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Cooling of a W-Si calorimeter.

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The W-Si calorimeter is made of a stacking of plates. Some of them support hybrid circuits, releasing heat. In the absence of cooling, the temperature has to increase regularly. To ensure a permanent state of the temperatures, certain plates must be cooled. The powers of the hot sources must be balanced by cold sources.

I - Thermal properties of the calorimeter components.

Nature	Density	Conductivity	Specific heat
Units	Kg / m3	W / m °K	J / kg °K
Tungsten	19220	160	134
Carbon/Epoxy	1570	0,6	1100
Aluminium	2700	170	902
Glue	1000	0,2	1000
Silicium	2329	124	702
Glass/Epoxy	1900	0,6	900
Air	1,213	0,025	1010

II - Transverse composition.

Name	Width en μm	Material
Air gap	100	Air
Carbon fibre	150	Carbon/epoxy
Radiator	1400, 2800 or 4200	Tungsten
Carbon fibre	150	Carbon/epoxy
Air gap	100	Air
Cap	200	Aluminium
Air gap	100	Air
Integrated circuit into Al	1000	Aluminium
Printed circuit	1700*	Glass/epoxy
Glue	20	Glue
Central wafer	525	Silicium
Air gap	100	Air
Carbon fibre	150	Carbon/epoxy
Radiator	1400 or 4200	Tungsten
Carbon fibre	150	Carbon/epoxy
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Air gap	100	Air
Cap	200	Aluminium

The use of the average temperatures of the plates and the sums of their thermal powers simplifies the analysis. Under these conditions, the three-dimensional thermal problem is solved by a one-dimensional treatment. The two-dimensional treatment of each plate can be applied later.

The properties of the components of the calorimeter are listed in the table I. The calorimeter is made of a set of boxes, which are inserted into a tungsten/carbon/epoxy composite structure. A possible geometry is given in tables II.

One-dimensional analysis.

A virtual tower of section of one cm² is cut out in the stacking of the plates. From tables I and II, one evaluates the thermal resistances between the heated towers elements, which receive heat. These resistances are alternatively equal to R_1 = 166 °K/W and R_2 = 188 °K/W. The first value corresponds to a box and the second to a wall. Tungsten is a good conductive, the thickness differences have a negligible incidence on R_1 and R_2. The main contribution is due to the air gaps. Their thickness is supposed to be equal to 100 µm that gives a resistance of 40 °K/W. One has a large uncertainty on this estimation. The value of the electronic power is taken equal to W = 5 mW per cm².

Without internal cooling, the two external surfaces, which are isothermal, absorb the whole heat. Their temperature is T_0. The maximum temperature T_{max} is reached in the middle. In the case of a calorimeter with n wafers, that is n/2 boxes, the result is $T_{max} - T_0 = W n^2 (R_1+R_2) / 8 = .22 n^2$. Finally, with n = 40 heated plates, one obtains $T_{max} - T_0$ = 350 °K.

A cutting of the calorimeter into 4 stacks whose edges would be cooled and maintained at the temperature $T_{0,}$ would divide $T_{max} - T_0$ by 16 that gives 22 °K. A space of 3 mm would be sufficient to provide the cooling.

One cooling per wafer would lead to differences of temperature lower than .5 °K. The problem would be to realise a liquid circulation into capillary pipes, inside a gap of 1 mm.

The results have to be multiplied by the effective duty cycle. With 1%, the 350 °K becomes 3.5 °K.

These estimations takes into account the air gaps between plates. A pile-up without air gaps gives R_1 = 86 °K/W and R_2 = 68 °K/W. Factor 2.3 divides the temperature differences. One understands the importance of air gaps thickness and the consequences of their uncertainties.

Cooling of an aluminum plate.

The microchips are fixed on the PCB plates, which ensure connections with the pads of the wafer. Their thickness are of the order of one millimetre. There is one chip of 1 cm² for 81 pads of 1 cm². To have a good cooling, it is excluded to leave air around the chips. It is necessary to fill this space with a high conduction material like aluminium. The challenge is to cool this aluminium to realise an isothermal plate.

The suggested solution consists in making circulate a coolant in a capillary conduit in the thickness of 1 mm of the aluminium plate. This goal can be reached under two conditions. First is to obtain a specified flow with a rather small internal diameter and an acceptable pressure. Second is to have a rather large heat exchange between the liquid of cooling, the aluminium of the plate and the chip.

Diameter and pressure.

If the flow in the capillary is laminar, the pressure loss per unit of length Δp/Δl is related by the Poiseuille formula to the diameter D of the pipe with a supposed circular section.

$$\Delta p/\Delta l = 128\ \mu M/(\rho \pi D^4)$$

The parameters µ and ρ are the dynamic viscosity and the density of the liquid. The variable M is the weight rate of flow. A flow of 1 g/sec of water ($\mu/\rho=10^{-6}$ m²/s) inside a pipe with a diameter of 1 mm gives a Reynolds number of 1300 < 2200. The flow is laminar. That gives a pressure drop of 0.4 bars per meter, which is 1.2 bars for 3 meters. One needs 7.2 W to evacuate 5 mW per cm² over a surface of 1.6x 0.09 m². The flow of 1 g/sec of water will give a difference of temperature of 1.7 °K between entrance and output.

A flow of 10 g/sec into a pipe of 3 mm gives a Reynolds number of 4300. The flow is turbulent. It generates a pressure drop of .25 bars per meter.

Heat exchange.

A bad heat exchange between the coolant and the aluminium plate will not allow cooling, even with an oversize flow. Thermal resistance between the liquid and the aluminium is the sum of three terms. There is initially the exchange between the liquid and the internal wall of the tube. It is necessary to add the resistance of the tube wall. Lastly, there is the exchange between the external wall and the aluminium.

Conductance between coolant and wall.

The calculation of the exchange between the laminar flow of a fluid and the wall of a tube is complicated. There is a simple solution if the heat exchanged per unit length is constant along the tube. The radial distribution of the temperature is then equal to $T(0) – T(r) = 2.4\ \Theta\ (r^2/R^2 - r^4/4R^4)$. The parameter Θ is the average of $T(0) - T(r)$. Exchanged heat is then $4.8\pi K$ W/m/°K. Using water, the conductivity K is 0.6 W/m/°K. The conductance is then 90 mW/cm/°K, independently of the pipe diameter.

Conductance of the pipe wall.

The interior and external radius are respectively R_i and R_e. The temperature varies like ln(r). One obtains thus the heat dW/dx through the wall, per unit of length of pipe, as a function of T_i and T_e that are the interior and external temperatures.

$$dW/dx = 2\pi K\ (T_e - T_i) / \ln(R_e/R_i)\ \text{W/cm/°K}$$

Using a plastic tube with K = 0.1 W/m/°K and $R_e / R_i = 2$, one obtains 9 mW/cm/°K. Using a stainless steel tube with K = 15 W/m/°K and $R_e / R_i = 1.2$, one reaches 5 W/cm/°K.

Conductance between the tube and the aluminium.

The tube has to be carefully inserted into the aluminium with glue into a groove. In such a case, the conductance is about 100 mW/cm/°K. It is clear that with a straightforwardly deficient contact the conductance may decrease less than 2 mW/cm/°K.

Cooling optimisation.

Using a direct fluid circulation into a groove, one can hope for a conductance between the fluid and aluminium from 50 to 100 mW/cm/°K. It is necessary to evacuate 7.2 Watts per plate. The difference in temperature between the entry and the exit of water lies between 0.25 °K and 0.5 °K. It is enough to a water flow from 0,15 to 0,3 g/sec. That is compatible with a diameter of pipe of 1 mm or even slightly smaller.

It is noticed that it would be possible to cool 10 wafers with a difference in temperature lower than 5 °K by using a 3 mm diameter tube.

Temperature of a PCB plate.

The mean temperature of a PCB plate is determined by the one-dimensional analysis, but the temperature distribution is not uniform.

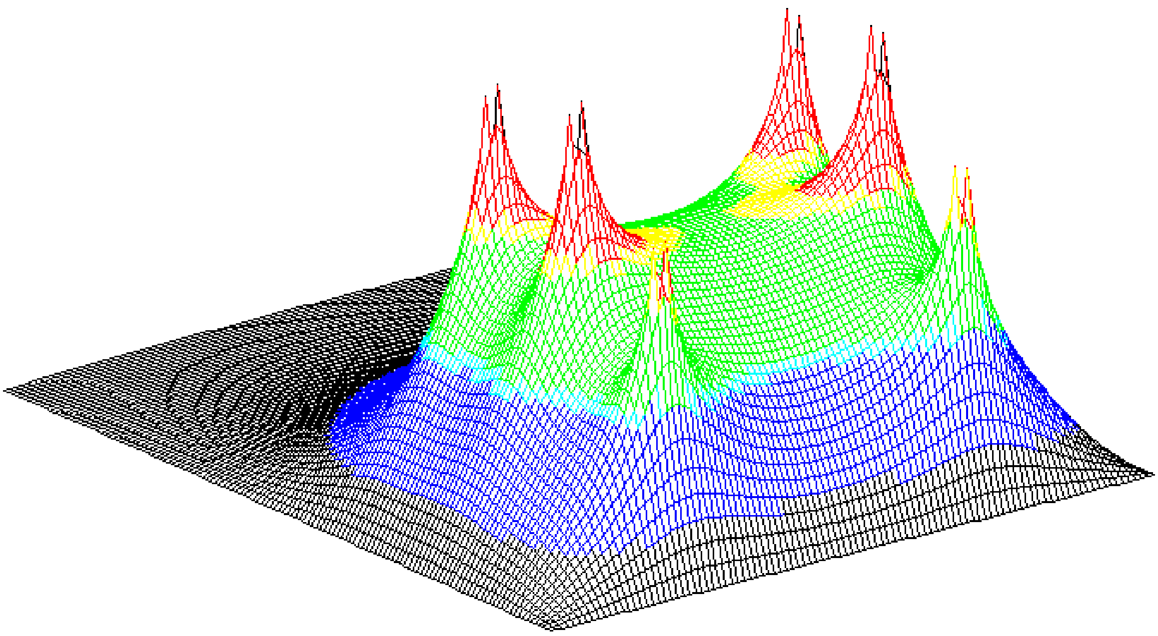
Isolated plate.

One considers a circular plate with radius R and thickness e. A circular source of radius r and of power W is put at the centre. Its isothermal circumference cools the plate. The difference of temperature between the source and the circumference is $\Delta T = W \ln(R/r)/2\pi Ke$. In the case of a PCB of conductibility K = 0.6 W/m/°, with e = 1 mm, R/r = 9 and W = 0.4 W, one obtains ΔT = 230 °K. One would find ΔT = 0.8 °K with an aluminium plate.

With several source on a rectangular plate the distributions are a little more complicated but the differences in temperature between the sources and the edges are of the same order of magnitude.

PCB plate PCB joined with an aluminium plate.

When PCB and aluminium are glued between them by a fine conducting layer, the Ke term is the sum of $(Ke)_{PCB}$ and $(Ke)_{Al}$. The system behaves like aluminium. It is not the case, if a layer of air separates the two plates and if the source is fixed on the PCB without touching with aluminium. Heat starts by crossing the PCB before being diffused towards aluminium, through the air. Aluminium is almost isothermal. The differences in temperatures on the PCB are important, without however being as large as for a plate isolated from PCB. Experimental measurements are necessary to estimate with a good degree of confidence these differences in temperatures.



Six hot sources on a rectangular plate cooled on three sides.

Experimental tests.

A PCB plate was equipped with six heating resistances. These square resistances of 1 cm on side and 80 Ω are in close contact with the PCB. Eight thermistors are inserted in various points of the plate. Figure 1 shows their layout. An aluminium plate is slightly tight against the PCB. Between the two, the thickness of air is evaluated to 100 µm.

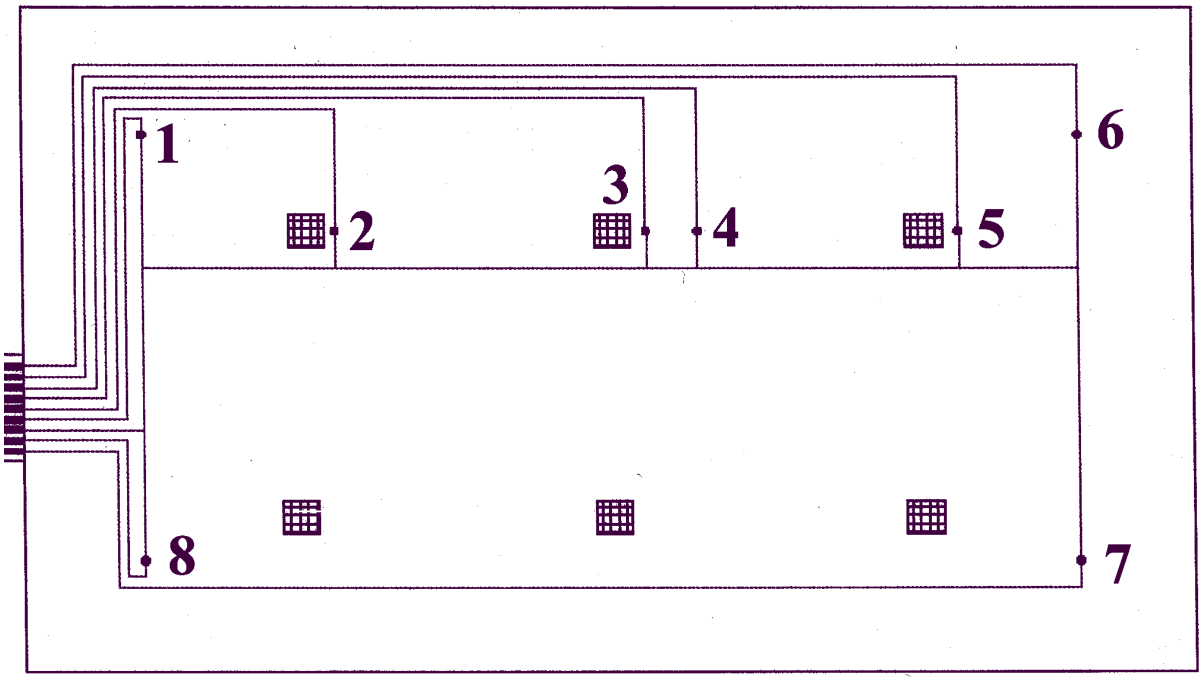


Figure 1 - Schematic view of the PCB plate.

Without internal cooling.

The system of plates is isolated from the ambient environment by two thick insulating slabs of 5 cm placed on both sides. A tension of 4 volts is applied to the heating resistances delivering a power of 6x16/80 = 1.2 W, that is 5.5 mW per cm². The time evolution is shown on the figure 2. The bottom curve is the ambient temperature. Initially, the system is in balance with the ambient conditions. As soon as the tension is put on heating resistances, the temperatures become different. Then, the system evolves slowly to a permanent state. The relative distribution of the temperatures remains unchanged. The difference between the points the hottest neighbour of a heating resistance and the points located close to the edges of the plate is of 3.3 °K. One measures a difference of 5 °K between heating resistance itself and aluminium. It is acceptable. Otherwise, it would be necessary to put the chips directly in contact with aluminium. The difference of 14 °K between the ambient temperature and the aluminium gives an estimation of thermal resistance of the insulation. It is 2500 °K/W per cm². It corresponds to 30 calorimeter layers on each side.

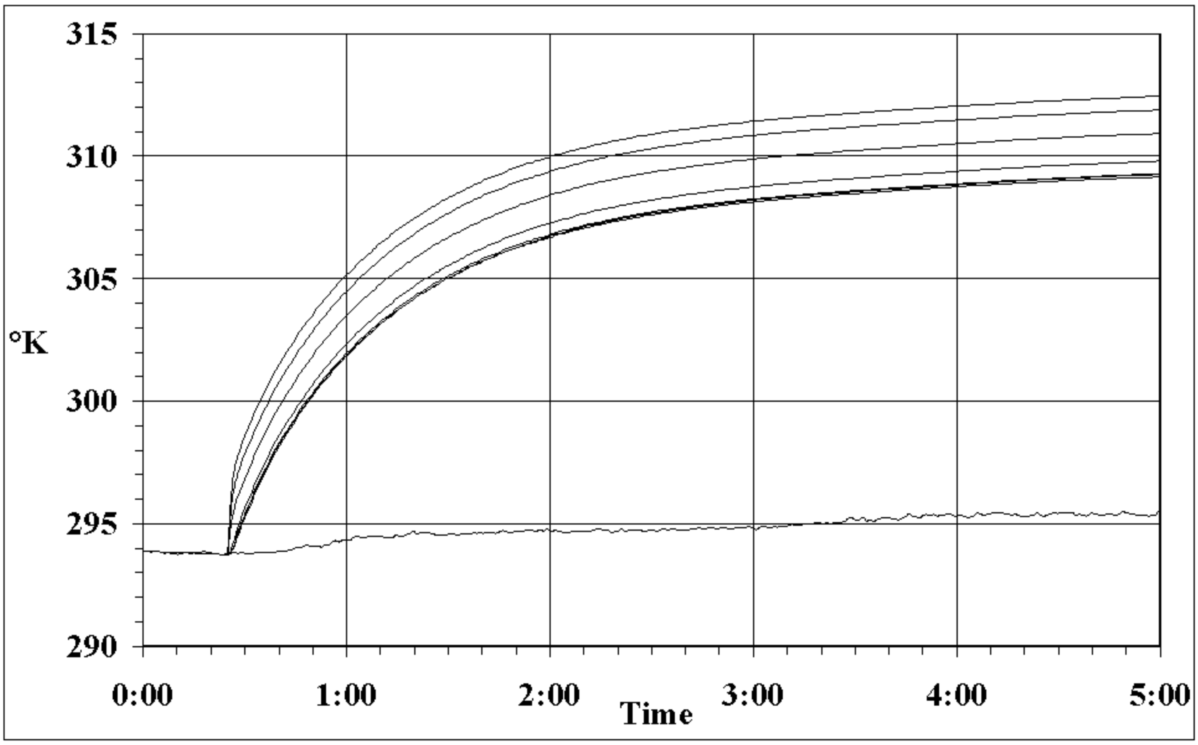


Figure 2 - Temperature evolution without internal cooling. Time in hours.

With internal cooling.

A plastic capillary pipe was glued over the medium of the aluminium plate. Its diameters interior and outside are respectively 600 µm and 1100 µm. The contact length is 18 cm. A water circulation cools the aluminium and the PCB. The measured flow is 0.07 g/sec. The temperatures variations are shown on figure 3. The relative distributions of the PCB temperatures remain unchanged. When a stable state is reached, the temperature difference with the ambient is 7 °K. The coefficient of heat exchange between water and aluminium is 5 mW/cm/°K. This measurement agrees with the calculated evaluations. First measurements with water directly in contact with aluminium are compatible with the calculated value.

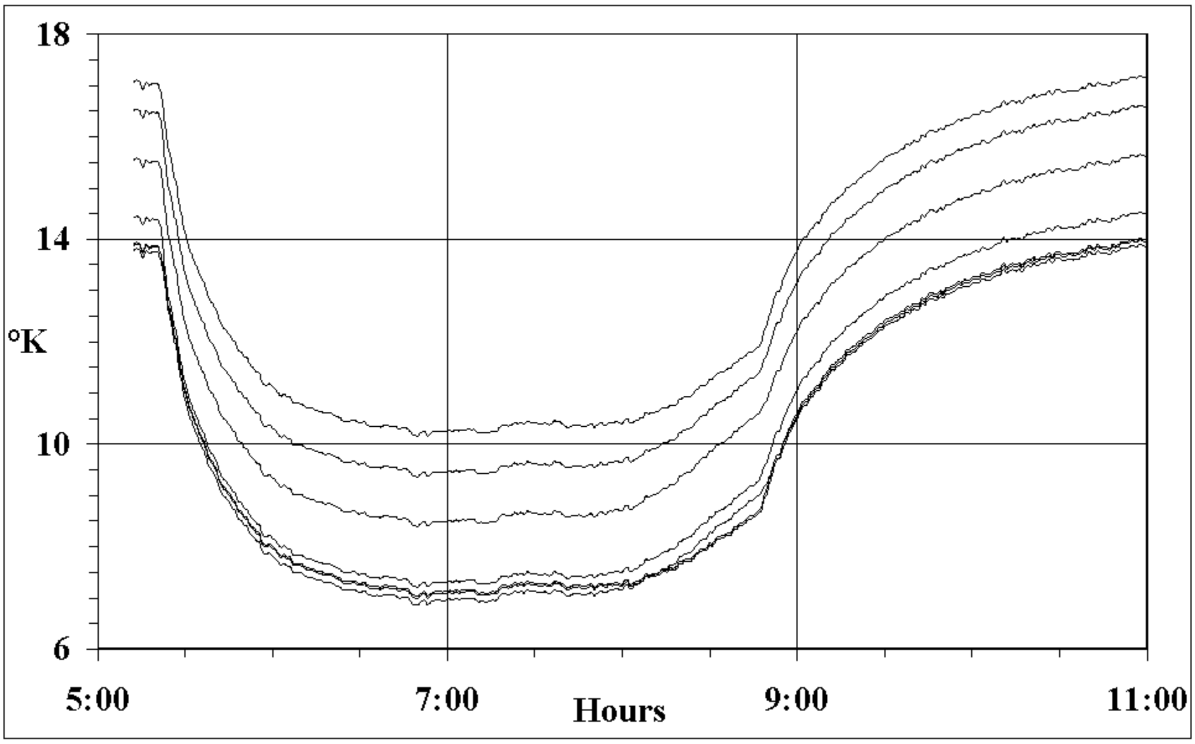


Figure 3 - Temperature difference with ambient when water is circulating.
The ambient temperature is less stable than that of the PCB.

Conclusion.

A very efficient cooling can be performed using an aluminium plate of 1 mm with water circulating inside a groove of .6 mm of depth. The difference of pressure between entrance and output would be of the order of 1.2 bars. The problem of the plumbing connections is uneasy.

If one accepts a difference of some °K in the plates pile up, it is possible to divide the calorimeter into 4 stacks. Only one cooling plate can be put between stacks. The diameter of the cooling pipe has to be 3 mm. The pressure difference is about .6 bars. The plumbing problem is simplified. The main drawback is the air gaps uncertainty. A solution is to glue all the plates of a stack. It could be incompatible with the wafers fragility. Another solution would be to fill all the air spaces with a liquid. In any case, the conductibility of a liquid is at least 10 times larger than the air ones.