Thermal studies at Valencia

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Outline

Summary of measurements and new results

- First simulation results
- Air/liquid cooling influence
- Thermal studies of new materials

DEPFET Thermal mock-up

- Ideas and description
- Influence of air/liquid coling
- Cross-check with previous measurements

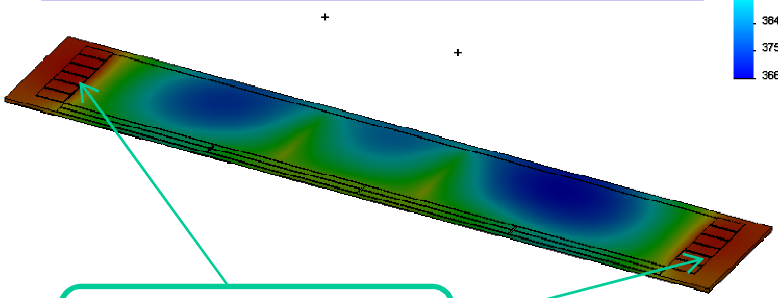
Options to discuss

- TPG/CVD-Diamond
- Glues
- Longer wafer

SUMMARY OF MEASUREMENTS AND NEW RESULTS

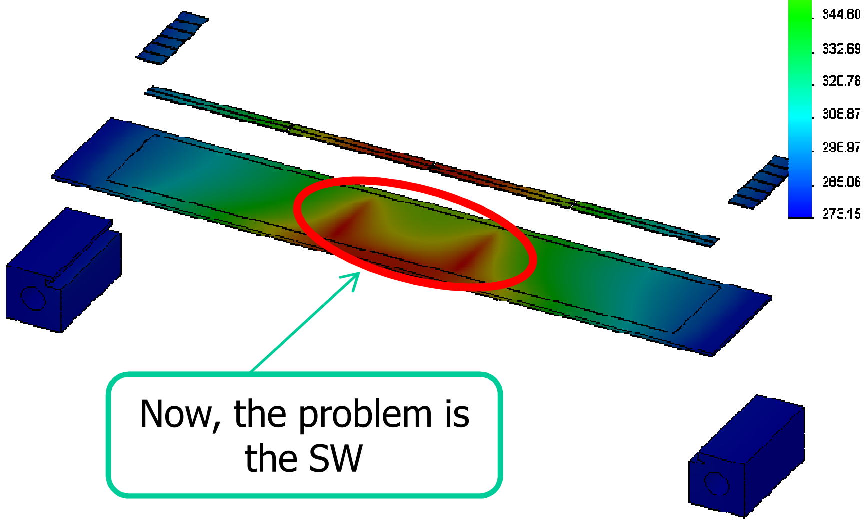
From simulation (at "tree level"): Steady state simulation

- DCDs always active: The hottest points
- 2 Switchers active
- 2 pixel stripes active



We need to cool down the DCD

- DCDs active: Solved with cooling blocks
- 2 Switchers + 2 pixel stripes active: Very hot!



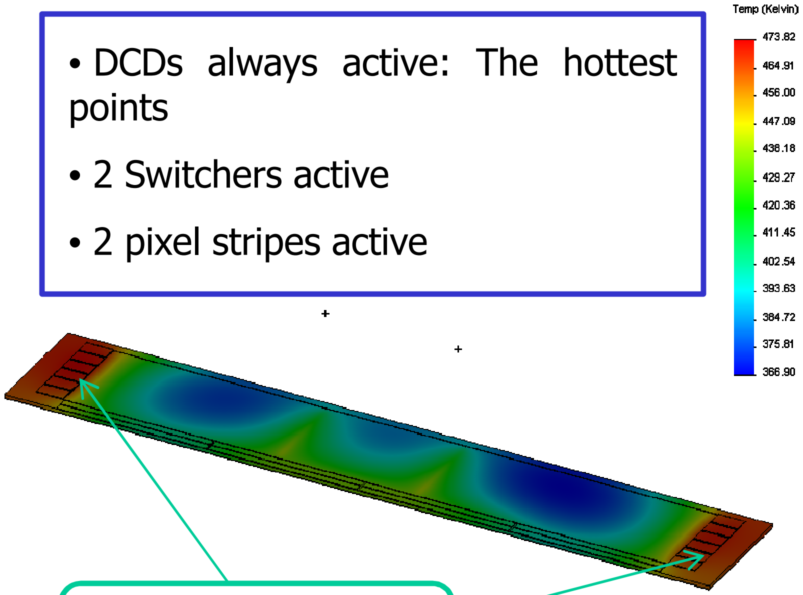
Now, the problem is the SW

- DCDs: High T at the edges. Problem solved using cooling blocks (decide the adequate T)
- Switchers and pixel stripes: High T in the middle of the module. Not solved with cooling blocks.

→ We have to use air for cooling the center of the module

From simulation (at “tree level”): Steady state simulation

- DCDs always active: The hottest points
- 2 Switchers active
- 2 pixel stripes active



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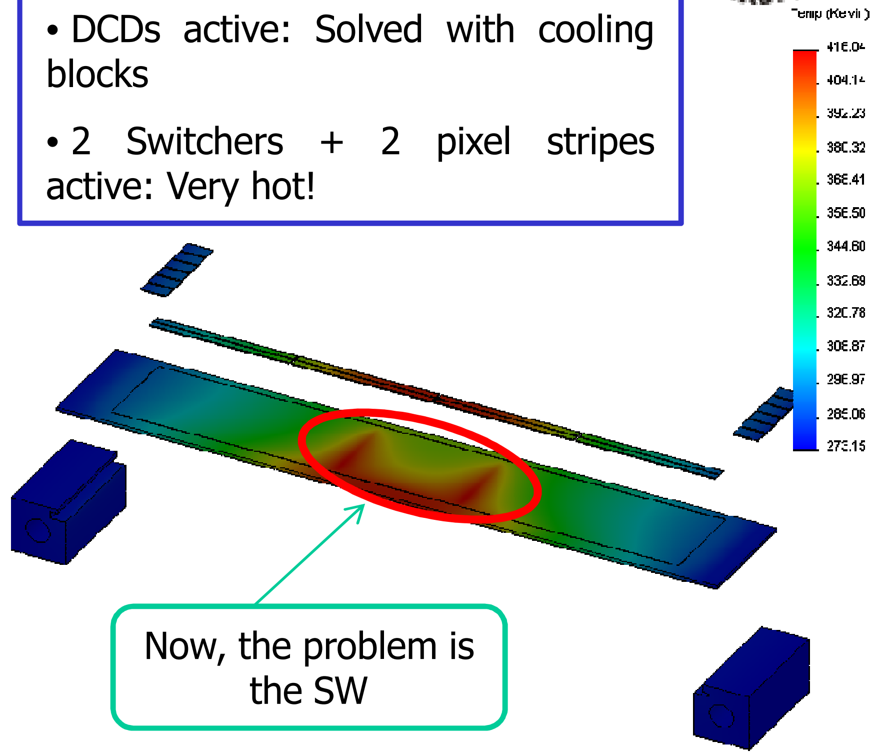


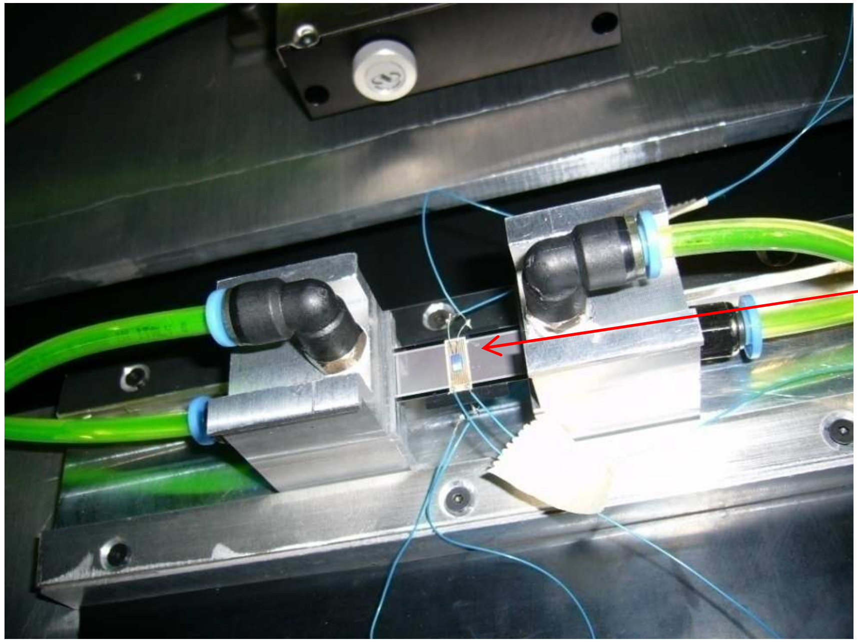
Now, the problem is the SW

•This is a personal estimation on power consumption! Just qualitatively results! **We need to agree on some numbers to do this studies!**

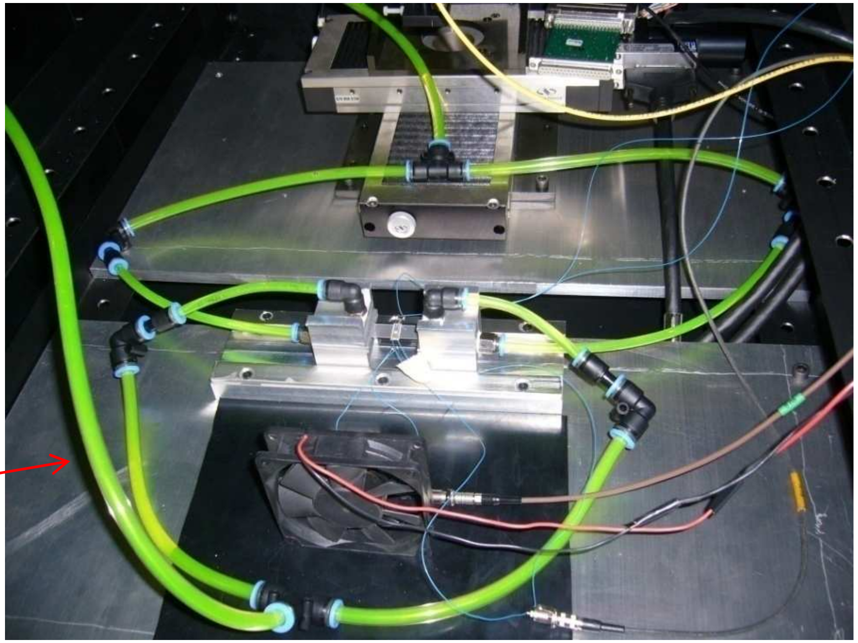
• Next more accurate simulation is in progress, including real dimensions, materials....

• Preliminary parameters are used between groups involved in thermal issues (Karlsruhe and Valencia, regular meetings). Cross-check between measurements and simulation is on the way.

Set up

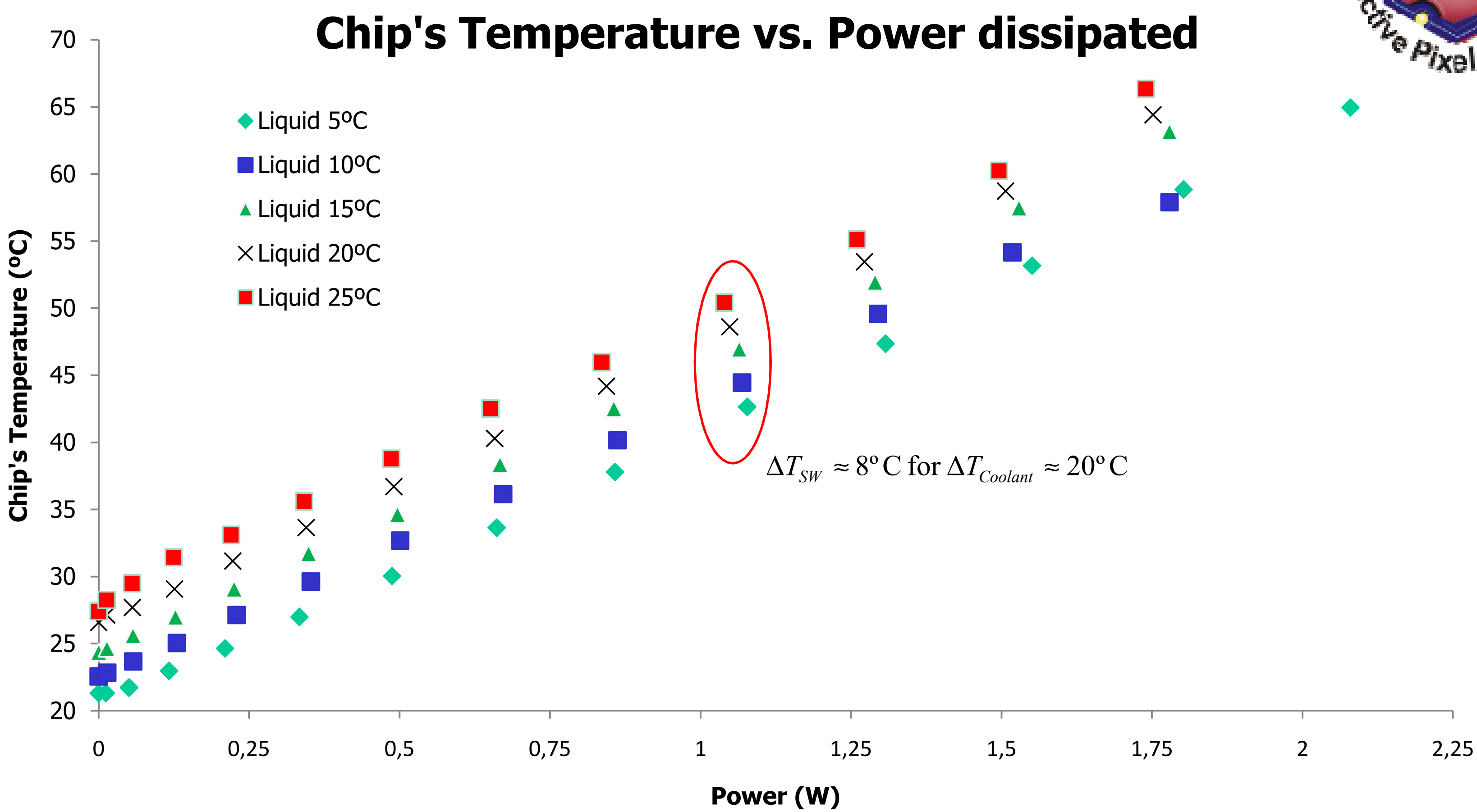


- Measurements made on a small microstrip detector.
- The heater is placed in the middle of the sensor.
- Pt100 resistance for temperature measurement
- Dimensions 34x14 mm^2
- Thickness 300 μm



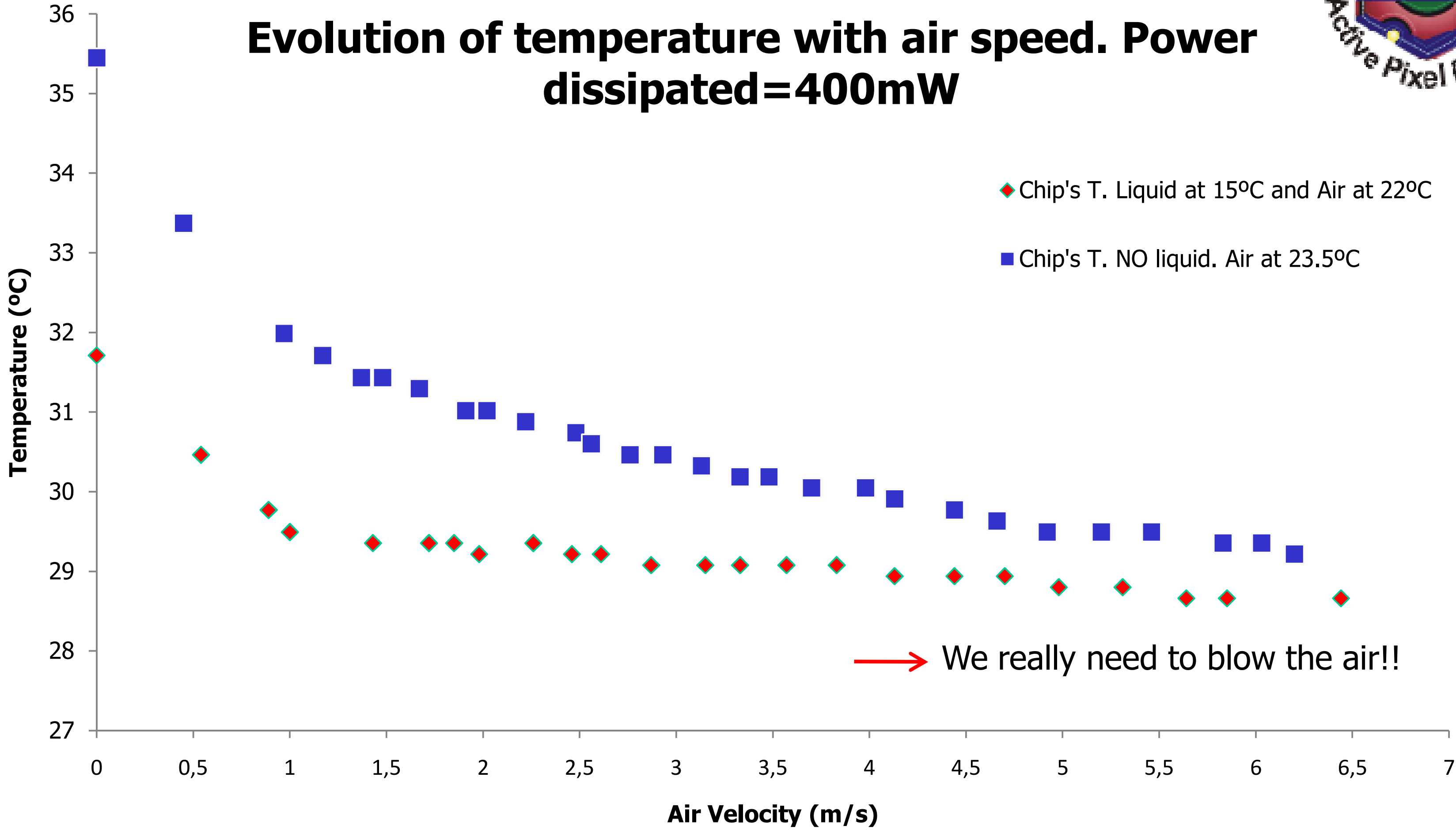
- Coolant coming from a chiller
- Desired T over a wide range

Influence of conduction



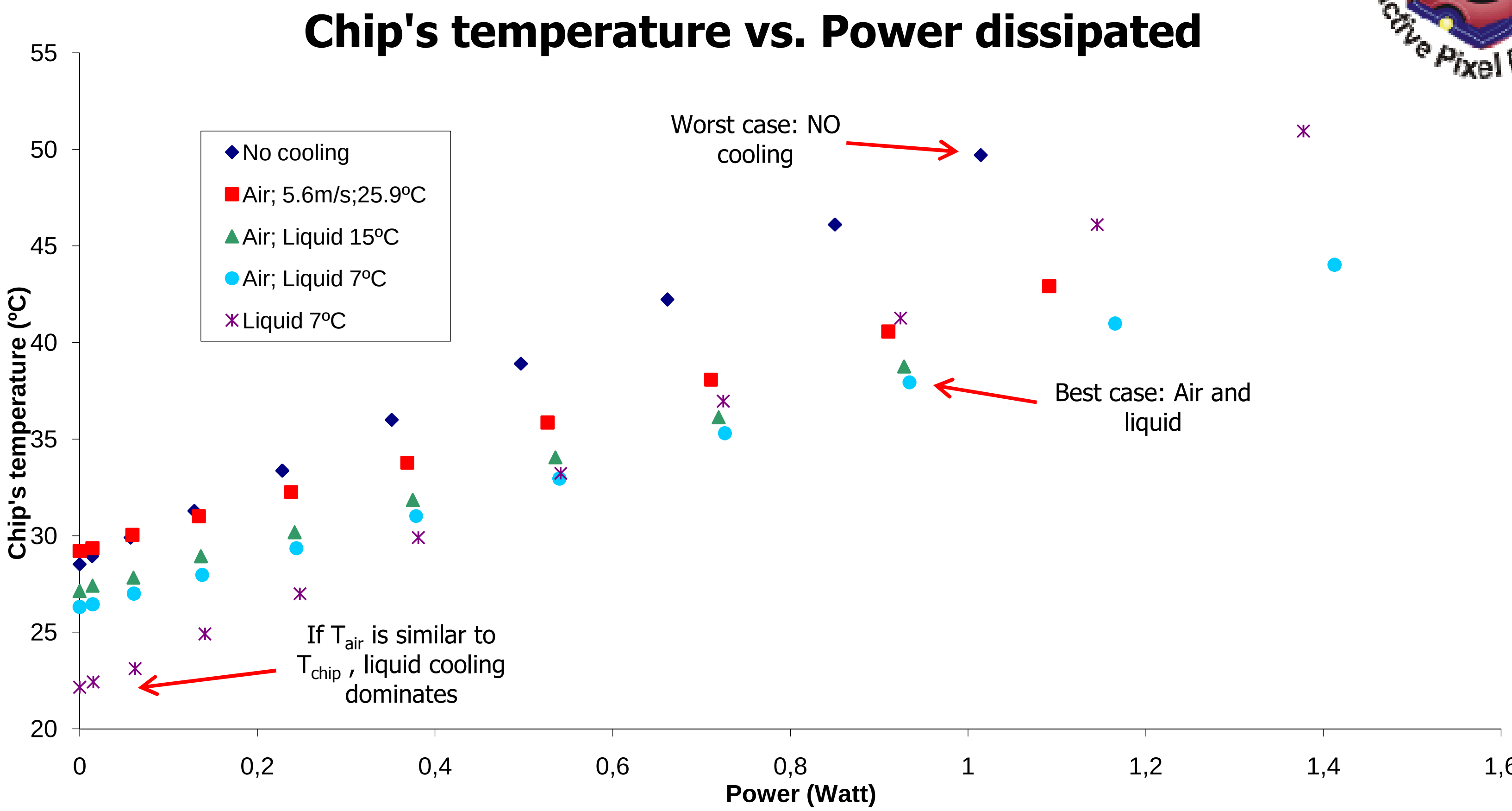
- Evolution of the switcher, for different temperatures of the cooling blocks, as a function of power dissipated by the chip.
- The slope is always the same. The difference is the offset.
- The influence of the cooling blocks in the center of the module is not so big.

Influence of convection



- Evolution of the chip’s temperature, as a function of speed of air for 0,4 Watt of power.
- The air flowing is an effective mechanism for cooling the center of the module. For higher power, the effect is even bigger
- Once the air is blowing, the T varies slow, independently of the speed (at this range).

Miscellaneous

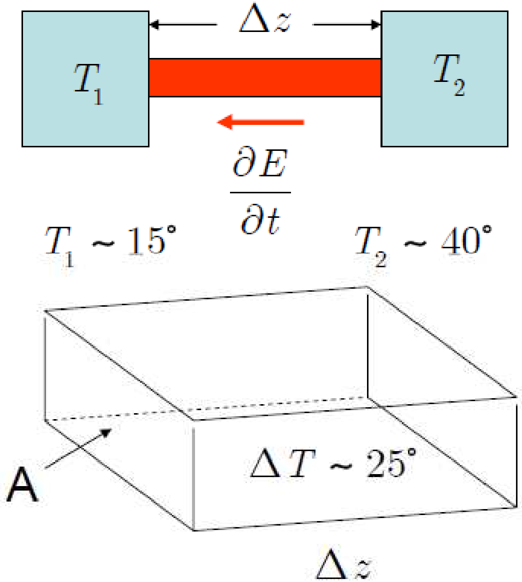


- Evolution of the switcher, for different cooling conditions, as a function of power dissipated.
- The liquid cooling modifies the offset wrt the NO cooling situation in the middle.
- The air modifies the slope; the temperature increases more slowly.

The heat removal using the support bars

- From C. Kiesling talk's in Valencia, option number 1:

Why does this not Work? The Cooling Issue



$$P = \frac{\partial E}{\partial t} = \lambda \cdot A \cdot \frac{\Delta T}{\Delta z}$$

$$J\left[\frac{W}{m^2}\right] = \lambda\left[\frac{W}{mK}\right]\frac{\partial T}{\partial z}$$

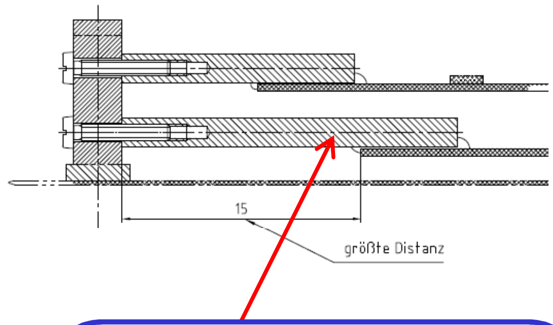
$$\text{Al:} \quad \lambda = 200\left[\frac{W}{mK}\right]$$

$$P = 5\ \text{W} \quad \Delta z \sim 2\ \text{cm}$$

$$A \sim 20\ \text{mm}^2$$

Steel: Factor 4 more !!!

Need Cu (λ=380) $\longrightarrow$ 10 mm²



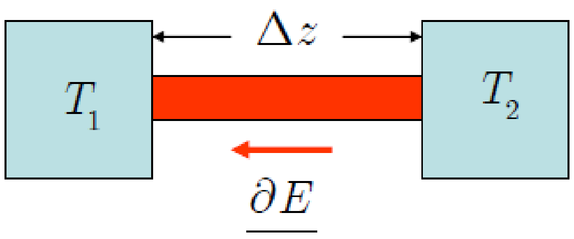
- A big thickness is needed with this material (Al or Cu).
- Gluing the support structure underneath the module is not possible due to the lack of space!

But…

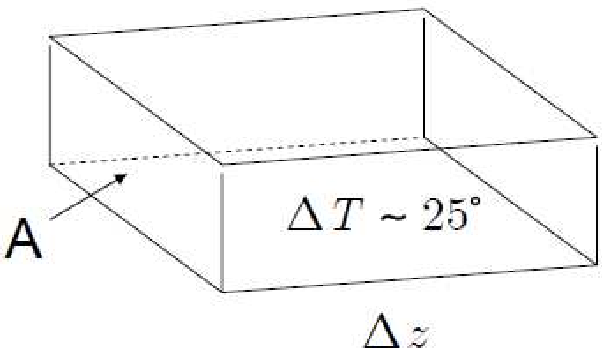
Thermal studies of new materials

- Replace the Al for synthetic diamond (H.J. Simonis) or TPG:

Why does this could Work? The Cooling Issue



$T_1 \sim 15^\circ$ $T_2 \sim 40^\circ$



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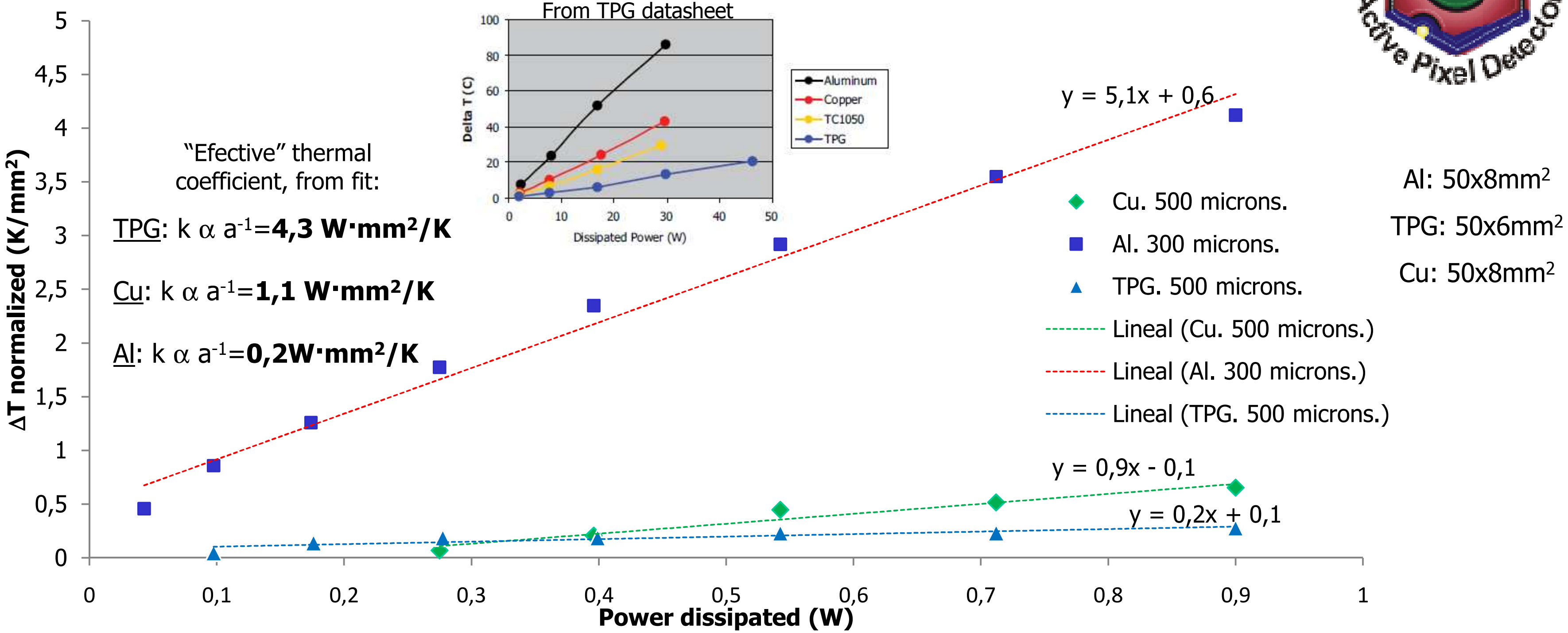
~~Al: $\lambda = 200\left[\frac{W}{mK}\right]$~~

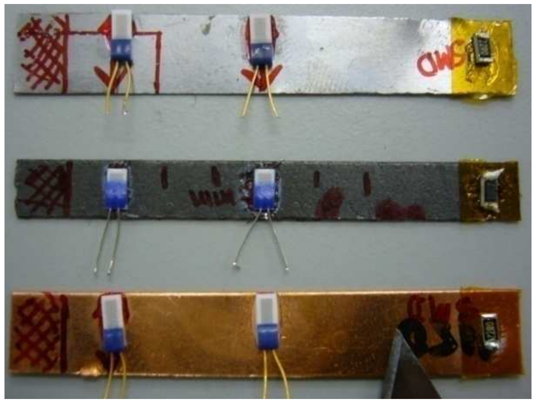
$P = 5\ \mathrm{W}$ $\Delta z \sim 2\ \mathrm{cm}$

$$\text{TPG or diamond}: \lambda \cong 1600\left[\frac{W}{mK}\right]$$

$A \approx 2mm^2$ → Very small transverse area

Thermal conductivity of various materials



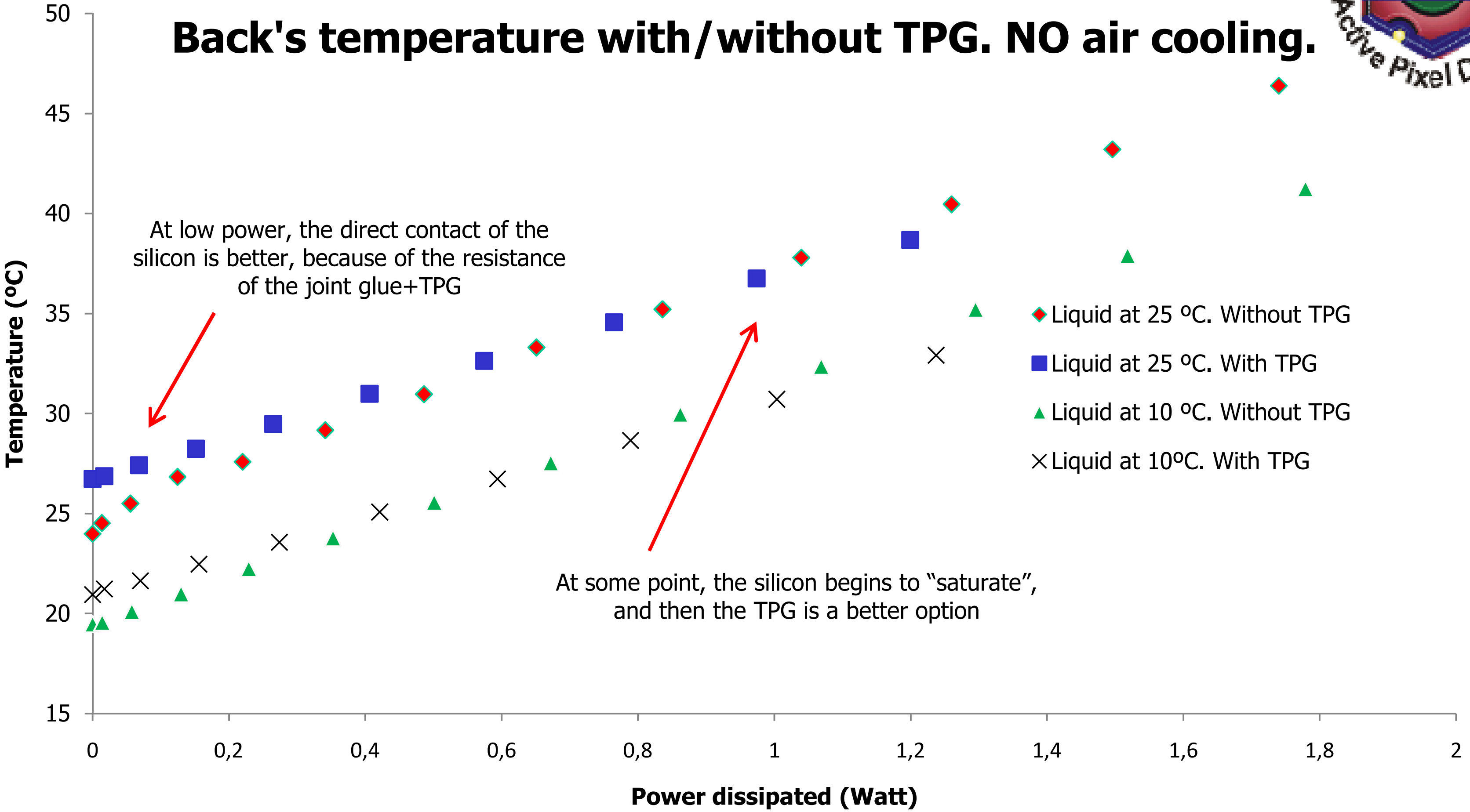


$$\frac{k^{Measured}_{TPG,effective}}{k^{Measured}_{Copper,effective}} = \frac{k^{Theoretical}_{TPG}}{k^{Theoretical}_{Copper}} = \frac{1600\, W/mK}{400\, W/mK}$$

- The cold end is in contact with the cooling block.
- The power is dissipated by means of a SMD resistor in the hot end
- Y axis is de temperature (measured with Pt100 sensors) difference between the center and the cold end, normalized to the transverse area.

The **TPG** capability for heat transfer through it, is definitely much better rather than Al or Cu

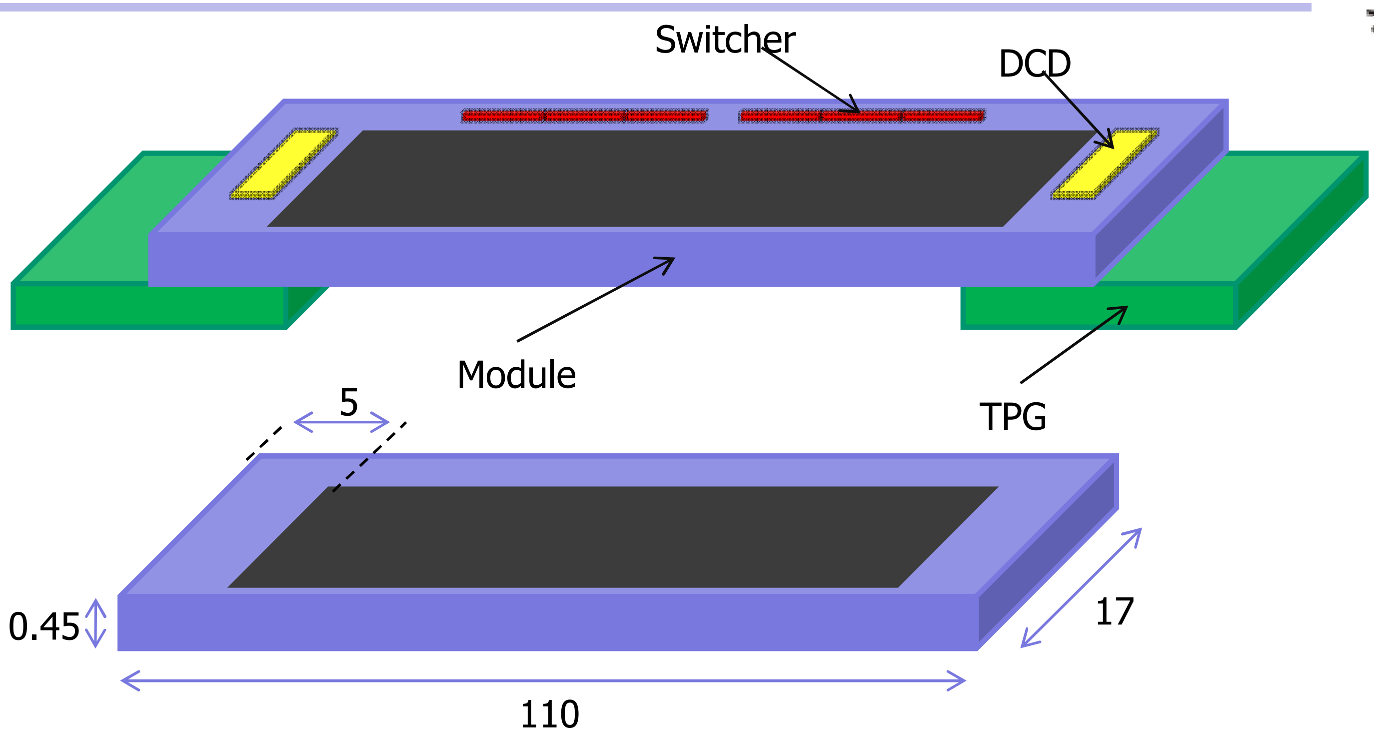
Silicon and TPG as thermal contacts



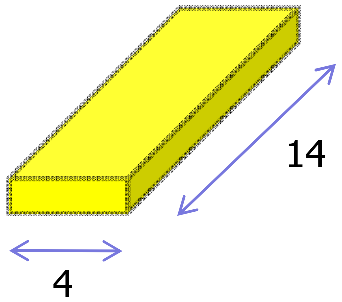
- Sensor temperature as a function of power dissipated in the heater. The heat removal is only by means of convection directly throught the silicon sensor or through the TPG to the cooling block.
- The overlap of the TPG with the microstrip detector is $2x14mm^2$.
- The overlap of the silicon and TPG with the cooling block is $1x14mm^2$

DEPFET THERMAL MOCK-UP

First DEPFET thermal mock-up

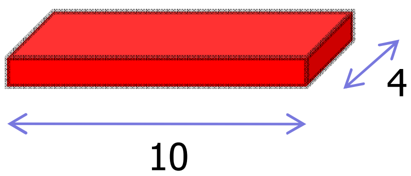


In mm



DCD's

- 1 heater on each end
- Always powered on
- 1.6 Watts each



Switchers

- 6 switchers
- Switched on/off sequentially
- (0,1s ON/0,2s OFF)
- 0.4 Watts each

Estimation of power consumption

Pixels

- Active: $800\,\text{pixels} \times 0.5\,\text{mW/pixel} = 0.4\ \text{Watts/each half sensor}$

SWITCHERS

- Active: $[(1\,\text{gate} + 1\,\text{clear}) \times 4\,\text{rows}] \times 225\,\text{mW/active row} = 1.8\ \text{Watts/Switcher}$
- Idle: $10\,\text{mW/Switcher}$

DCD

- Always active: $(200\,\text{columns} \times 4\text{rows}) \times 5\,\text{mW/channel} = 4\ \text{Watts/module end}$

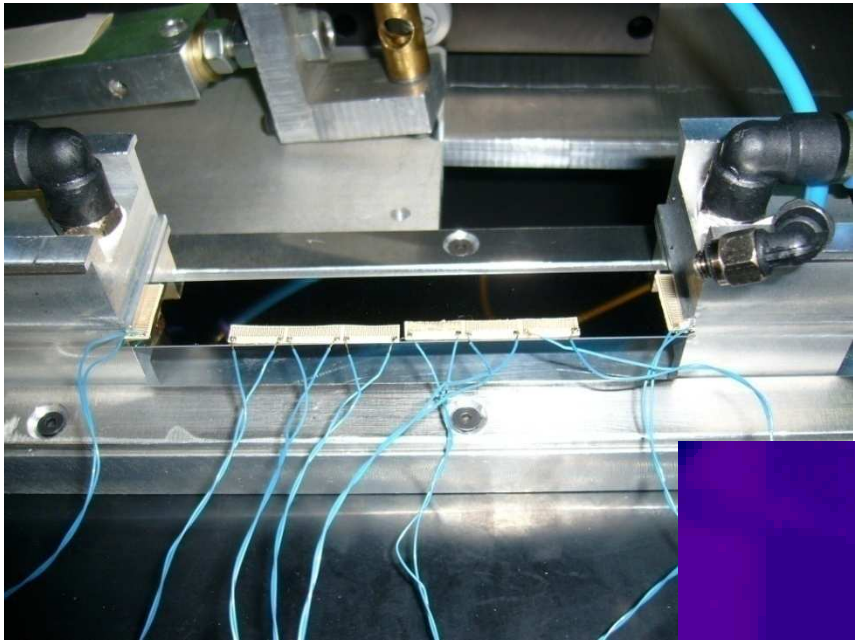
- Comparison between real values and what I have used:

	Real value	Used value
Switchers	1.8 W each	0.4 W each
DCD	4 W each end	1.6 W each end
Pixels	0.8 W	0 W

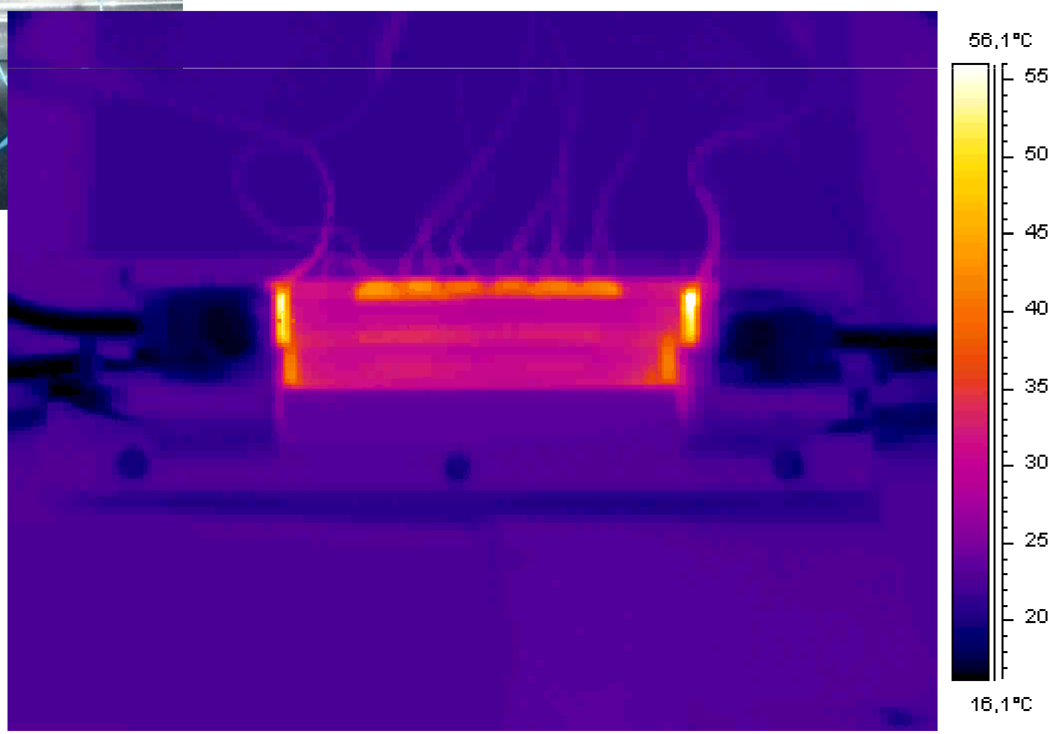
It is not easy to achieve such a high power with the heaters!

→ **What you are about to see is just to calibrate our simulation!**

Real thermal mock-up working!



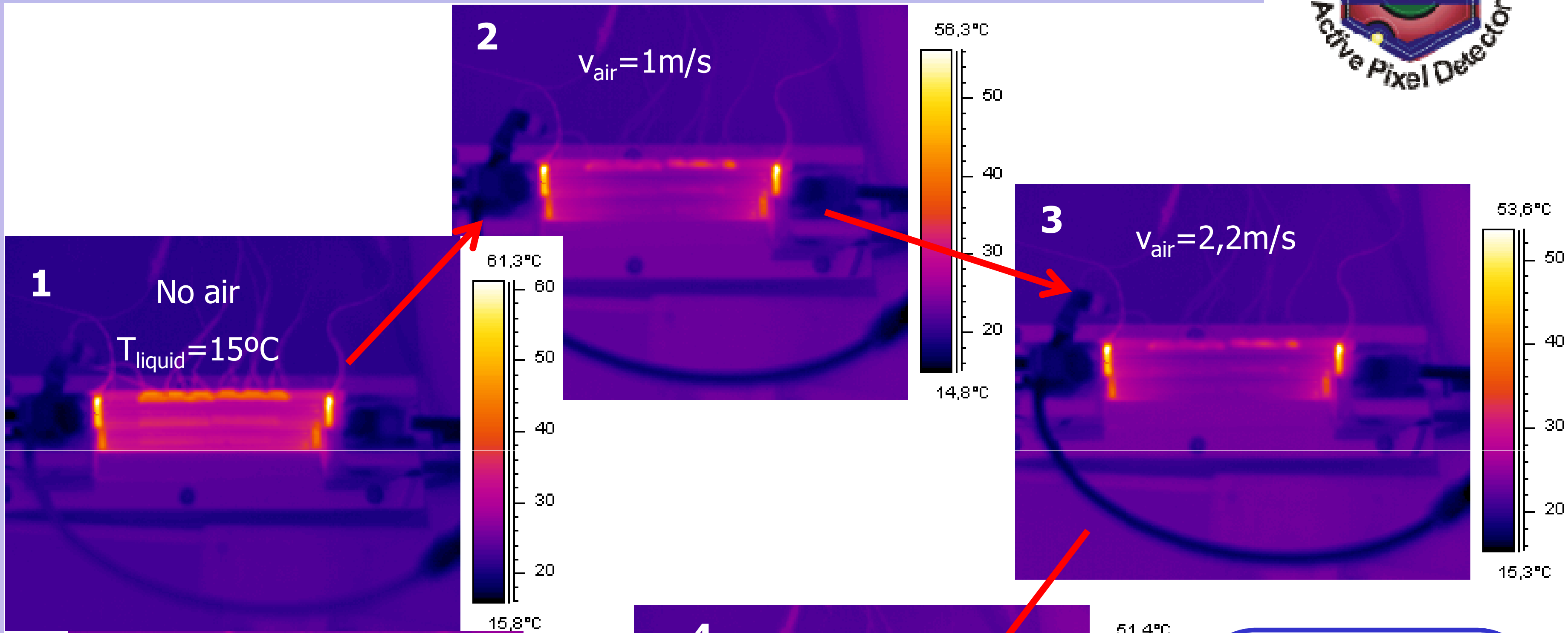
DEPFET ILC-module with DCD's and SW's like heaters between the cooling blocks. The air connector is also visible

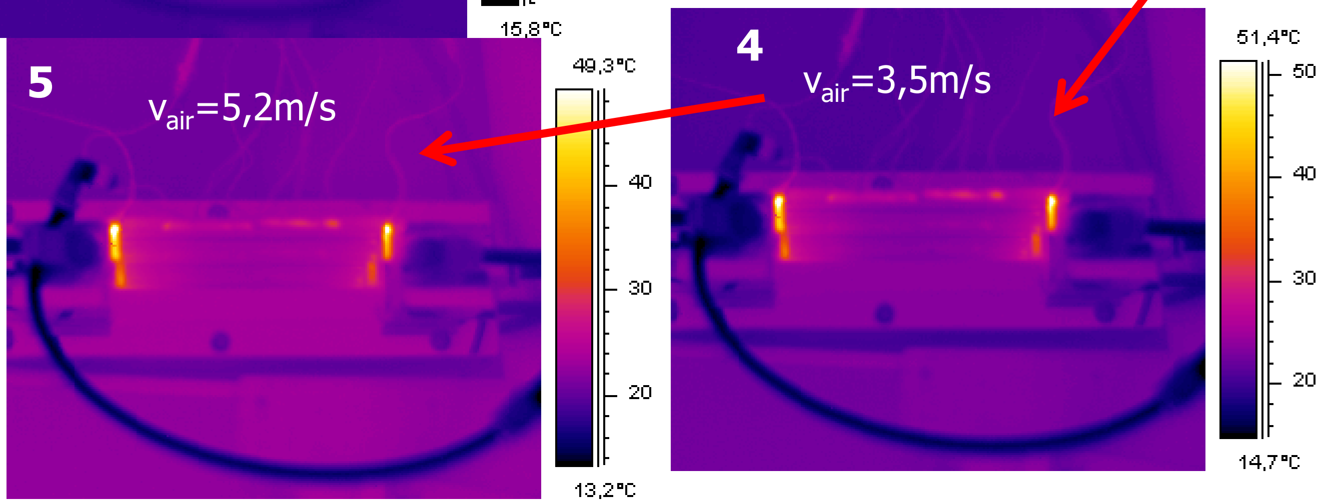


- Movie with the switcher sequence. In this case, the sequence is slower to see the effect of switching
- You will not see this effect anymore due to the fact that the camera is slower rather than the switching time (0,1s ON/0,2s OFF)

Influence of air

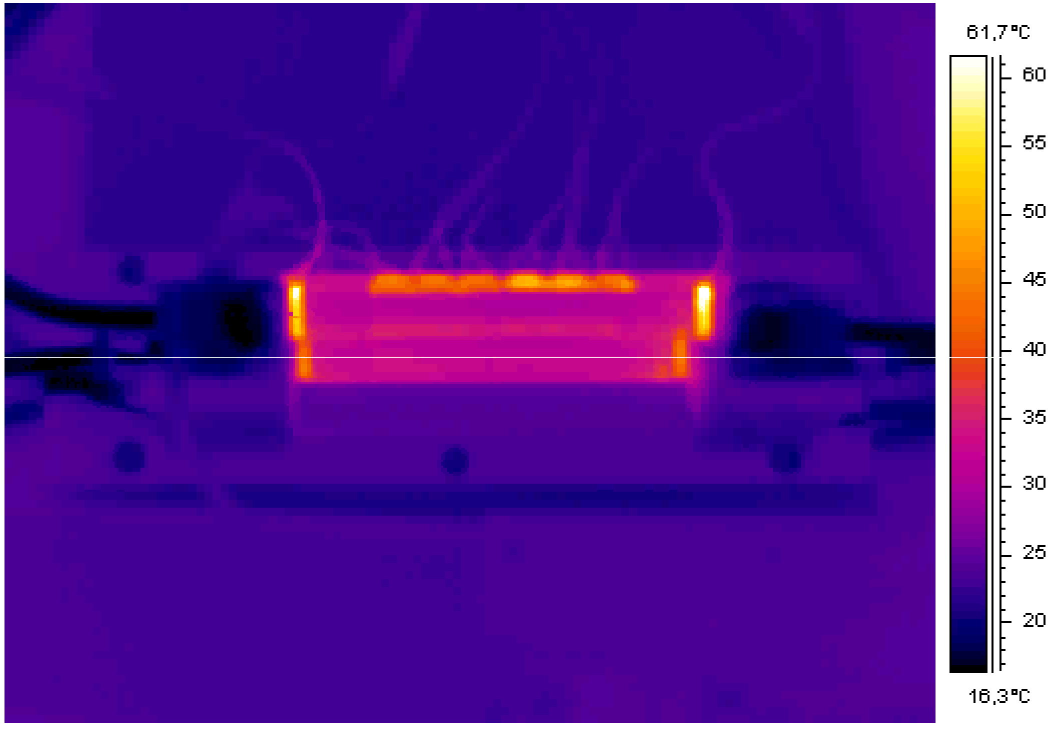
Always look the scales!!!!!!!





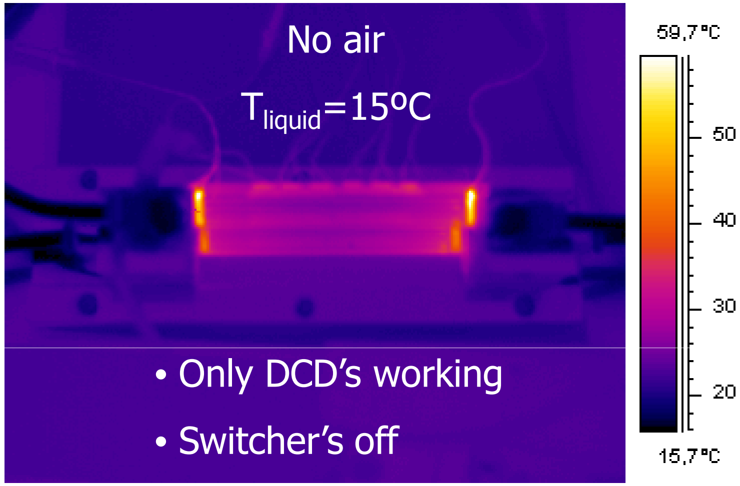
- Air has major effect on cooling the middle sensor
- At high speeds, the effect between measurements is less significant

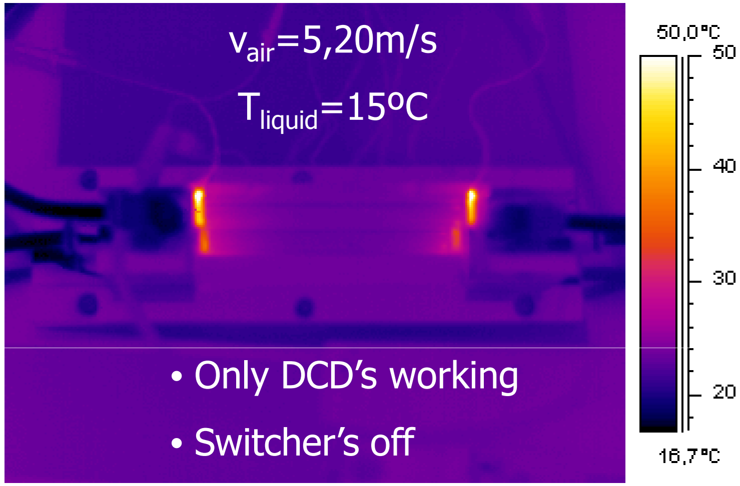
Influence of air in a movie



1. DCD's and SW's working. Only cooling blocks at 15ºC
2. Air begin to flow. T_{air}=26ºC, v_{air}=5,20m/s
3. The air is off again

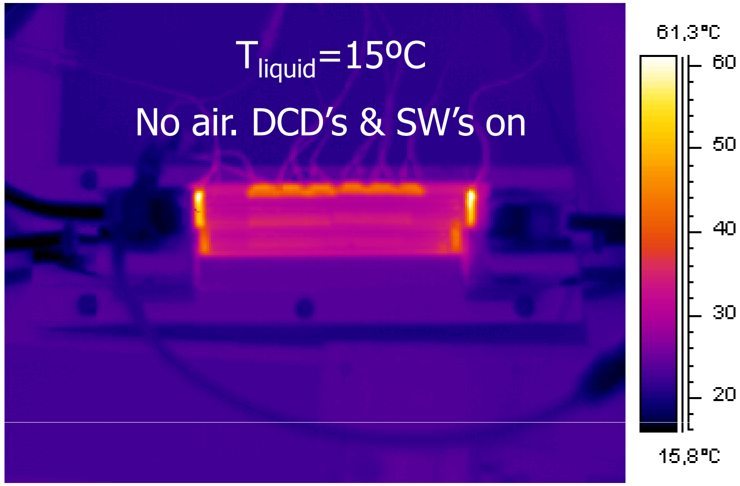
Air influence in the center of the module

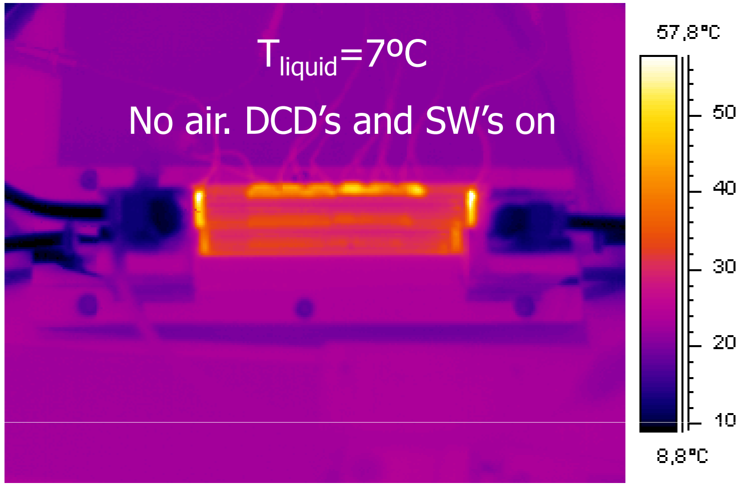


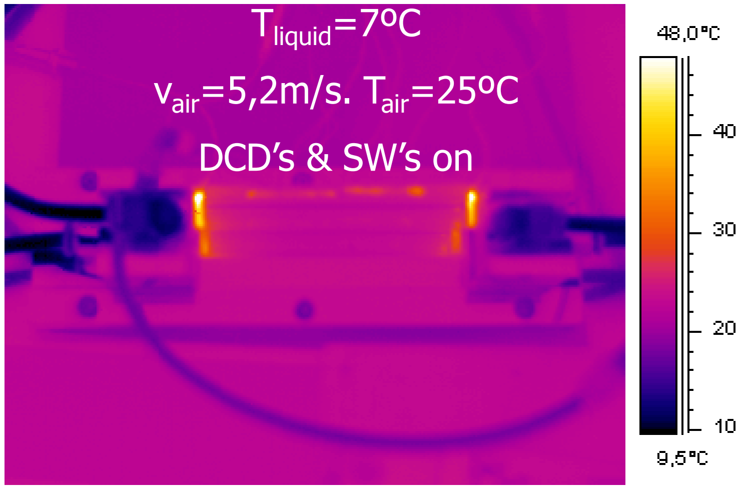


- Even with the Switchers in idle state, the DCD's generate enough power to heat the middle of the sensor.
- With lower temperatures of the cooling blocks, the DCD's heat is more constrained on the end of the module.
- The main work in the middle of the sensor, has to be done by the air!

Temperature cooling blocks

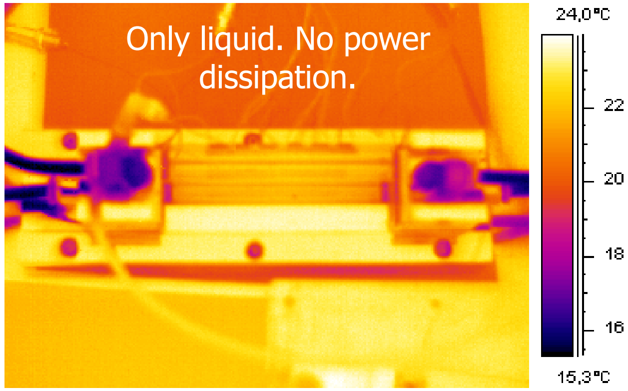


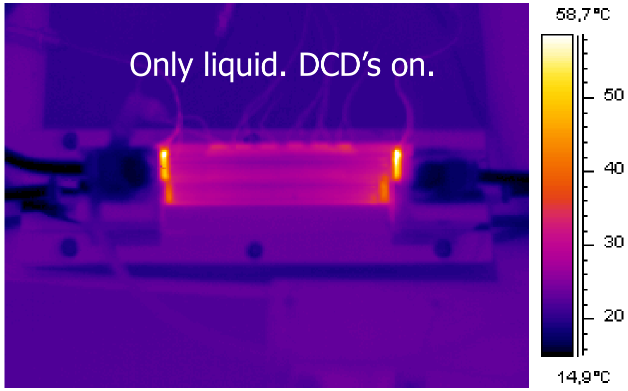


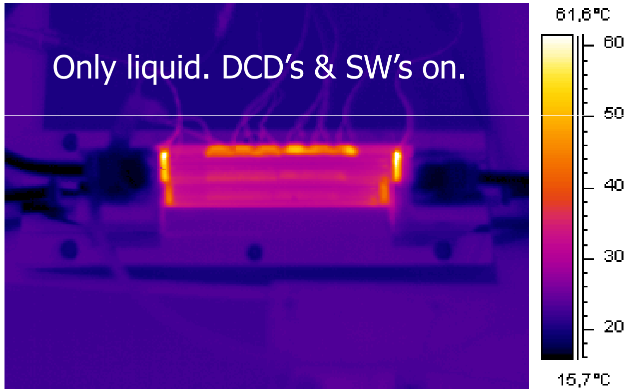


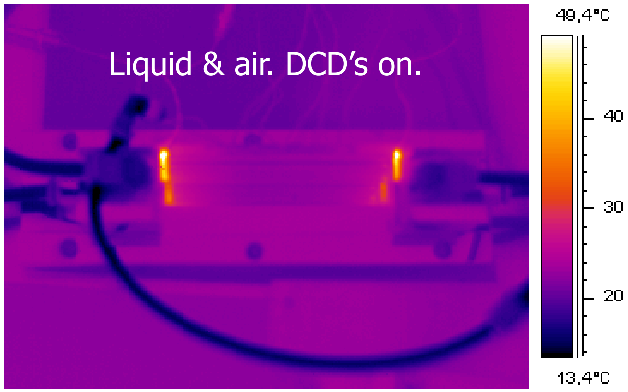
- The cooling blocks help the DCD's on both ends
- $\Delta T_{DCD} \approx 3^{o}\,C$ for $\Delta T_{Coolant} \approx 8^{o}\,C$
- A big price for a small gain
- The cooling blocks act as a barrier for the heat wanting to go the center of the module but don't cool the middle of the sensor.
- For the middle, we need air.

Summary of all the effects





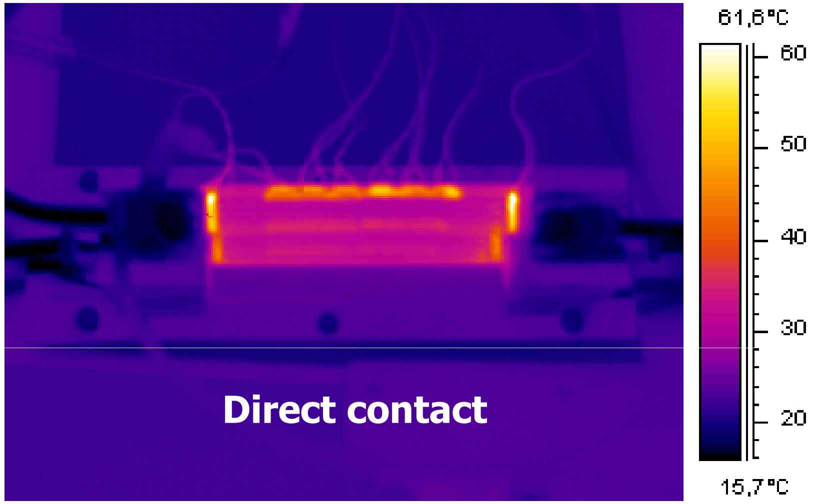


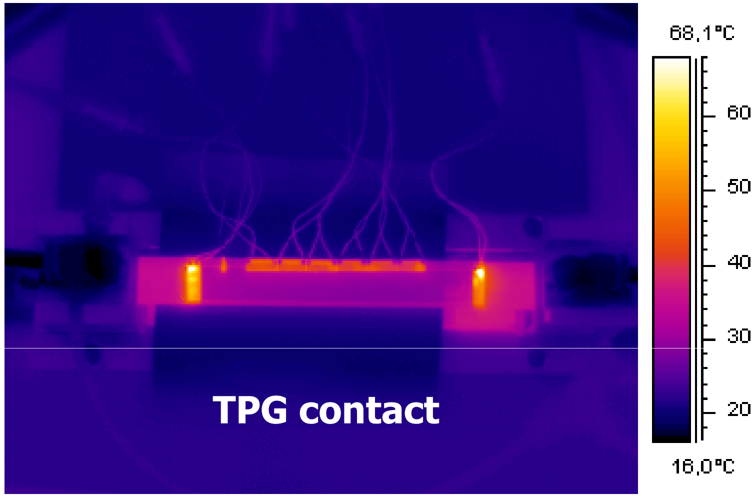


- T_{liquid}=15ºC
- V_{air}=5,2m/s
- T_{air}=24ºC

With and without TPG

Let's see the effect if we introduce the TPG as a contact between the sensor and the cooling blocks:





- Switchers: 0,4 W
- DCD: 1,6 W
- Direct contact with the cooling block at 15ºC

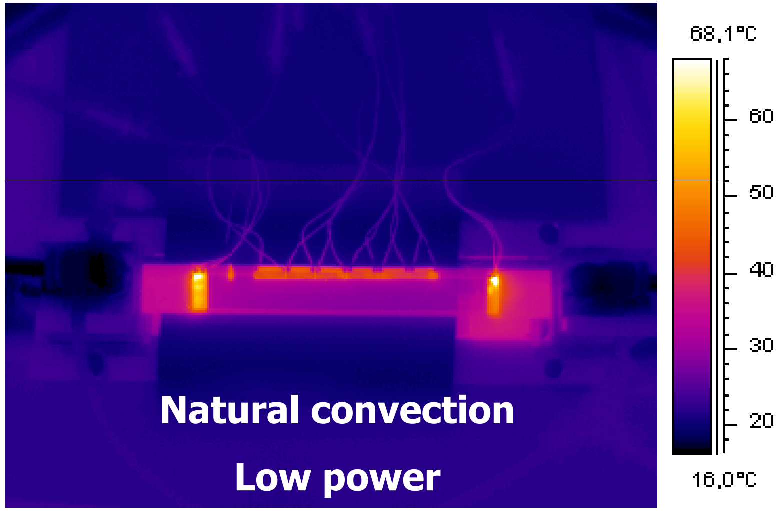
- Switchers: 0,4 W
- DCD: 1,6 W
- TPG. Overlap 85mm^2 underneath the balcony

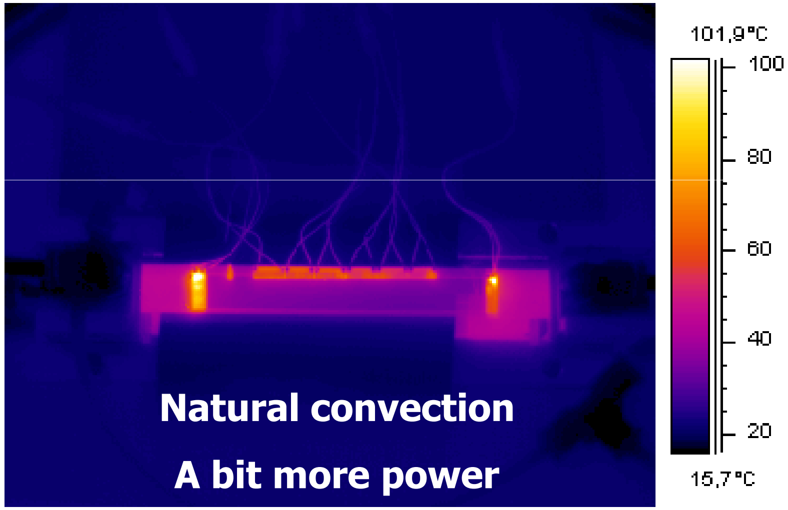
- Not such a big temperature difference in the sensor: around 35ºC in both cases
- TPG plays its roll, as expected!

A more realistic approach…

• Now the power disipated by the Switchers and DCD's is bigger than before but half the expected value in the final module.

• The contact with the cooling blocks is made by a couple of sheets of TPG. 500µm thick, 20 mm long and 17 mm wide. Overlap of 85mm² underneath the balcony .





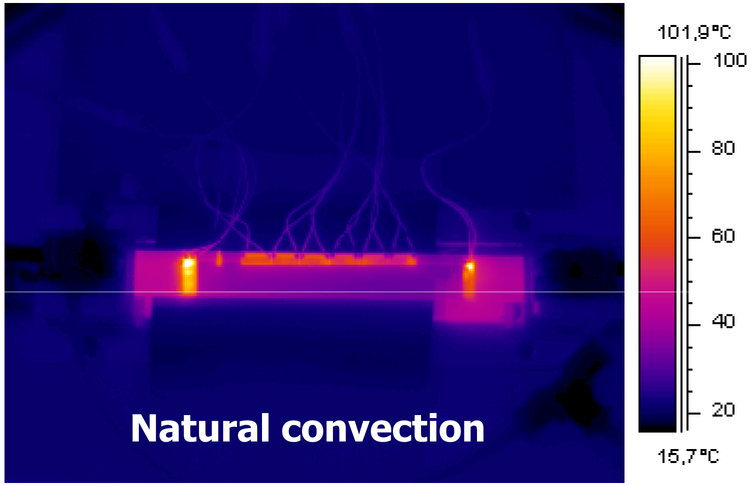
- Switchers: 0,4 W
- DCD: 1,6 W
- **The sensor is around 39ºC**

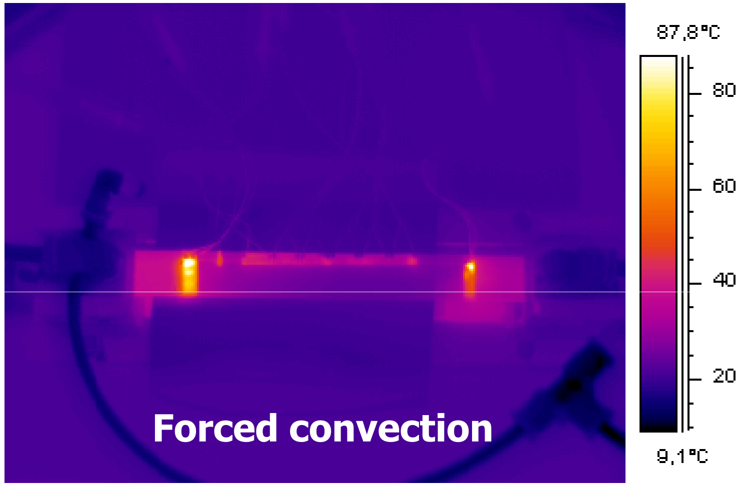
- Switchers: 0,8 W
- DCD: 2 W
- **The sensor is around 50ºC**

Without air, the temperature of the sensor increases a lot, even with powers half the final ones.

Not everything is lost… Blowing the air:

- Conduction through the TPG to the cooling blocks. 500µm thick, 20 mm long and 17 mm wide.
- Forced convection.





- Switchers: 0,8 W
- DCD: 2 W
- No air
- **Temperature sensor=50ºC**

- Switchers: 0,8 W
- DCD: 2 W
- T_{air}=20ºC; v_{air}=5m/s
- **Temperature sensor=41ºC**

→ Now the situation is more favorable

OPTIONS TO DISCUSS

• We have to pump out of the sensor a big amount of power… but there are several things that we can do:

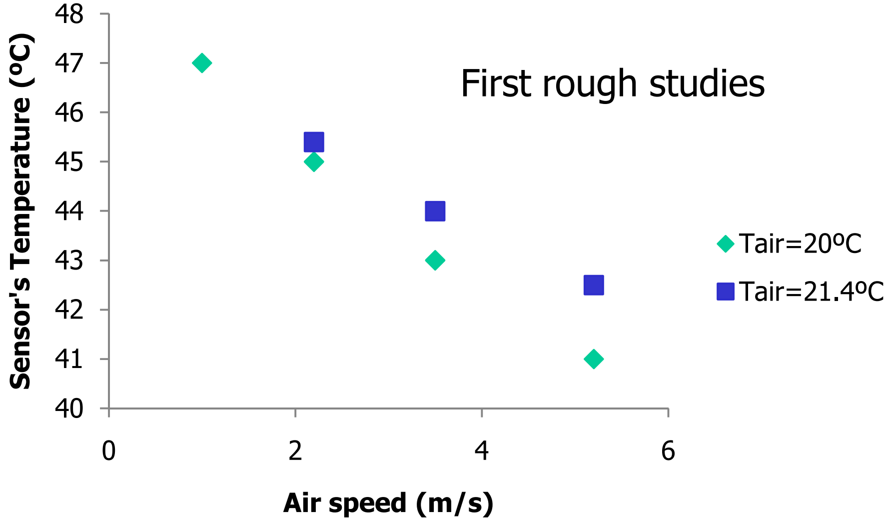
  • Decrease the temperature of the cooling blocks to the lower value possible. Is 7ºC or 8ºC achievable? Condensation?

  • Decrease the length that the heat must cover. Is there a possibility to move the support structure closer to the modules? Longer modules?

  • Decrease the temperature of the air

  • Increase the air flow

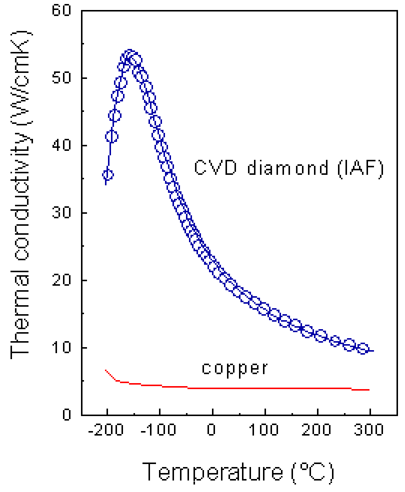
  • Introduce materials with better thermal coefficient

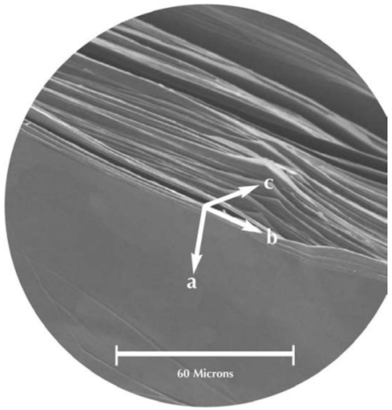


A couple of options

TPG

- In-plane thermal conductivity: 1550 W/mK (at 20ºC)
- Out of plane thermal conductivity: 20 W/mK (no matter! small thickness)
- Density: 2.15 g/cm3
- Well studied material: Already tested in ATLAS SCT
- Very soft material





CVD (Chemical Vapor Deposition)-Diamond

- In-plane and out of plane thermal conductivity: 1800 W/mK (at 20ºC)
- Density: 3.515 g/cm3
- The thinner the cheaper
- Good rigidity
- “Cleaner”
- Better for mechanical stability?

Glue or grease?

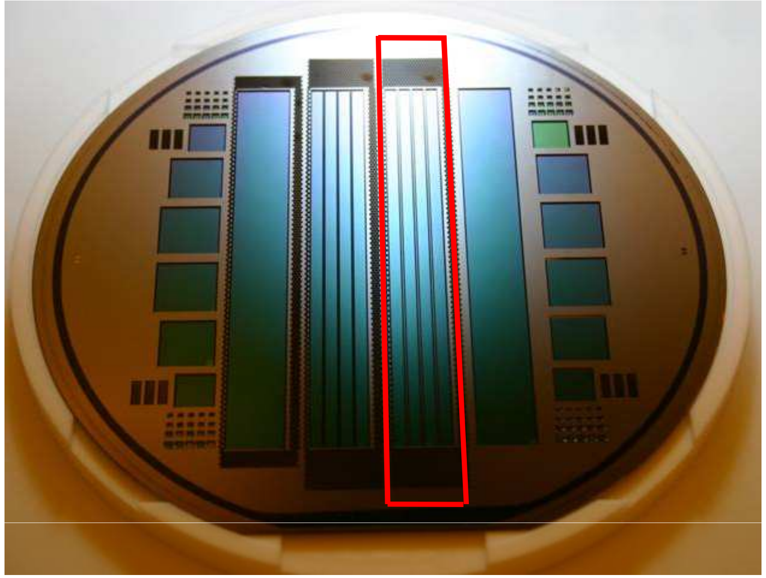
Only glue

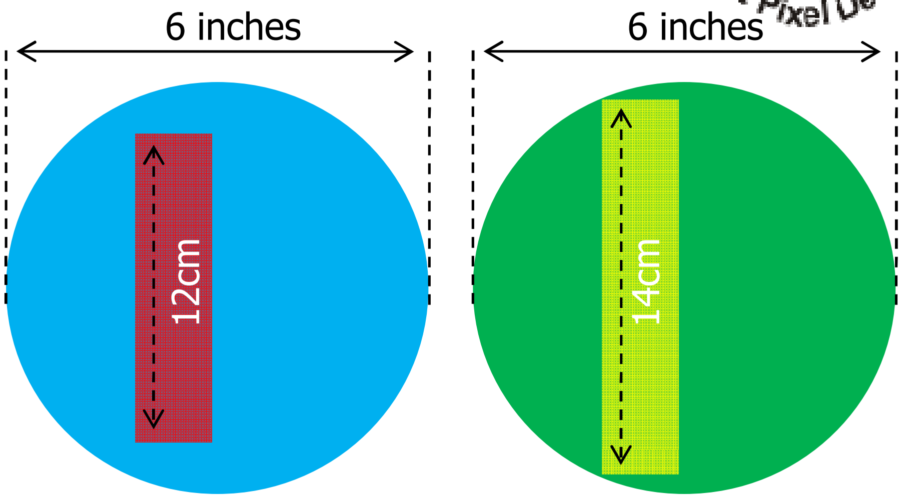
- For example: Elastosil 137-184 (available in Russia)
- Used in the ATLAS-SCT for gluing the spines
- Thinned down to 50 microns
- Thermal conductivity: 1,79 W/mK
- Good thermal and mechanical properties
- Good performance after irradiation with protons (photons??)
- Expert "at home": H.-G. Moser

Grease in the center+glue at the edges

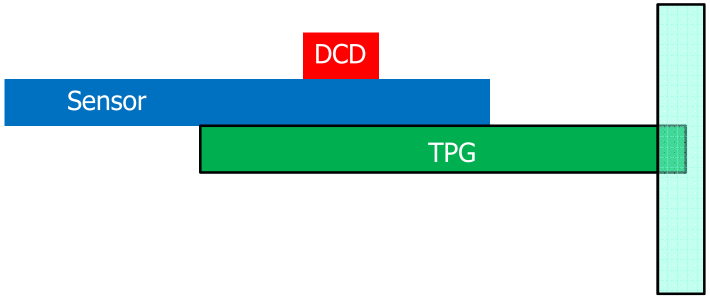
- Several conductive substantes: Ceramic, metal, carbon, liquid metal based.
- Higher thermal conductivity (up to 10,5 W/mK)
- For example: Fischer Elektronik-WLPG 02- Heat Sink compound, Graphite (Farnell ref: 1315295)
- No aging, radiation or mechanical studies made yet.

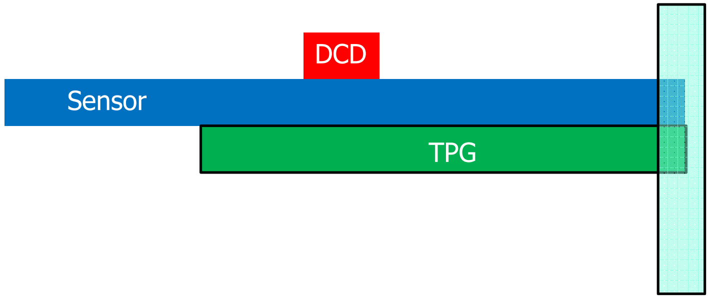
Longer modules?



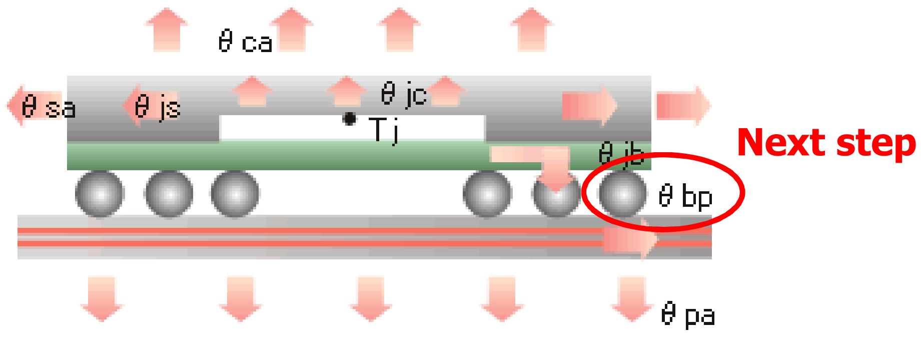


- The idea is to increase the length of the module, using the whole wafer
- There is no need of grinding or polishing this area... we just need a big area for conduction
- Then we increase the area for heat exchange with the TPG/diamond on the DCD's balcony
- Handle wafer engineering: New materials for the handle wafer better suited than bulk silicon?





Heat exchange in a chip?



Heat flow paths

- θja(°C/W): Thermal resistance from junction to atmosphere (junction to ambient air). Reduce this value when a package is used alone..
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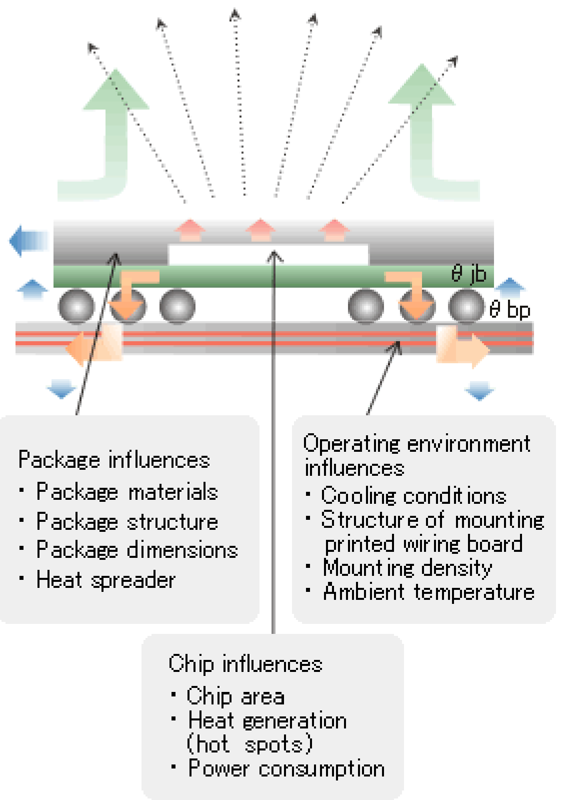
- **θbp: Thermal resistance from ball lands to printed wiring board surface (ball to PWB).**
- θca: Resistance composed of heat convection and heat radiation from package surface to atmosphere (case to ambient)
- θpa: Resistance composed of heat convection and heat radiation from printed wiring board to atmosphere (PWB to ambient)
- θjs: Thermal resistance from junction to side of package (junction to side)
- θsa: Thermal resistance from side of package to atmosphere (side to ambient)



Summary

- **Simulation:**
  - First qualitatively results are in good agreement with measurements.
  - New and more detailed simulation is in progress. New results will be presented soon.
  - **Simulation parameteres are not well stablished**! We need to know the numbers to introduce in the simulation!
  - Karlsruhe and Valencia groups working together on this item. Good communication and useful ideas arised from our regular meetings. Cross-check between groups.
- **Measurements:**
  - An infraestructure is created in Valencia for thermal studies.
  - Air and liquid cooling, power cycling and heaters are working.
  - First results using a microstrip detector are obtained.
  - TPG/CVD-Diamond (expected!) are valid solutions for heat removal.
- **DEPFET thermal mock-up:**
  - First DEPFET thermal mock-up is done in Valencia.
  - Useful for calibration of the simulations.
  - First results corroborate what expected:
    - Cooling blocks needed for keep the DCD's at a reasonable temperature
    - Air cooling needed for cooling the center of the sensor
    - **A lot of power to be dissipated! We must think how to manage it!**

➢ Heat dissipation is not a minor issue… we have to use all the posibilities!

- Maximize the conduction through the cooling blocks and the forced convection with air
- Use materials with good thermal properties
- Minimize the thermal resistance of any joint

Thank you very much!

Remember the mechanical module…

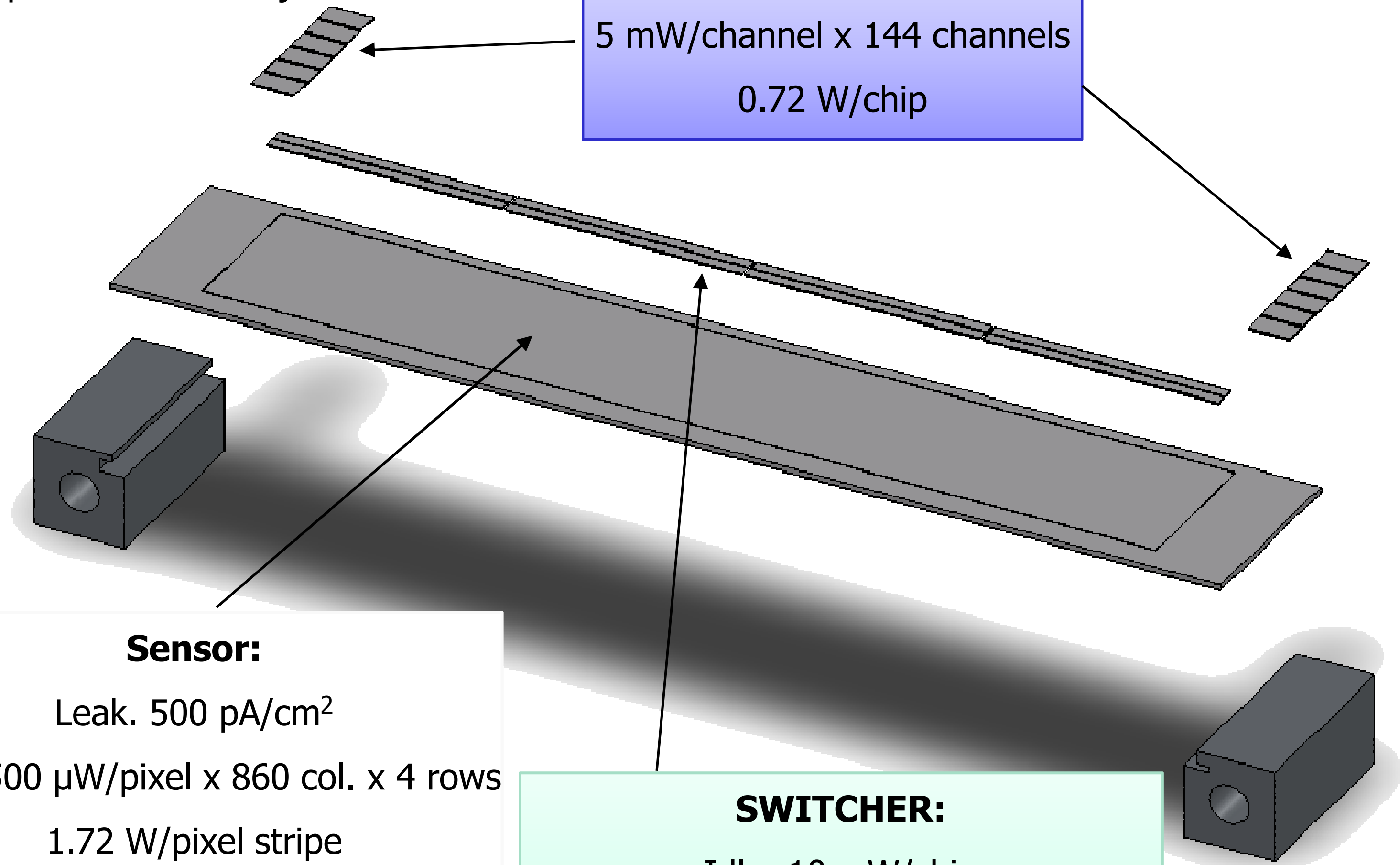
Following DEPFET layout in HGM's table

Support is not real... just an sketch

DCD:

5 mW/channel x 144 channels

0.72 W/chip



Sensor:

Leak. 500 pA/cm^2

Pixel: 500 μW/pixel x 860 col. x 4 rows

1.72 W/pixel stripe

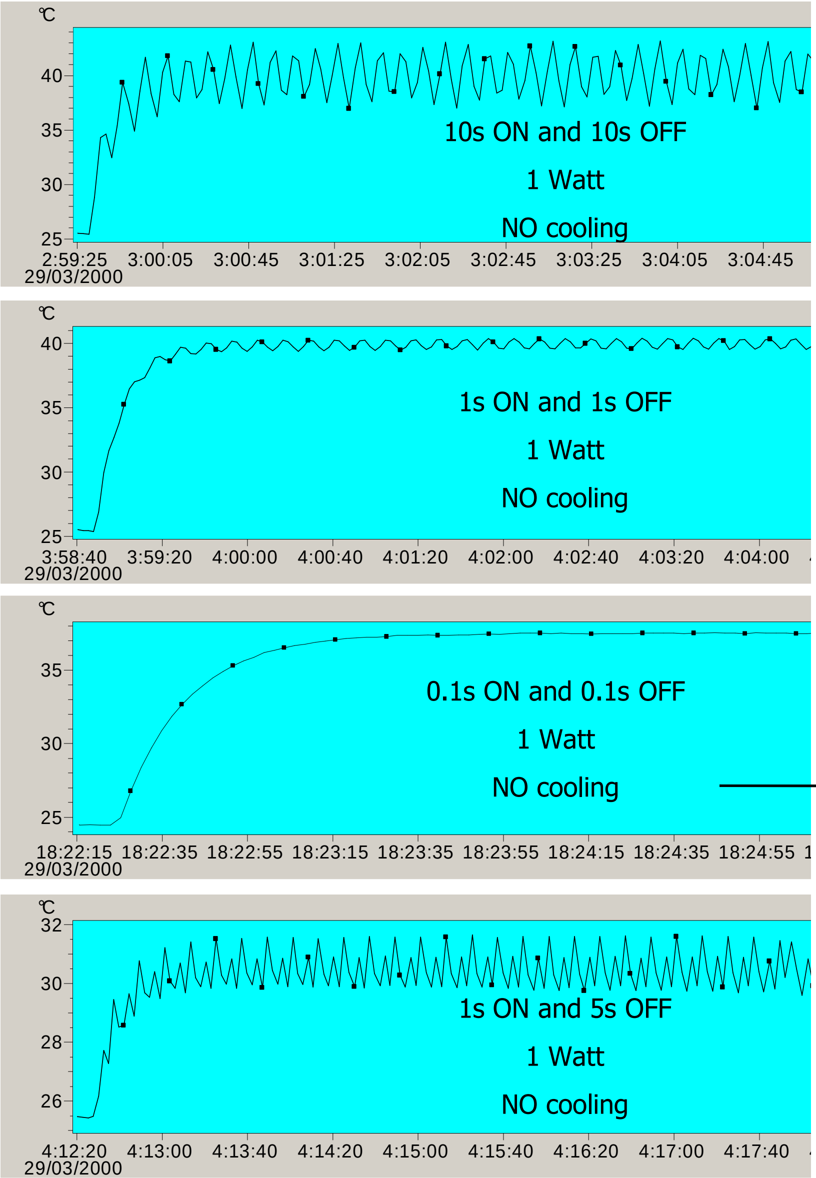
SWITCHER:

Idle: 10 mW/chip

Active: 225 mW/row x 4 rows + 50 mW

0.95 W/chip

Power cycle



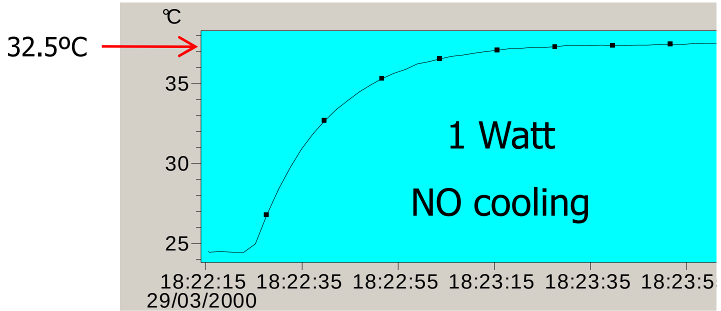
- We always reach a *plateau* independently of the ON/OFF time
- The final temperature is always the same, under the same cooling conditions
- If the ON and OFF cycles are longer, we will see bigger oscillations around the equilibrium temperature

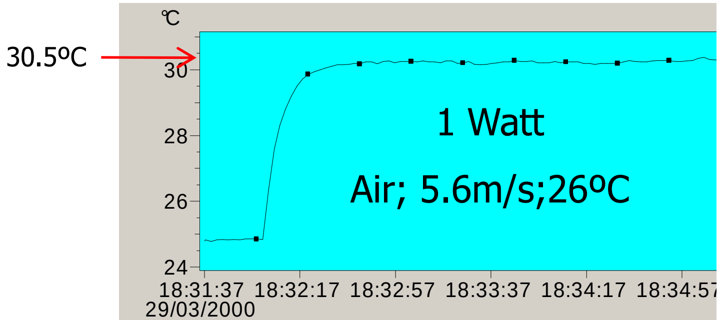
In this case, the camera is slow and could not follow the oscillation of the signal

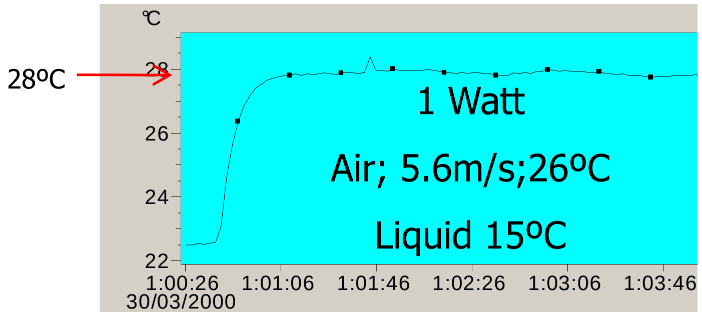
- If the OFF state is bigger than the ON time, we also reach a plateau but at lower temperature

→ This is our case!

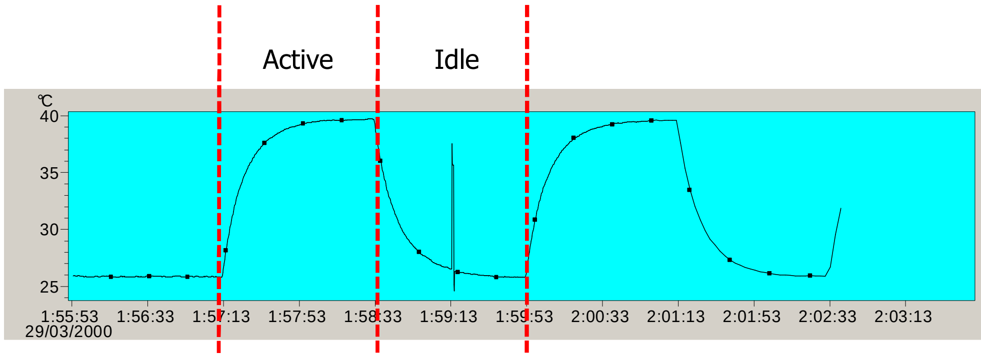
Transient state of Switchers: 0.1s ON and 0.1s OFF







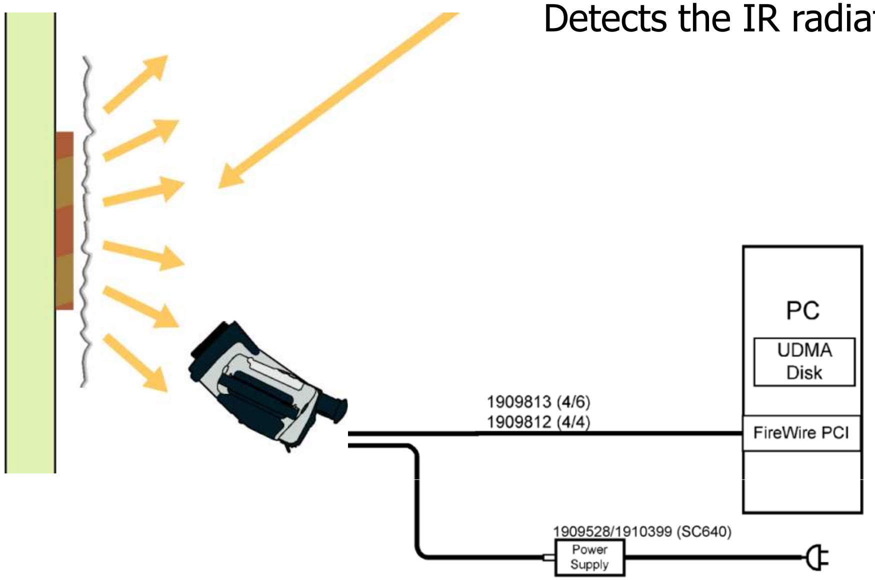
- Always get the plateau after a certain time, independently of the cycle time.
- Using cooling, we decrease the plateau temperature, but it is always reached.
- 1 Watt pulsed is equivalent to 0.5 Watts in continuous mode.
- This plateau will be shifted up in the real situation because the SW will never be off completely and there will be another heat sources powered on near it.

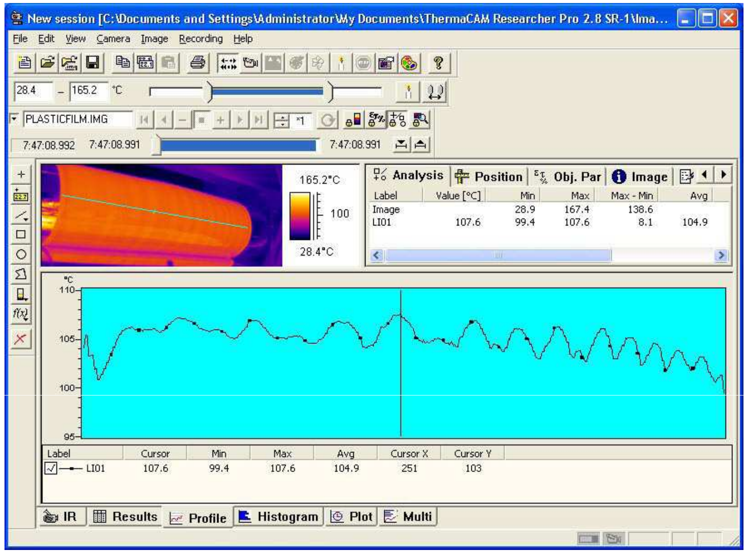


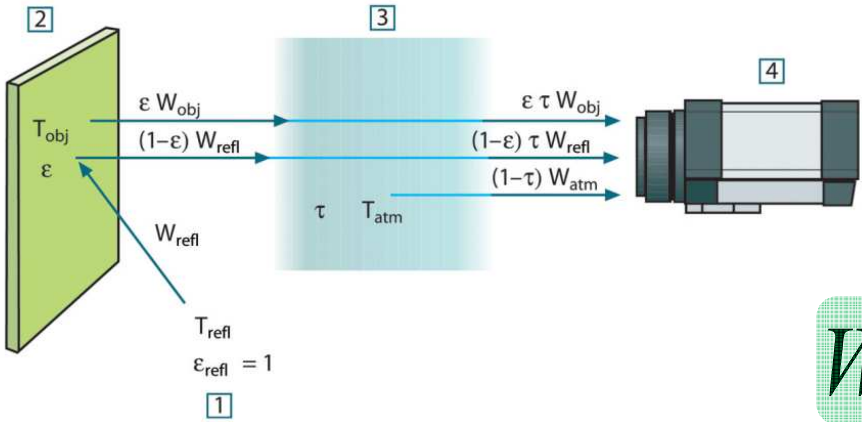
2 heater power cycles. 90 seconds ON and 90 seconds OFF each cycle.

InfraRed Camera

Detects the IR radiation from the objects







Measured — Input — Constant — Unknown

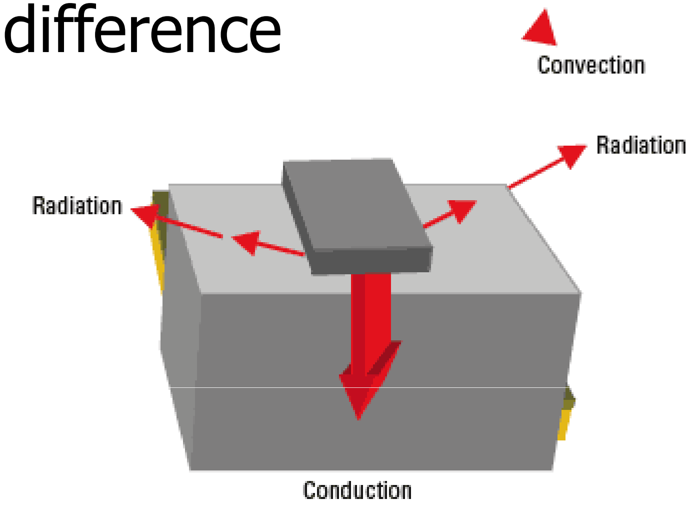
$$W\,(W/m^2) = \varepsilon \cdot \sigma \cdot T^4$$

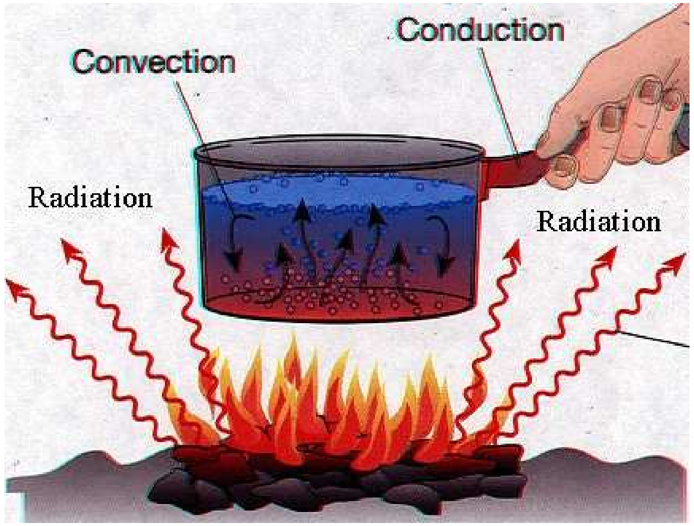
Basic concepts

Heat transfer is thermal energy in transit due to a spatial temperature difference

Heat is transferred by three kinds:

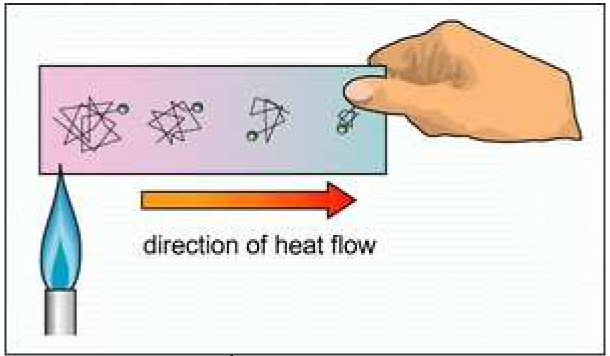
1. Conduction: Heat transfer occurs across the medium
2. Convection: Heat transfer between a surface and a moving fluid
3. Radiation: Emission of energy in the form of e.m. waves





Conduction

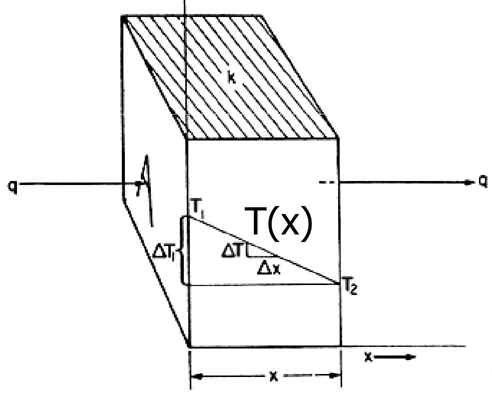
- Conduction is the process of heat flow from regions of higher temperatures to regions of lower temperatures through a medium



- To quantify the heat transfer processes → Fourier's Law

$$q''_x = -k\frac{dT}{dx} = -k\frac{T_2 - T_1}{L} = k\frac{\Delta T}{L}$$

↑ Steady state: T linear



$q''_x \equiv$ Heat flux (W/m^2) → Transfer rate in the x direction per unit area normal to the direction of transfer

$k(T,P) \equiv$ Thermal conductivity $(W/m\cdot K)$ → Transport property, characteristic of the wall material

$dT/dx \equiv$ Temperature gradient

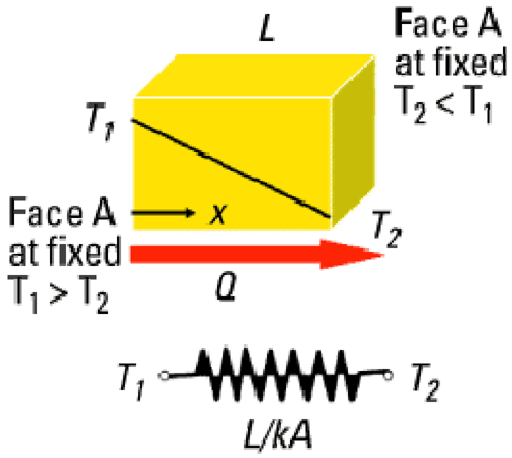
$$q_x(W) = q''_x \cdot A = k \cdot A \cdot \frac{\Delta T}{L}$$

Heat rate by conduction through a plane wall of area A

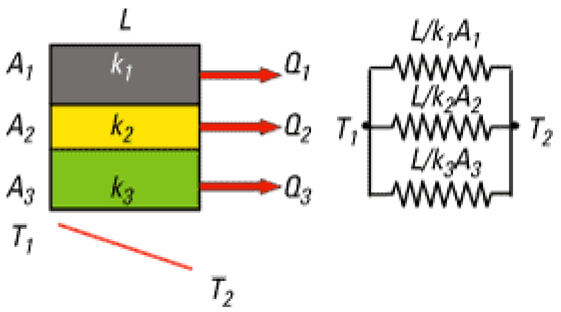
Diffusion of heat and electrical charge

- <u>Thermal resistance:</u> This concept provides an alternative to Fourier's Law, analogous to Ohm's Law:

$$R_k(K/W) = T/Q = L/kA$$



As an electrical resistance is associated with the conduction of electricity, a thermal resistance may be associated with the conduction of heat

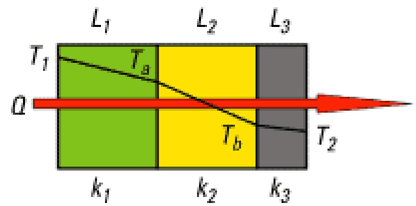


Resistances in parallel

$Q = \Delta T * (1/R_1 + 1/R_2 + 1/R_3) = Q_1 + Q_2 + Q_3$

Parallel

Series

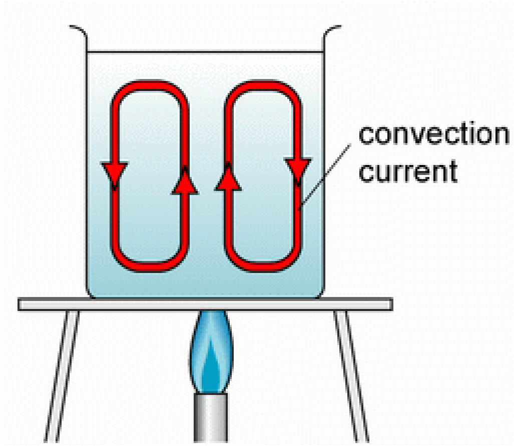


Resistances in series

$Q = \Delta T / (L/k_1A_1 + L/k_2A_2 + L/k_3A_3) = \Delta T / (R_{k1} + R_{k2} + R_{k3})$

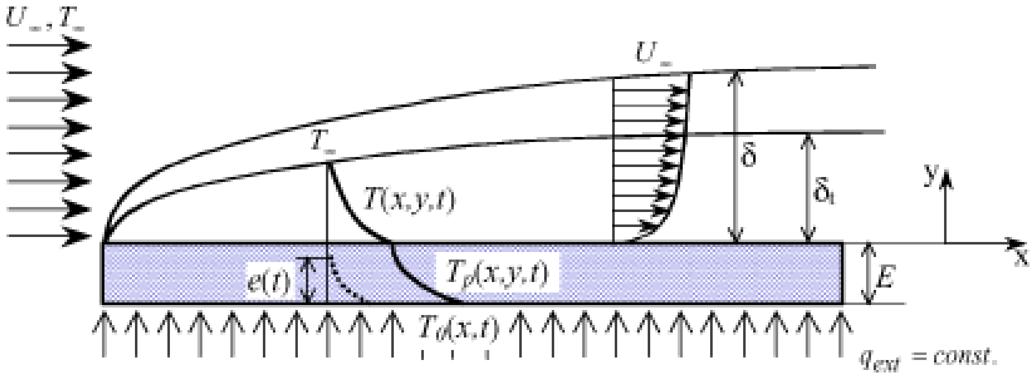
Convection

- Convection is the process of heat transfer by the bulk movement of a fluid, i.e., liquids or gases (no in solids)
  - Forced: The flow is caused by external means (fan, pump)
  - Free: Due to density differences in the fluid



- Newton's law of cooling

$$q'' = h(T_s - T_\infty)$$



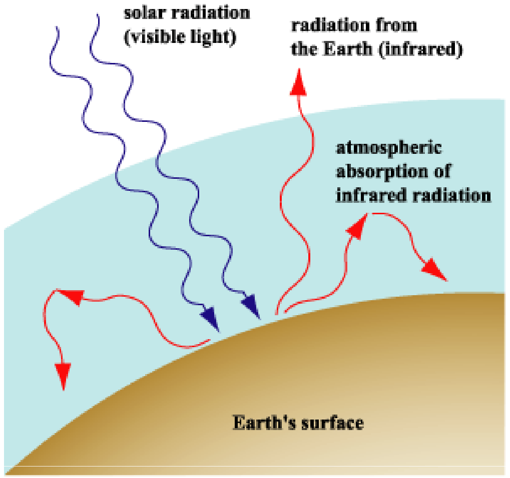
$T_s, T_\infty \equiv$ Surface and fluid temperature

$q'' \equiv$ Convective heat flux (W/m^2)

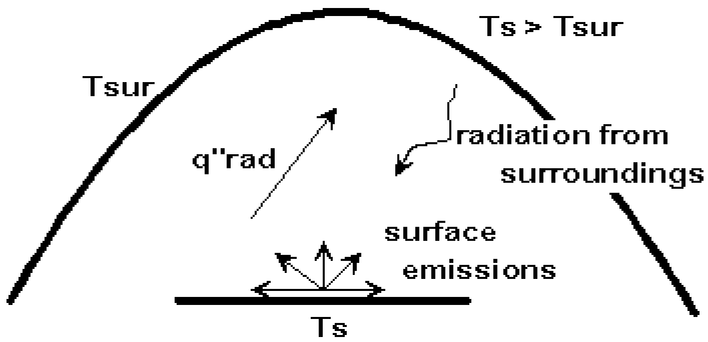
$h \equiv$ Convection heat transfer coefficient $(W/m^2 \cdot K)$ → Depends on the surface geometry and the nature of fluid motion

Radiation

- Radiation is the process of heat emission by matter that is at nonzero temperature.
  - Energy transmitted by e.m. waves
  - No material medium is required
- At normal temperature range, the main part is I.R. radiation
  - Metallic surfaces emit or absorb radiation energy slowly
  - Dark surfaces emit or absorb more effectively
- Stefan-Boltzmann law



$$E = \varepsilon \cdot \sigma \cdot T_s^4$$



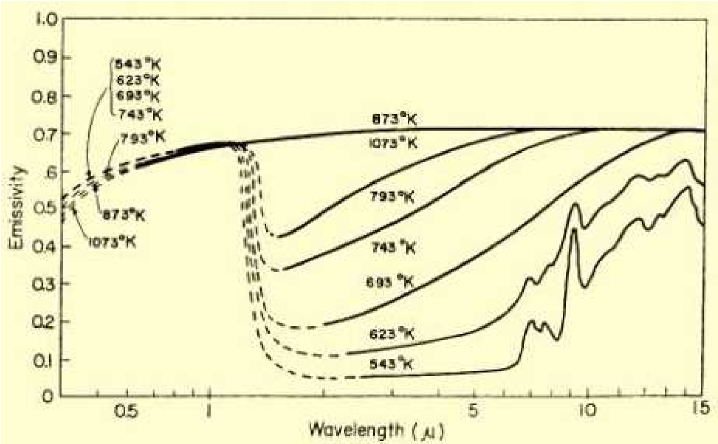
$E \equiv \text{Emissive power } (W/m^2)$

$\sigma = 5.67 \cdot 10^{-8}\, W/m^2 \cdot K^4 \equiv \text{S.B. Constant}$

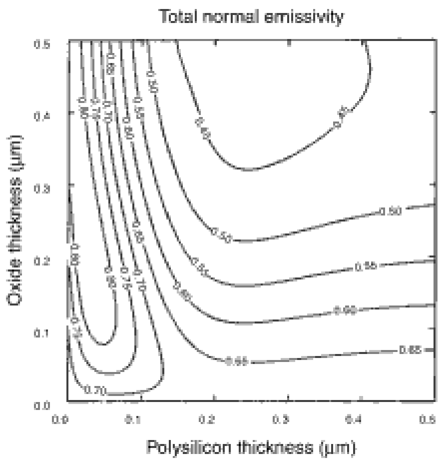
$T_s = \text{Surface temperature}$

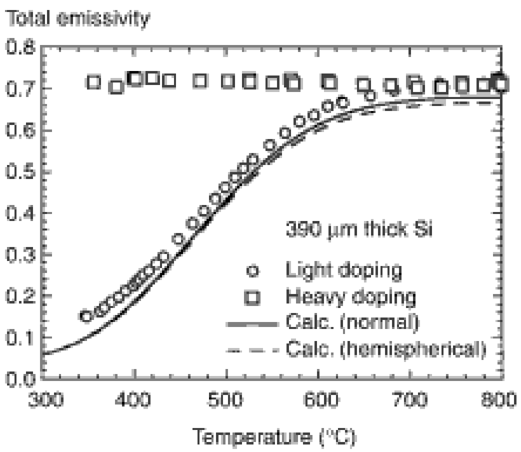
$0 \le \varepsilon \le 1 \equiv \text{Emissivity}$ → Radiative property of the surface. Provides a measure of how a surface emits energy relative to a blackbody. Depends on the material, the surface and the finish. If blackbody, emissivity=1.

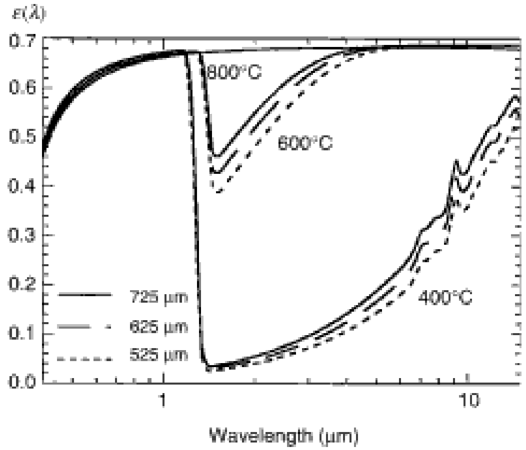
Emissivity… not such an easy thing…



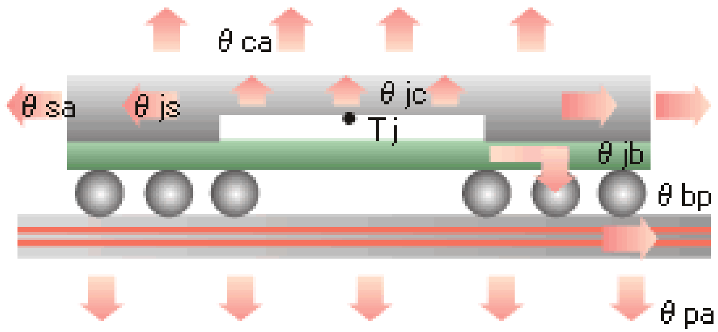
- Emissivity: Ratio of the radiation emitted by a real material from a blackbody at the same temperature
- Silicon emissivity depends on:
  - Surface temperature
  - Wavelength
  - Dopant concentration (n or p type)
  - Surface conditions (rough/smooth)
  - Thickness







Heat exchange in a chip



Heat flow paths

- θja(°C/W): Thermal resistance from junction to atmosphere (junction to ambient air). Reduce this value when a package is used alone..
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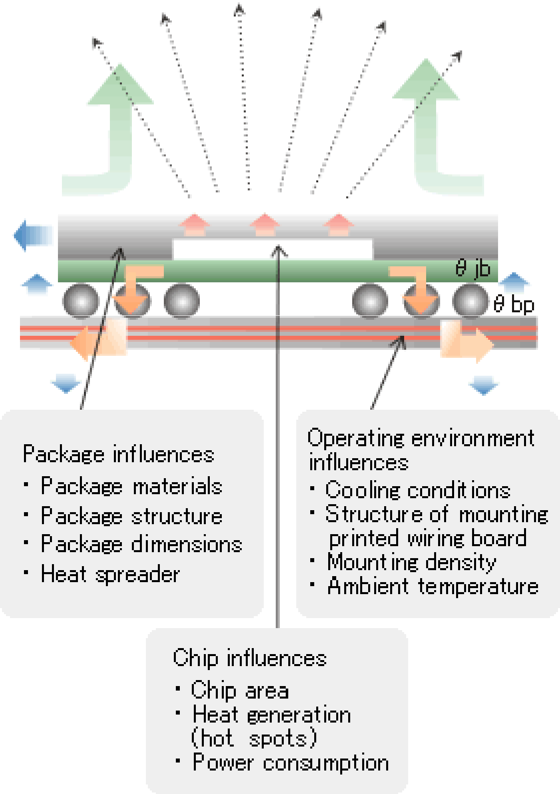
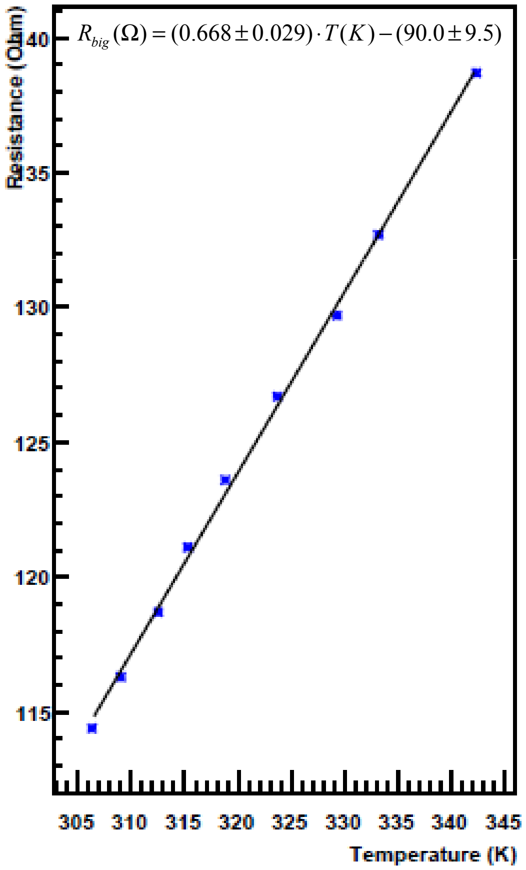
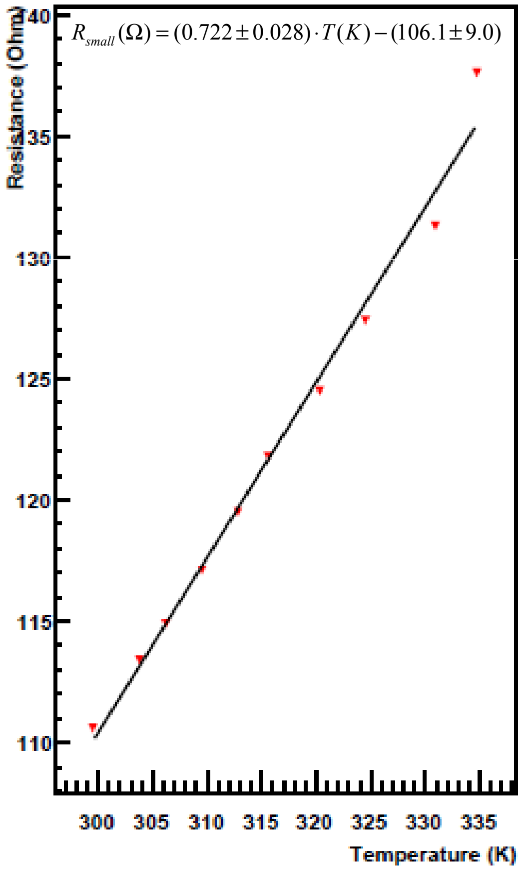


Calibration Pt100 resistances

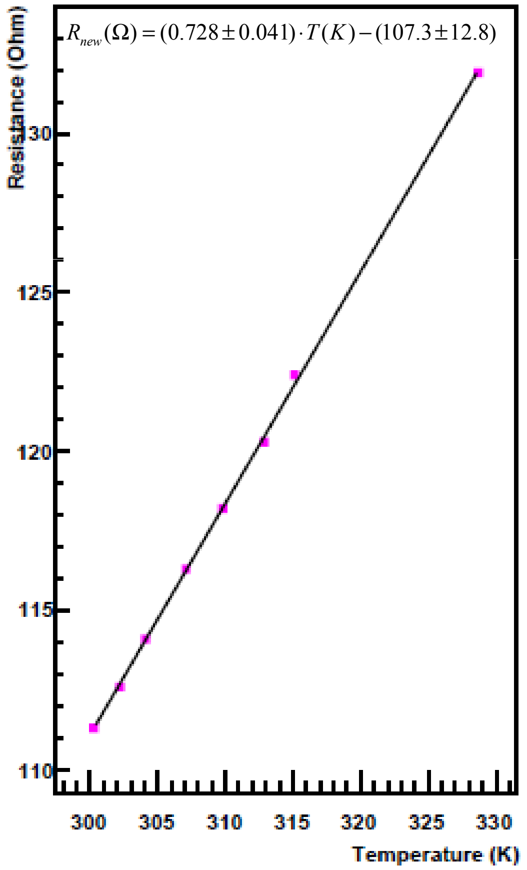
Calibration Pt100 big

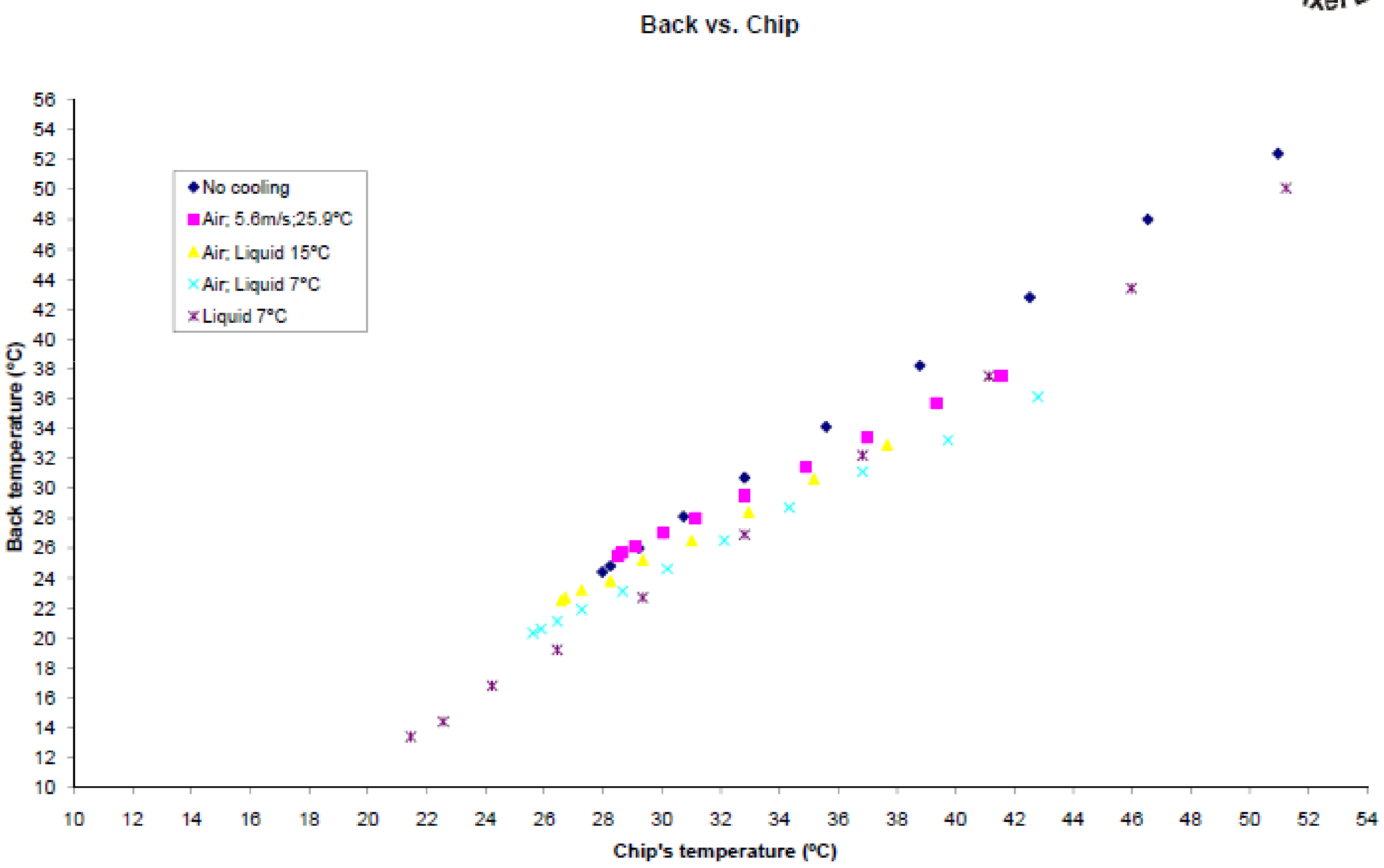


Calibration Pt100 small



Calibration Pt100 new





Back vs. Chip
Back temperature (ºC)
Chip's temperature (ºC)
No cooling
Air; 5.6m/s;25.9°C
Air; Liquid 15°C
Air; Liquid 7°C
Liquid 7°C
10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56