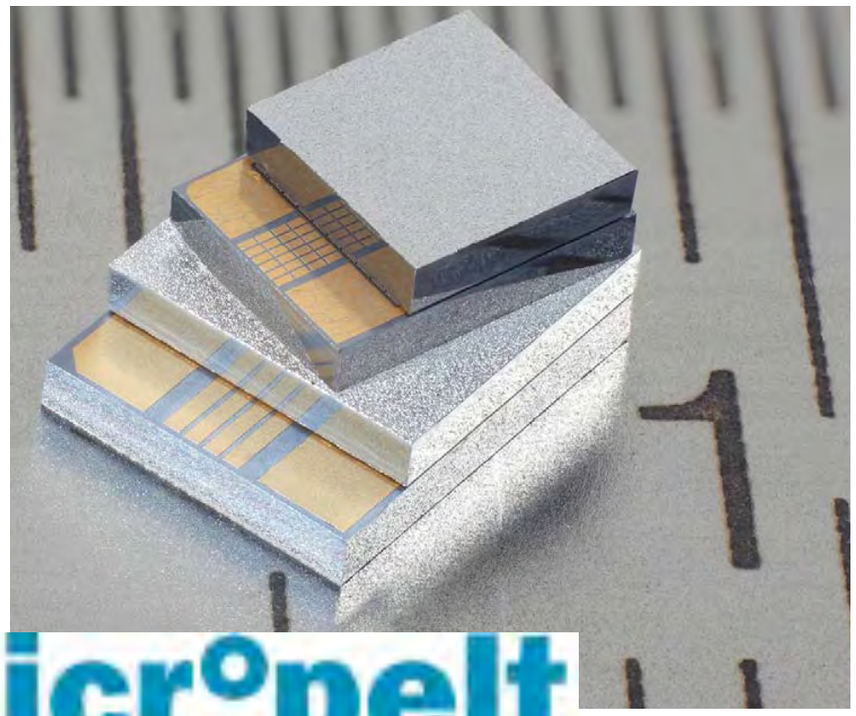
Micropelt MPG-D751 TEG Modules

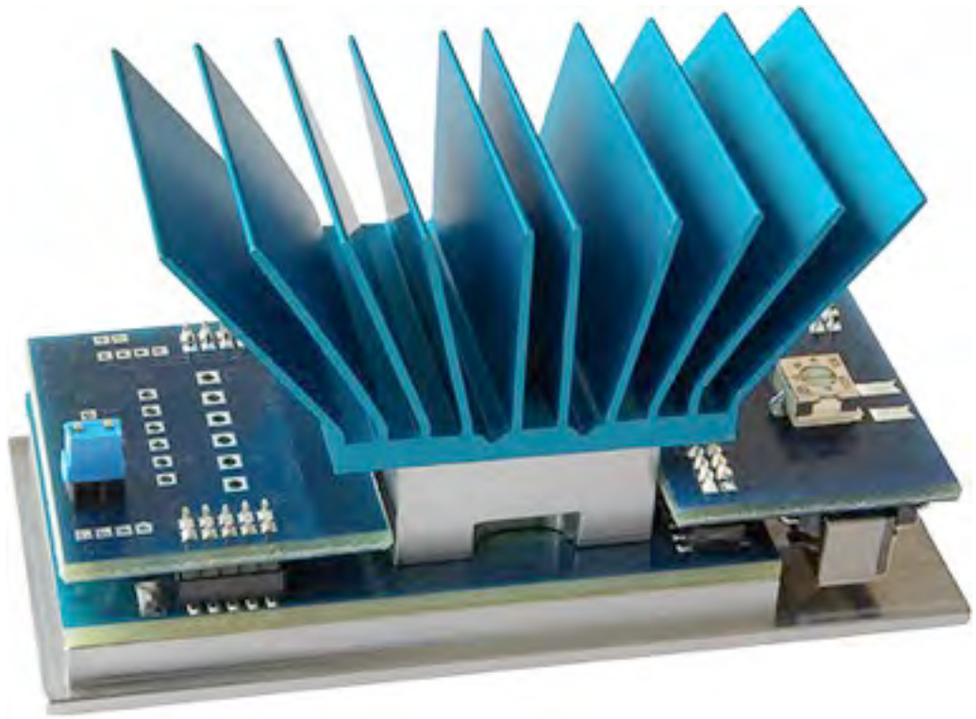




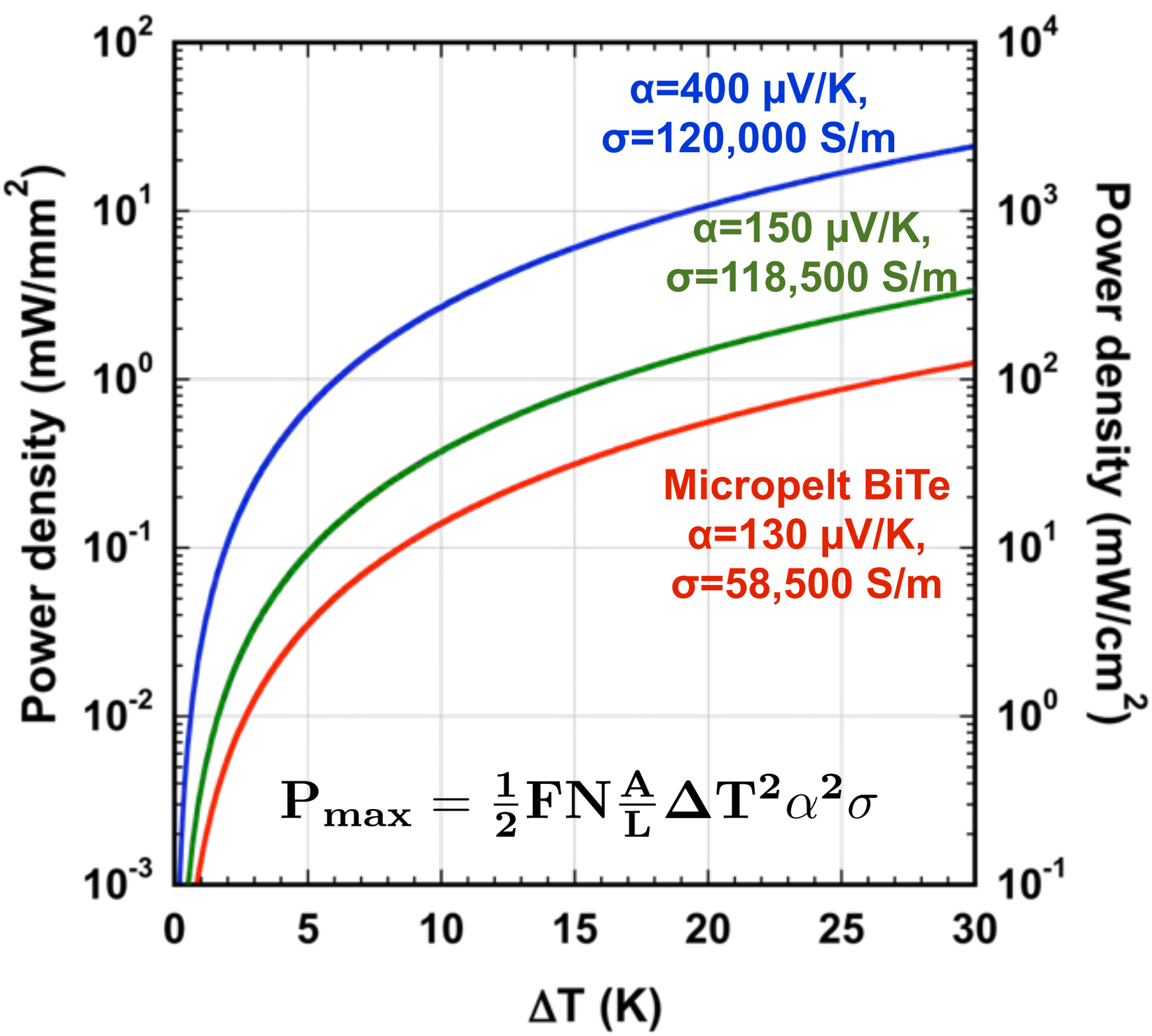


micropelt

3.4 x 3.4 mm



Power Density Estimates



Micropelt MPG-D751

n-BiTe / p-SbTe

N legs = 540

A = 35 μm x 35 μm

Leg L = 40 μm

F = 0.95

Delivered into load = 400 Ω

NB Heat sinking and impedance matching key for maximum power

Present Thermoelectric Research @ Glasgow

- BiTe / SbTe nanostructures for thermoelectrics
- Si/SiGe micro-thermoelectric generators
- Thermal & electrical modelling (transport to bulk systems)
- Maximum power point tracking for thermoelectrics
- Thermoelectric (module) test (micro and macro: 270 to 800 ˚C)

micropelt

NPL National Physical Laboratory

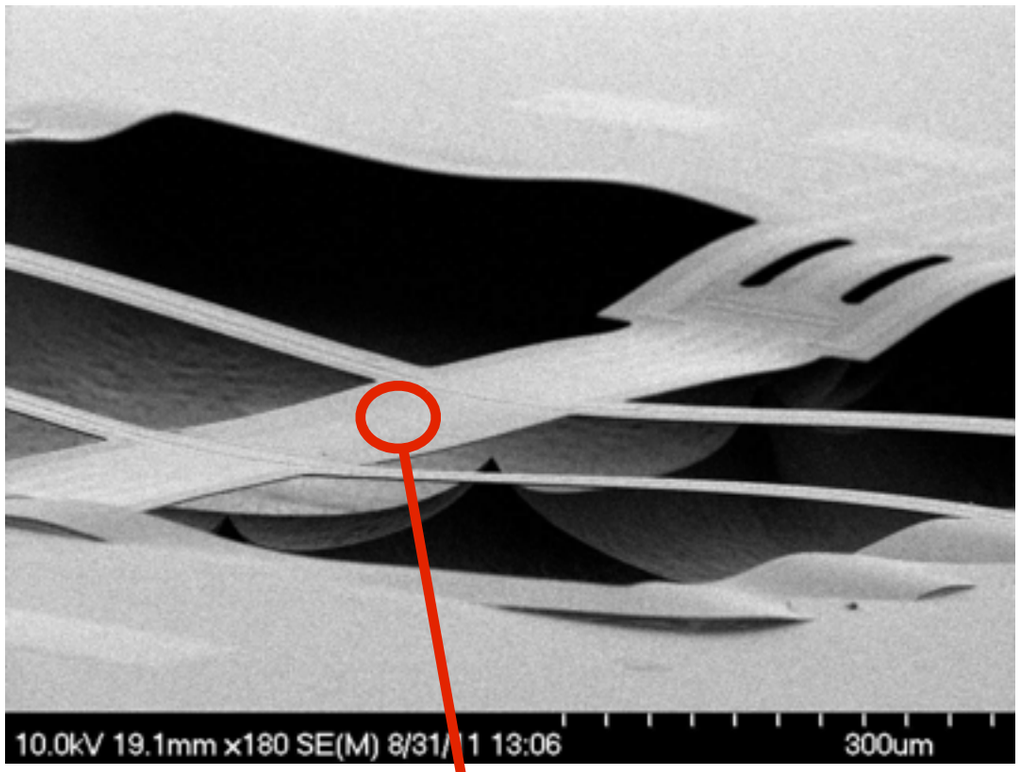
European Thermodynamics Limited
Intelligent Thermal Management

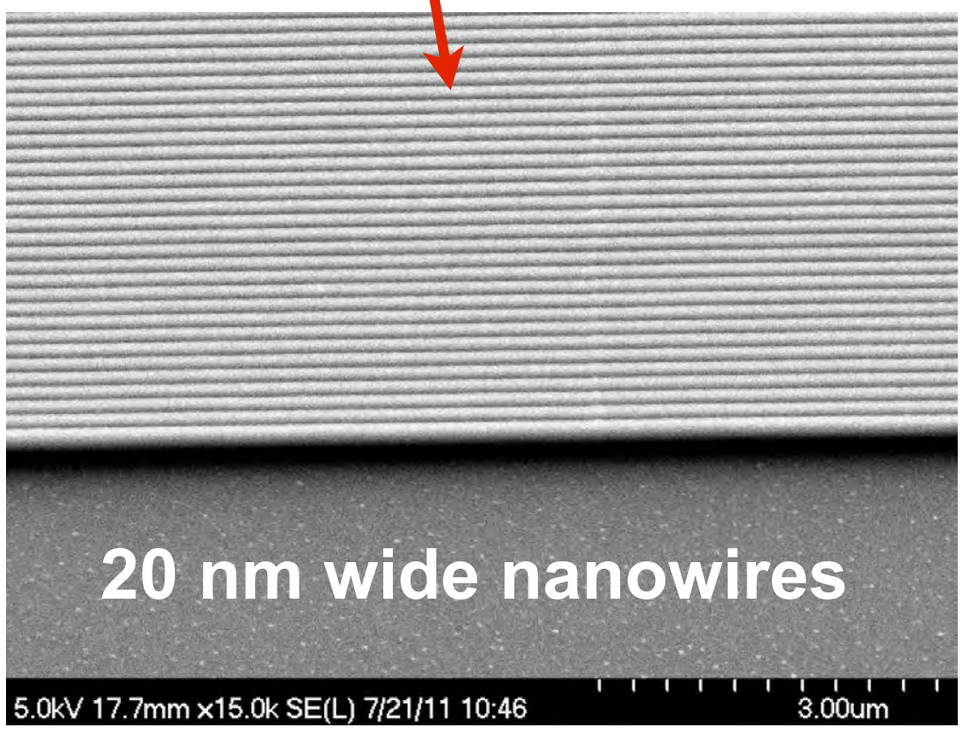
DOOSAN Doosan Babcock

University of Glasgow

1D Nanowires

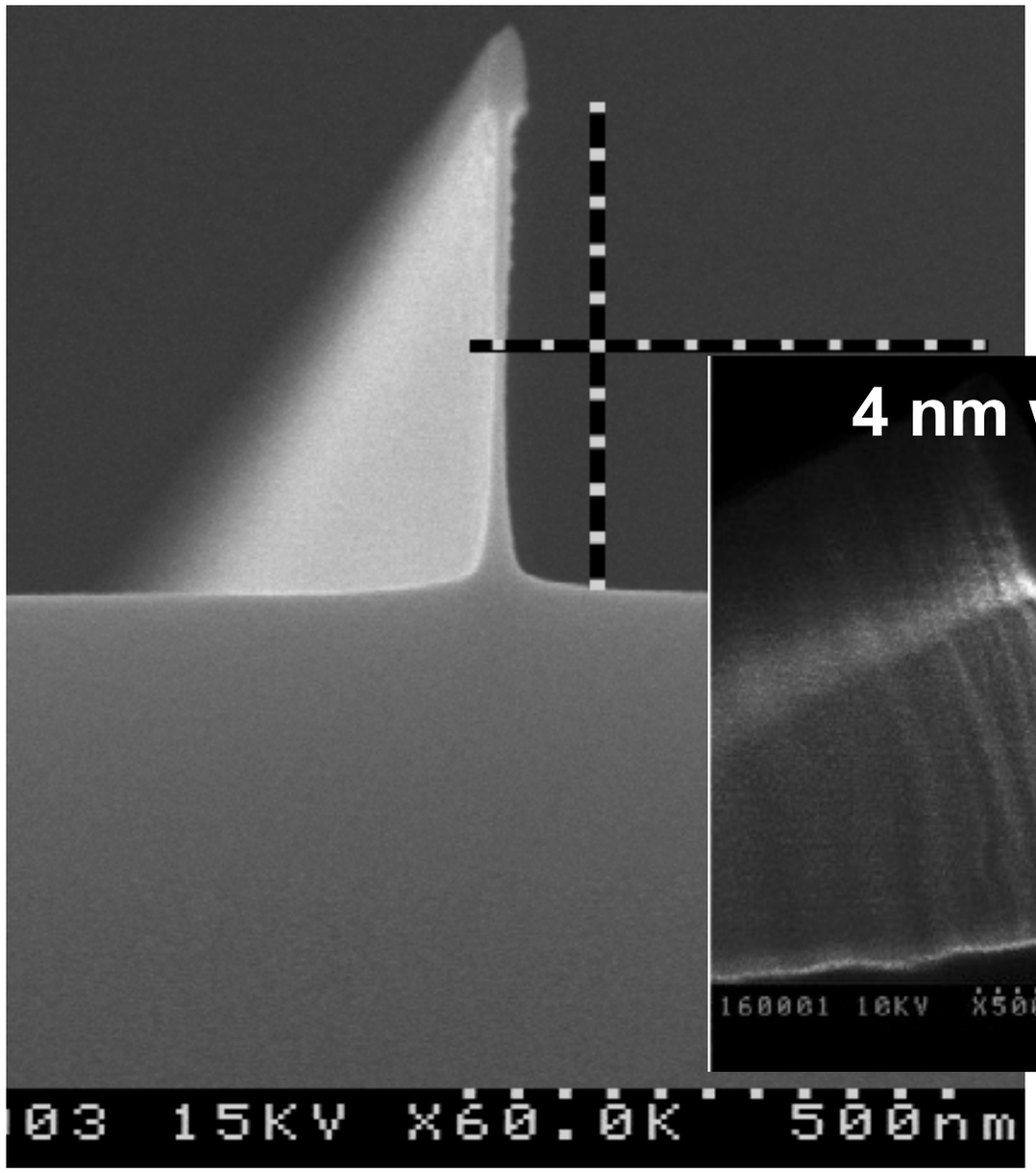
Lateral Nanowires





Vertical Nanowires

10 nm wide
500 nm tall
Si nanowire



Co-ordinated Action for EC ICT FET Proactive Initiative "Towards Zero Power ICT"

Network: energy harvesting & energy efficient ICT for autonomous ICT projects

Partners: Luca Gammaitoni, University of Perugia, Italy
Giorgos Fagas, Tyndall Institute, Ireland
Gabriel Abadal Berini, UAB, Barcelona, Spain
Douglas Paul, University of Glasgow, U.K.

http://www.zero-power.eu/

EC ICT FET Project No. 270005

Summary

- Si/SiGe heterostructures for engineered electron & phonon transport towards enhanced thermoelectrics
- Impedance matching, maximum power point tracking and heat sinking are key for thermoelectrics
- Powers of 10 mW/cm^2 from ΔT = 5 to 10 ˚C feasible in theory with Si-based technology - practical powers will be lower
- http://www.greensilicon.eu/GREENSilicon/index.html

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University of Glasgow

EC ZEROPOWER Energy Harvesting Industrial Workshop

ZEROPOWER

3rd and 4th July 2012
University of Glasgow

http://www.zero-power.eu/