The Thermal Performance of Forward SCT Module Prototypes

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Abstract

This note summarises results from an ongoing program of work to design a forward module which avoids thermal runaway and has the mimimum possible mass. We describe measurements and simulations of the thermal performance of the old "TPG spine" module design and two variants of the new baseline "composite spine" module design. We find that one of the composite spine modules meets the required thermal specification; when mounted on cooling blocks which are held at $-10°$C, it does not go into thermal runaway until the wafer power exceeds 220 $\mathrm{Wm^{-2}}$ at $0°$C.

1 Experimental Setup

Figure 1 shows the apparatus used in all tests. The module is mounted in a vertical position on cooling blocks having the baseline dimensions but without any split. The blocks are cooled by Peltier devices which pass the heat on to a large aluminium heat sink. The module is enclosed in a plastic box for protection and to provide a controlled environment. The whole box plus heat sink is in a freezer placed up against the cooled wall. Nitrogen is flushed through the box and then out through the freezer to avoid icing. A CAL 9900 is used to control a heater pad and the freezer compressor so as to automatically maintain a set temperatue on the heat sink. The environment within the box follows this set temperature within two degrees.

Thermocouples are used to monitor the environment, the cooling blocks and several points on the module. Heat (4.5 W unless otherwise stated) is supplied to the dummy hybrid by resistor packs in place of the front end chips. A fine nichrome wire glued on the surface supplies heat to the dummy silicon modules. For the real, irradiated silicon module a Keithley 237 was used to bias the detectors and measure the leakage current. When two-point cooling was used we always kept the two cooling blocks at the same temperature by adjusting the current in each Peltier independently.

2 Experimental Problems

Convection and radiation

In previous experiments at room temperature [1] we measured a "convection coefficient", by which heat is transferred between the environment and the surface of a dummy module, to be 11 $\mathrm{Wm^{-2}K^{-1}}$. In fact, this coefficient represents the combined effect of convection and radiation in the particular environment of that experiment. In our first attempts at measurements in the freezer we did not try to match the environment temperature to the module temperature. The environment differed from the module by several degrees and we tried to correct with the previously measured coefficient. The correction amounted to more than 0.5 W and the results were not repeatable. Therefore we have modified our procedure to only take data when the environment is within 1 degree of the average silicon surface temperature. We still apply the "convection" correction but it is always less than 0.2 W and the results are consistent. All data presented below are taken with this improved procedure.

Grease layer

When we first found the difference in thermal resistance between two supposedly identical modules, described below in section 4, we suspected that it might be due to unequal thickness of the thermal grease layer between the module and the cooling block. The grease layer thickness was investigated in three ways:

1. We removed and replaced a module twice and always measured the same thermal resistance between the module and the block within $\pm 10\%$.

2. We mounted a perspex piece on the cooling block and visually examined the grease, seen through the perspex. A 30 micron feeler gauge was used to set a known thickness of grease and the appearance of this this was compared with the appearance of the grease when the mounting screw was tightened up. Thirty microns of grease was almost opaque and it became progressively more transparent as the screw was tightened.
3. We also measured the height of the perspex with and without grease and with and without the feeler gauge, which confirmed that we were able to directly measure the thickness of anything between the perspex and the block to an accuracy of ± 10 microns.

We concluded that, however much grease is put on the block at first, a moderate pressure from the mounting screw will reduce its thickness to 10-20 microns with the rest sqeezing out at the sides. With a grease thickness of 30 microns the module feels distinctly loose.

3 Analysis Method

Our analysis makes use of a simple model which aims to separate the thermal conductivity of the module from the properties of radiation damaged silicon. The module is characterised by the thermal resistances of the cooling paths between a few key points and the cooling block. The silicon properties are characterised by a radiation damage parameter and the temperature dependence of the leakage current.

Thermal resistance

The thermal resistance was measured by putting heat into the silicon and measuring the temperature of points on the silicon or spine relative to the cooling block. A small convection correction was applied to the heat input and then the results were plotted. Figure 5 is an example of one of these plots. The results typically have a small temperature offset due to heat leaking from the hybrid to the silicon. The gradient has units of K/W so it is like a thermal resistance. However, the only case where this resistance can be simply related to the material properties of the module is at the "tongue" where the heat flow lines are approximately parallel to each other and perpendicular to boundaries between materials.

Leakage current versus temperature

Several measurements were made of leakage current versus voltage and temperature in the irradiated module TPG2. These measurements were all done with two point cooling to ensure that the silicon temperature was as uniform as possible. Figure 2 shows an I-V curve at low temperature. Figure 3 shows an Arrhenius plot made with three different voltages. The formula

$$I = NT^{3/2} \exp \frac{-E_{gap}}{2K_B T}$$

fits the data well. We find slightly different values of E_{gap} depending on the voltage and all of our values are above the accepted energy gap in silicon of 1.1 eV. For the purposes of understanding the thermal runaway we use $E_{gap} = 1.20$ eV throughout the following analysis. The normalisation factor, N, is dependent on radiation dose and annealing effects. With a bias of 300 V we measured a power of 96 Wm^{-2} at 0°C in the first part of our experiment when the module had been irradiated with 2.8×10^{14} protons cm^2 and then kept at room temperature for 18 days. After subsequent warm-ups it decreased to 80 and then to 73 Wm^{-2} at 0°C.

Thermal runaway

If we make the approximation that all of the silicon within a module is at the same temperature, and if we know the thermal resistance between the silicon and the cooling block, then we can predict the thermal runaway curve of the module. We chose the middle of the module as a measure of the typical silicon temperature. This choice makes our runaway predictions pessimistic because the mid-point is the hottest with two-point cooling and is close to the hottest with one-point cooling. Suppose that the temperature of this point above that of the cooling block, ΔT, was found to be related to power input, Q, by $\Delta T = T_{off} + R.Q$, where T_{off} is a temperature offset due to heat leakage from the hybrid and R is a thermal resistance. Then we can derive;

$$\frac{Q_0}{A} = \frac{1}{A}.\frac{\Delta T - T_{off}}{R}.(\frac{273}{\Delta T + T_{cool}})^{\frac{3}{2}}.\exp(\frac{E_{gap}}{2K_B}(\frac{1}{T_{cool}+\Delta T} - \frac{1}{273}))$$

Where Q_0 is the power generated in the silicon at 273 K, A is the area of the silcion (0.016 m^2) and T_{cool} is the cooling block temperature. We generate a runaway curve by scanning ΔT in small steps from T_{off} to $T_{off} + 10$ and calculating Q_0/A at each point.

This simple model of runaway can be compared with measurements in which the cooling blocks are maintained at constant temperature and the bias voltage is increased to the maximum safe level (about 500 V). An example is shown in Figure 7. As ΔT gets close to 10 °C we find that measurements become difficult as the module is really close to running away. Also, with large ΔT the approximation of uniform silicon temperature gets worse, so the simple model becomes more and more pessimistic.

4 TPG Spine Modules

Both of these modules were made on TPG spines according to the design shown in NP27-03-103 issue B [2]. That was the version which had a one-piece TPG spine 40 mm wide and 0.5 mm thick. The spines are coated with a polyimide layer of nominally 20 microns thickness. The dummy hybrids are made from 0.78 mm thick aluminium. Figure 4 shows the shape of these modules and the points where thermocouples are glued on to monitor their temperature. Module TPG1 has dummy silicon pieces of the correct thickness to simulate the detectors. Module TPG2 is equipped with working n-in-n detectors and was irradiated at the PS in September 1998. The only other difference in construction between the two modules is in the washer which connects the TPG spine to the hybrid and makes contact with the cooling block. In TPG1 this washer is made from 0.78 mm aluminium, whereas TPG2 requires a ceramic for electrical isolation so 1.2 mm machineable aluminium nitride (Shapal-M) is used.

Thermal resistance

The thermal resistance of the two modules, with both single and double cooling, is shown in Figures 5 and 6. These plots caused us a lot of trouble because the gradients are so different from each other. After eliminating the grease layer and poor convection corrections as sources of error, we are forced to conclude that there really is a difference between the two modules. The difference is mainly in the resistance between the tongue and the cooling block, which is 1.76 K/W in TPG1 and 2.56 K/W in TPG2. Table 1 shows how this difference could be ascribed to quite reasonable variations in the glue and polyimide thicknesses. Based on our own tests [5] in which pairs of microscope slides were glued together under various pressures we believe that glue thicknesses between 10 and 25 microns are reasonable. The recent note from QMW [3] reports polyimide thickness variations in the range 18 to 33 microns.

TPG1				TPG2			
Material	thick. (mm)	cond. (W/m/K)	res. (K/W)	Material	thick. (mm)	cond. (W/m/K)	res. (K/W)
TPG	0.25	8.	0.35	TPG	0.25	8.	0.35
Coating	0.012	0.2	0.75	Coating	0.020	0.2	1.25
Glue	0.015	0.63	0.30	Glue	0.025	0.63	0.50
Washer (Al)	0.78	220.	0.04	Washer(AlN)	1.2	90.	0.17
Grease	0.02	0.9	0.28	Grease	0.02	0.9	0.28
TOTAL fitted			1.72				2.55
TOTAL measured			1.76				2.56

Table 1: Materials in the tongue which can account for the thermal resistance. The thicknesses of TPG, washer and grease are fixed parameters while plausible values of the coating and glue thickness have been picked to account for the measured resistance.

Thermal runaway

We have used the measured thermal resistance of the poorer module (TPG2) to predict a set of runaway curves shown as solid lines in Figures 7 and 8. The Figures also show measurement results of TPG2 which agree reasonably well with the simple model. A finite difference simulation [4] predicts the curves shown by the dashed lines, which are somewhat closer to the measured points. Our target is to design a module which can survive up to a radiation damage level of 220 Wm^{-2} at 0°C.

Conclusion

We conclude that a TPG spine module with single point cooling needs a block temperature of less than -15°C to be safe against runaway, whereas with two point cooling the block temperature must be below -10°C. A block temperature of -10°C is expected to be achievable so this module is good enough for two point cooling. However it is far from optimal because of two faults. Firstly, the thermal resistance between the tongue and the cooling block dominates the performance of the module, so the large area of TPG between the wafers is doing little for the performance but is adding significant mass to the module. Secondly, there are mechanical weak points in the module where it is supported only by the TPG plus its coating. Both modules were rigid when first built, but after all the handling involved in the thermal tests they both developed a "crease" along the line between the fan-ins and the wafers; they could be flexed by several degrees with minimal applied force.

5 Composite Spine Modules

These modules aim to solve the problems of the TPG spine design by using a spine built up from aluminium nitride and TPG. The TPG provides maximum thermal conductivity per unit mass. The AlN combines mechanical strength with reasonable thermal conductivity. Figure 9 shows the outline of a composite spine module and marks the points where temperature was measured on both modules COMP1 and COMP2.

As implied by the names, we built two versions of the composite spine module. Figure 10 shows how they differed in the details of how the TPG bar overlaps the cooling block at each end. In both modules the crucial lap joint between the TPG and AlN was made with BN loaded epoxy having conductivity of 0.9 Wm^{-1} K^{-1} [5], but in the case of COMP1 this layer was 0.07 mm thick while in COMP2 we managed to reduce it to 0.04 mm thick. In module COMP1 the TPG bar was coated with polyimide except in the area of the lap joint, while in COMP2 it did not have any coating. In all other respects the two composite spine modules were identical.

Thermal resistance

The thermal resistance of both modules with two point cooling is shown in Figure 11. It can be seen that COMP2 is much better than COMP1. COMP1 has a large resistance between point R6 and the far end cooling block in spite of the short distance between them. This is caused by heat having to flow several millimeters through thin AlN to reach the cooling block. COMP2 is much better in this respect because the TPG bar extends over the cooling block and heat has only to cross perpendicularly through the thin AlN. There is a smaller but also significant improvement in COMP2 at the hybrid end (R3) due to the greater TPG area and thinner glue layer.

Both modules are built with unprocessed BeO blanks for their hybrids and both show the same temperature distribution on the hybrid at a given power load. The temperature difference between R1 and the cooling block is measured to be 3.0 K per Watt of power applied to the dummy chips. For point R2 it is measured to be 0.62 K/W. These thermal resistances were constant, at least up to 7.5 W, as one would expect.

Heat leakage between hybrid and wafers

The forward module design is intended to thermally isolate the silicon wafers from the hybrid. This is demonstrated by data taken with module COMP1 with hybrid powers of 4.5 W and 7.0 W and with wafer powers from 0.0 to 2.0 W. Figure 12(b) shows the temperature measured at point R3 on the tongue, which is a good indicator of the amount of heat flowing out from the wafers to the cooling block. The gradient is 2.28 K per Watt of wafer power and the offset is shifted up by 0.23 K per Watt of hybrid power. This indicates that there is a leakage of about 0.7 W from the hybrid to the wafers when the hybrid is running at 7 W. This leakage will be partly through the fan-ins and partly through the cooling block itself. The same leakage in the opposite direction is indicated by the slight rise of hybrid temperature with wafer power shown in Figure 12(a).

Thermal runaway

Both of the composite spine modules were built with dummy wafers so we can not measure their thermal runaway directly. Instead we can use the measured thermal resistance and the model described in section 3 to make a prediction. This prediction is only approximate because (unlike the TPG spine case) there is a large temperature variation within the silicon in the composite spine module. We take 2.13 K/W to be a typical thermal resistance between silicon and cooling block for the COMP2 module and use this to generate the runaway curves shown as solid lines in Figure 14.

For a more accurate prediction we use the finite difference model [4]. Figure 13 shows that this model fits the measurements of COMP2 rather well. When we switch the model to simulate temperature-dependent wafer power it predicts for COMP2 the runaway curves shown as dashed lines in Figure 14.

Conclusion

The composite spine module with extended TPG bar, COMP2, meets the thermal specification which we were aiming for. When mounted on cooling blocks which are held at $-10°$C, it does not go into thermal runaway until the radiation damage exceeds 220 Wm^{-2} at $0°$C. We believe that this design is close to the optimum compromise between thermal performance, mechanical strength and low radiation length.

6 Future Work

We can not yet say that the COMP2 design is exactly the one that should finally be used in ATLAS because the SCT cooling system is not yet defined. It turns out that defining a fixed cooling block temperature of $-10°$C in the module thermal specification was not realistic because there is a large thermal resistance between the block and the cooling fluid. So the hybrid block temperature is strongly influenced by the power from the hybrid. It is proposed to overcome this problem by splitting the hybrid cooling block into two parts. We can say from our measurements that as long as the wafer part of the split block remains below $-10°$C when 1.5 W is flowing from it into the coolant, then the module will not run away below 220 Wm^{-2} at $0°$C. Final confirmation of the suitability of this module design for ATLAS can only come from tests with prototypes of the real cooling system and final cooling blocks. If it turns out that a small improvement of this module's thermal performance is required, then it could be achieved by widening the TPG bar to 20 mm along all of its length except at the tongue. This would not affect the important dimensions of the module so it could be done at a late stage.

References

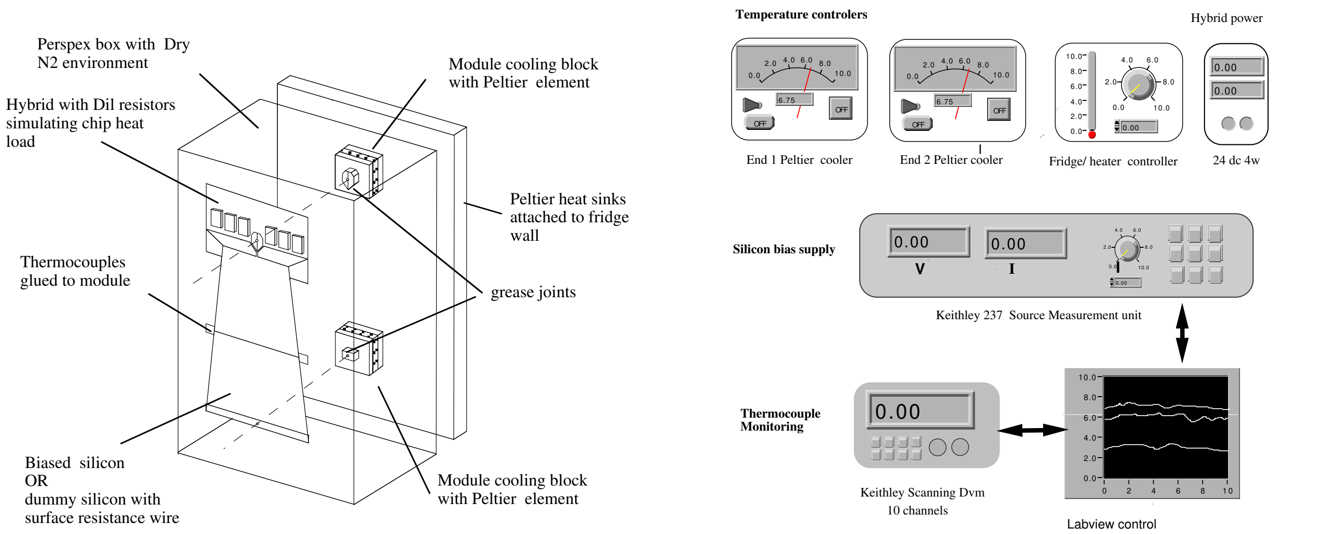
[1] Convection measurement is described in the writeup of results on the old BeO spine module from 1997, available at http://hepwww.ph.man.ac.uk/groups/atlas/module/therm1.html

[2] Forward module drawings at http://jupiter.ph.liv.ac.uk/ peter/atlas/atlas.html

[3] "Measurements of the Thermal Conductivity of Pyrolitic Graphite Substrates for use in SCT Modules", G.A.Beck, A.A.Carter, J.F.Morris. INDET-98-221.

[4] Description of a finite difference model for thermal simulation of modules, from http://hepwww.ph.man.ac.uk/groups/atlas/module/feather.html

[5] We have measured the thermal conductivity and thickness of various samples of Boron Nitride loaded epoxy. The main result is that for a resin:hardener:BN mixture of 5:4:4 by mass we measure a conductivty of 0.63 W/m/K, while for a 5:4:6 mixture we measure 0.88 W/m/K. Details are available at http://hepwww.ph.man.ac.uk/groups/atlas/module/glue.html



Exploded view of thermal rig : The module is cooled at either end by seperate peltier coolers.The entire apparatus sits in a fridge (with heater pads) giving control of the surrounding temperature..

The irradiated silicon is biased up to 500v 10ma with a Keithley 237 SMU. The dummy silicon module is heated via a surface nicrome wire. Thermocouples are readout via a 10 channel scanning DVM . Data is collected and displayed via a LABVIEW progam.

Figure 1: Experimental setup

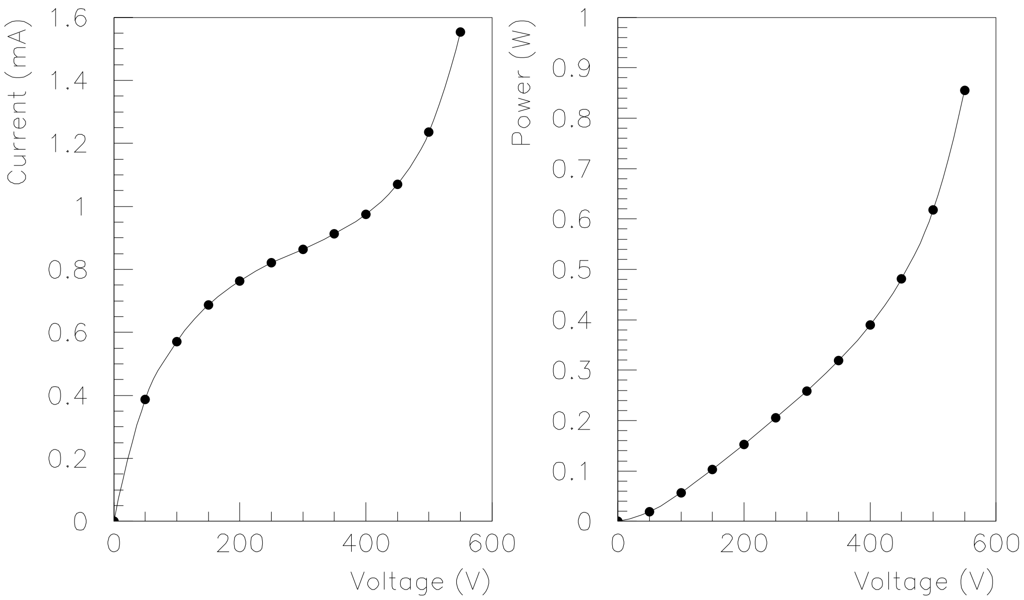


Figure 2: Current and power versus voltage in module TPG2 at -14.5 C.

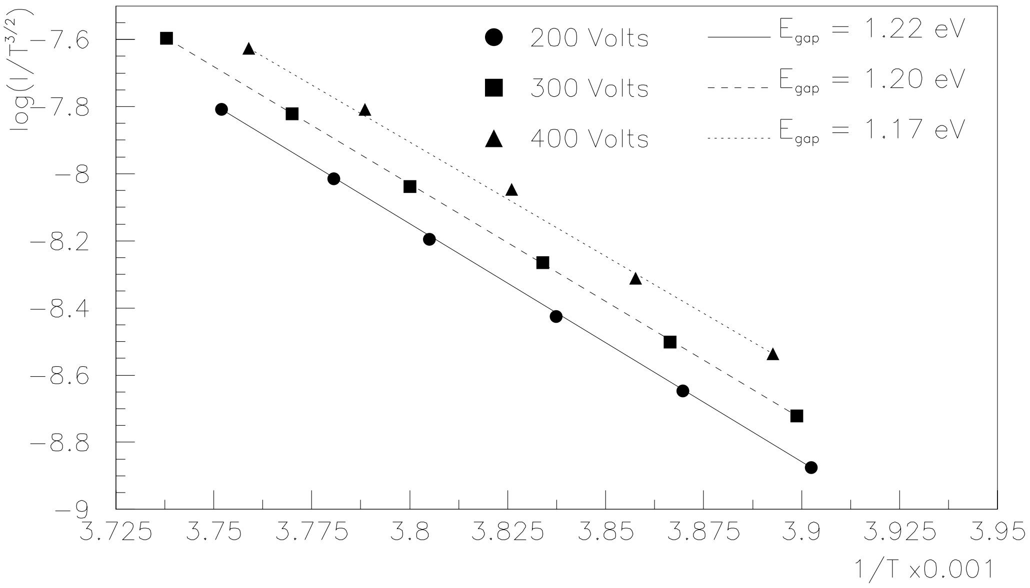


Figure 3: Arrhenius plot of the leakage current, I, and temperature, T, in module TPG2 at three voltages.

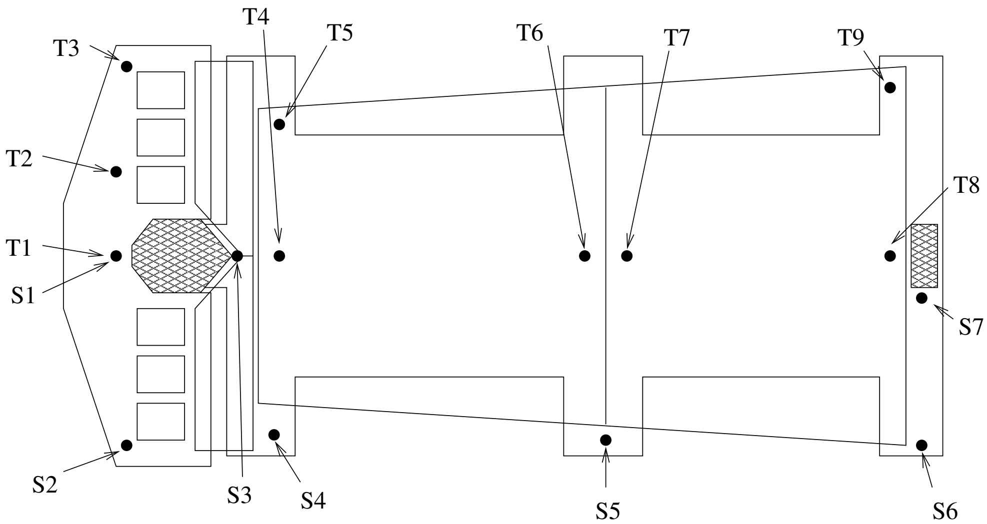


Figure 4: An outline of the TPG spine module design. The temperature was measured at points T on module TPG1 and points S on module TPG2. The shaded areas indicate where washers make contact with the cooling blocks via a thermal grease layer.

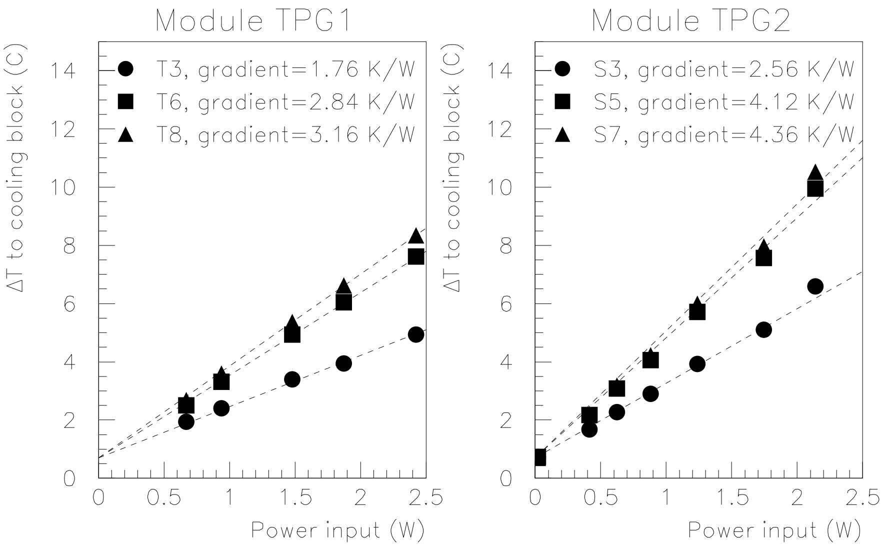


Figure 5: The temperature difference between three key points and the **single cooling block** is plotted against the power input. The performance of modules TPG1 and TPG2 are compared. Dashed lines show fits (chosen to meet at zero power) from which the gradients are determined.

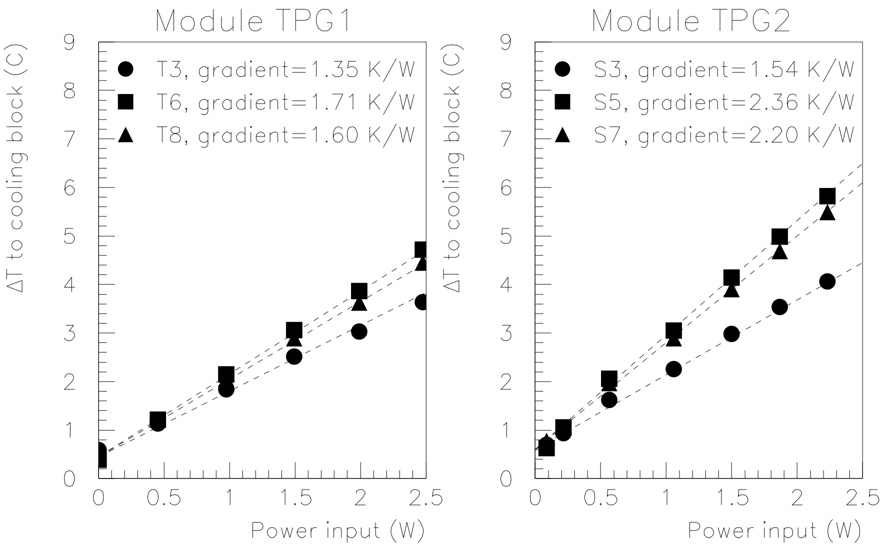


Figure 6: The temperature difference between three key points and the **two cooling blocks** is plotted against the power input. The performance of modules TPG1 and TPG2 are compared. Dashed lines show fits (chosen to meet at zero power) from which the gradients are determined.

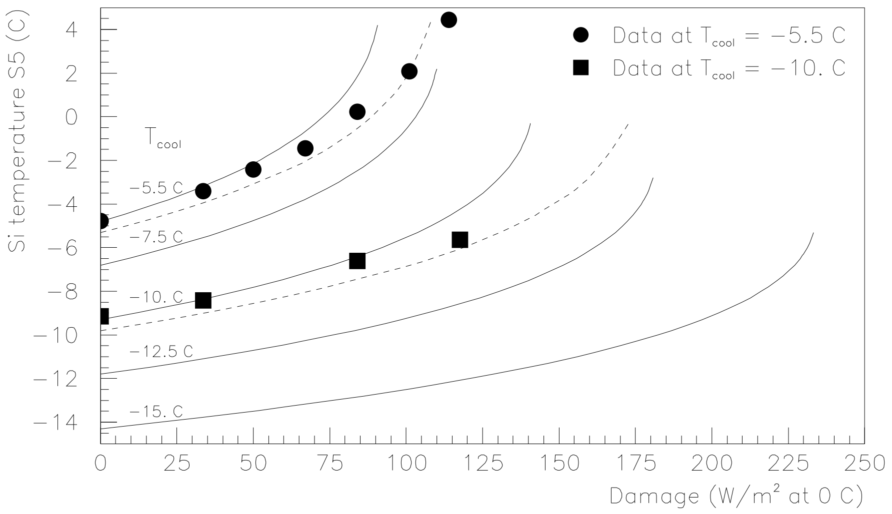


Figure 7: The temperature of point S5 on module TPG2 is plotted against a measure of radiation damage at fixed cooling block temperature. The module is cooled at a **single point**. The solid lines are the prediction of the simple model described in Section 3. The finite difference model predicts the dashed curves.

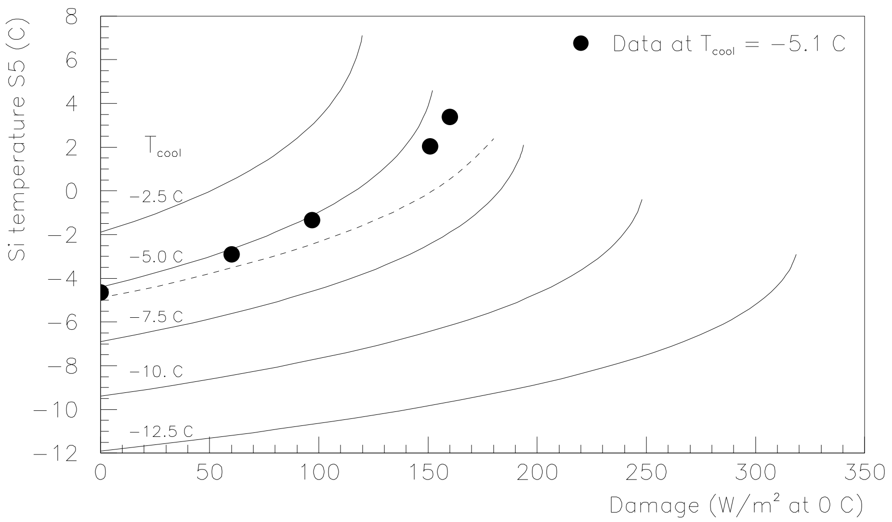


Figure 8: The temperature of point S5 on module TPG2 is plotted against a measure of radiation damage at fixed cooling block temperature. The module is cooled at **two points**. The solid lines are the prediction of the simple model described in Section 3. The finite difference model predicts the dashed curve.

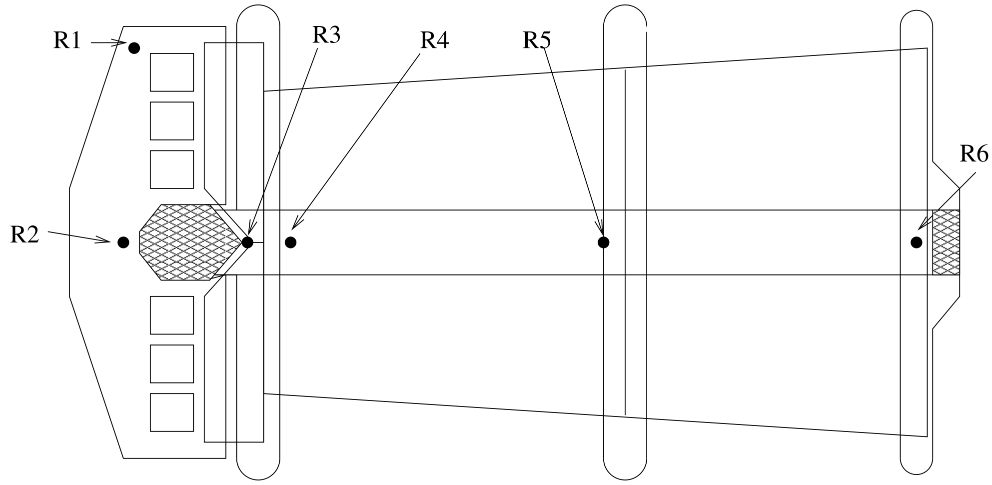


Figure 9: An outline of the composite module design showing the points, R, at which the temperature was measured. The shaded areas indicate where washers make contact with the cooling blocks via a thermal grease layer.

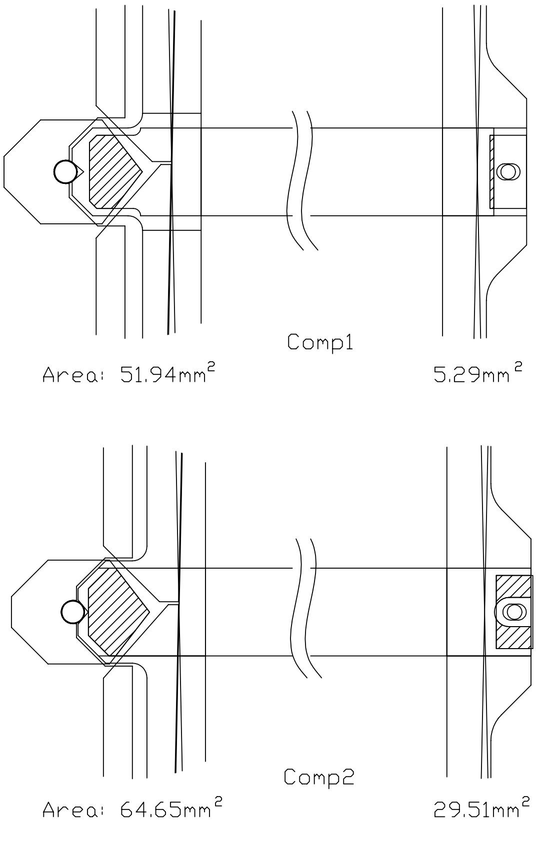


Figure 10: Detail of the TPG bar and its overlap with the cooling block contact area on modules COMP1 and COMP2.

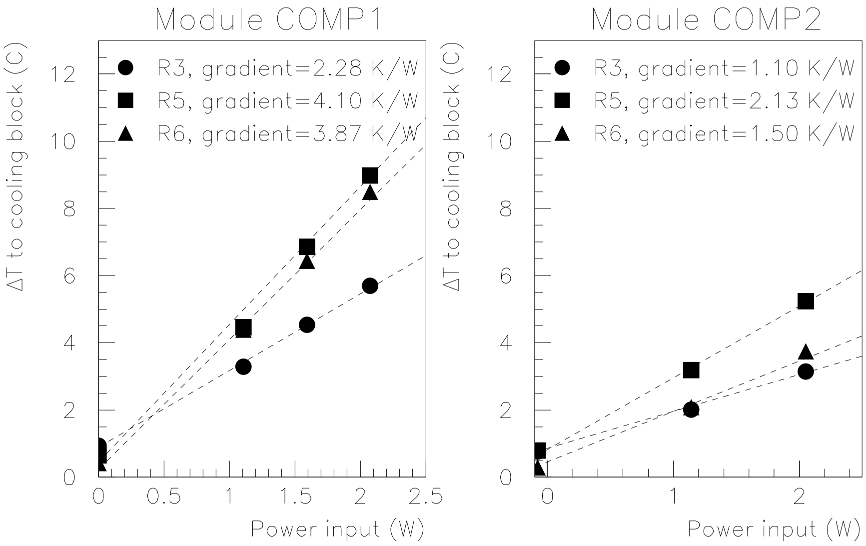


Figure 11: The temperature difference between three key points and the two cooling blocks is plotted against the power input. The performance of modules COMP1 and COMP2 are compared. Dashed lines show fits from which the gradients are determined.

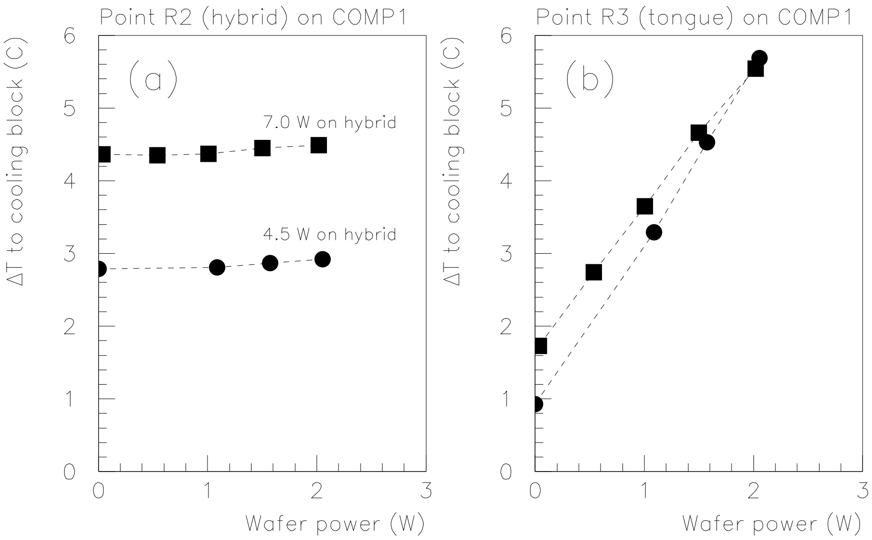


Figure 12: This plot demonstrates the good thermal isolation between the hybrid and the wafers in the composite spine module. Part (a) shows that the temperature of the hybrid is almost independent of the power applied to the wafers. Part (b) shows that there is only a slight temperature offset in the wafers when the hybrid power is increased from 4.5 to 7 W.

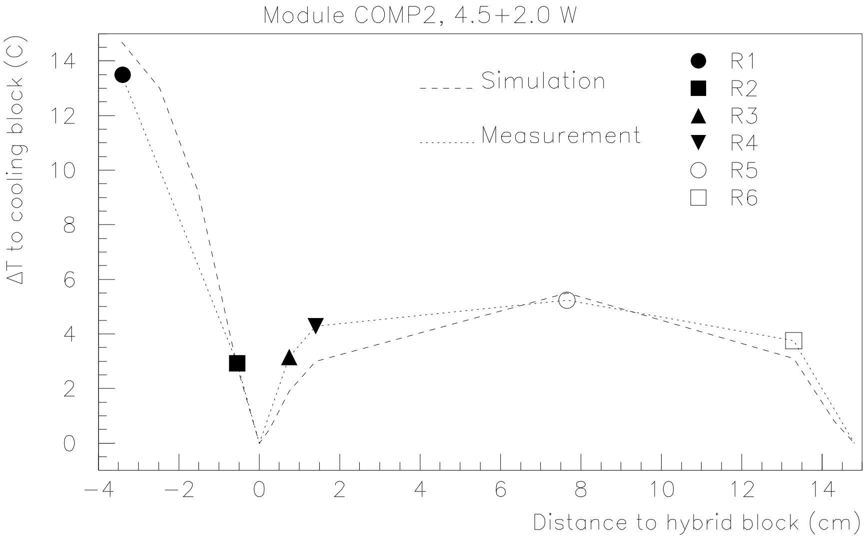


Figure 13: A comparison of the measured and simulated temperature profile of module COMP2.

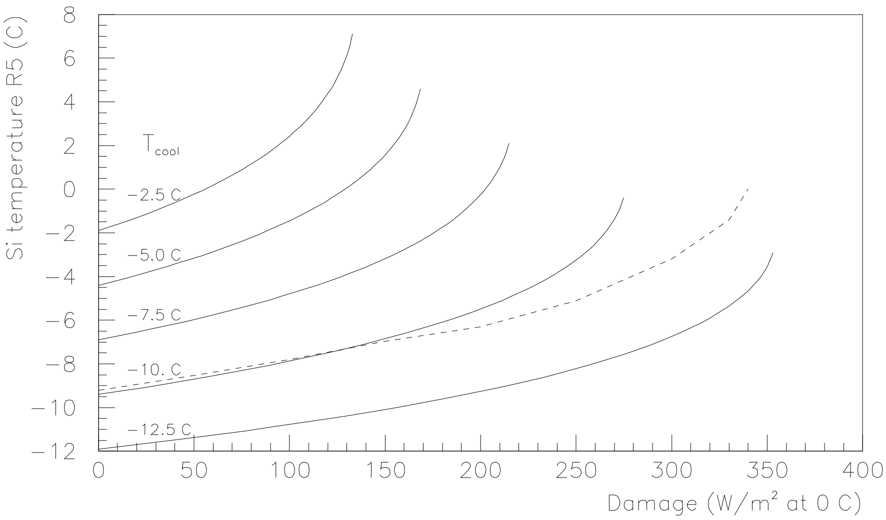


Figure 14: The predicted thermal runaway behaviour of module COMP2. The solid lines are the result of the simple analysis of section 3 with various cooling block temperatures. The dashed line is prediction of the more detailed simulation with a cooling block temperature of -10°C.