UNIVERSITY
of
GLASGOW

Nanoelectronic Thermoelectric Energy Generation

Lourdes Ferre Llin
l.ferre-llin.1@research.gla.ac.uk

Overview:

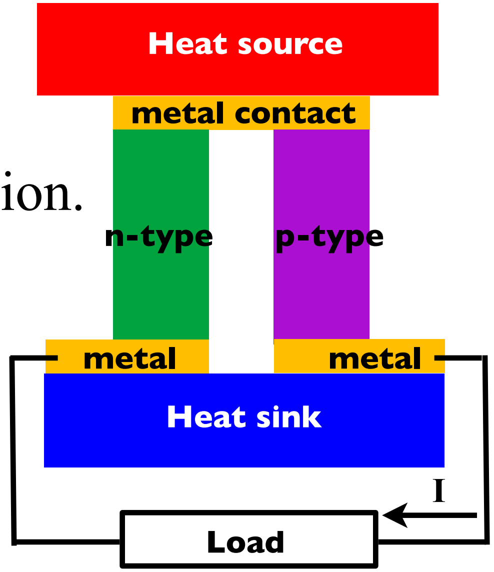
- Brief introduction on Thermoelectric generators.
- Goal of the project.
- Fabrication and Measurements for different devices.
    - Thermal conductivity.
    - Electrical conductivity.
    - Seebeck coefficient.
- Conclusions and future work.

Thermoelectric devices:

- Are used in applications for generating electricity due to a difference of temperature and also for producing cooling in presence of electricity.

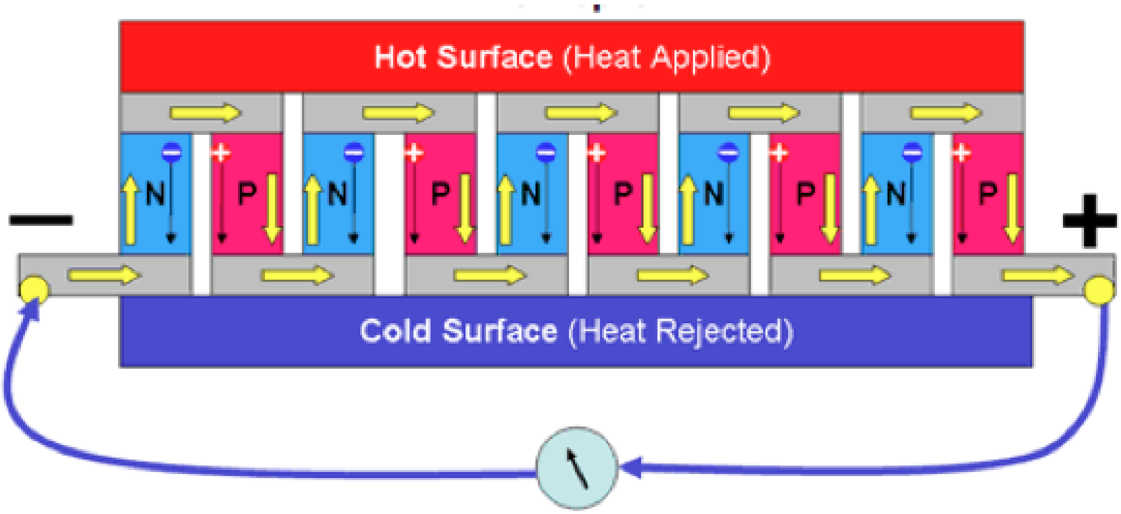
- There are three stablished thermoelectric effects, known as:
  - Peltier effect.
  - Thomson effect.
  - Seebeck effect.

- The Seebeck effect is the responsible for power generation.
  - Their fabrication consists of pairs of p-type and n-type semiconductor materials forming a thermocouple.



How does it work?

- These thermocouples are then connected electrically forming an array of multiple thermocouples.
- When we apply heat and cold, it is generated a difference of temperature that will generate electricity.



Thermoelectric generators.

- Applications:
  - Almost any heat source could be used to generate electricity, such as natural sources (solar heat) and waste heat of any device or machine that generates heat as a by-product.
  - Recovering the energy lost as heat could improve drastically the efficiency of a device or machine.

- Problem of thermoelectric devices to date:
  - Low efficiency.
  - Commercial devices produced using Bi and Te.

- Advantages:
  - Not moving parts.
  - Require very little maintenance
  - Can provide energy as long as there is a difference of temperature.

Objective of this project.

- Fabricate micro/nano structures to study the improvement of the efficiency.
- The heterostructures technology made of Si/SiGe that will be investigated are:
  - ❑ 2D superlattices.
  - ❑ 0D quantum dots.
  - ❑ 1D nanowires.
- The final thermoelectric design will be integrated on a mm-sized single silicon chip. This will be used to power a CMOS sensor .
  - ❑ The generator will work as a power source for an autonomous system

Efficiency & Figure-of-Merit

- The efficiency of a generator is given by:

$$\theta = \frac{energy\ derived\ to\ the\ load}{heat\ energy\ absorbed\ at\ hot\ \ junction}$$

- Maximum efficiency → $\theta_{\max} = \eta_c \cdot \lambda$

$$\eta_c = \frac{T_H - T_C}{T_H}$$

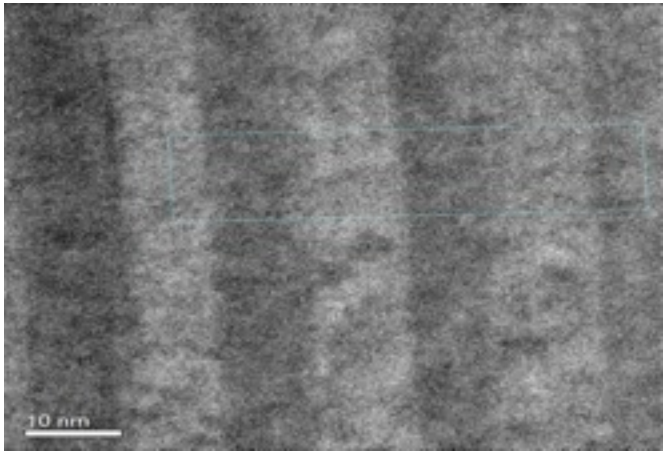
Product of the Carnot efficiency times the thermoelectric properties of the materials.

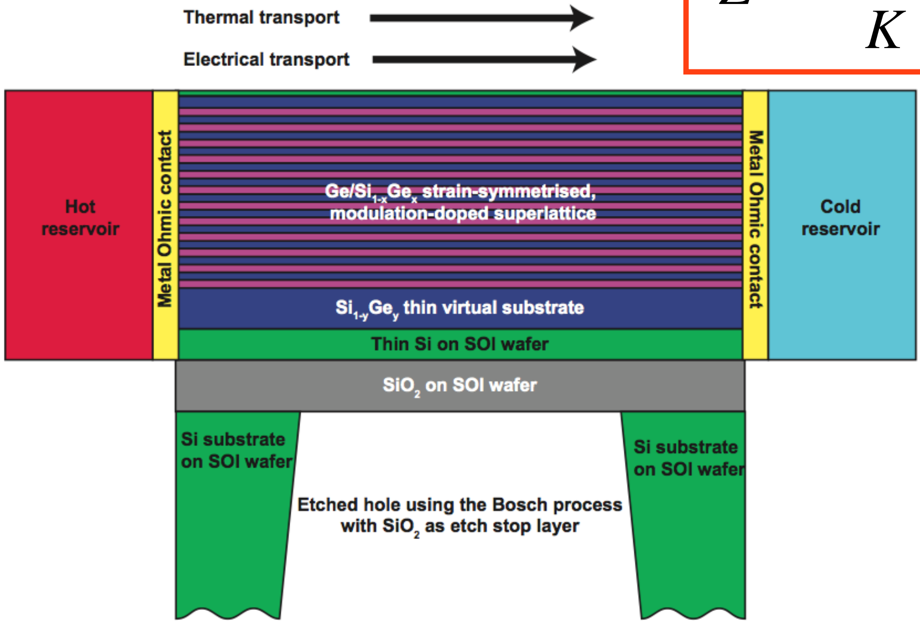
$$\lambda = \frac{\sqrt{1 + Z \cdot \overline{T}} - 1}{\sqrt{1 + Z \cdot \overline{T}} + \frac{T_C}{T_H}}$$

Figure-of-Merit $Z = \dfrac{\alpha^2 \cdot \sigma}{K}$

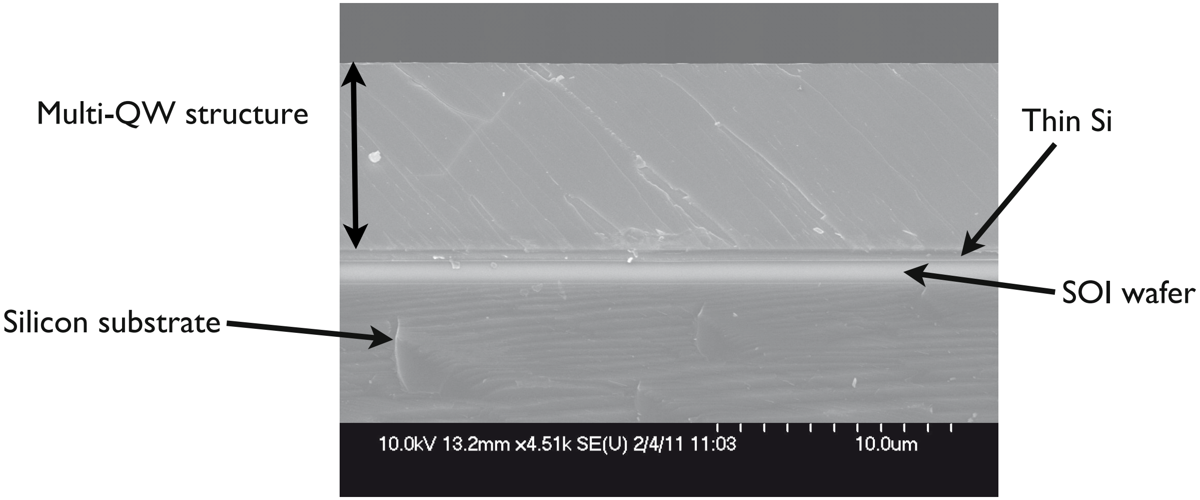
2D Superlattice

$$Z = \frac{\alpha^2 \cdot \sigma}{K}$$



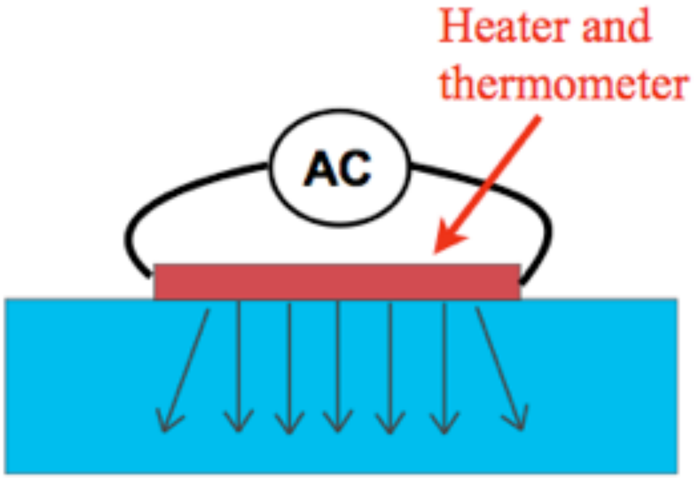


Measure thickness of the Multi-QW layer each time we process a new sample. This thickness changes from 5 um to 10 um.



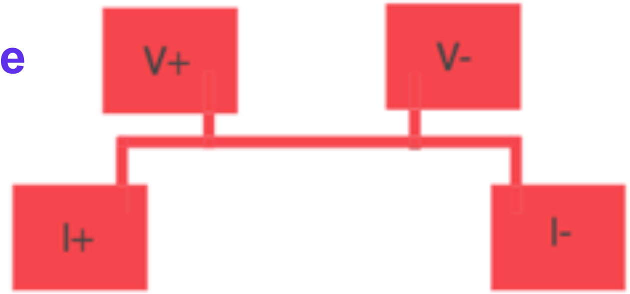
Thermal conductivity ⟷ $(W \cdot m^{-1} \cdot K^{-1})$

- **3-omega method:**
  - Placing a directly conductor on the surface of the material, which will serve as a heater and as a thermometer.
  - Driving an AC current through this line at frequency 1-omega.
  - This current will heat the conductor, which in return will be measurable as a resistance change at the frequency 3-omega.



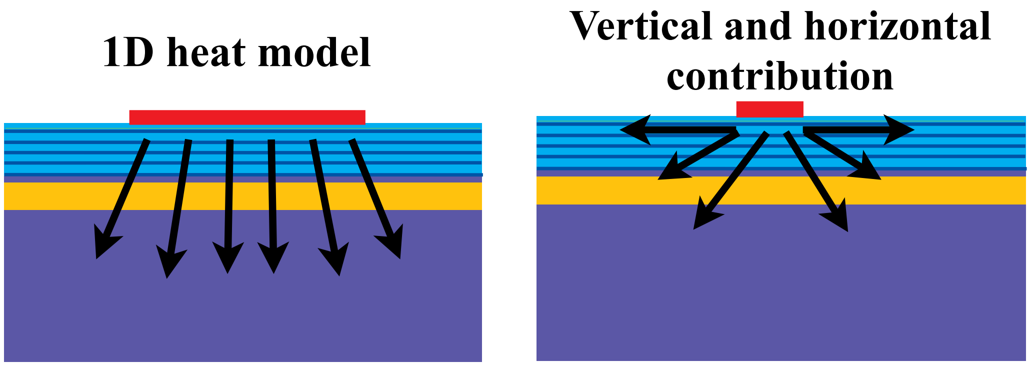
$$\Delta T = 2 \cdot \frac{dT}{dR} \cdot \frac{R}{V_{1w}} \cdot \boxed{V_{3w}}$$

Allows to measure the temperature oscillation of the line.

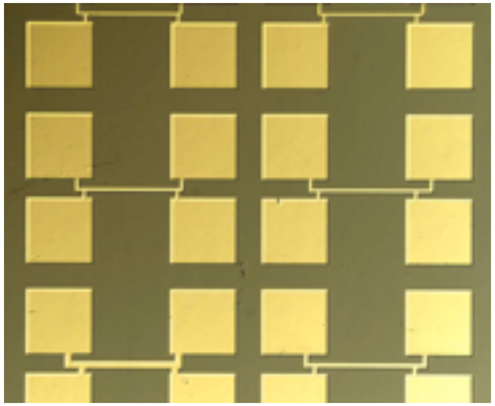


Thermal conductivity: 3-omega method

- Anisotropic material:

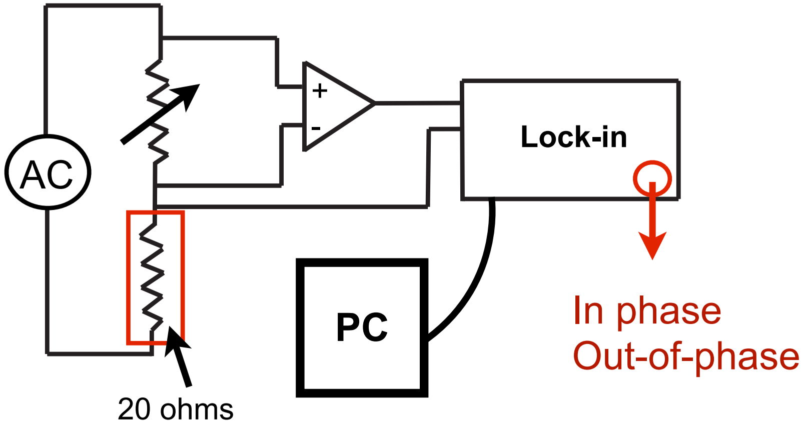


Heaters: 10 nm NiCr + 50 nm Au



-Different widths for the line, from 5um up to 200um.
-Length of the line variable to change the resistance of the metal line.

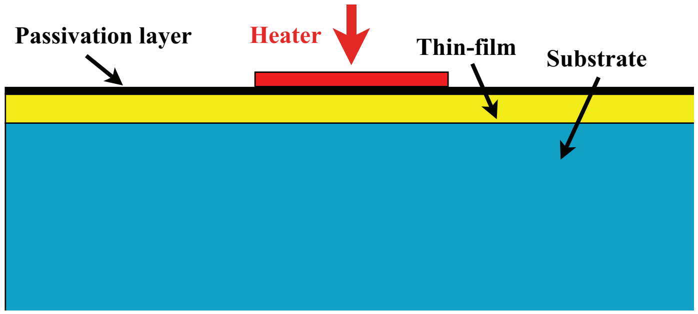
- To measure the V_3w we need to cancel the voltage at 1w



-Difficulty to measure the V_3w that is typically one thousandth off the primary voltage V_1w

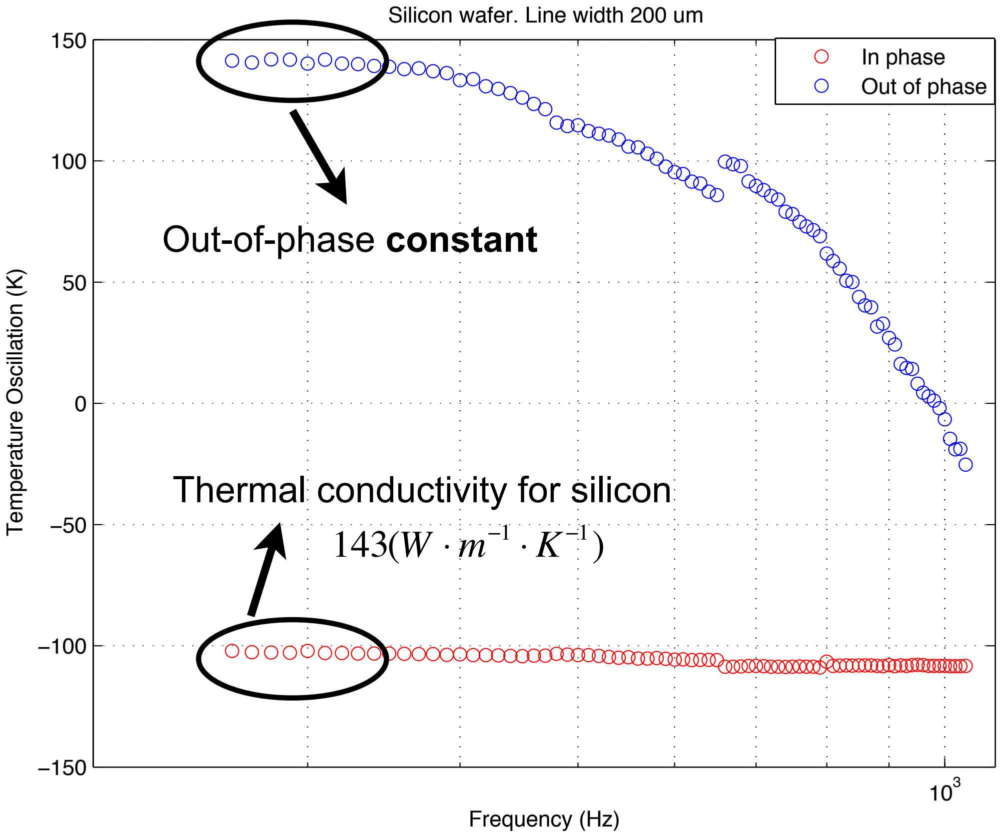
Thermal conductivity: 3-omega method

- Analysis ‘Slope-method’ for low frequencies: measuring K for substrate.



$$(T) = \frac{P}{\pi \cdot K} \cdot \left(\frac{3}{2} - \gamma - \frac{\ln \Omega}{2} - \frac{i \cdot \pi}{4}\right)$$

- Only valid for small arguments
- Not dependant of the frequency



Out-of-phase **constant**

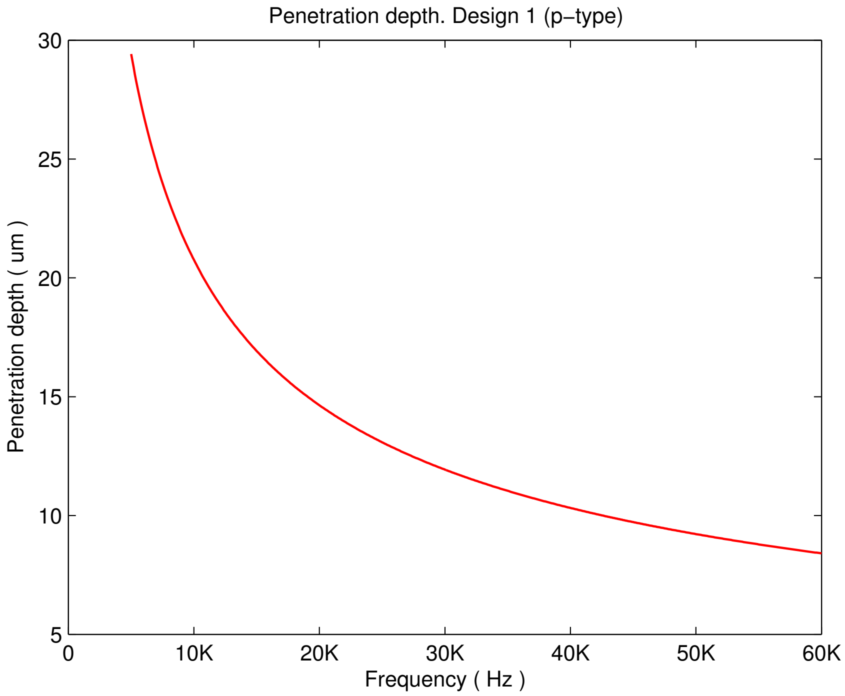
Thermal conductivity for silicon

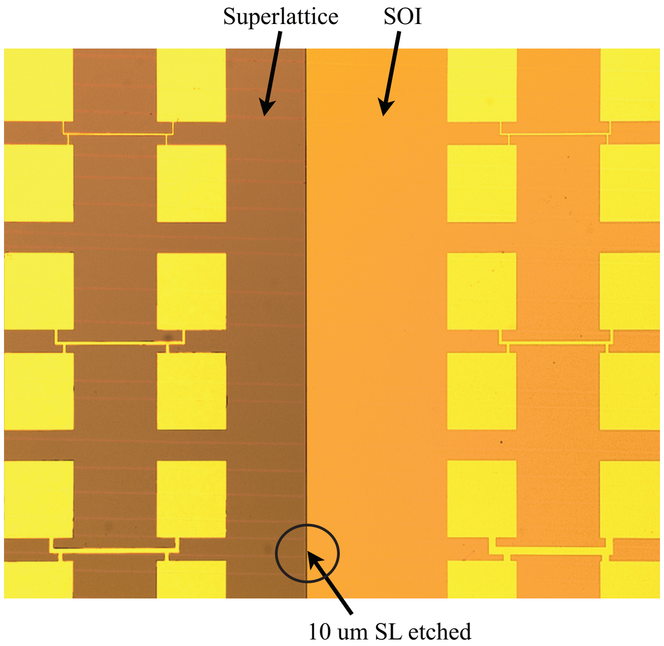
$143(W \cdot m^{-1} \cdot K^{-1})$

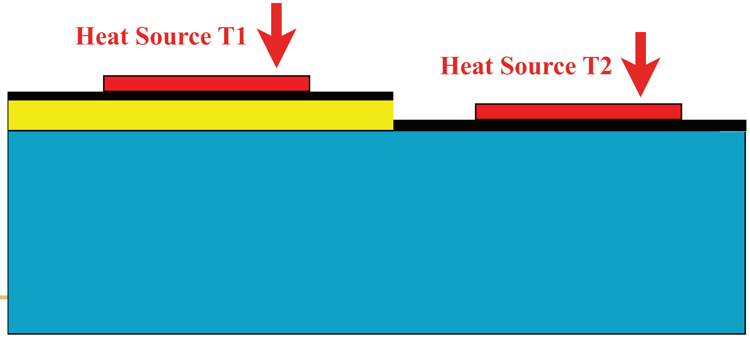
Thermal conductivity: 3-omega method

- Analysis ‘Differential method’ for high frequencies:

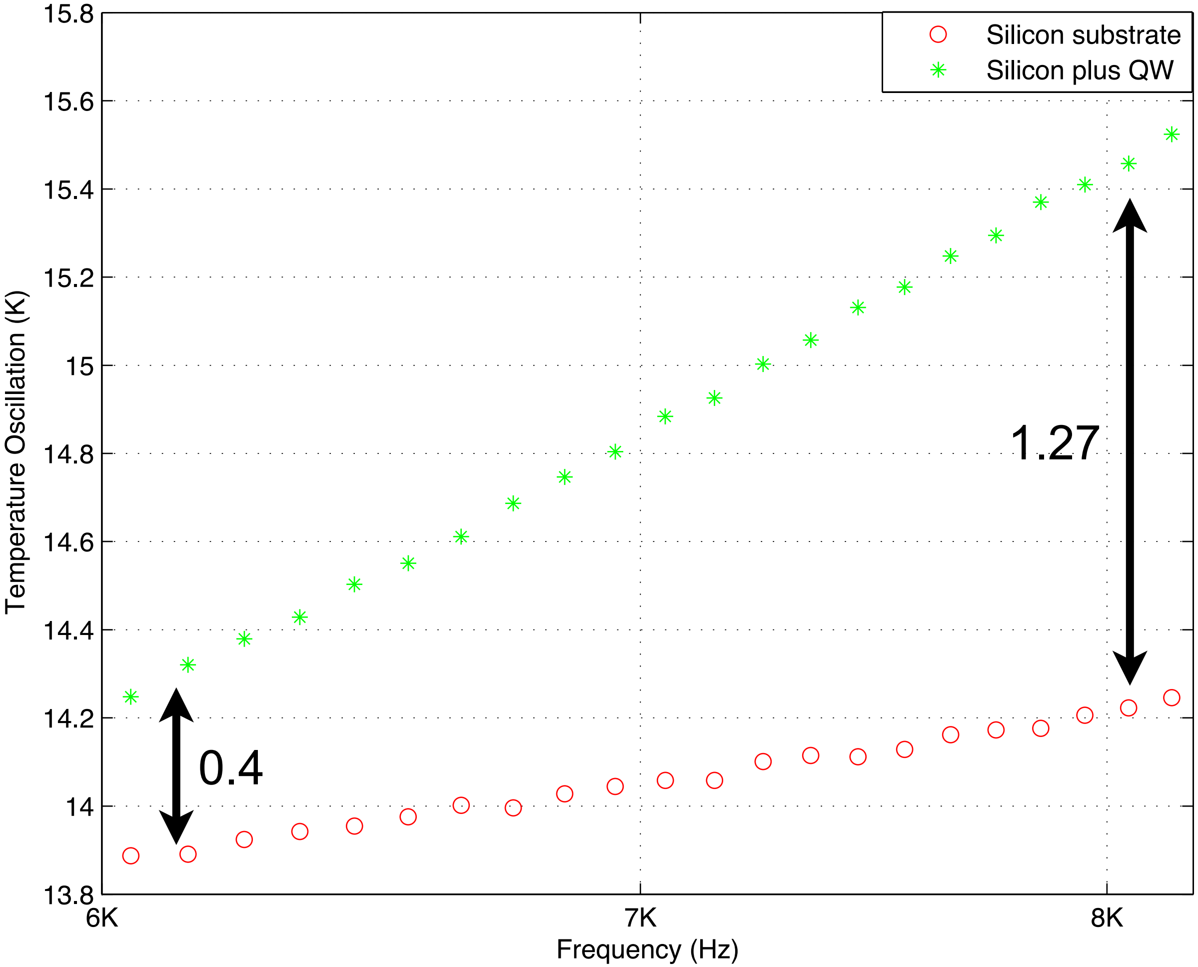
$$\alpha = \frac{K}{\rho \cdot C_p} \Longrightarrow q^{-1} = \sqrt{\frac{\alpha}{2 \cdot w}}$$







Thermal conductivity: 3-omega method



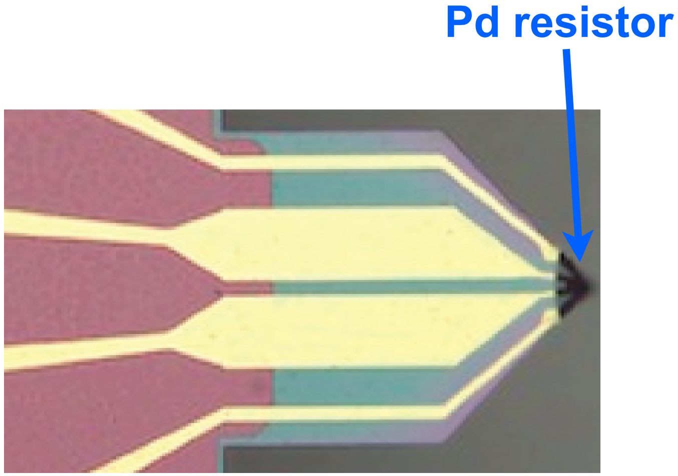
$$k_f = \frac{P \cdot d_f}{2 \cdot b \cdot (\Delta T_{s+f}(\omega) - \Delta T_s(\omega))}$$

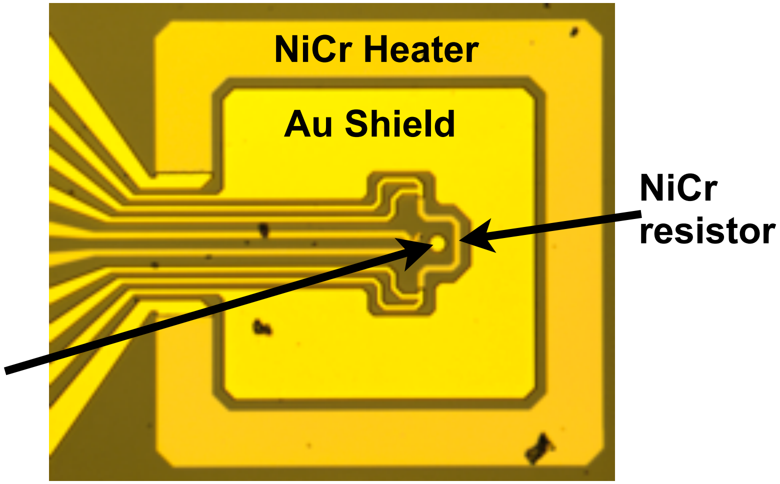
- Cross check results with other technique.

Thermal AFM

Thermal conductivity: Thermal AFM

- Thermal probe fabricated in JWNC.
  - Palladium resistor located at the end of the tip.
  - Four gold lines that allow a standard four-point measurement.
- Set up:
  - A fixed temperature is needed as a reference.
  - Reference obtained by calibrating the system.
    - Instrument used for calibration is able to define an absolute temperature based on the measurement of Johnson noise.

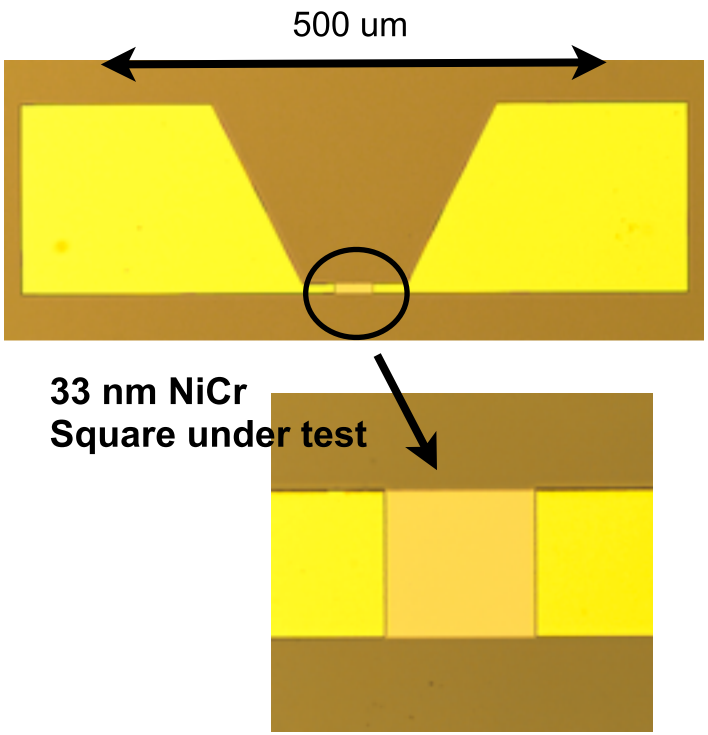


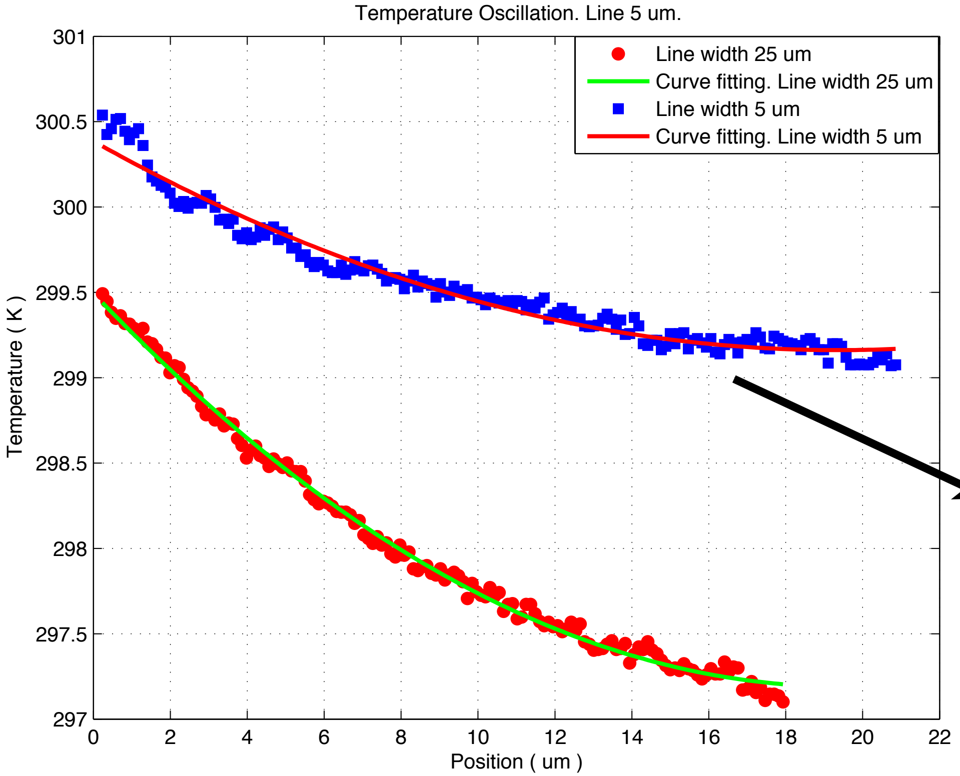


Dot with known temperature used to calibrate the thermal probe.

Thermal conductivity: Thermal AFM

- Fabrication:
  - Passivation layer (15 nm)
  - Deposition of NiCr (33 nm) + Gold (100 nm)
  - Etching gold to open a window with only NiCr





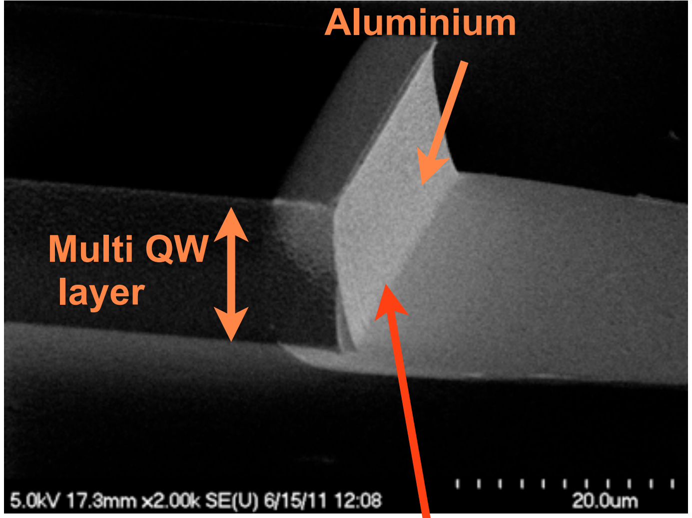
Bigger contribution by the lateral thermal conductivity

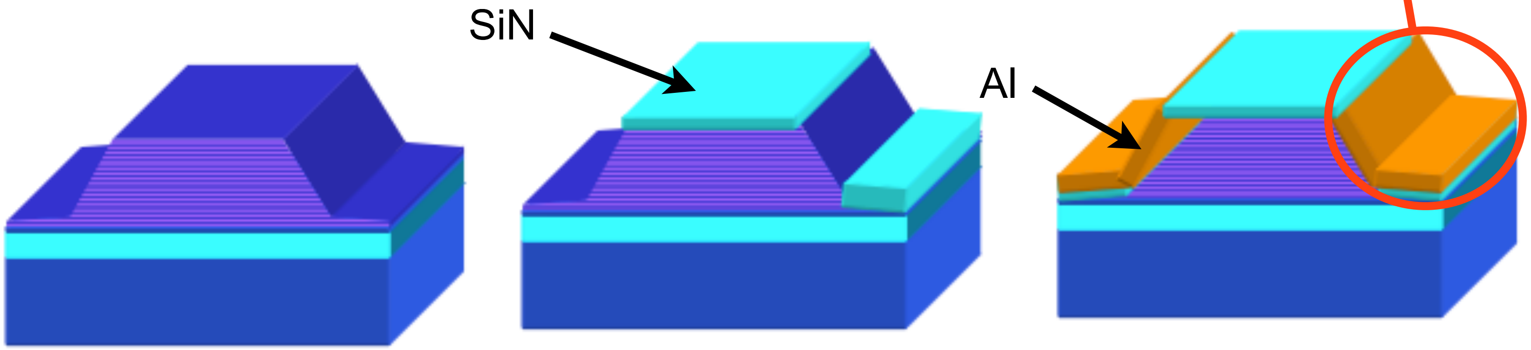
$$K \simeq 6.36$$

Electrical conductivity

- Interested in measuring the lateral electrical conductivity.
- Fabrication:
  - Development of an etch profile to contact all the QWs.
  - Deposition of SiN as a passivation layer.
  - Open windows on SiN to create ohmic contacts.
  - Deposit metal.

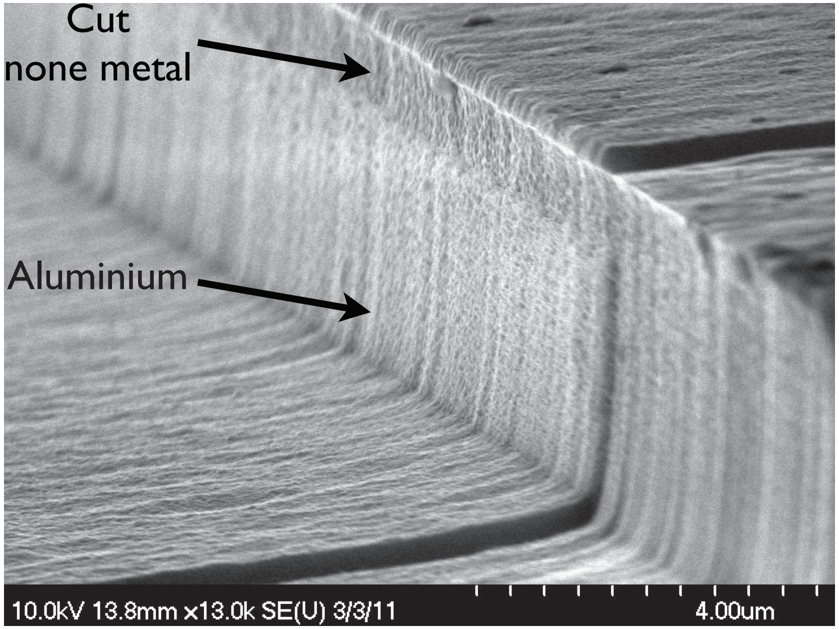
Ohmic contact created by sputtering Aluminium

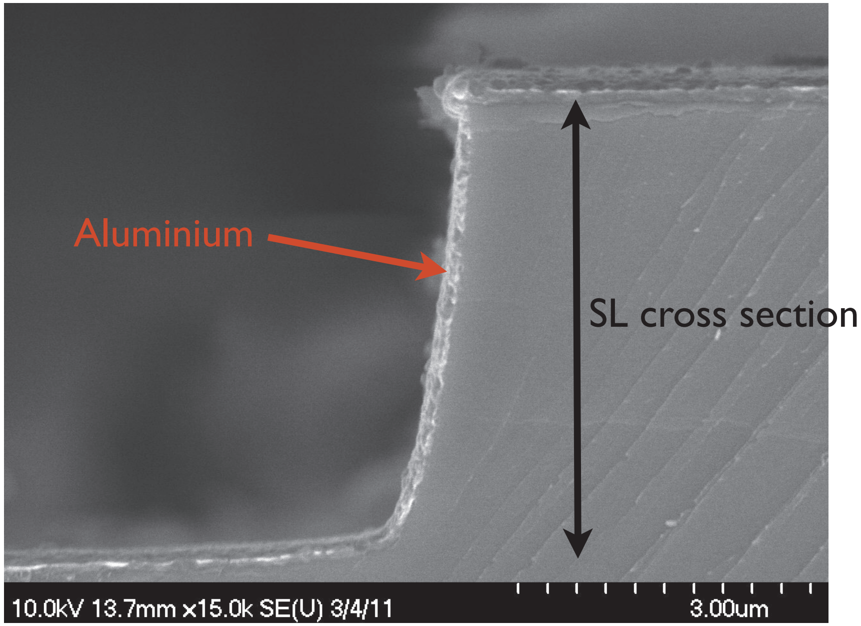




Electrical conductivity

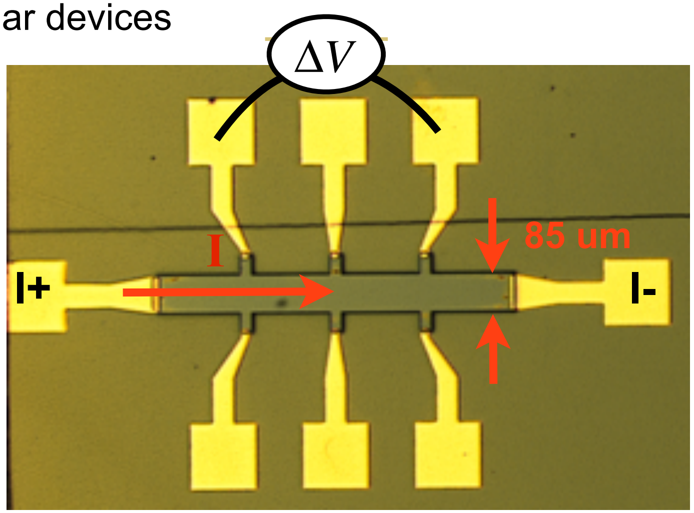
- Mixed process etch ↔ good profile for the side walls.
- Still the presence of an undercut at the top part of the side wall.

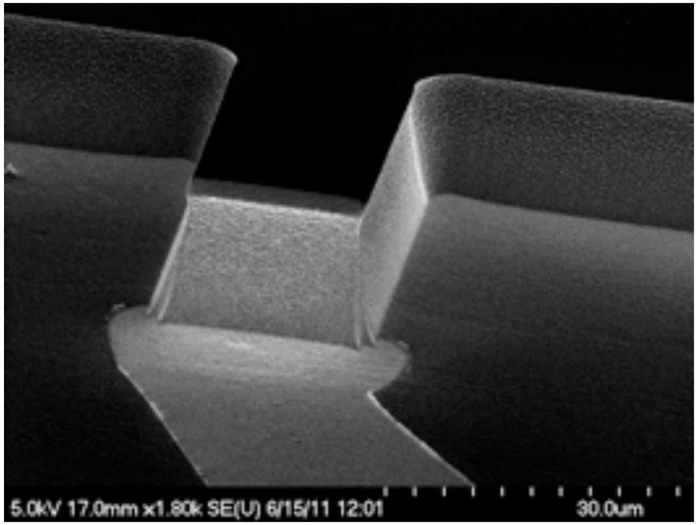




Electrical conductivity

Hall Bar devices





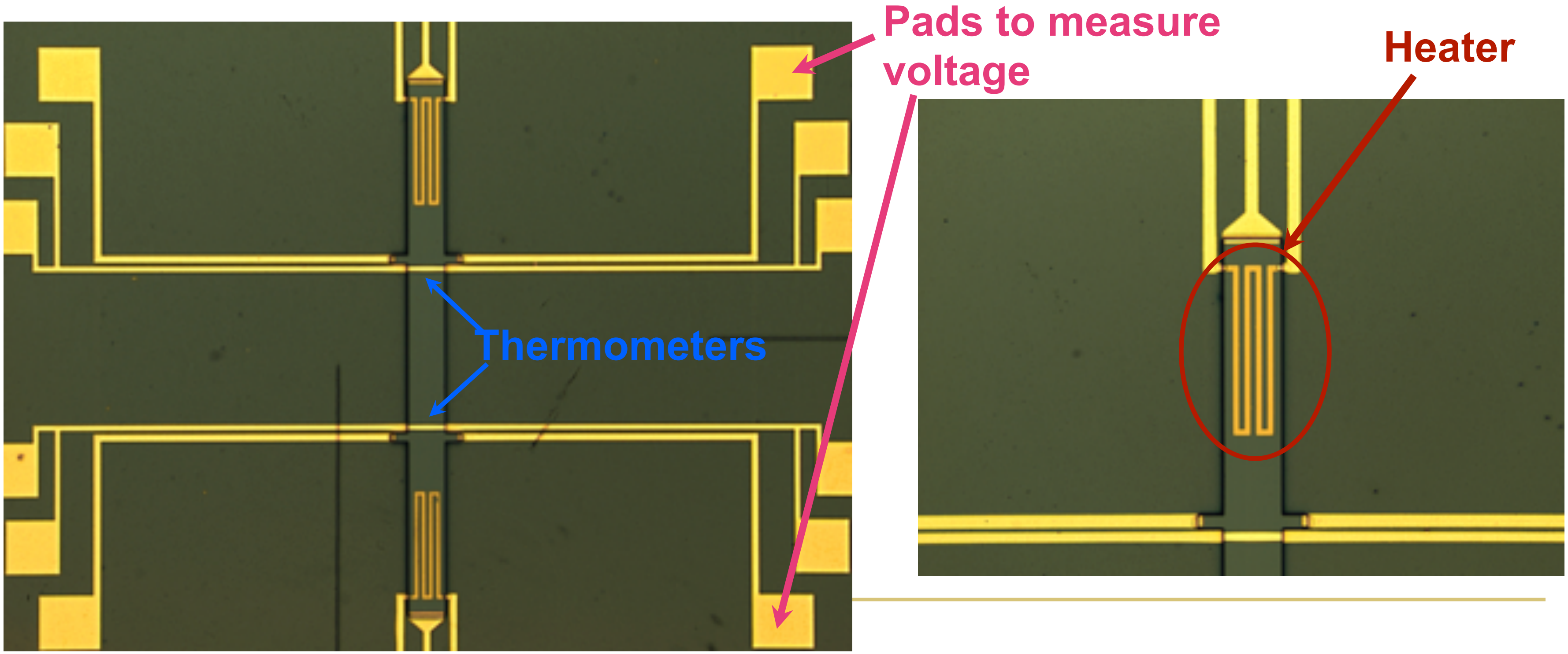
Sample_ID	Design p-type	$N_A(cm^{-3})$	Thickness	$\rho(\Omega \cdot \mu m)$	$\sigma(S \cdot m)$
8557_J6	2	$1 \cdot 10^{19}$	3.268 um	9.54	104,733
8569_I8	2	$1 \cdot 10^{18}$	6.048 um	26.14	38,255
8482_E4	2	-	11.340 um	299.14	3,343
8572_D2	2	$1 \cdot 10^{19}$	6.804 um	53.024	18,859
8579_E2	1	$1 \cdot 10^{19}$	6.048 um	11.327	88,284

Seebeck coefficient/Thermopower

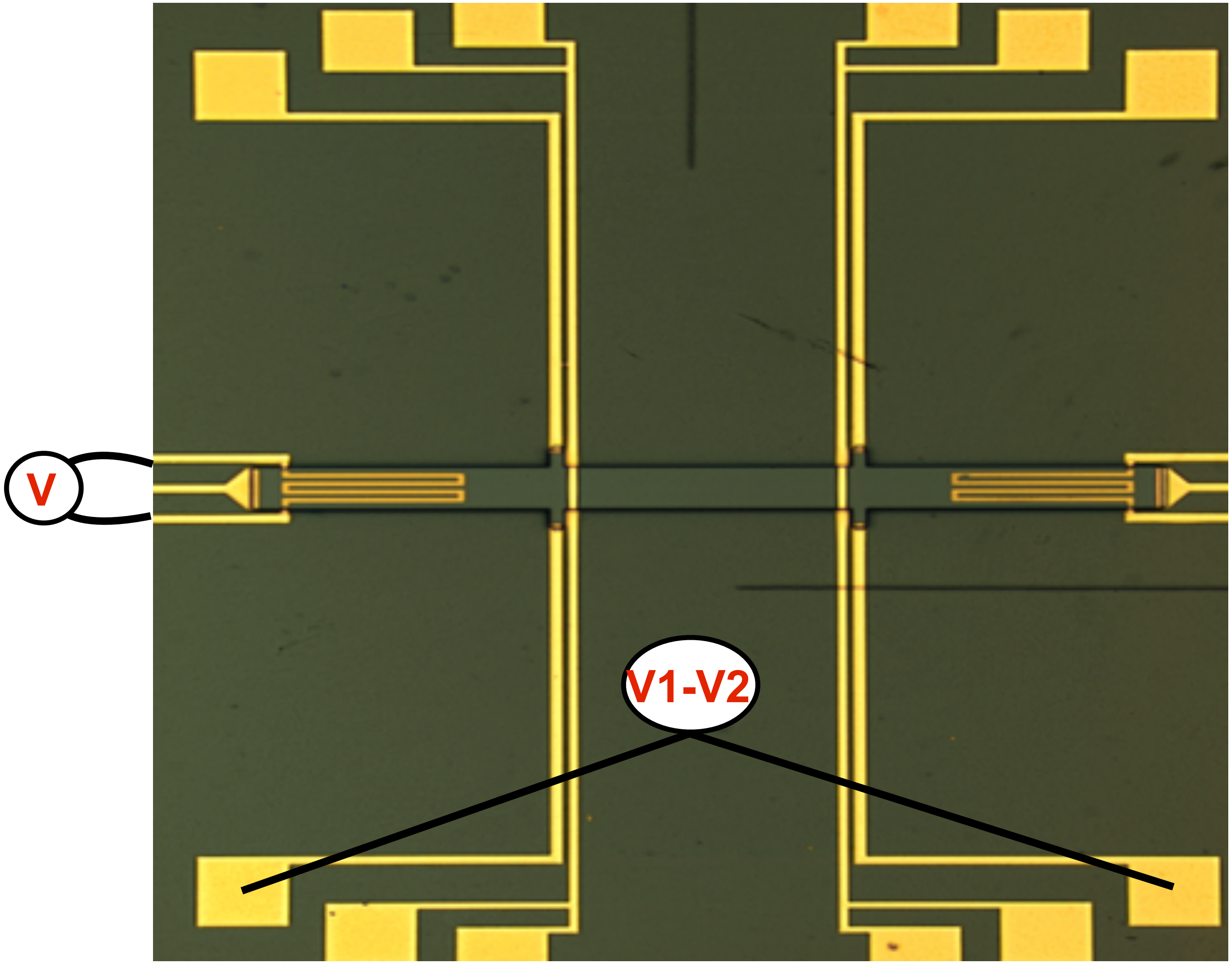
- Voltage produce across two points on a material divided by the temperature difference between them.

$$\boxed{\alpha = \frac{\Delta V}{\Delta T}}$$

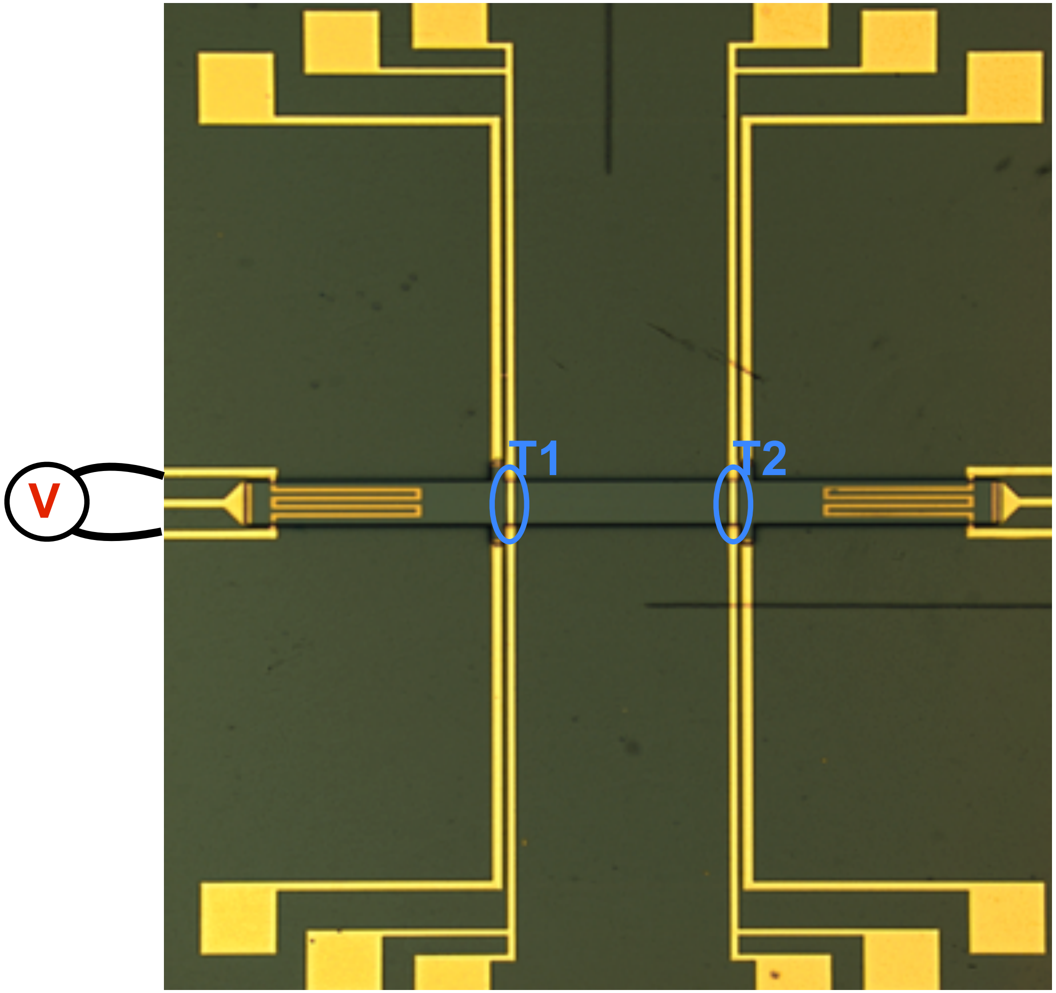
- Standard Hall Bar device with the addition of having two heaters and two thermometers on top of the bars.
  - This design allows to measure the three parameters on the same device.



Seebeck coefficient/Thermopower



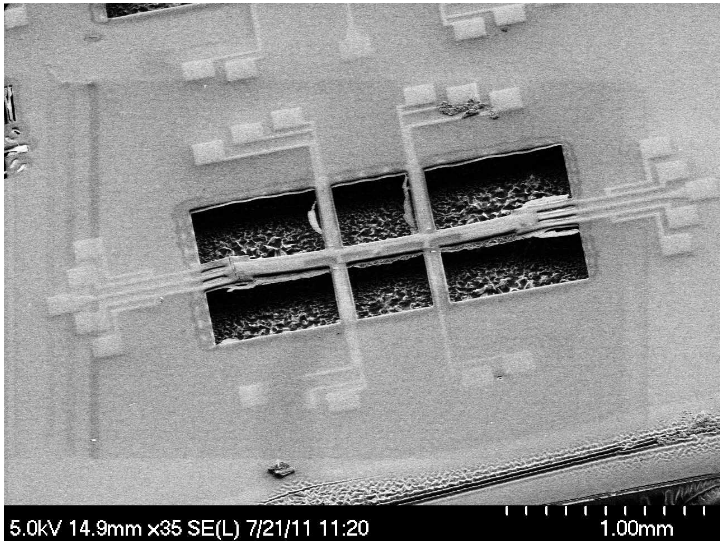
Seebeck coefficient/Thermopower

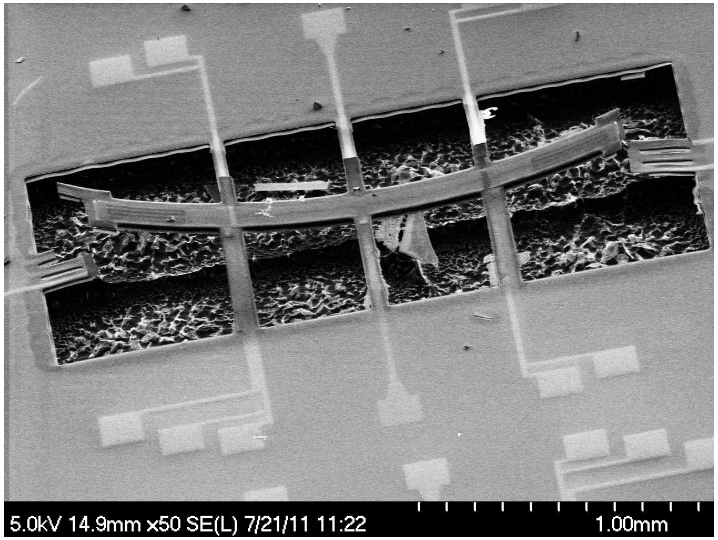


$$R_2 = R_1 \cdot (1 + \underset{\substack{\big\downarrow \\ \text{TCR}}}{\beta} \cdot (T_2 - T_1)$$

Seebeck coefficient/Thermopower

- Problems:
  - Results show a big influence of the substrate thermal conductivity.
    - Silicon ⟶ $150\ (W \cdot m^{-1} \cdot K^{-1})$
  - Necessary to remove the substrate of the final devices.
    - Very thin membranes, easy to break them as well due to the stressed material under test.





Conclusions and Future work

- Optimise substrate etch in order to get accurate results.
- Cross check thermal conductivity results with the thermal AFM, to know the error of our measurements.
- Design and fabricate future devices for measuring the vertical thermal and electrical properties of the different wafers obtained so far.
  - Easier fabrication process as it will not be necessary to remove the substrate.

Participants in the project

- University of Glasgow
  - Device processing
  - Material characterisation
- Politecnico di Milano, Como Italy
  - Epitaxial growth (LEPECVD)
- University of Linz, Austria
  - Material characterisation (XRD)
- ETH in Zurich, Switzerland
  - Material characterisation (TEM)

Thanks!