Laser Soldering and Thermal Cycling Tests of Monolithic Silicon Pixel Chips

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September 11, 2015

Abstract

An ALPIDE-1 monolithic silicon pixel sensor prototype has been laser soldered to a flex printed circuit using a novel interconnection technique using lasers. This technique is to be optimised to ensure stable, good quality connections between the sensor chips and the FPCs. To test the long-term stability of the connections, as well as study the effects on hit thresholds and noise in the sensor, it was thermally cycled in a climate chamber 1200 times. The soldered connections showed good qualities like even melting and good adhesion on pad/flex surfaces, and the chip remained in working condition for 1080 cycles. After this, a few connections failed, having cracks in the soldering tin, rendering the chip unusable. Threshold and noise characteristics seemed stable, except for the noise levels of sector 2 in the chip, for 1000 cycles in a temperature interval of 10° and 50° C. Still, further testing with wider temperature ranges and more cycles is needed to test the limitations of the chip.

Introduction

During Long Shutdown 2 of the LHC in 2018, a new inner tracking system based on monolithic silicon pixel sensors will be installed in the ALICE detector [1]. A few different chip architectures are being considered, one of which is the ALPIDE pixel chip. The ALPIDE chip is a monolithic, active silicon sensor, designed to cope with higher interaction rates and to improve the resolution of the current ITS [2]. Furthermore, it is divided into four sectors, sector 0-3, which all have small architectural differences to one another. The chips are connected to copper flex printed circuits (FPCs) for power supply and data transfer, and they are installed in modules of several chips in a row (nine on the inner barrels, for example) [3].

A novel interconnection technique based on flux-less laser soldering has been developed for the upgrade. The chips are soldered to the FPCs by means of Sn/Ag solder balls and a laser. [3] To ensure the optimal stability and reproducibility of these connections, each step in the production needs to be optimised. Studies are currently being conducted to find the optimal temperature profile of the laser and to test the repeatability of this technique.

Another aspect currently under study is the effects of thermal expansion and contraction on the chip's sensing properties, namely the hit thresholds and noise in each pixel, as well as the long-term stability and quality of the soldered connections. The difference of the linear expansion coefficients for the flex and the chip causes stresses on the solder joints. Such thermal effects could occur during operation of the detector or in the event of cooling failure, for example.

In this report, we present results from a full-scale prototype of the ALPIDE version 1, which was soldered in June 2015 and thermally cycled in a climate chamber until it stopped working. Threshold and noise scans were made regularly during this process.

Laser soldering

The connection between the monolithic silicon pixel chip and the FPC is established by melting 200 micron diameter Sn/Ag solder balls placed on the chip pads inside metalised flex holes. The melting occurs due to laser exposure which ensures localised heating and the temperature is controlled by a feed-back system connected to the laser.

The chip is placed onto a vacuum jig, and the FPC is placed on top of the chip with the flex holes carefully aligned with the chip pads. A grid is placed on top of the flex to help the solder ball placement into the holes, a cover with a window is placed on top, and finally, it is evacuated to keep impurities like dust from disturbing the process. This is necessary because of the small size of the solder balls and flex holes, since even small dust particles may reduce the quality of the connection significantly.

To optimise the process, we vary the temperature and duration of laser exposure. A temperature profile is created to vary these parameters in time, and it is desirable to keep as low temperature as possible while ensuring a good wetting on the contact surfaces. Too high temperature may damage the FPC. The profile that was tested is shown in figure 1.

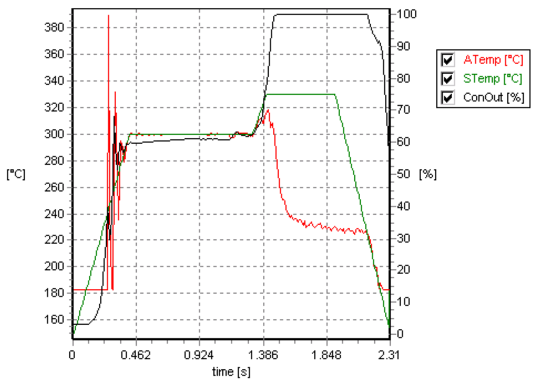


Figure 1: Laser soldering profile 213, with total duration of 2.3 s. The graph shows the target temperature (green), measured temperature (red), laser power output (black), and duration. The first plateau melts the solder ball using low temperature. The second plateau ensures melting by increasing the temperature for a short time.

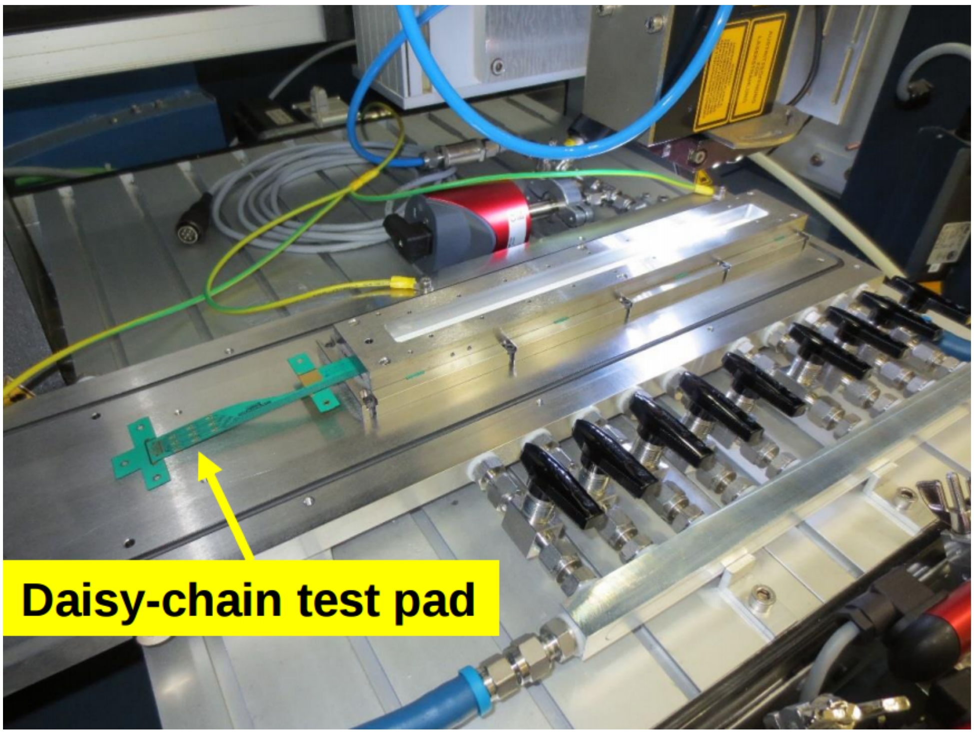


Figure 2: Laser setup, displaying the chip cover and laser. The chip and flex is in vacuum under the chip cover, the flex sitting on top of the chip with the flex holes and chip pads carefully aligned. The flex is seen sticking out from under the chip cover.

Thermal cycling and chip testing

To investigate the effects of thermal expansion and contraction of the components of the chip and the FPC, the soldered chip sample was put in a climate chamber of the type Climats EXCAL Spirale3. In this chamber, the sample was thermally cycled between 10° and 50° C with a ramp of 15°C/s and flat top of 15 min 1000 times. After this, the temperature interval was changed to 0° and 60° with a 22.5°C/s, with same flat top duration. This process simulates wear and tear over the chip's lifetime and exposes weaknesses in the chip/flex connections.

The hit threshold and noise properties of the chip was tested by analogue injections every 40 cycles, and sometimes 120 cycles for weekends. This was done with 1% scans of the chip, to gather data to observe the gradual effects of thermal stresses. Before any cycling was done, a 100% scan (the full chip) was performed, and the same was done after 1000 cycles.

Results

The chip was thermally cycled for a total of 1200 cycles, where the first 1000 was with a $10° - 50°$ C interval, and the last 200 was with a $0° - 60°$ C interval. It stopped working during the last 120 cycles, failing to write to the chip in the FIFO test. A metallurgical cross-section cut was made, revealing defects in the chip connections at the contacts A00, A01, A02, A04, A06 and A30. The defects were all in the soldering tin. A cross-section of the A00 connection is shown in figure 3. The tin has a crack all the way through, close to the chip pad, severing the connection. At the same time, the wetting of the hole surface by the tin is demonstrated.

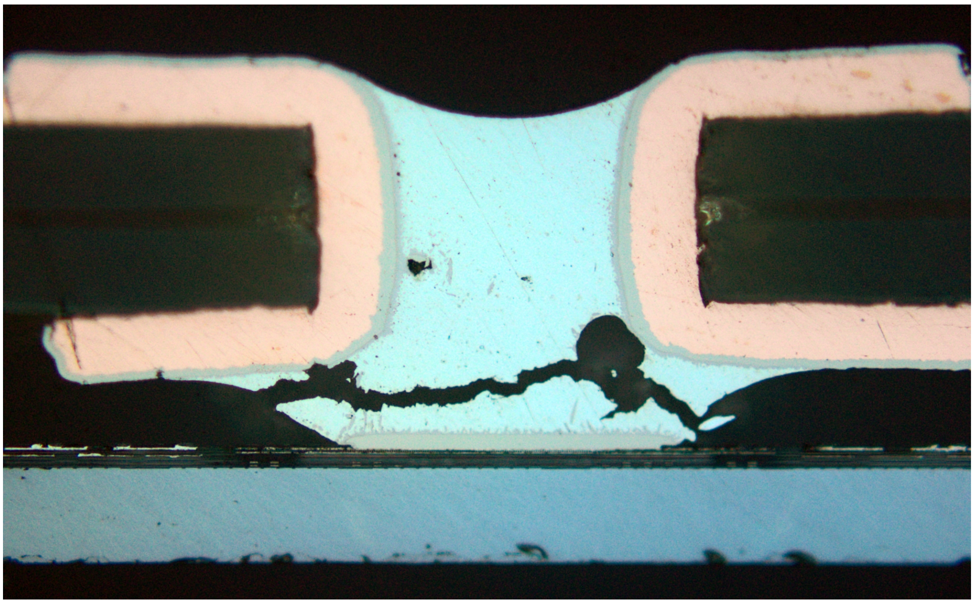
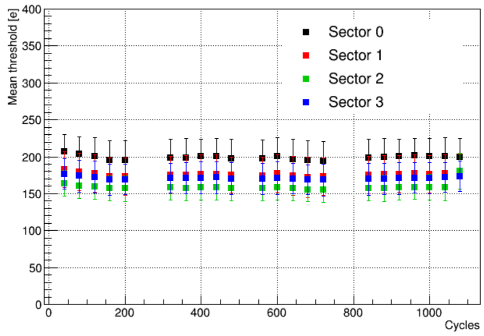


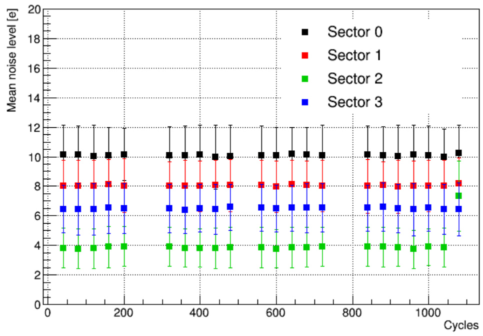
Figure 3: Cross-section of the A01 pin. A clear crack is revealed in the tin, going through a bubble close to the chip pad.

The effects on hit thresholds and pixel noise was investigated by studying the threshold and noise distributions and their means. Figure 4a shows the mean thresholds for each sector as a function of the number of cycles. Figure 4b shows a similar plot for the mean noise. They use data from threshold scans of 1% of the pixels in the chip. Bots plots show little or no change in the mean threshold and noise values. In addition, full threshold scans (100% of the pixels) were made before thermal cycling and after 1000 cycles. Comparison between the threshold and noise distributions are made sector by sector in figure 5 and 6, respectively.

The comparisons of the threshold distributions in figure 5 reveal little difference in the thresholds before and after thermal cycling. However, the noise distributions shown in figure 6 show increased noise in all four sectors. The differences in mean threshold and noise are summarised in table 1.

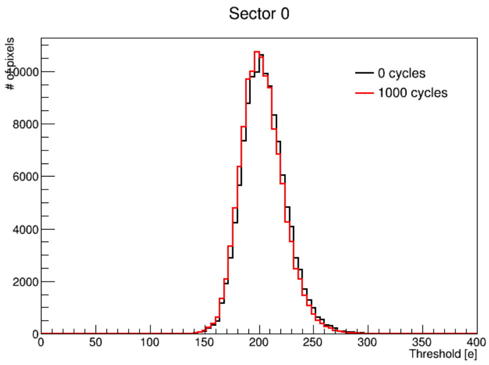


(a) Mean threshold.

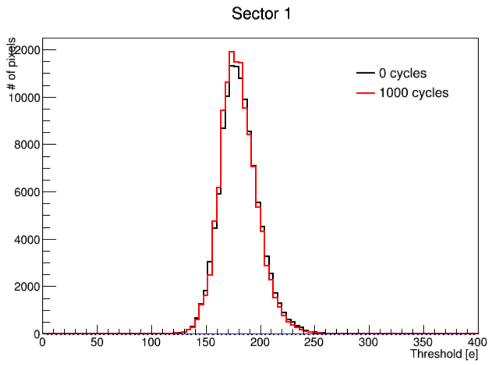


(b) Mean noise.

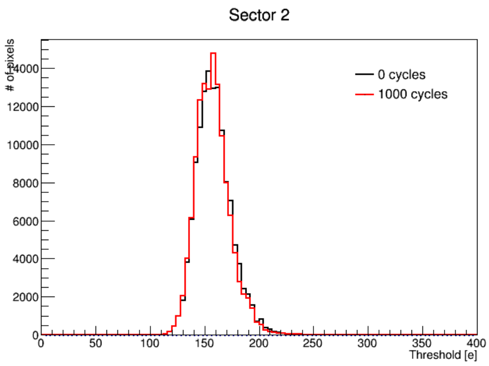
Figure 4: Mean threshold and noise values as functions of the number of cycles completed, from 1% threshold scans. The last scanned point was at 1080 cycles. No clear change is seen in both thresholds and noise.



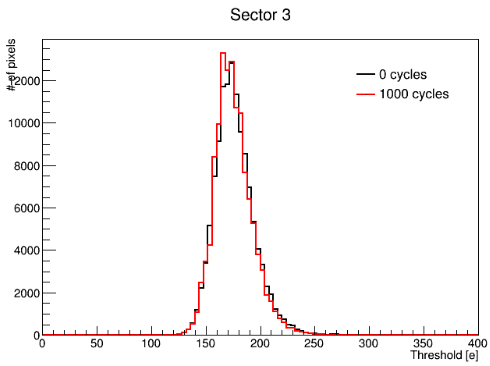
(a) Sector 0



(b) Sector 1



(c) Sector 2

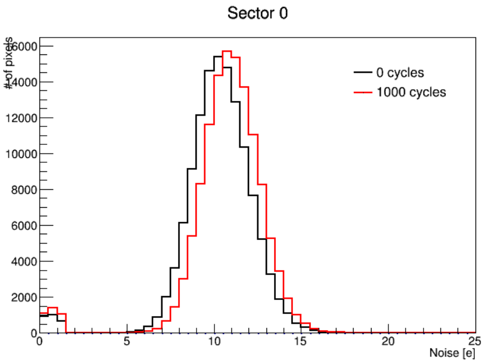


(d) Sector 3

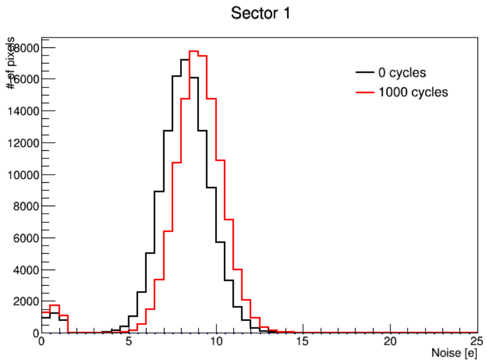
Figure 5: Comparison between the threshold distributions for each sector before and after thermal cycling. The data is after 1000 cycles, after which the temperature interval increased. No change in mean values or shapes of the distributions.

Discussion

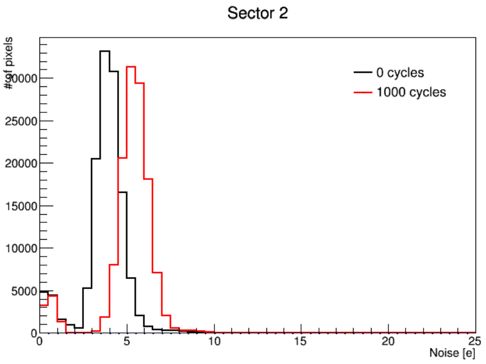
The results from the metallurgical cross-sections made from the thermally cycled chip indicate that temperature profile 213 melts the solder balls well most of the time, wetting the flex surface and creating good connections. It also seems that the contact between the tin and the pad/flex surfaces were of good enough quality to withstand the thermal cycling without taking damage. This, however, is difficult to say with certainty since we would have to have cross-section images of the connections before any thermal



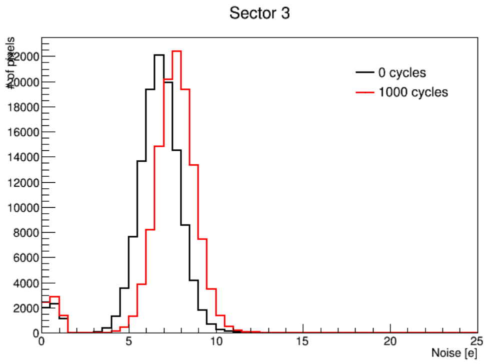
(a) Sector 0



(b) Sector 1



(c) Sector 2



(d) Sector 3

Figure 6: Comparison between noise distributions for each sector before and after thermal cycling, similar to figure 5. Small increases in mean noise is seen, and for sector 2 a 38.4% increase is observed.

cycling. The broken connections were all due to cracked soldering tin near the chip pads. All had what looks like a bubble in the tin, through which the cracks passed, as in figure 3. It is, at this point, unclear what may have caused bubbles to form in the tin, since the soldering is done in vacuum.

13 out of 103 connections had to be reprocessed using a stronger, longer lasting temperature profile due to bad melting of the ball, creating a flat connection (tin wetting the flex surface but not the pad), or not melting at all. It is not always clear why some of the solder balls does not melt properly, although many times there were clear signs that there were some contaminations present, like dust particles near the hole. These showed up as visible flashes of light as they burned when the laser turned on. Dust and other impurities will dissipate energy from the laser, thus preventing the solder balls from reaching high enough temperatures to melt properly. The geometry of the flex holes themselves are also important. If they aren't circular enough, or have some irregularities of the shape or size, it may cause energy dissipation (like with dust), or make for uneven distribution of the melted tin in the hole.

Mean threshold values seem to take little or no effect of thermal cycling between 10° and 50° C ($< 1\%$), for every sector, as indicated in figure 4a, 5, and table 1. Moreover, the character of the threshold distributions seem unchanged. The mean noise levels seem to increase, however, especially in sector 2. These noise levels are still significantly lower than the thresholds, so that false hits are still unlikely.

Conclusion

In this project, a full-scale prototype of the ALPIDE-1 sensor has been laser soldered using temperature profile 213 and thermally cycled 1200 times. Laser soldering profile 213 seems to be working as desired, minus a few reprocessed connections. However, the exact reasons for needing to reprocess still need to be confirmed, although dust is a recurring problem. The hit threshold and noise characteristics show little change in response to the chip being thermally cycled 1000 times with a temperature interval of 10° and

Table 1: Relative differences of the mean threshold and noise values before/after thermal cycling, sector by sector.

Sector	Relative difference in threshold [%]	Relative difference in noise [%]
0	-0.9	5.0
1	-0.4	7.9
2	-0.6	38.4
3	-0.6	12.3

50° C, except the mean noise values of sector 2 which increased by 38.4%. To provide an assurance that the ALPIDE chip will survive the working conditions in the ALICE detector, more statistics is needed, with wider temperature ranges and a greater number of cycles.

References

[1] ALICE Collaboration. *ALICE Letter of Intent*, 2012. `https://cds.cern.ch/record/1475243/`.

[2] ALICE Collaboration. *Upgrade of the Inner Tracking System, Conceptual Design Report*, 2012. `https://cds.cern.ch/record/1475244?ln=en`.

[3] ALICE Collaboration. *Upgrade of the Inner Tracking System, Technical Design Report*, 2013. `http://cds.cern.ch/record/1625842?ln=fr`.