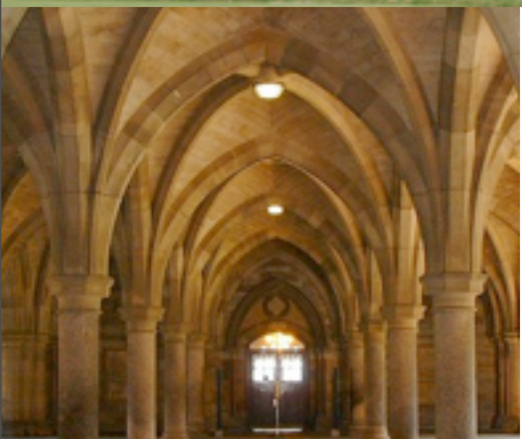

Nanoelectronic Thermoelectric Energy Generation

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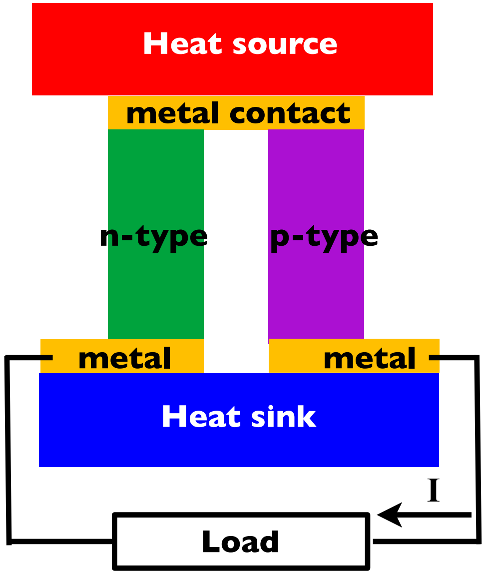
Overview:

- **Brief introduction on thermoelectric generators.**
- **Goal of the project.**
- **Fabrication and measurement for lateral devices.**
  - **Thermal conductivity.**
  - **Electrical conductivity.**
  - **Seebeck coefficient.**
- **Fabrication for vertical devices.**
- **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.

Thermoelectric generators:

- **Applications:**
  - A 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:**
  - No 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** ⟶ $\theta_{max} = \eta_c \cdot \lambda$

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

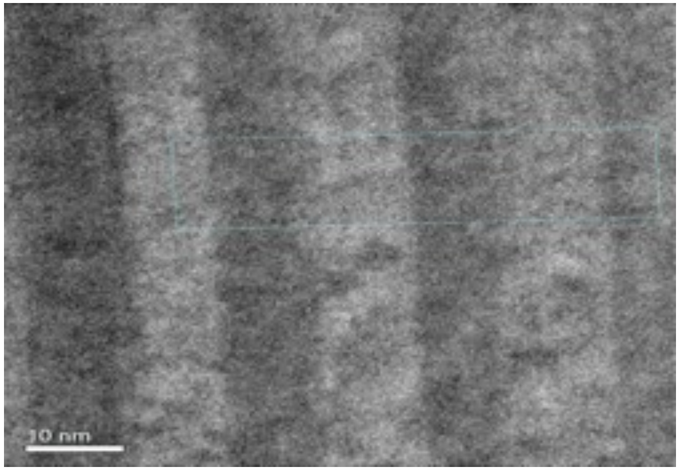
Product of the Carnot efficiency times the thermoelectric properties of the materials.

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

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

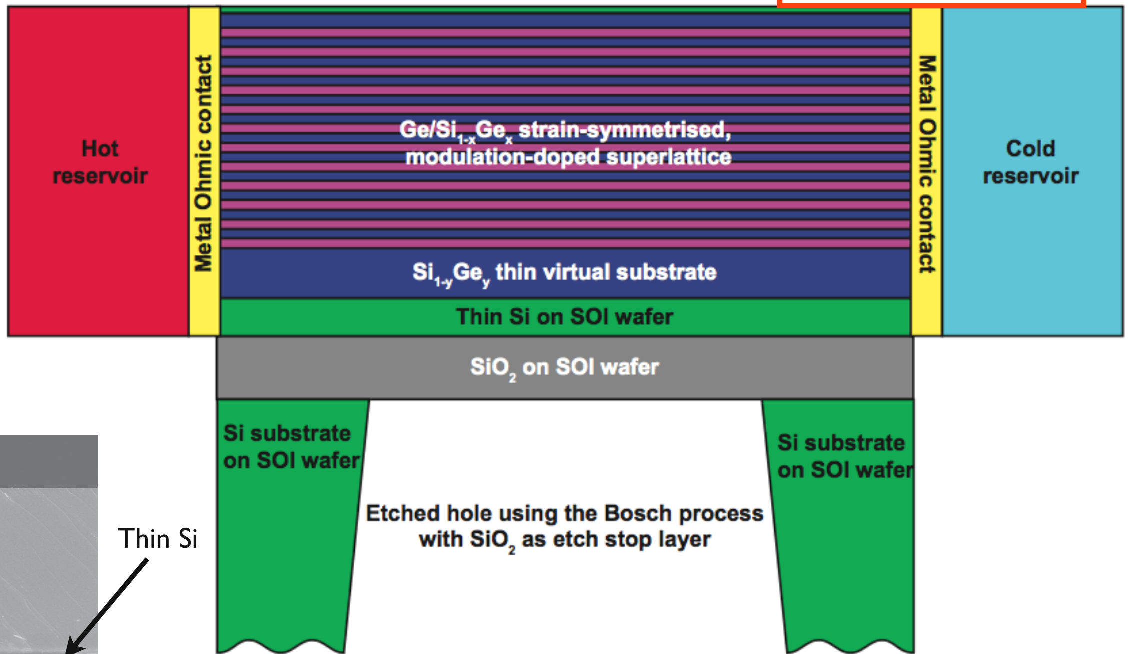
2D Superlattice: Lateral devices

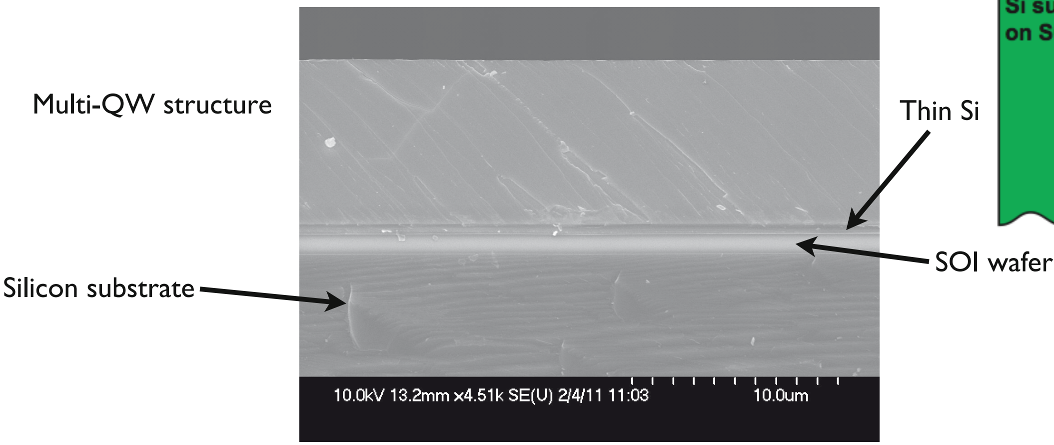
$$Z = \frac{\alpha^2 \cdot \sigma}{K}$$



Thermal transport →

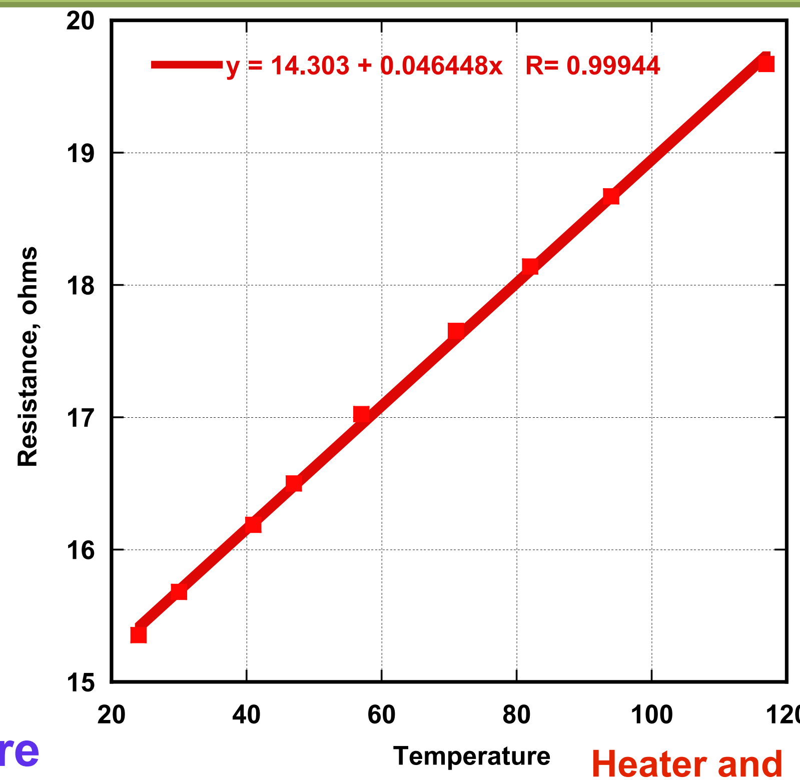
Electrical transport →





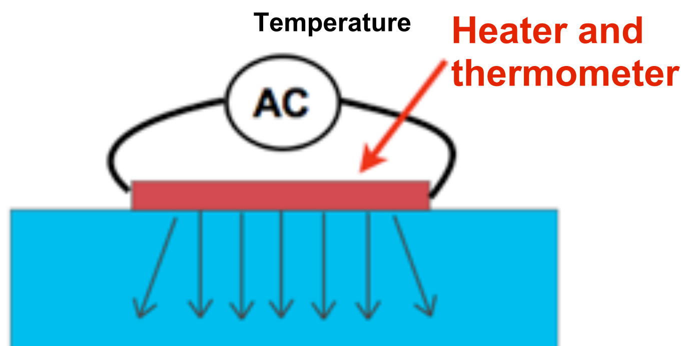
Thermal conductivity $\longleftrightarrow (W \cdot m^{-1} \cdot K^{-1})$

- **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.



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

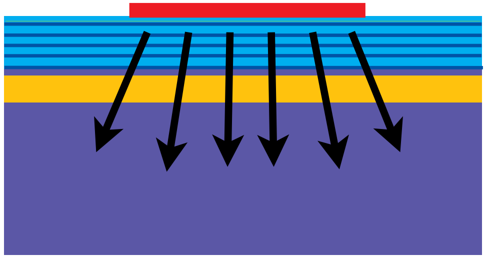
Allows to measure the temperature oscillation of the line.



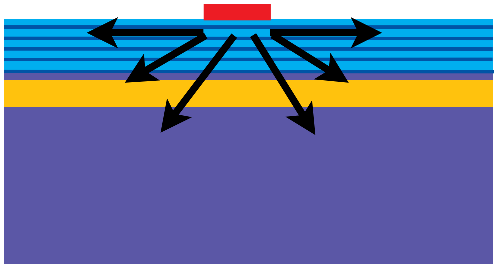
Thermal conductivity: 3-omega method

- Anisotropic material:

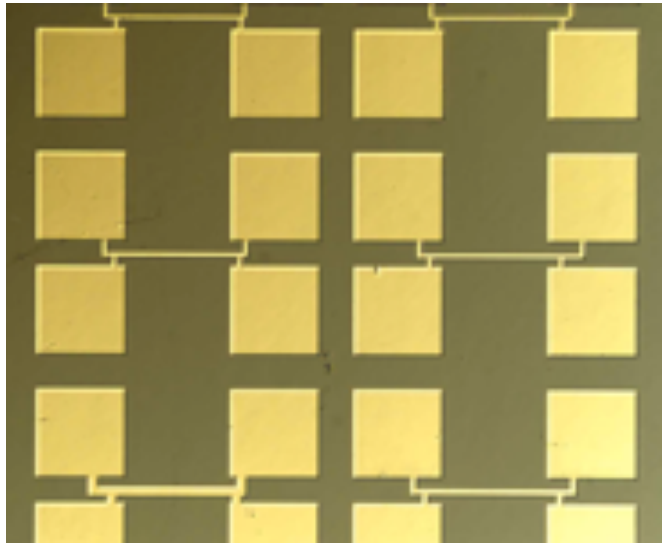
1D heat model



Vertical and horizontal contribution

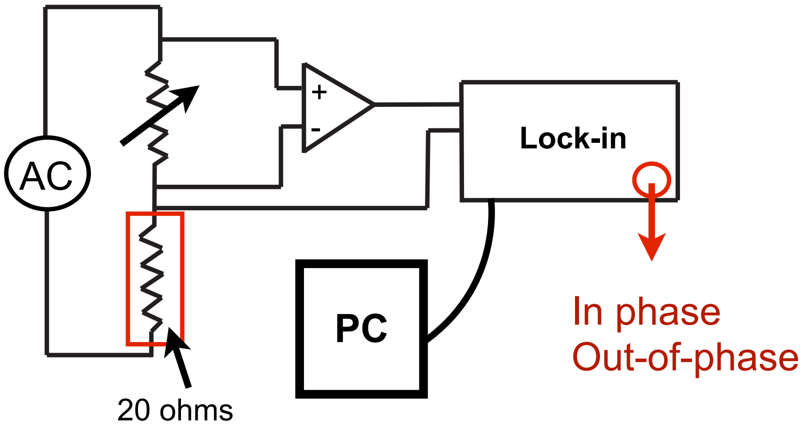


Heaters: 10 nm NiCr + 50 nm Au



-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

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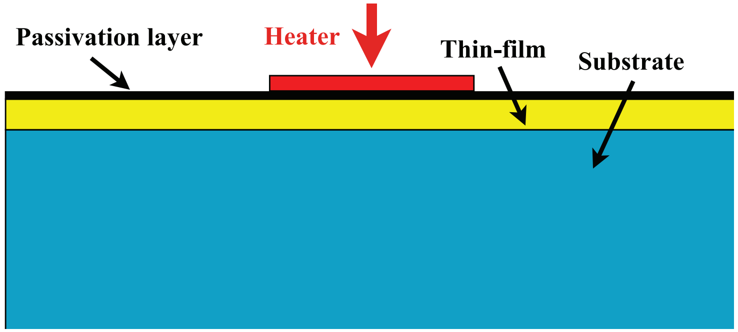
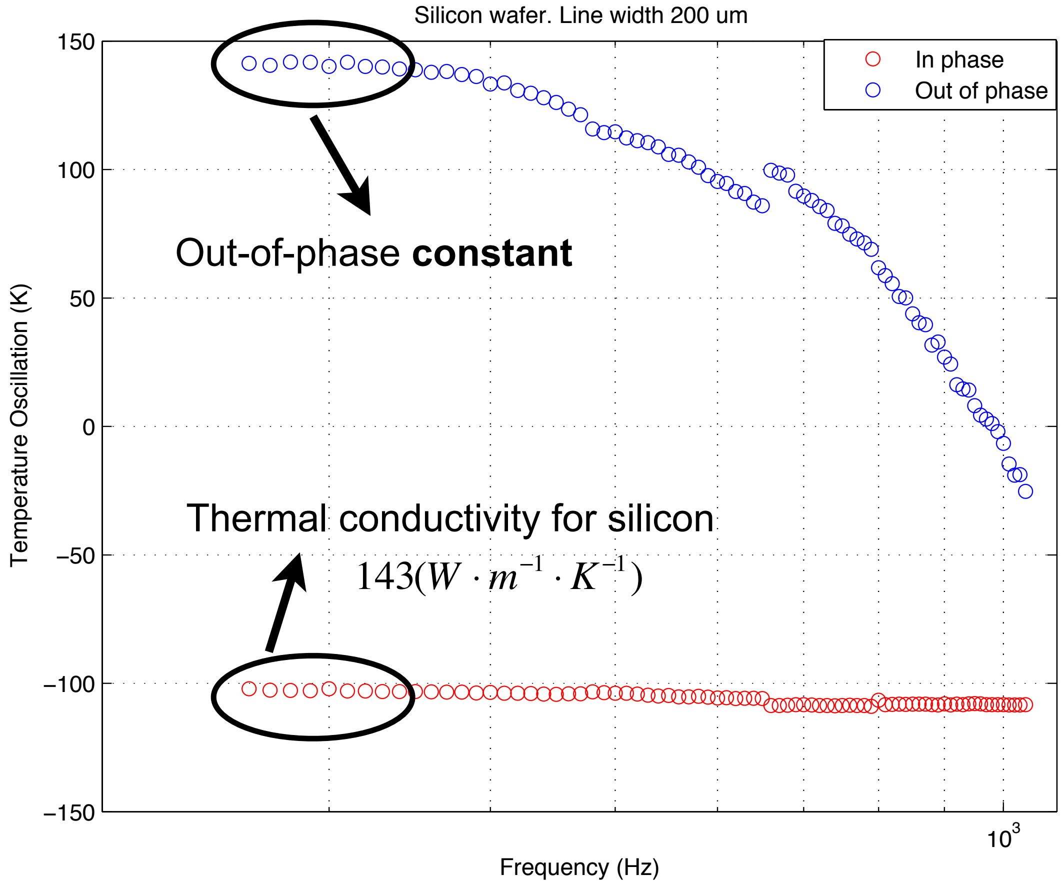
Thermal conductivity: 3-omega method

- **Analysis 'Slope-method' for low frequencies:measuring K for substrate.**



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

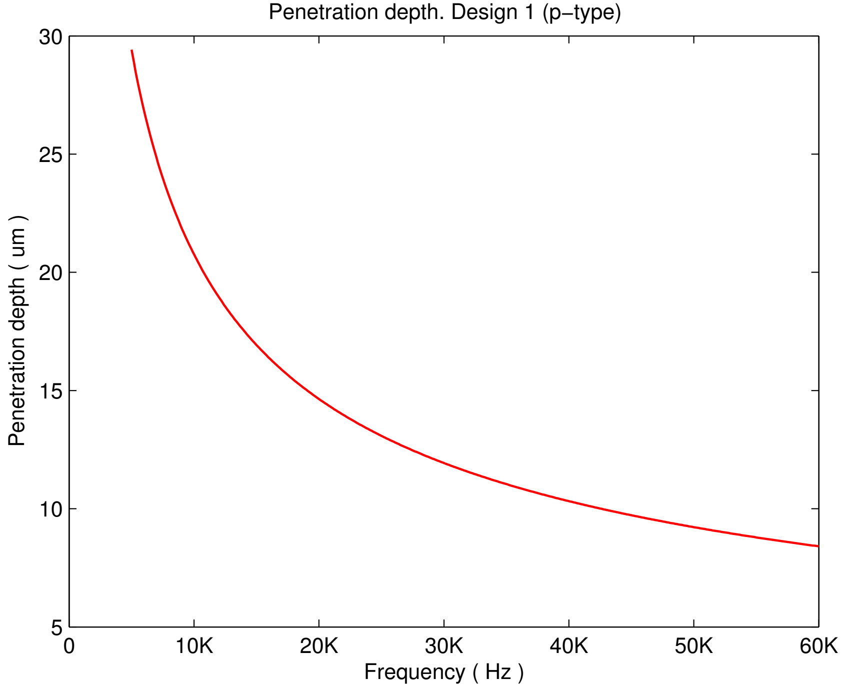
- Only valid for small arguments
- Not dependant of the frequency

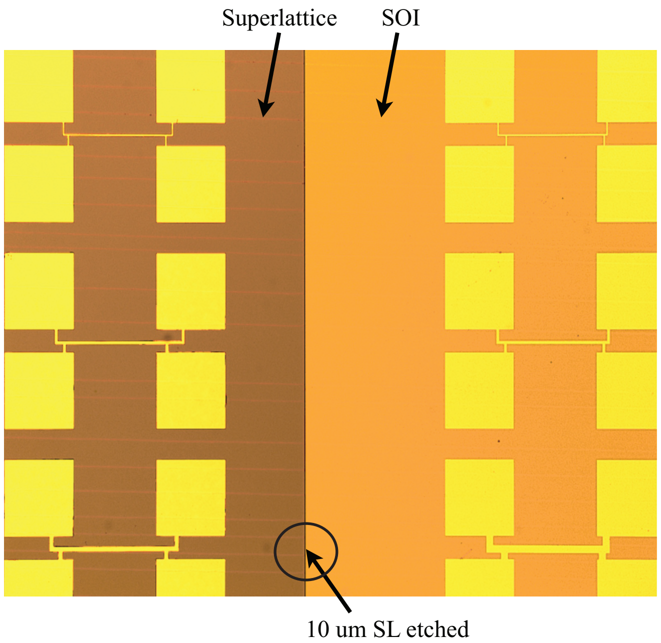


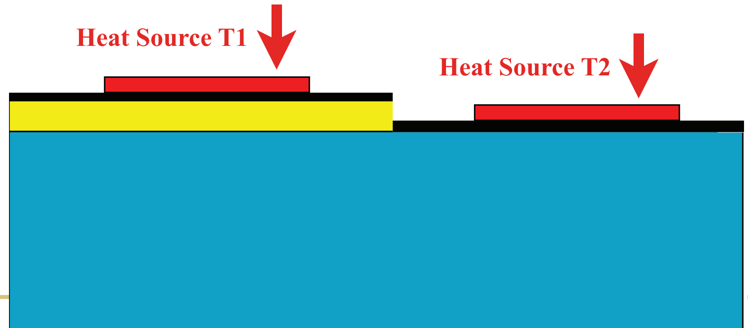
Thermal conductivity: 3-omega method

- **Analysis 'Differential method' for high frequencies:**

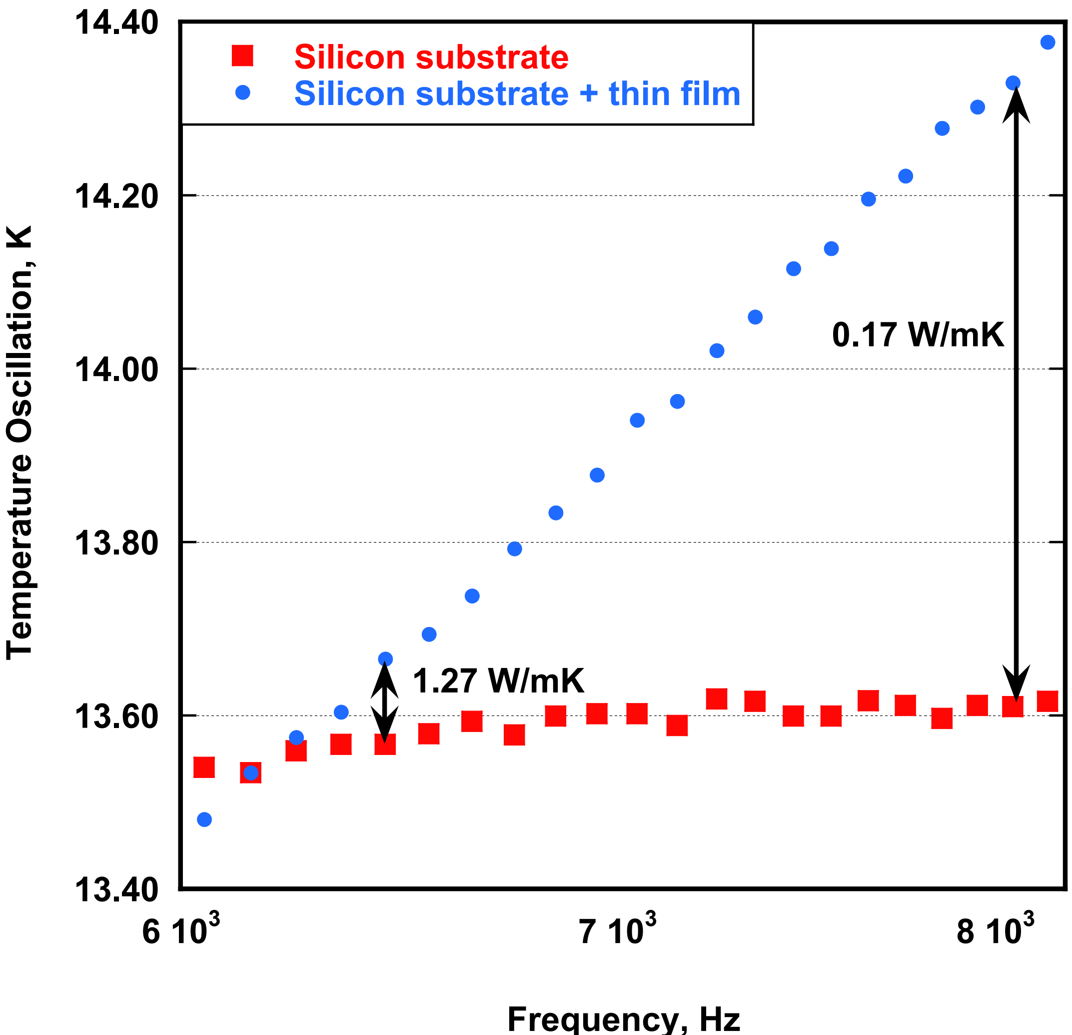
$$\alpha = \frac{K}{\rho \cdot C_p} \Rightarrow q^{-1} = \sqrt{\frac{\alpha}{2 \cdot w}}$$







Thermal conductivity: 3-omega method



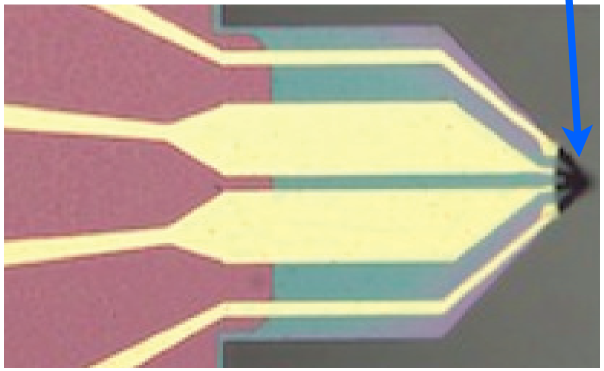
$$k_f = \frac{P \cdot d_f}{2 \cdot b \cdot (\Delta T_{s+f}(w) - \Delta T_s(w))}$$

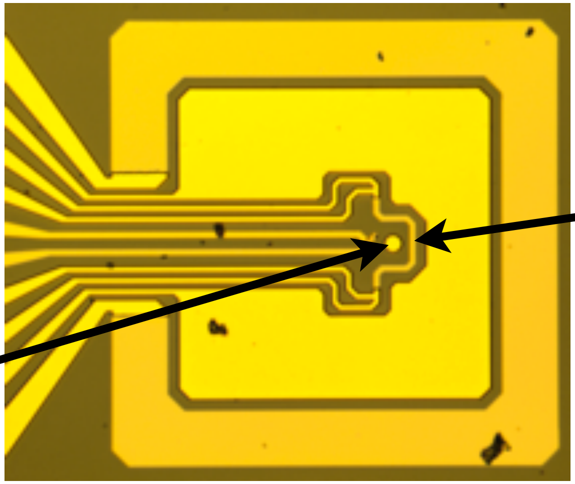
Cross check results with other technique

AFM

Thermal conductivity: Thermal AFM

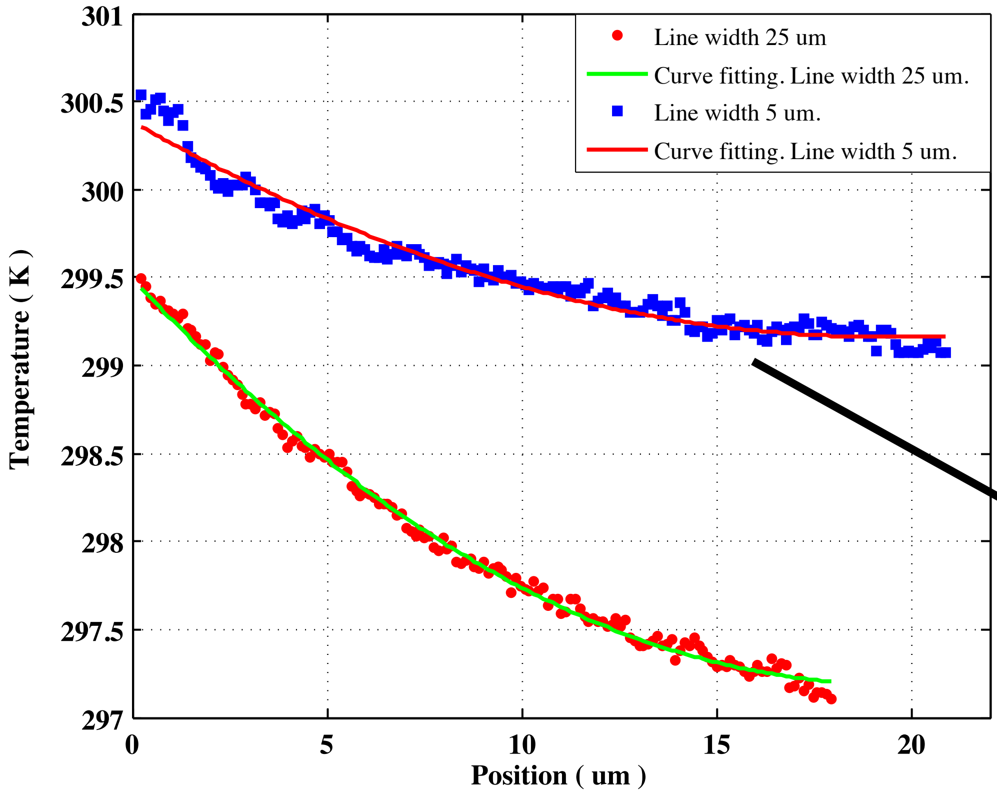
- **Thermal probe fabricated in JWNC.**
  - Palladium resistor located at the end of the tip.
  - Four gold lines that allow a standard four-point measurement.
- **Set up:**
  - A fixed temperature is needed as a reference.
  - Reference obtained by calibrating the system.
    - Instrument used for calibration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

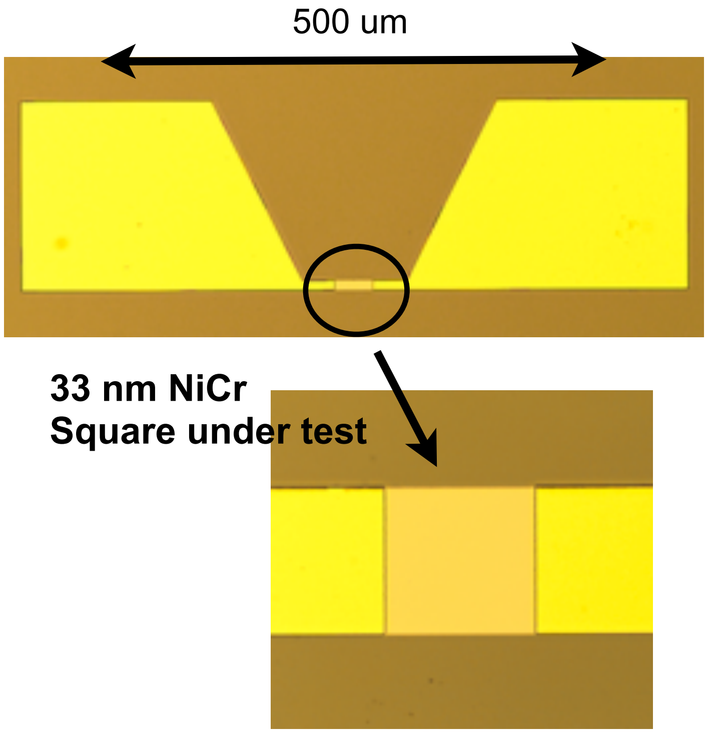




Thermal conductivity: Thermal AFM

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



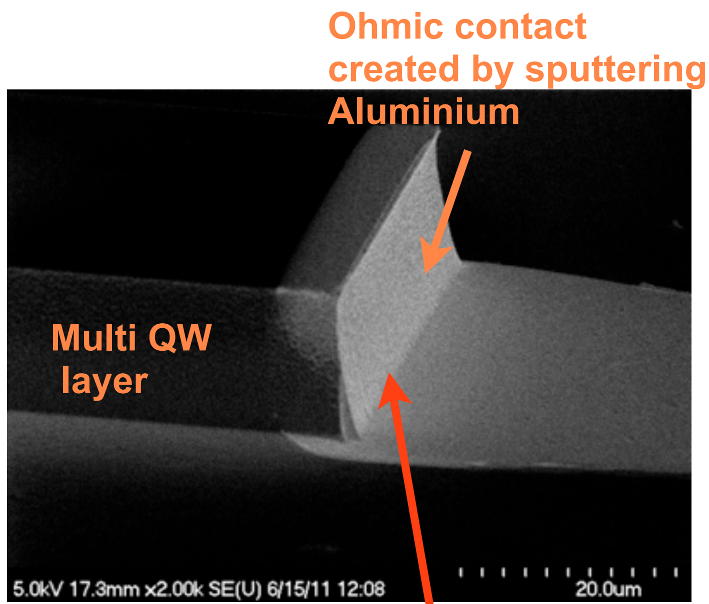


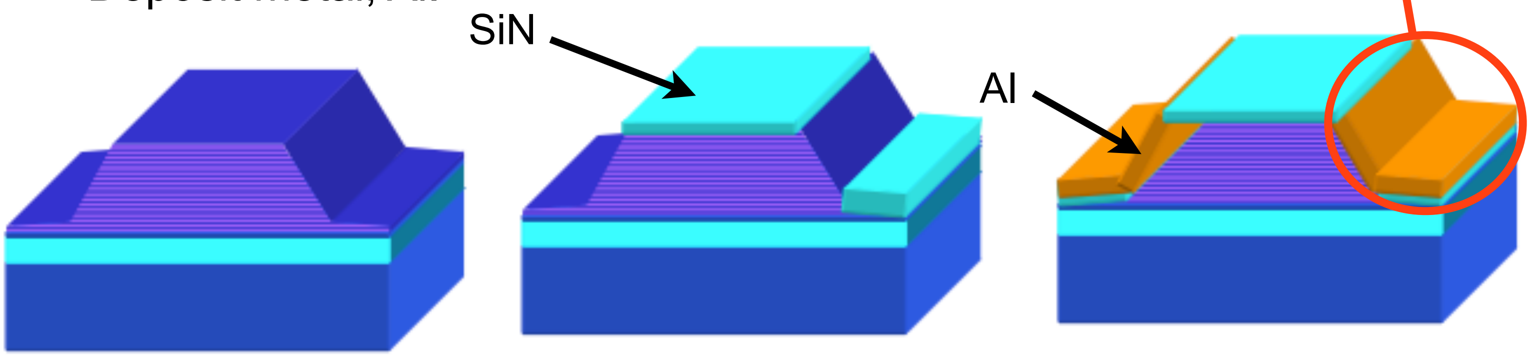
Bigger contribution by the lateral thermal conductivity.

$$K \simeq 6.36$$

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, Al.

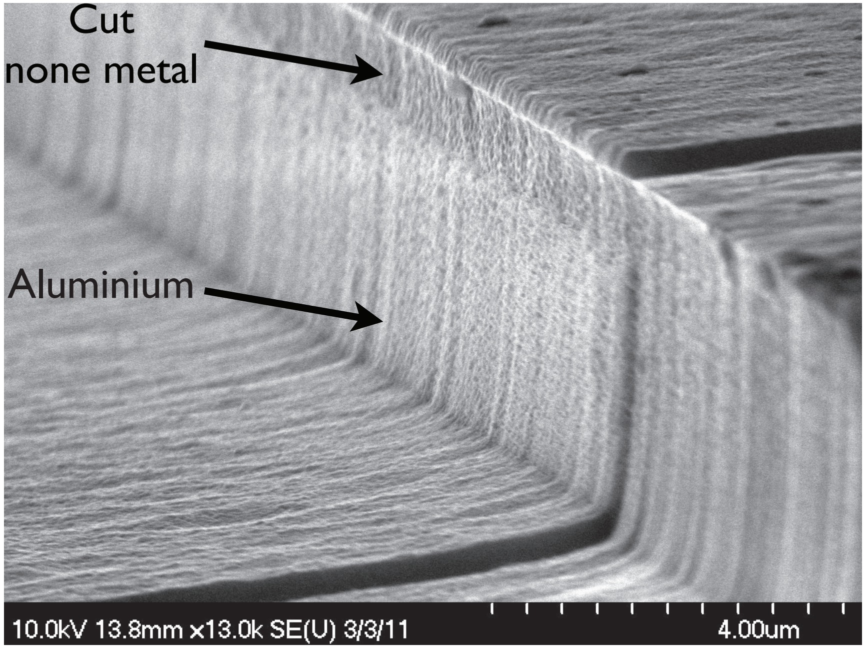




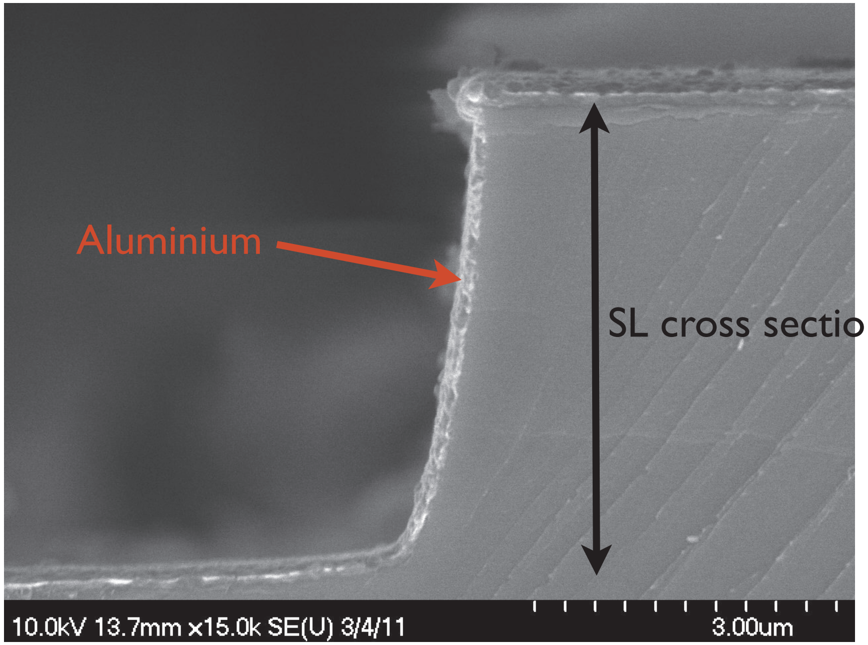
Electrical conductivity

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

Metal evaporation

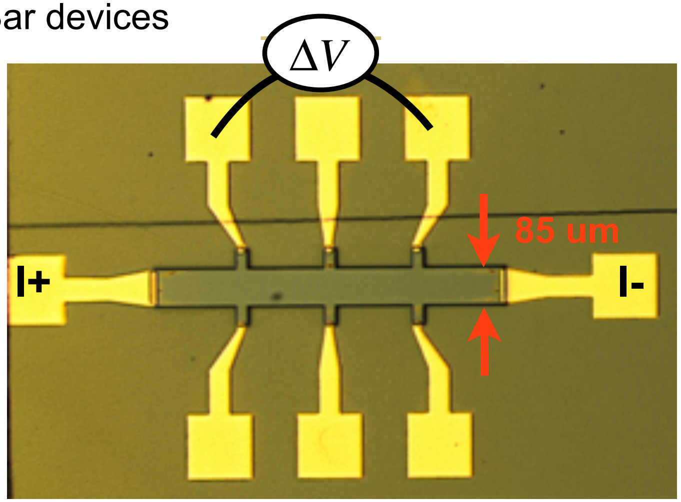


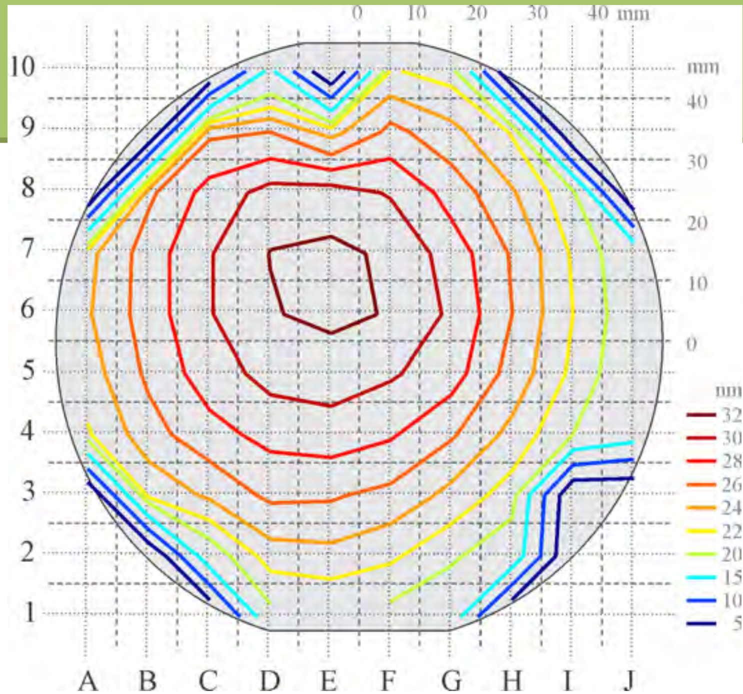
Sputtering



Electrical conductivity

Hall Bar devices

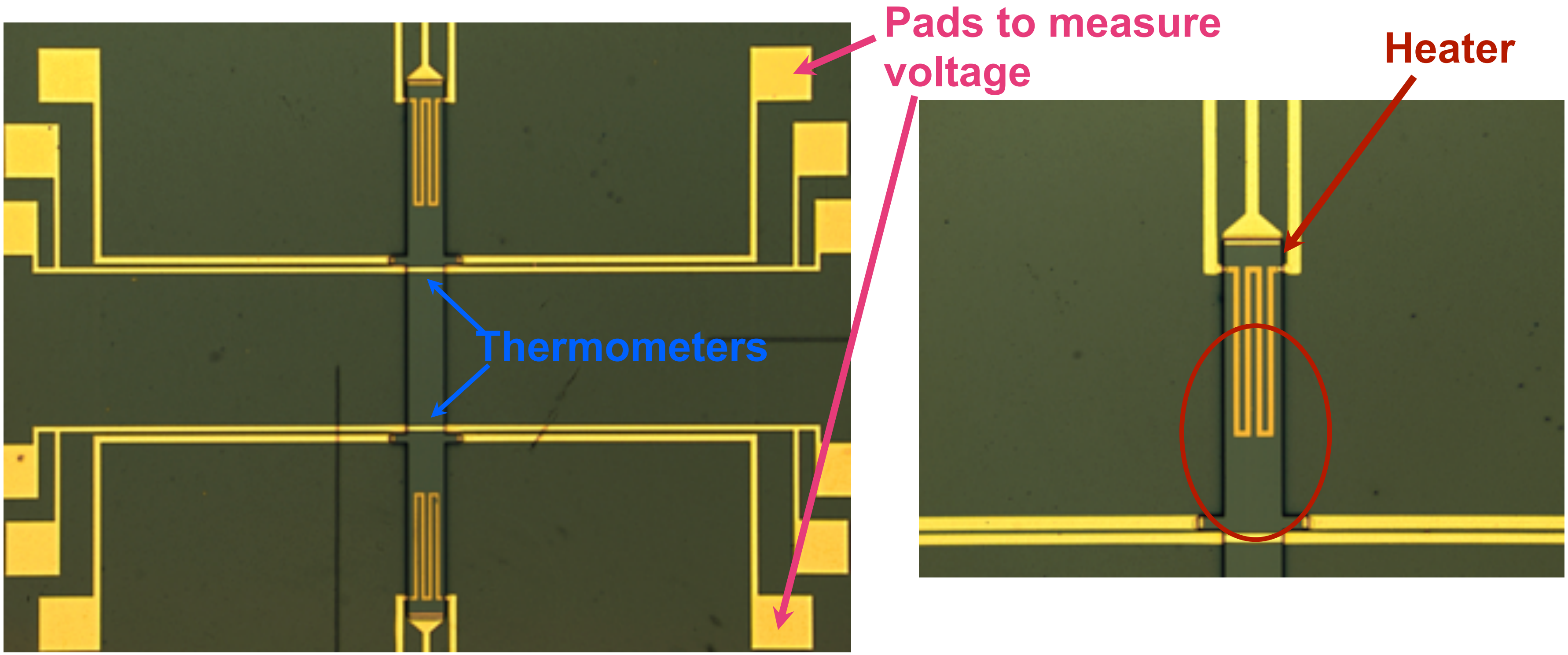




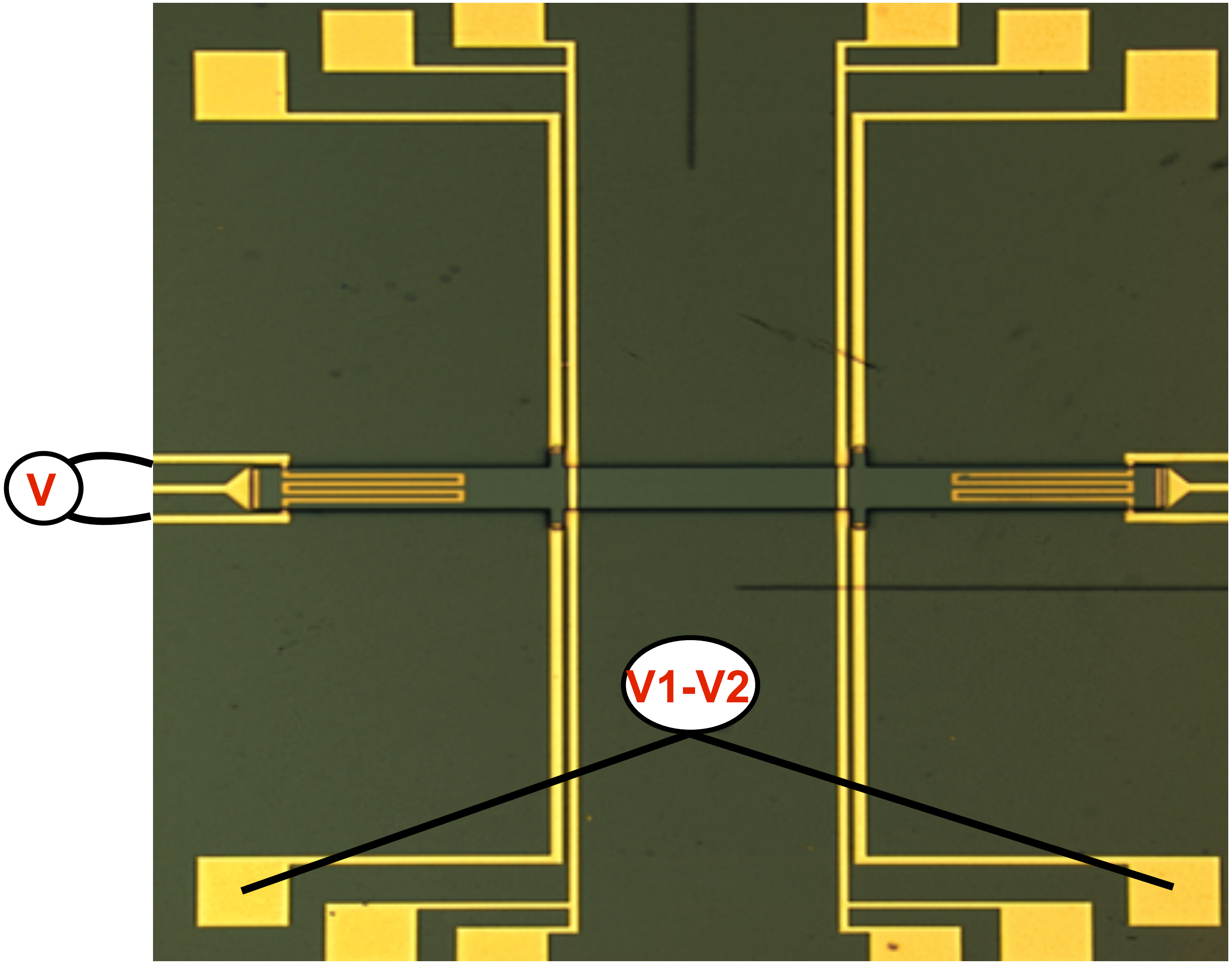
Sample_ID	Design	x %	$N_A(cm^{-3})$	Thickness (um)	$\sigma(S/m)$
8482 E4	p-Ge design 2	75	$1\cdot10^{19}$	11.34	3,490 ± 290
8557 J6	p-Ge design 2	75	$1\cdot10^{19}$	3.268	118,500 ± 15,000
8569 I8	p-Ge design 2	75	$1\cdot10^{19}$	6.048	38,660 ± 1,460
8569 I7	p-Ge design 2	75	$1\cdot10^{18}$	6.426	25,850 ± 2,620
8569 F2	p-Ge design 2	75	$1\cdot10^{19}$		41,100 ± 11,600
8579 E2	p-Ge design 1	80	$1\cdot10^{19}$	6.048	72,730 ± 29,700
8572 D2	p-Ge design 2	75	$1\cdot10^{19}$	6.804	26,012 ± 11,000

Seebeck coefficient/Thermopower

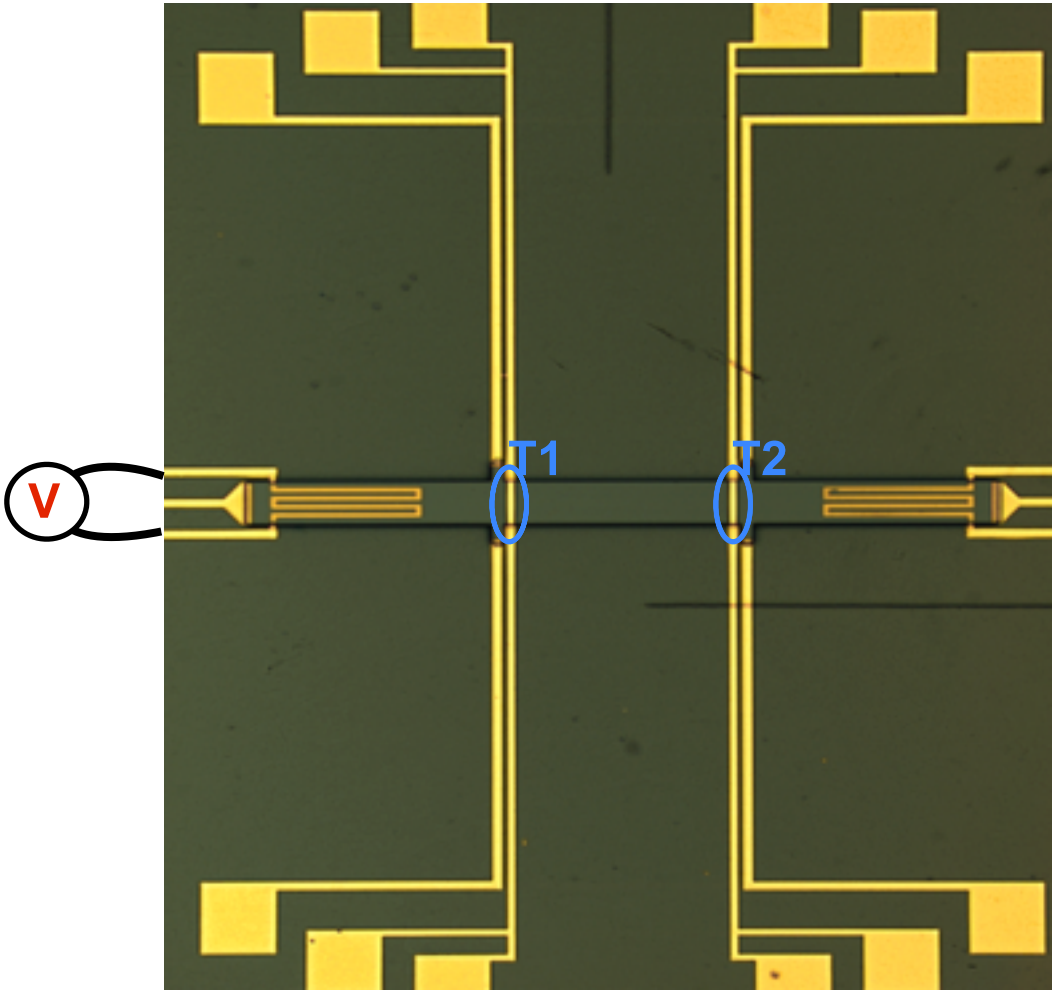
- **Voltage produce across two points on a material divided by the temperature difference between them.**
- **Standard Hall Bar device with the addition of having two heaters and two thermometers on top of the bars.**
  - This design allows to measure the three parameters on the same device.



Seebeck coefficient/Thermopower



Seebeck coefficient/Thermopower



$$R_2 = R_1 \cdot (1 + \beta \cdot (T_2 - T_1))$$

↓

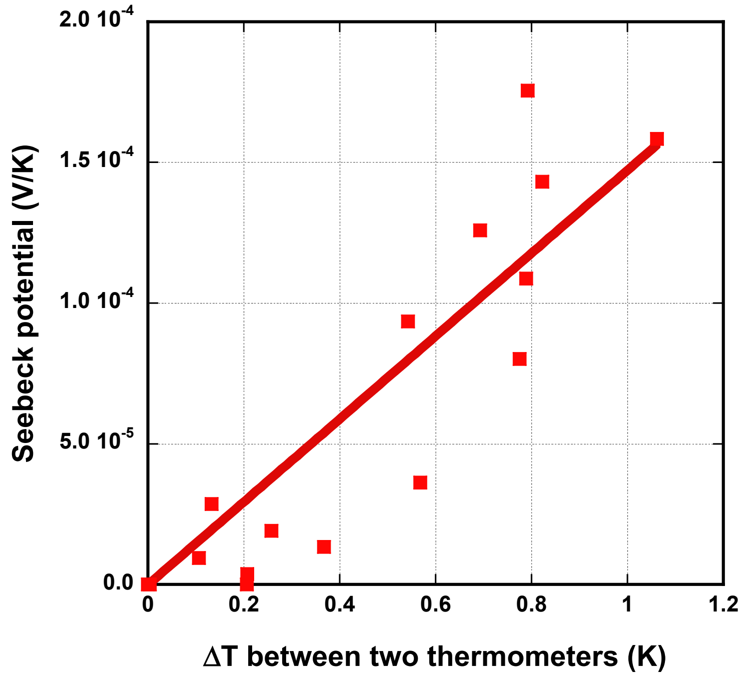
Temperature coefficient of resistance

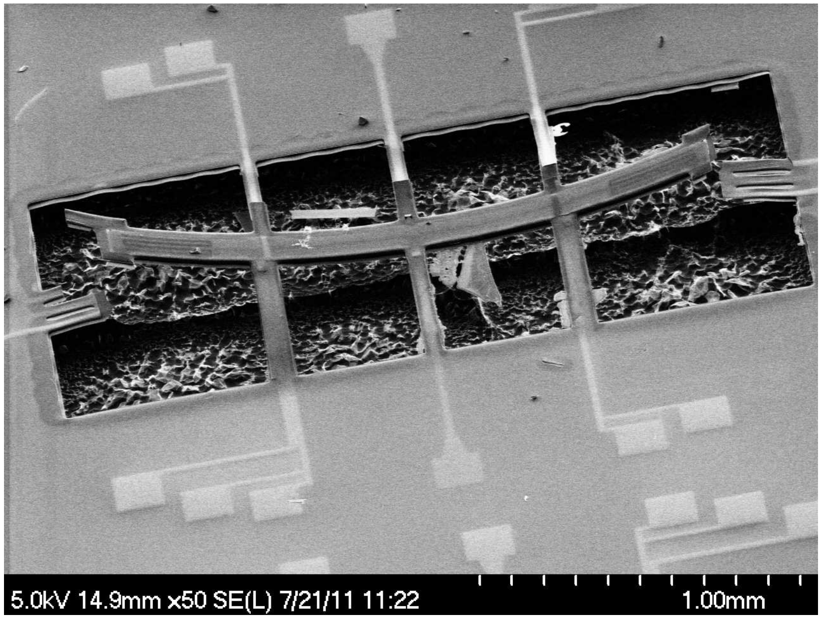
↓

$$\beta = \frac{\Delta R}{\Delta T} \cdot \frac{1}{R_0}$$

Seebeck coefficient/Thermopower

- **Problems:**
  - **Results show a big influence of the substrate thermal conductivity.**
    - Silicon → $150\ (W \cdot m^{-1} \cdot K^{-1})$
      → $\frac{\Delta V}{\Delta T} = 150 \pm 13\ (\mu V / K)$

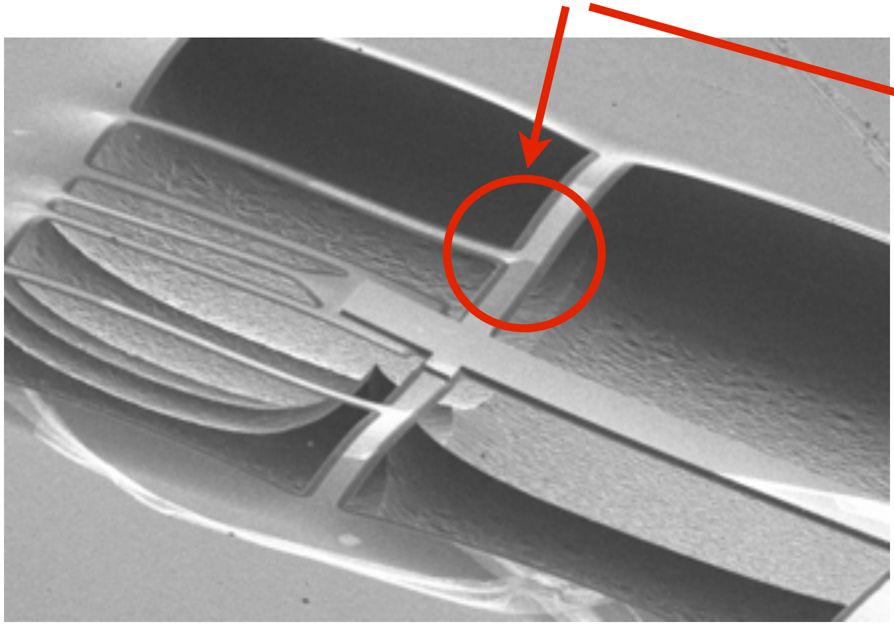


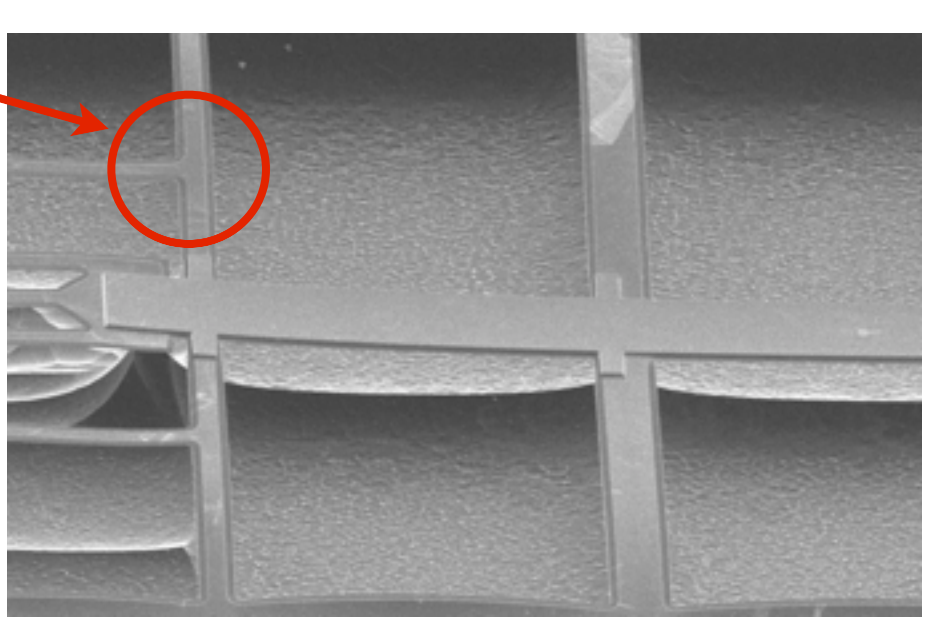


  - **Necessary to remove the substrate of the final devices.**
    - Very thin membranes, easy to break them as well due to the stressed material under test.

Seebeck coefficient/Thermopower

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



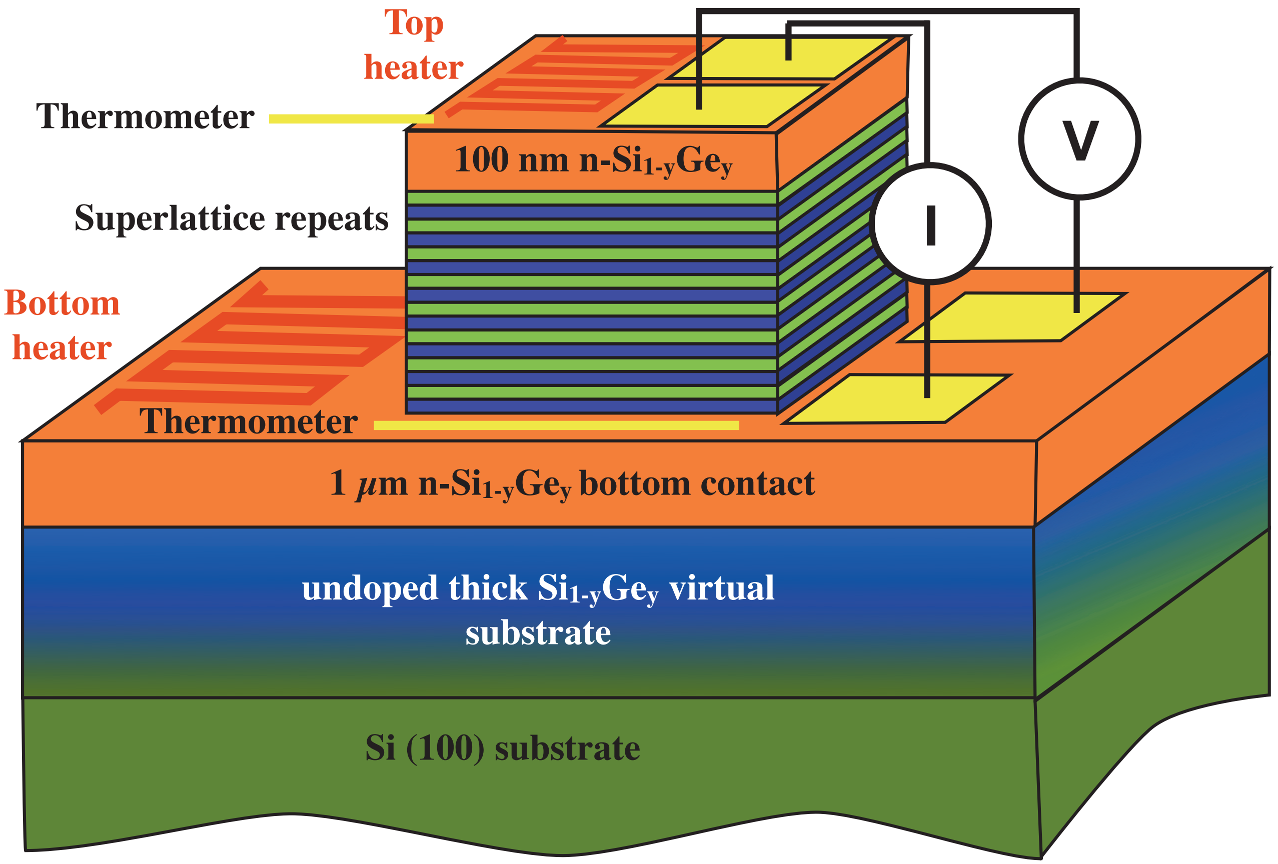


- Patterning new shorter Hall Bars to help the curvature of the membranes.

2D Superlattice: Vertical devices

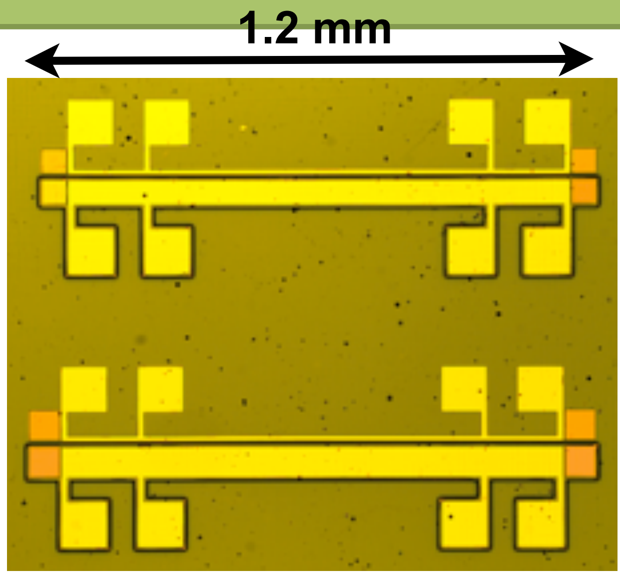
- **Easier fabrication as there is no need of removing substrate.**

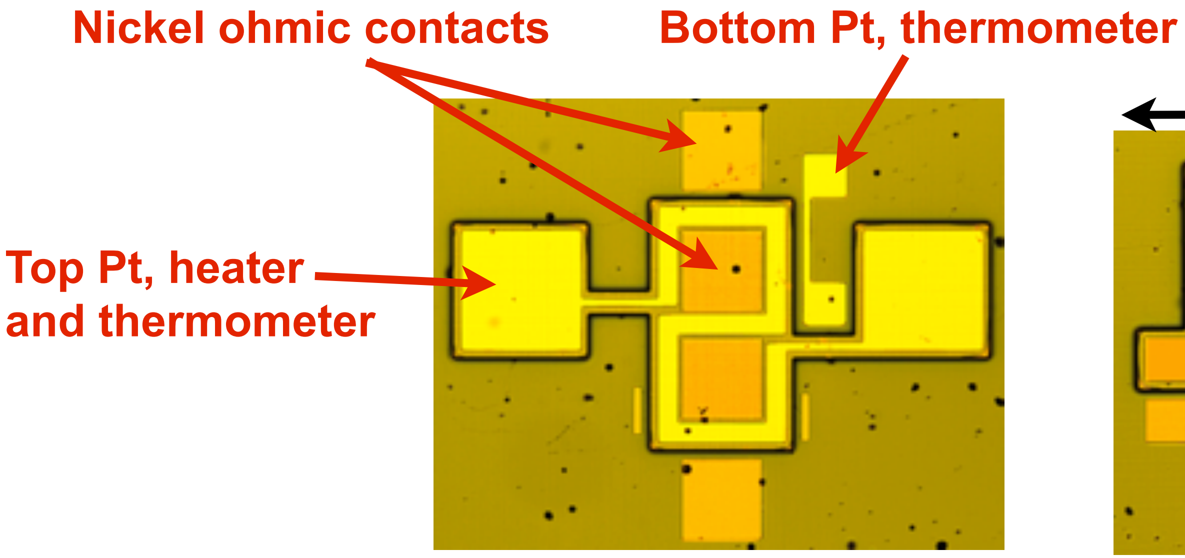
- **Make sure that there is an homogenous heat flux going down the mesa structure.**

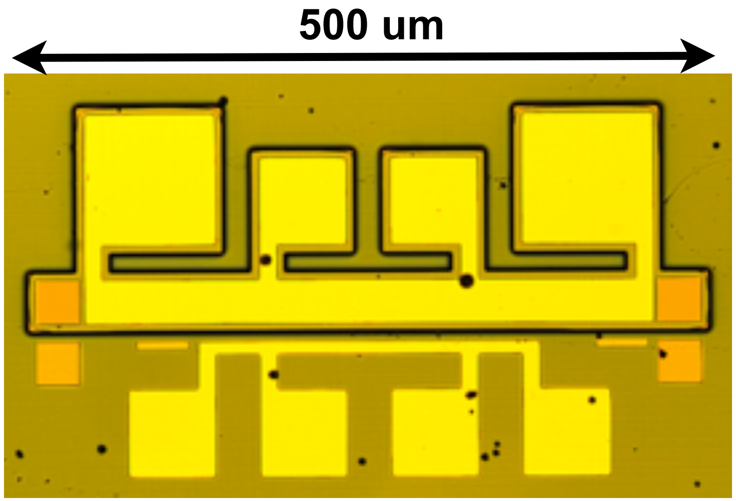


Vertical devices

- Patterning different devices to measure the vertical properties of the material.
- This time using heaters as thermometers as well to reduce the top surface of the mesa.
- Make sure that there is an homogeneous heat flux going down the mesa structure. Check accuracy of heating system and thermometers with the AFM group.

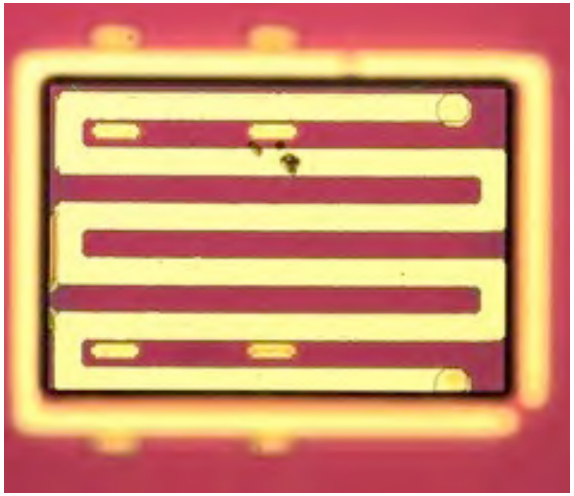




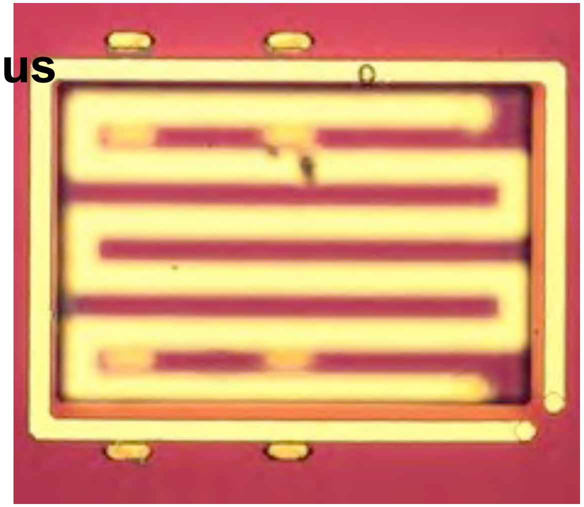


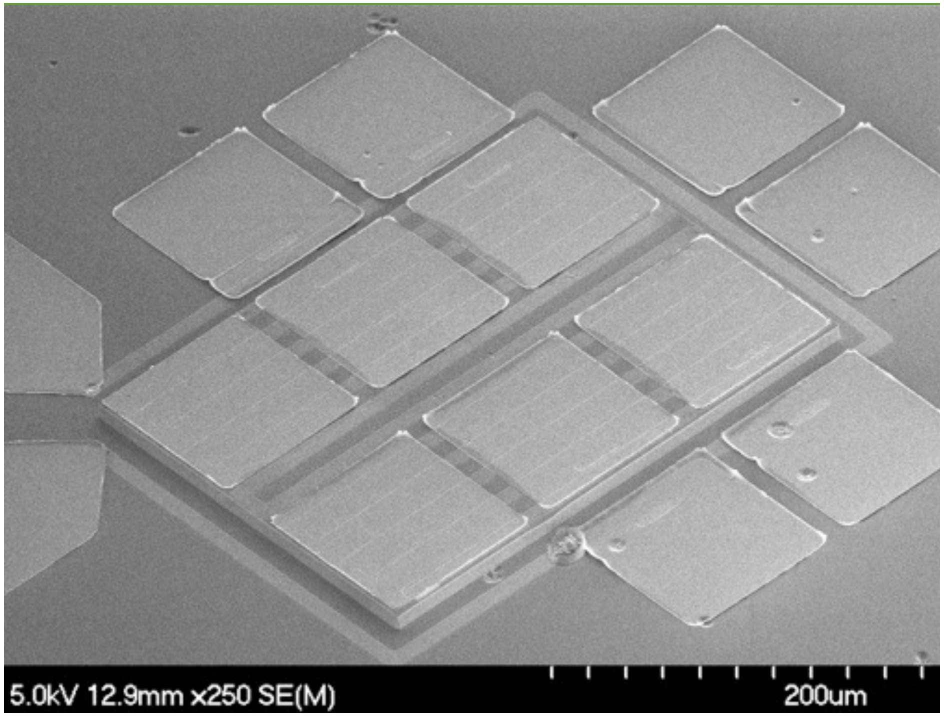
Vertical devices

Top focus



Bottom focus





Conclusions and Future Work

- **Measure and analyse all the vertical devices fabricated to get an optimum device that gives accurate results.**
  - **Need of the thermal AFM to cross check all these results.**

- **Fabrication on suspended membrane structures with good mechanical stability and good reproducibility.**
  - **Optimise thermal measurements. Easier estimation of the heat flux due to the substrate removal.**

Thank you!

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