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Nanoscale heat transport

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http://empir.npl.co.uk/3dstack/

UK thermoelectric Network - 21 April 2016

Energy conversion efficiency in solid state materials across length scales

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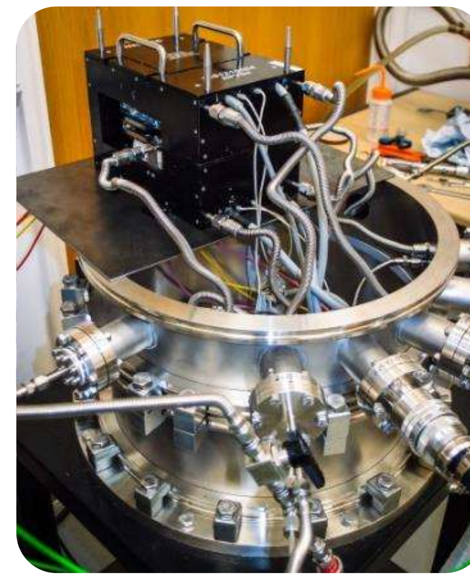
Accurate measurement of **heat flux** and energy **conversion efficiency** in solid state materials across length scales

Energy transport and dissipation in materials at the micro-nanoscale are key to

- **Direct Energy conversion**: thermoelectric, electrocaloric, photovoltaic,…
- **High current-density devices**: power electronics or emerging logic devices



Accurate characterisation of thermoelectric generators up to 900K

We are developing new traceable **nanoscale methods** to measure materials properties that link directly to **power conversion** in devices

SPM measurement of transport properties at the nanoscale
Cuenat et al, Nanotechnology 23 045703 (2012)

Performance improvement in TE

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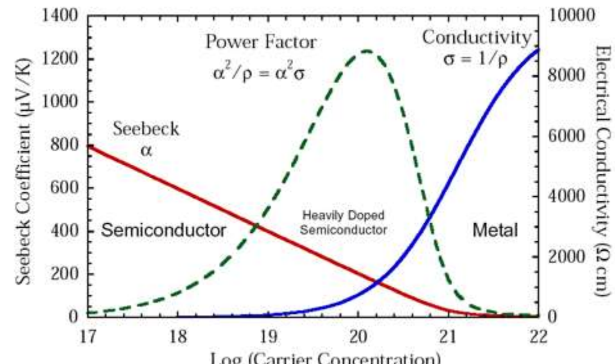
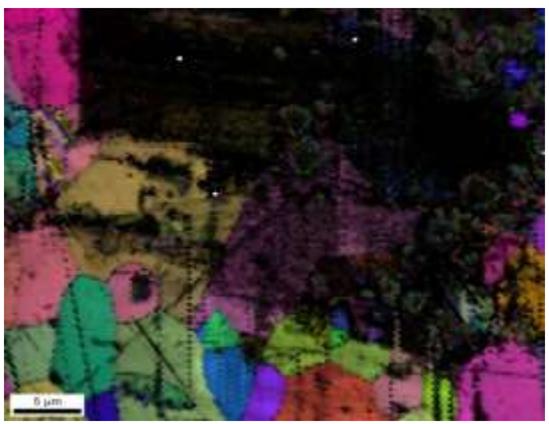
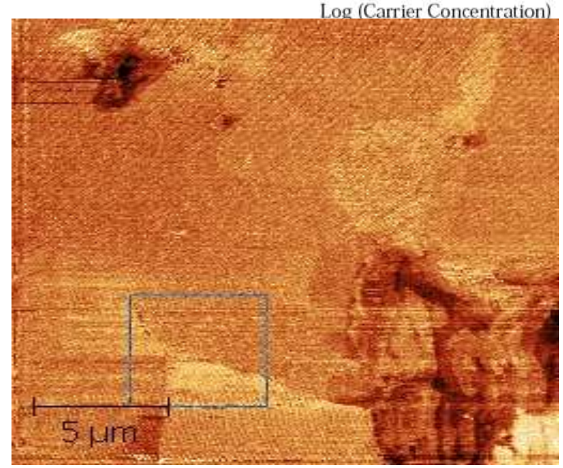
$$ZT = \frac{S^2\sigma}{\kappa} T = \frac{Power\ factor}{Thermal\ cond.}\ T$$







Most of current improvement comes for thermal conductivity reduction

Heating in current-carrying nanostructures

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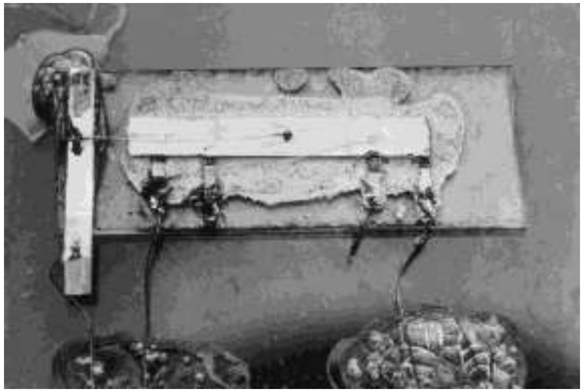
The basic problem of thermoelectricity is the following:

"Given a system consisting of one or several chemical phases and having a specified temperature distribution, it is required to determine the electronic electrochemical potential at any and all points within the system as well as at points in the immediate surroundings of the system." Domenicali RMP 1954

We are not alone to have this problem

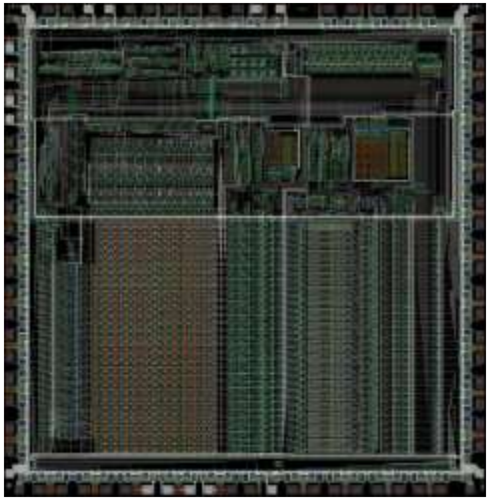
A Brief History

- 1958: **First integrated circuit**
  Flip-flop using two transistors
  From Texas Instruments



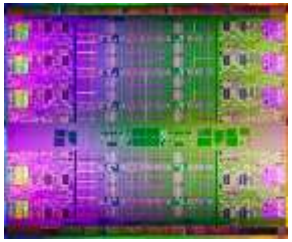
Source Texas Instruments

- 1985 **ARM1**
  25’000 transistors
  3’000 nm process



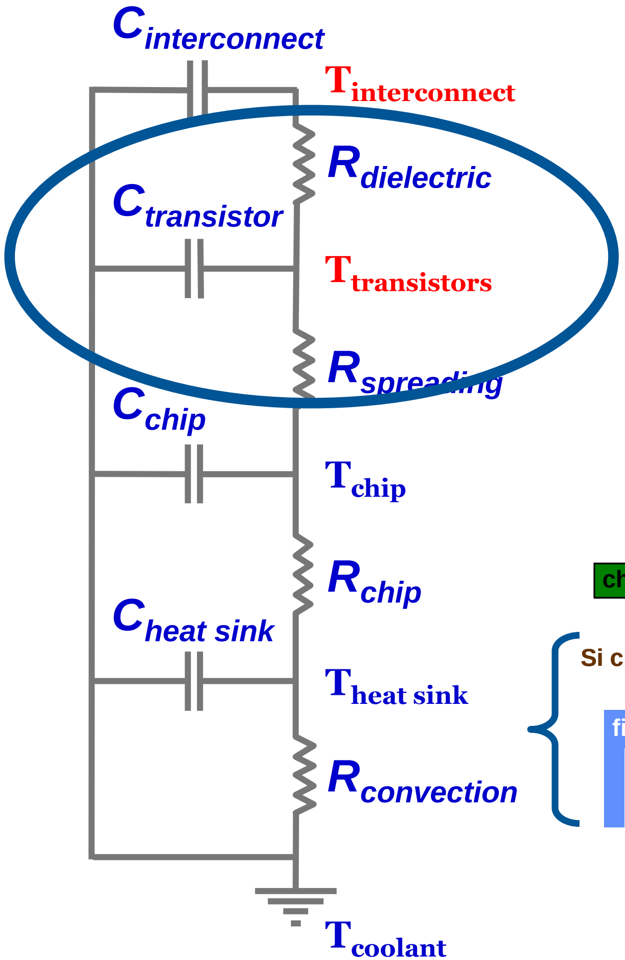
Source visual6502

- 2016 **Intel 22 Core Xeon Broadwell**
  7.2 billion transistors
  14 nm process

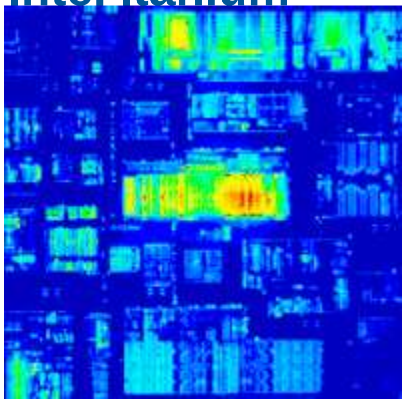


Source: Intel

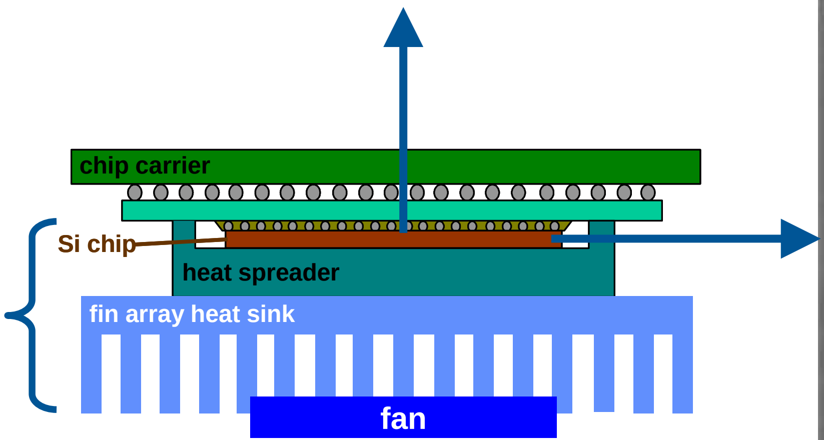
Where Does the Heat Come From?



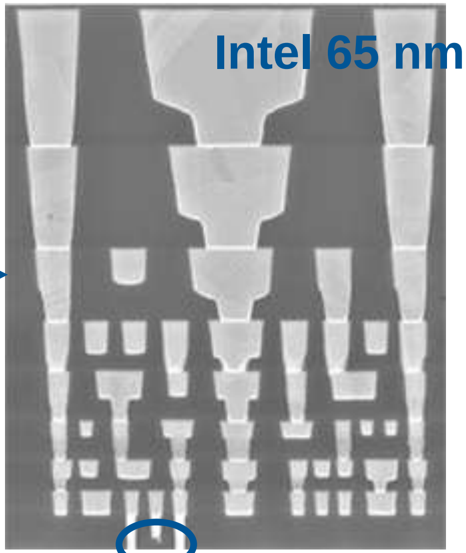
Intel Itanium



Top view
Hottest spots > 300 W/cm^2



Cross-section
8 metal levels + ILD



Transistor < 100 nm

Power Dissipation: Transistor → CPU

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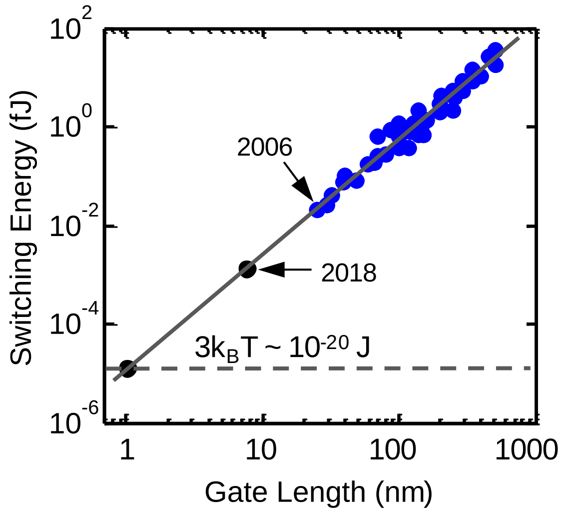
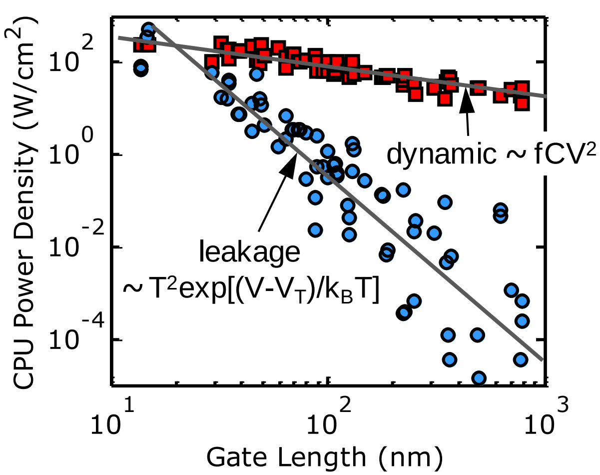
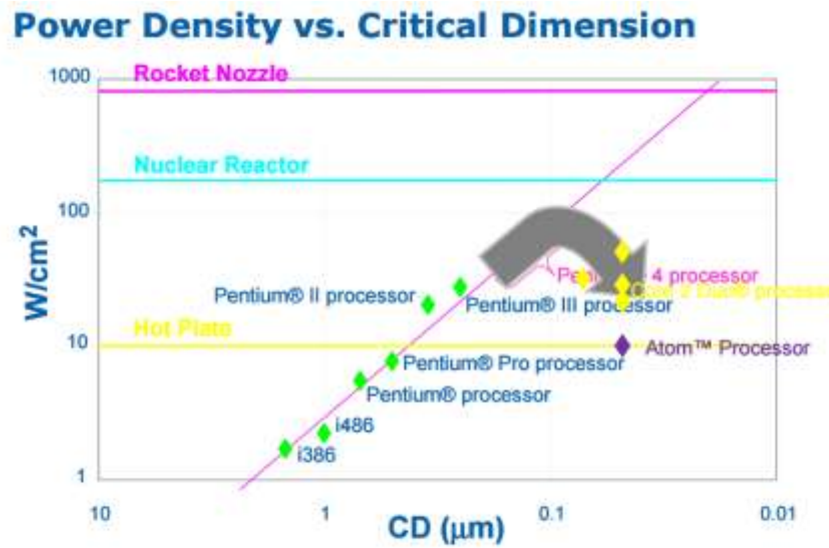
Single Transistor



x 1,000,000,000 Transistors?





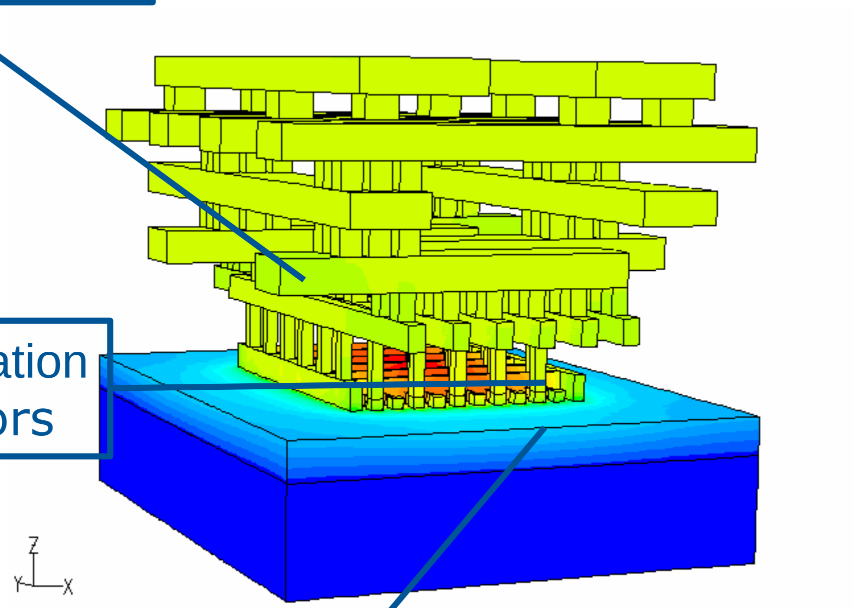
E. Pop, *Nano Research* 3, 147 (2010)
W. Haensch, *IBM J. Res. Dev*. 50, 339 (2006)
R. Cavin, *J. Nanoparticle Res.* 8, 841 (2006)

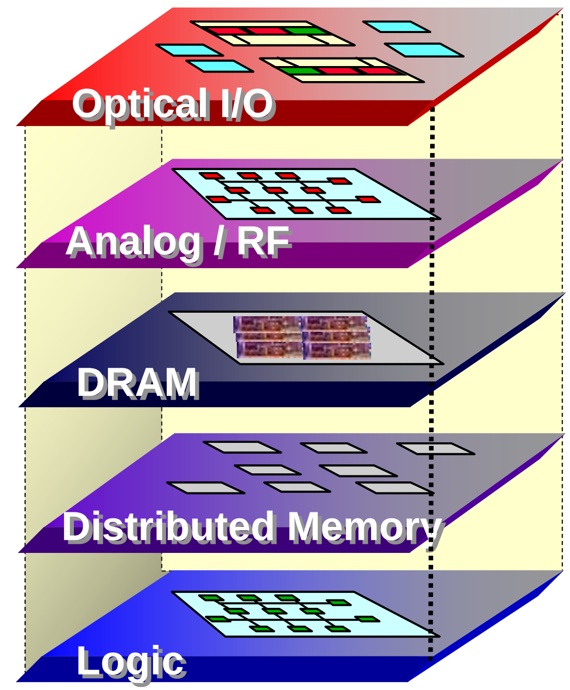
More on Chip-Level Complexity

Power dissipation in interconnects

Power dissipation in transistors

Thermal conductivity of substrate, heat sink





3-D integrated circuits = the ultimate density limit

How do we get the power in?
How do we take the heat out?

Metrology for manufacturing 3D stacked integrated circuits

EMPIR – Industry June 2015-May2018

3D-devices will combine logic, memories, imagers and MEMS **from different wafers of various foundries using different manufacturing processes** optimized at the right node.

- ✓ **Traceability of the measurement and standardization will be mandatory**

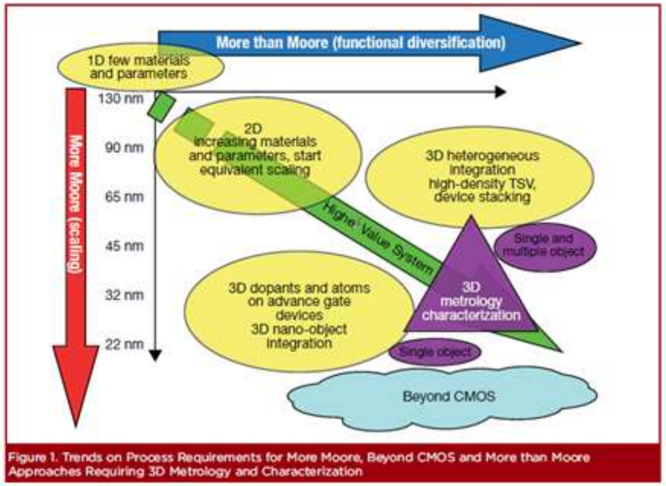


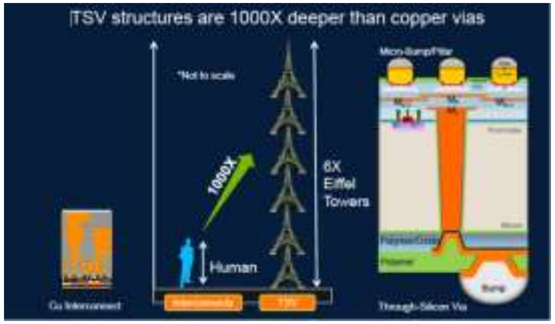
Figure 1. Trends on Process Requirements for More Moore, Beyond CMOS and More than Moore Approaches Requiring 3D Metrology and Characterization

European Industrial Roadmap 2014

Devices are “stacked” and connected with Through Silicon Vias (TSV)

Increased integration, means

- Increase Cu resistivity (smaller grains)
- Increase heat (higher current density)
- Larger Thermomechanical stress



NPL will develop tools to measure energy dissipation with better lateral resolution, better accuracy and develop new procedures for conformity assessment at the wafer level

Heating in current-carrying nanostructures

Question 1: how is a local temperature defined and calculated?

Question 2: how is a heat defined?

Surface temperature measurement

- ‘Surface’ is an infinitely thin boundary between two objects
- No ‘system’ into which a thermometer can be immersed
- Does ‘surface temperature’ exist?
- What do you actually want to know?

Key equations

- All three partial errors are proportional to heat flux that flows up the probe due to the temperature gradient from object to probe
- If the heat flux is reduced, the measurement error is reduced

'surface loading'

$$\Delta T_1 = -\frac{R_\mathrm{T}}{\lambda_\mathrm{b}} F_\mathrm{m} q_\mathrm{T}$$

'contact resistance'

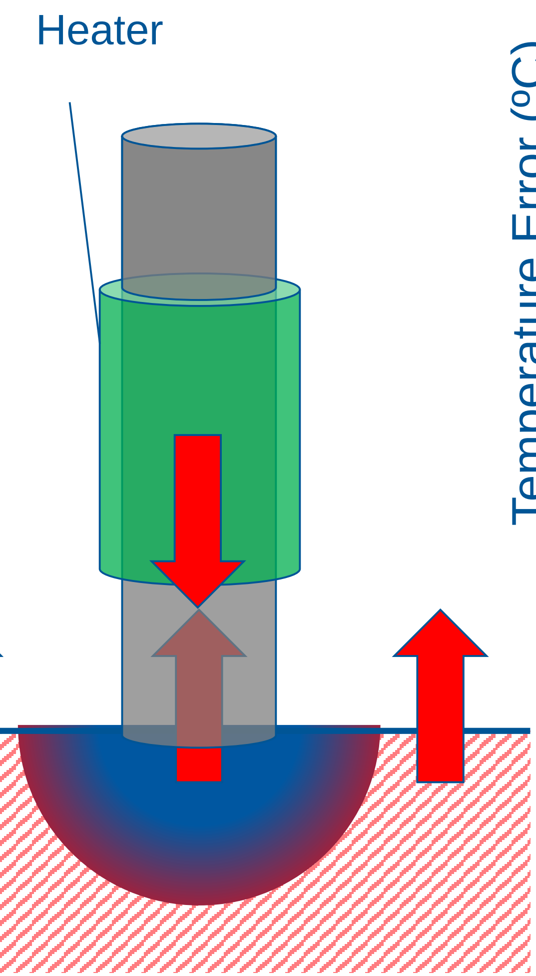
$$\Delta T_2 = -W_\mathrm{C} q_\mathrm{T}$$

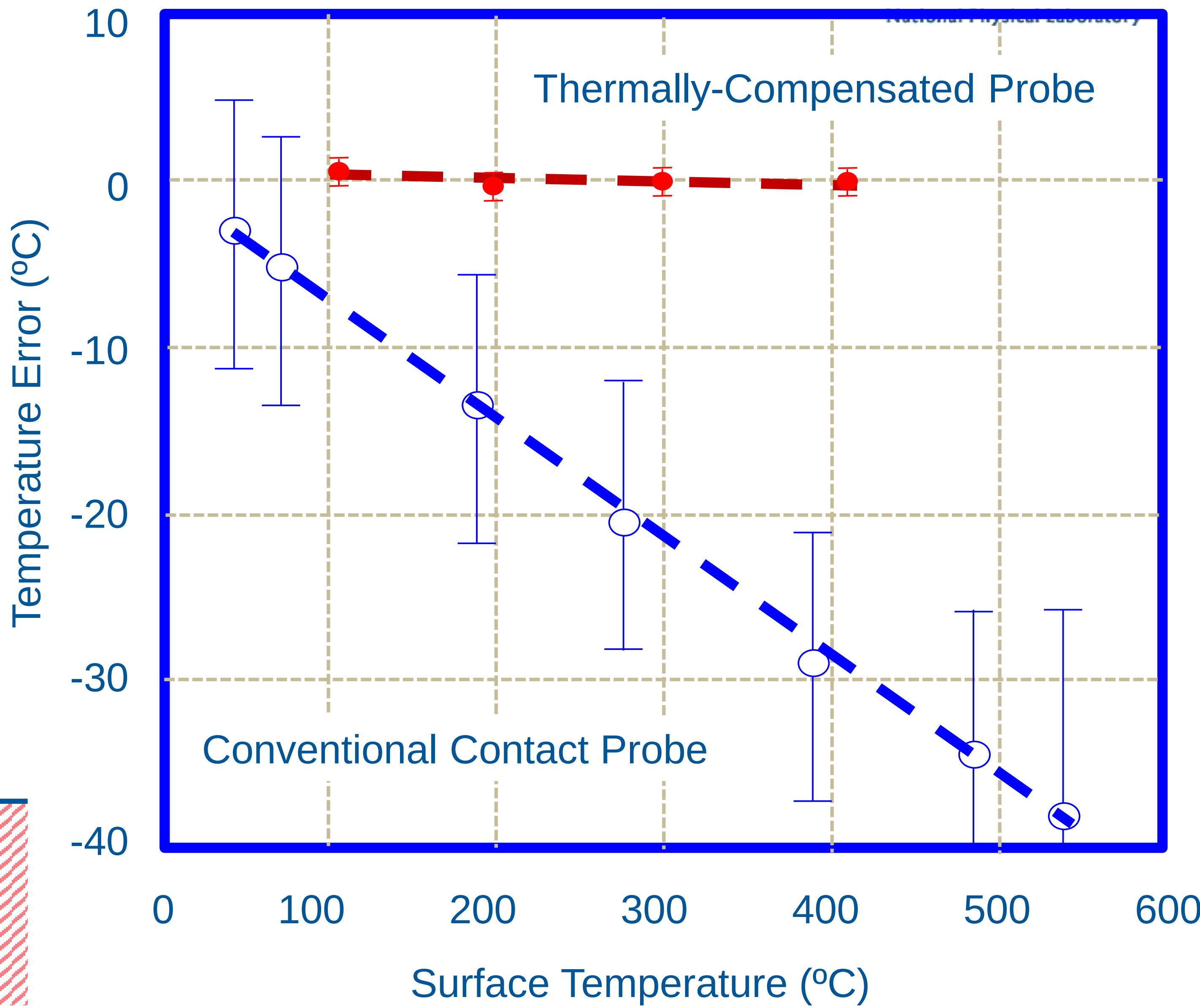
'probe resistance'

$$\Delta T_3 = -\frac{L}{\lambda_\mathrm{T}} q_\mathrm{T}$$

L. Michalski, K. Eckersdorf, J. McGhee,
Temperature Measurement,
John Wiley & Sons, New York and London,
1991 pp 317-350.

Thermally-compensated probe





B.D. Foulis, in "Industrial measurements with very short immersion", J.P. Tavener, D. Southworth, D. Ayres, N. Davies
http://www.isotech.co.uk/files/document_library_file-11.pdf

How do we measure temperature

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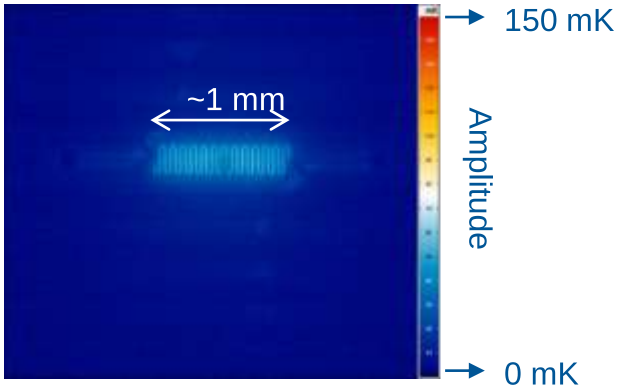
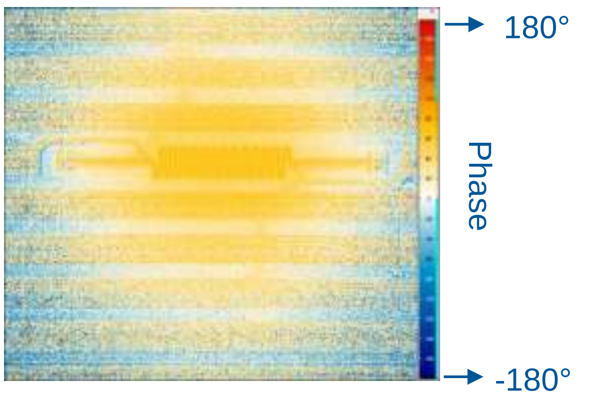
- Resistance
- Thermocouples
- Coulomb blockade
- MEMS based resonator quality factor
- Fermi-level shift
- Themochromic liquid crystals
- Infrared thermography
- Fluorescence
- Thermoluminescence
- Thermoreflectance
- Raman,

Near-field scanning optical or thermal microscopy

Lock-in infrared thermography





Measurement capabilities

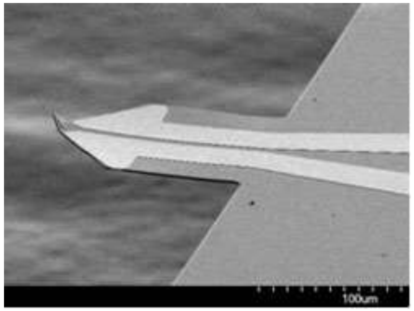
- Traceable temperature measurement
- mK change sensitivity
- Environmental enclosure with temperature control
- Capture rate up to 1.2 kHz

Scanning Thermal Microscopy

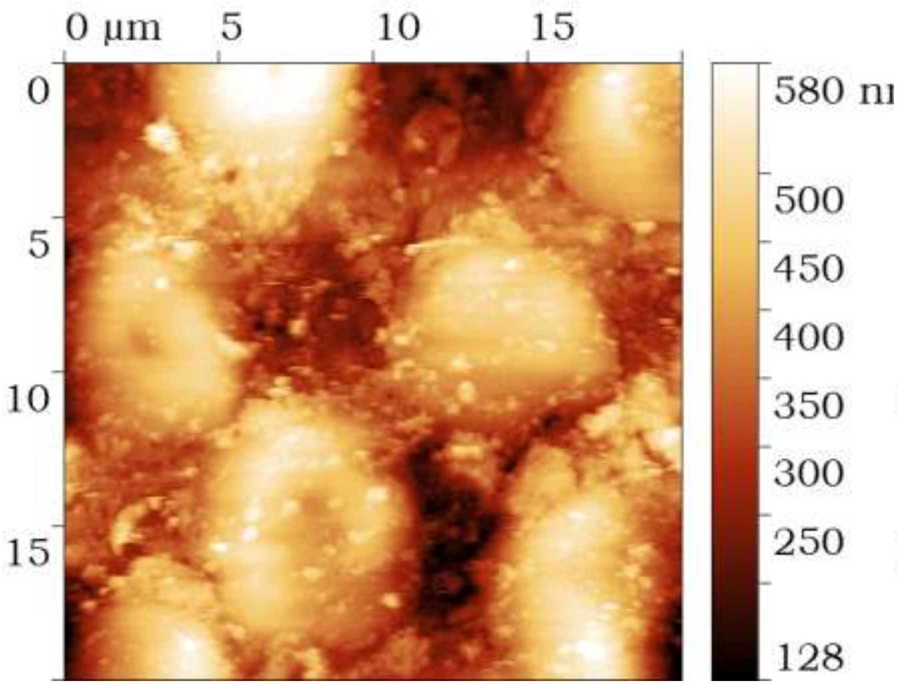
- A thermal sensor is mounted on a force sensitive cantilever and a feedback loops is used to maintain a constant tip-surface force while scanning
  - Cantilever deformation – bimorph effect
  - Thermal Drift and convection too slow to be a problem

- Thermal conduction = Thermal Transfer of heat through a material not involving mass transfer or emission of electromagnetic radiation

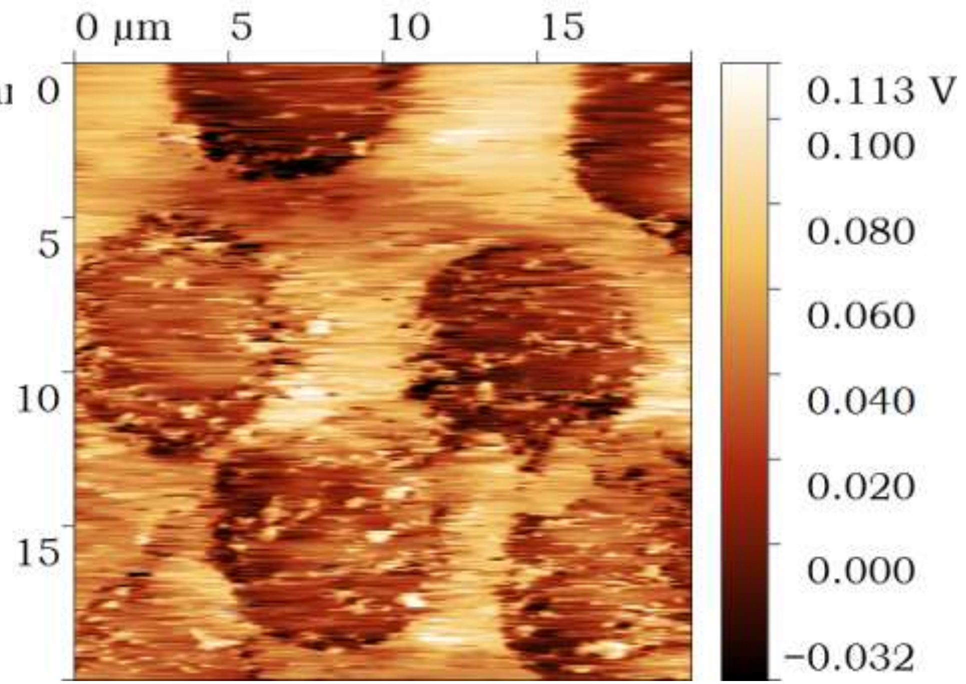
- Thermal conduction between the tip and the sample, change the temperature of the sensor



SThM Standard: carbon fibres in polymer matrix



Topography



Tip Voltage

Limitations

- So far mostly "limited" to materials with low thermal conductivity $0.1 < \kappa < 1$ W/(m K)
  - Good for some polymers and thermoelectric !
  - Too low for semiconductors and metals, need to extend the range

- Heat transfer between the tip and the sample, change the temperature of the sensor

- Need to predict thermal resistance of nanosized contact

Transport regime in STM

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Estimation of tip-sample contact radius

Derjaguin, Muller, Toporov approximation

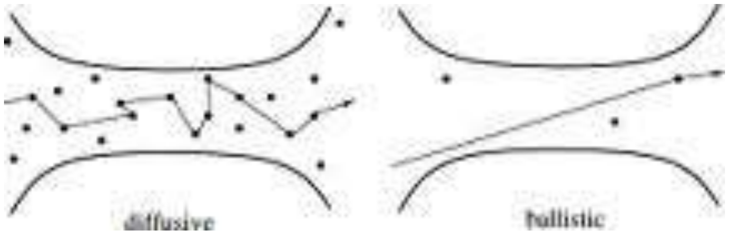
Derjaguin et al J. Colloid Interface Sci. 53, 314 (1975)

$$\left(\frac{3\, r_{tip}\, (F + 2\pi w r_{tip})}{4E^*}\right)^{1/3} = a_{DMT}$$

R_{tip} is measured by SEM,
W the work of adhesion extracted from force-curve,
F the contact force is directly measured
E* the effective Poisson's ratio can be estimated using nano-indentation

For Bi_2Te_3 the contact radius is approximately:

a_{DMT} = 5 nm for platinum tip
a_{DMT} = 15 nm for diamond tip



Transition between ballistic (Sharvin) and diffusive (Maxwell) regime
Nikolic and Allen, PRB 60,3963 (1999)

Conclusions

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While the materials maybe different, the measurands : heat dissipated in current carrying semiconductor is identical to IT and consumer electronics sector

Take home message:
Energy transport at the nanoscale is not obviously defined
Anisotropy matters

Department for Business Innovation & Skills

FUNDED BY BIS

3D Stack

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