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Curved CMOS imaging sensor: development and reliability test results

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ABSTRACT

Curved imaging sensors bring significant size, weight and cost reduction to imaging systems while mitigating off-axis optical aberrations, as opposed to current flat sensors. Unlocking these key features has captured the interest of major players over the last two decades. SILINA has been developing a CMOS image sensor curving process which adapts to various sensor characteristics. This process enables the deformation of image sensors to various shapes to specifically maximize the performance of every single imaging system. Indeed, curved CMOS image sensors (CIS) help to create compact optical instruments, notably imagers, telescopes and spectrographs. Simplifying optical systems enables to release opto-mechanical constraints from the design to the integration phase. Nowadays, freeform optical elements participate in the development of solutions that meet the common needs of compact, fast, wide-angle and high-resolution systems. Nevertheless, freeform surfaces remain extremely expensive in terms of manufacturing and metrology. Moreover, field curvature aberration is still difficult to correct and curved CIS bring a suitable solution for that. Early 2021, SILINA has demonstrated the manufacturing of spherical and aspherical CIS, opening a new area to optical system design. Optical designers can now consider various sensor shapes to optimize their systems by considering spherical, aspherical or more complex focal surfaces.

In 2022, SILINA is generating a data set of electro-optical performances of curved CIS. EMVA1288 compliant CMOS image sensor characterization test beds are being developed in order to fulfill this challenge. Experimental data of dark current, photo-response non-uniformity, fixed pattern noise, quantum efficiency and more can be measured. Furthermore, characterizing a large number of curved CIS will enable to assess the influence of SILINA's curving process on key performance criteria and extract statistic results. In parallel to the electro-optical characterization campaign, reliability tests such as thermal tests, thermo-vacuum cycle and aging tests, following the ECSS norms, will be performed in order to qualify the robustness of the curving process .

This paper gives an overview of SILINA's activities. The benefits of curved CIS are illustrated through on-going projects, the main features of the curving process and the electro-optical characterization are introduced. A focus is done on the improvement of shape accuracy and on the performances of visible curved CIS. Finally, the results of reliability tests are presented.

Keywords: Curved, CMOS, Image sensor, Optical system, Electronics, Electro-optical performance, Thermal test, Reliability

1. CURVED CMOS IMAGE SENSOR FOR HIGH END OPTICAL SYSTEMS

One of the most efficient imaging system we know is our eye. Our eye is very compact, offering a good image quality, sensitivity, with a large field of view. Still, the eye presents a really simple system that can be approximated to a single optical element : the crystalline. This simplicity comes from the fact that the retina is curved.

Today, imaging systems are very complex, using numerous and expensive optical elements to deliver a good image quality. These limitations come from the fact that the sensor is flat. However, optical systems always face a significant field curvature optical aberration that needs to be corrected to create an image on a flat image

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sensor. To do so, field flattening optical elements are added to mitigate the field curvature. Adding elements brings additional optical aberrations and make the system more complex, sensitive to misalignment, heavy and expensive.

As a solution, a curved focal surface can correct the field curvature while reducing the complexity of the optical architecture. It brings significant size, weight and cost reduction to imaging systems while mitigating their off-axis aberrations. Unlocking these key features captured the interest of major players of the semiconductor industry for the last two decades. Innovative lens designs and CMOS curved sensor manufacturing techniques have been investigated by various companies like Sony[1] or Microsoft[2] through patents and papers. Uncooled infrared curved sensor prototypes have also been manufactured and demonstrated functional performance.[3,4] Yet, the research has been limited to non-scalable manufacturing processes, only suitable to low-volume applications which can offer high pricing.

SILINA is a semiconductor company developing an innovative process enabling to curve existing imaging sensors at scale. Our technology enables to curve multiple sensors at the same time, making the process scalable and repeatable for both low volume and high volume applications. The curving process adapts to the format of the sensors, the sensor technology, the spectral bandwidth, and more. Spherical, aspherical, cylindrical, concave or convex shapes can be obtained. Custom shape can also be made on-demand.

We have curved multiple CMOS image sensors with various radii of curvature, measured the electro-optical performances and perform reliability tests (RT). In this paper, we propose to compare the performance of flat and curved image sensors before and after unbiased reliability tests. Curved CMOS sensors have been tested in Unbiased Highly Accelerated Stress Test (uHAST), High Temperature Storage Life (HTSL) and Thermal Cycling (TC). The methodology to perform these tests is described in this paper. The shape accuracy of curved sensors is then compared to the theoretical targeted shape.

2. SILINA: A SERVICE COMPANY FOR HIGH END OPTICAL APPLICATIONS

2.1 Optical design and image sensor curving

For low volume high end applications (e.g. space, scientific, astronomical applications, and more), SILINA is a service company to support the development of state-of-the-art optical instruments using curved image sensors. We can support on the optical design by considering the capability to curve the image sensor selected for the application / instrument.

SILINA does not develop new CIS. SILINA curves already existing CIS. We work closely with the instrument designers, manufacturers, integrators, but also with CMOS image sensor manufacturers. We can support the various players who discuss early stage mission phases to assess how a curved image sensor can improve the characteristics and boost the overall performance of the optical system. The curvature step is just an additional step to a full manufacturing process of an image sensor. The electronics control board and the package remain the same as for a flat image sensor.

2.2 Location and facilities

SILINA's technological development and production site is based close to Aix-en-Provence, in France. We operates in a fully equipped 700m^2 ISO 3 to 5 cleanroom dedicated to back-end semiconductor. We have access to a private area in which we can operate in total confidentiality and autonomy. We have been developing our own EMVA compliant and fully automated electro-optical test-beds (image 1(a)). We also have the capability to perform environmental tests: thermal cycling, thermal shock, vacuum, and humidity (image 1(b)).

2.3 The manufacturing process

The manufacturing process to obtain curved image sensors is decomposed by several steps. The first one consists of receiving CIS as wafer or bare die. Then, we perform a back grinding step : the wafers / sensors are thinned down to make them flexible. On wafers, we perform a dicing step in order to individualized the dies. At that step, the dies are ready to be curved. The process developed by SILINA enables to reach different shapes : spherical, aspherical, toroidal and custom shape based on instrument's needs. We can reach concave and convex shape but also extremely flat shape. The curving process can be applied to any CIS format from 1/3" to full

(a) EMVA 1288 electro-optical test bed (b) Thermal chamber

Figure 1. CIS characterization test beds and environmental test equipment

frame and more (no upper limit), either monochrome or color sensors, with or without micro-lenses. The process does not depend on the pixel pitch. We have already demonstrated the capabilities on front side (FSI) and back side (BSI) illuminated CIS and we are currently working on back side stacked image sensors.

2.4 Packaging capabilities

Once the sensor is curved, we can perform the final packaging steps: a wire bonding step and the bonding into the ceramic package. A glass lid on top of it can be added if needed.

Two characterization steps occur after curving and packaging : the shape analysis and the electro-optical performance characterization. The shape of the sensors is characterized with a confocal profilometer. We record the 3D shape after curving with a resolution that can reach the sub micrometer. From the 3D map, we can extract, among other parameters, the real radius of curvature and the deviations to the targeted shape. Regarding the electro-optical performance, we develop our own EMVA compliant fully automated test bed. Additional capabilities are currently integrated to perform MTF or angular response characterization, as well as a monochromator and an active thermal control. In order to assess the good operating of curved image sensors in their life condition, we perform reliability test and characterization at the end of the process.

3. CURVED CIS: ENVIRONMENTAL RELIABILITY TESTS

3.1 Test conditions

After having demonstrated the performance of CMOS image sensors after curving,[5] reliability tests are performed for the very first time on that technology. The main objective is to guarantee the good performance of curved CIS in real environmental conditions. These tests represent an important step toward the industrialization of the technology.

The standards and operating conditions are displayed in Table 1. Test conditions have been inspired from microelectronic consumers standards JESD22-A108D and JESD22-A103D. Normally, a duration of 1000 hours is required to comply with the requirement, but we decided to consider 100 hours per test since it is enough to detect early failure modes. For these tests, temporary glass lids are applied on top of the sensors and packages are made hermetic, as displayed in Figure 2. The glass lid is removed before every sample characterization step associated to the shape metrology and the electro-optical performance.

Three different environmental tests have been performed:

- **uHAST**: unbiased Highly Accelerated Stress Test consists in placing the sample in high temperature and humidity condition in order to simulate highly accelerated aging. A 85°C temperature with 85 % relative humidity is applied for 100 hours on the sensors, corresponding to an estimated equivalent life time between 1 to 5 years.

Figure 2. Picture of curved image sensor samples inside the thermal chamber

- **HTSL**: for High Temperature Storage Life test, the curved sensor is placed at 155°C for 100 hours with controlled humidity. It simulates normal temperature storage with an estimated equivalent life time between 6 months to 2 years to challenge the sensors and its bonding at the maximum value of its operating temperature range.
- **TC**: the sensors are exposed to thermal cycling (TC) tests from -40°C to 100°C with respectively 8°C/min and -6°C/min heating and cooling ramps and 20 min temperature stabilization. This test is set to simulate daily thermal fatigue as well as the sample operating state under huge temperature variations, inducing contraction and dilatation of each materials.

A CTS CS-70/200-5 climatic chamber is used for uHAST and TC tests and a CTS T-40/25 thermal chamber for HTSL tests.

Test	Duration (h)	Temperature (°C)	Humidity γ(% RH)	Nb. of cycles per hour	Temperature ramp (°C/min)	Equivalent time	Standard
uHast	100	85 ± 2°C	85 ± 5%RH	-	-	1 to 5 years	JESD22-A108D Condition A
HTSL	100	155 ± 5°C	-	-	-	6 months to 2 years	JESD22-A103D Condition B
TC	100	-40 to +100°C	-	1	up : 8 down : -6	NA	-

Table 1. Description of the different reliability test conditions with the corresponding standards

3.2 Samples description

In this paper, only concave spherical shapes have been considered, with two different radii applied on a 15.7x18.7mm CMOS FSI image sensors. The sensors are packaged into a ceramic package (see Figure 3). Results are compared to classical flat samples that undergone the packaging process. Sensor distribution per test is displayed in Table 2.

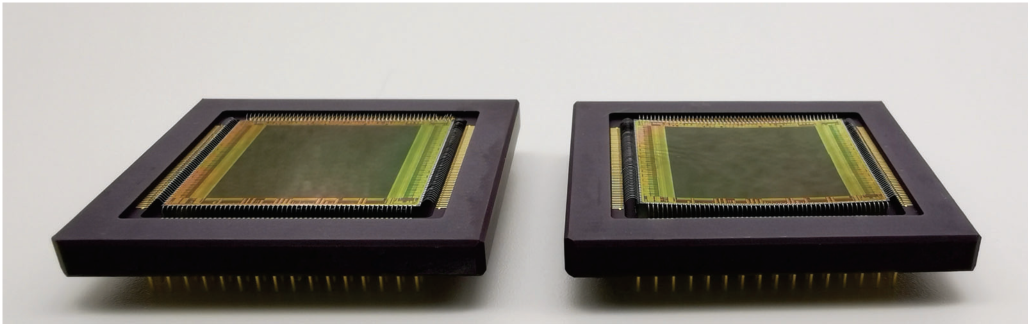


Figure 3. Pictures of packaged flat image sensor (left) and a curved image sensor(right)

Sample Reference	Radius of Curvature (in mm)	uHast	HTSL	TC
A	Flat	X		
B	Flat		X	
C	Flat			X
D	250	X	X	
E	250		X	
F	250			X
G	150		X	
H	150			X
I	150	X	X	X
J	150	X	X	X

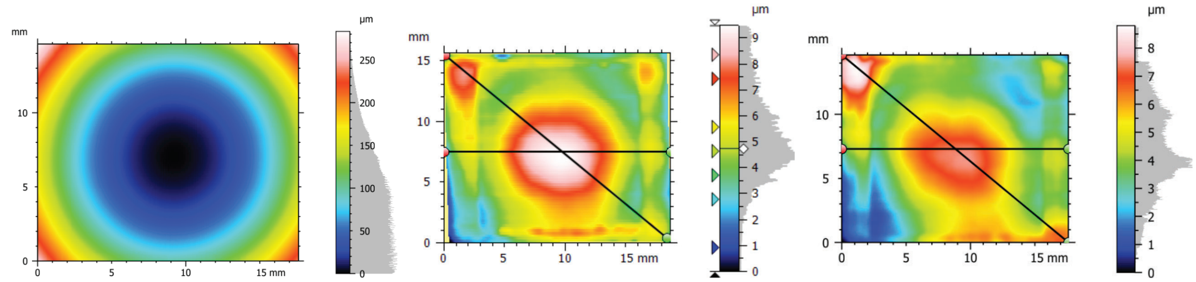
Table 2. Samples description and distribution

3.3 Measurement of the shape error

To determine the impact of the different reliability tests on the sensors, a metrology inspection of the front side is performed, in order to identify potential mechanical failure such as cracks, wire bonding pads corrosion or delamination. The characterizations occur in the 48 hours following the end of the test.

After the curving step, the shape of image sensors is measured with a confocal profilometer. A 3D map of the sensor surface is extracted (Part a, Figure 4). The theoretical shape is subtracted to the 3D map in order to observe the deviations to the target shape (Part b and c, Figure 4). Technical efforts are focused on the minimization of these residuals in order to make curved image sensor technology accessible to fast optics. Early 2022, we had a maximum deviation below 20 um peak to valley (PTV). Today we have divided it by 2 and we have recently achieved 4 um PTV.

The shape characterization is repeated after each reliability test in order to quantify the stability of the curved sensor shape. Table 3 describes the maximum deviation (Sz) seen on flat and curved sensor surfaces, before and after reliability test. Flat sensors are considered as the reference. We observe deviations Sz from the ideal flat shape up to 6 times higher than the ones of curved sensors from the ideal spherical shape. This means that the curving process we have been developing reaches better shape accuracy than traditional packaging techniques for flat image sensors. The Sz difference between before and after the reliability test does not exceed 4 um, with a median of 2 um all tests combined. The radius of curvature of the sensors does not change after the tests. The first three reliability tests in uHAST, HTSL and TC for 100 hours show no critical failure.



(a) Original map (b) Residuals (c) Residuals

Figure 4. Surface map of a CMOS sensor curved with a radius of 250mm. a) Original Map, b) Residuals to the theoretical shape after curving, c) Residuals to the theoretical shape after curving and HTSL test

Test	Sample reference	Radius of Curvature (in mm)	Sz before RT (in um)	Sz after RT (in um)	Sz difference before vs after RT
uHAST	A	Flat	19	21	2
	D	250	9	9	0
	I	150	10	12	2
	J	150	10	8	2
HTSL	B	Flat	53	54	1
	E	250	10	10	0
	D	250	9	9	0
	I	150	12	16	4
	J	150	8	11	3
	G	150	7	7	0
TC	C	Flat	63	66	3
	F	250	13	13	0
	I	150	16	14	2
	J	150	11	9	2
	H	150	18	14	4

Table 3. Peak to valley deviation to the theoretical shape of curved sensors before and after reliability tests

4. ELECTRO-OPTICAL CHARACTERIZATION

We have characterized the electro-optical (EO) performance of 20 CIS, 100 um thick, with radii of curvature of 150mm, 250mm, and 500mm, with a concave and convex shape. Curved image sensors have been compared to flat image sensors with the same thickness, considered as reference.

4.1 Before reliability test

Figure 5 shows the results of the characterization after the curving process. The first part of the EO characterization is done in dark condition. We measure the Dark Current (DC) and the Dark Signal Non Uniformity (DSNU) per radius of curvature (respectively Figure 5(a) and 5(b)). The DC of the curved image sensors are similar to the flat ones with a mean of around 33 e-/s/pix. The flat sensors have a DSNU of around 9.7e- while the curved image sensors have a DSNU of around 9.3e-. The results of the dark characterization are stable from one curvature to the others, both concave and convex. The second part of the characterization consists in measuring under homogeneous flat illumination at 530 nm. Figure 5(c) represents the photo-response non-uniformity (PRNU), Figure 5(d) the Quantum efficiency (QE), and Figure 5(e) the signal to noise ratio. Flat image sensors have a median PRNU of 0.58%. Curved image sensors have a median PRNU value of 0.61%.

Despite one single sample at 0.91%, we can observe that the performance are similar compared to flat image sensors and stable between samples. To be more precise, additional measurements must be performed on a large quantity of samples.

4.2 After reliability test

The same measurements have been performed on curved sensors post-reliability tests. Figure 6 shows the results of the characterization for the DC, DSNU, PRNU, QE and the SNR. As seen previously, curved and flat sensors with the same thickness respond the same way. Here, the results of curved and flat sensors have been grouped per reliability test and "T0" represents the performance before the tests. Curved sensors are functional after all tests and with the same performances as before. DSNU, PRNU, QE and SNR are stable.

We note on Figure 6(a) an increase of around 10e- for the DC post HTSL and TC, but the dispersion of the data covers the initial performances. During these measurement, the camera has not been thermally monitored and controlled. We do not know the temperature of the sensors during these EO measurements, so it is difficult to conclude for now. Additional measurements must be done in order to conclude on this effects. Moreover, the next upgrade of the test bed consists in measuring the temperature of the image sensor in real time during the EO measurements.

5. CONCLUSION

Curved image sensor is a key technology for a new generation of imaging instruments, enhancing their performance, footprint, and simplicity. We quantified the electro-optical performance of CMOS image sensors after the curving process at room temperature and we compared the results to standard flat sensors. Then we performed various environmental tests and we did measure the electro-optical performance after these tests. Results show that every curved CMOS image sensor has relatively similar performance to flat image sensors, also after being exposed to harsh thermal tests. The image sensor shape accuracy has been measured before and after thermal tests. Results show a good stability with a deviation median value of 2 um.

In order to reach the Technological Readiness Level up to 8, further environmental tests will be performed during the coming months, notably BHAST (Biased Highly Accelerated Stress Test), HTOL (High Temperature Operating Life), TVTC (Thermal Vacuum Thermal Cycling) and vibration. ECSS standards will be considered to complete the test phases.

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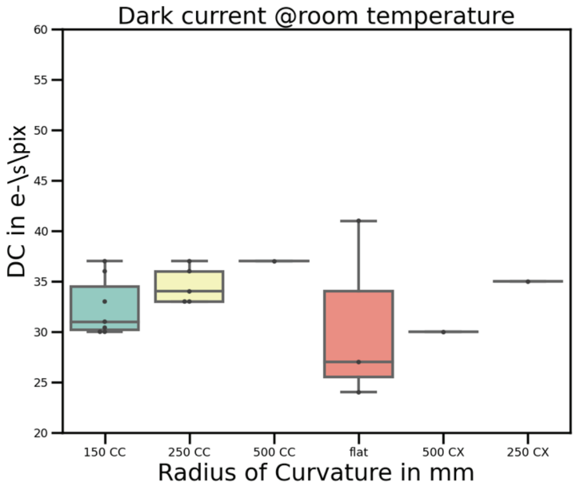
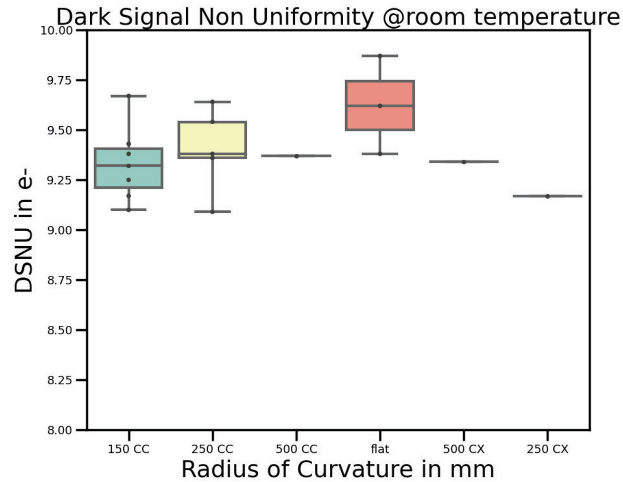
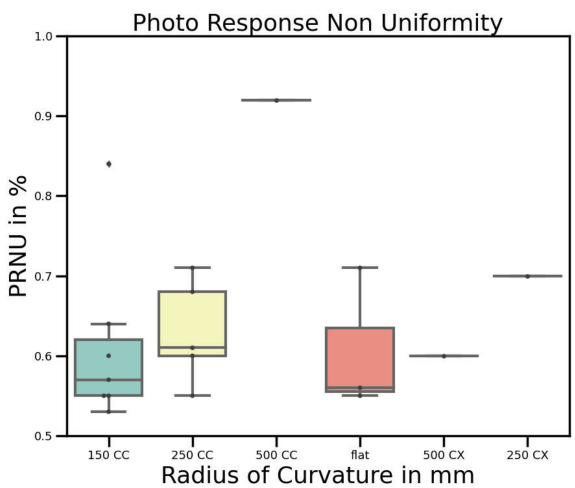


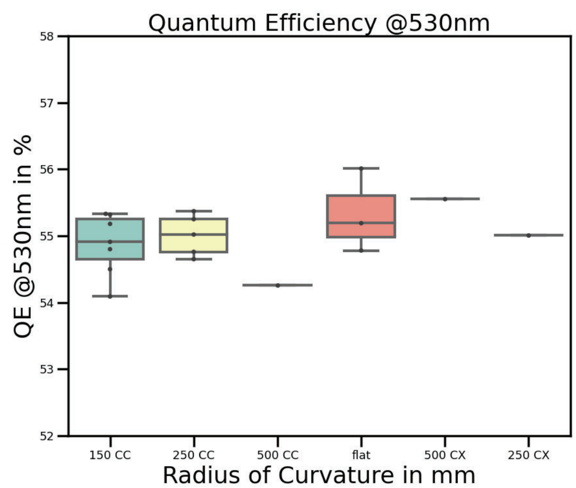
(a) Dark Current



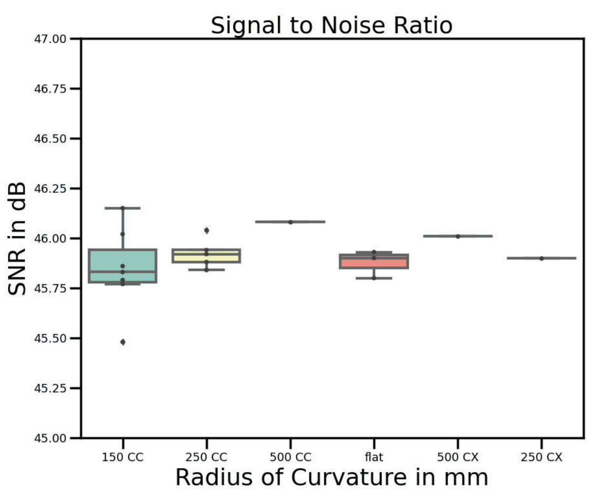
(b) Dark Signal Non Uniformity



(c) Photo Response Non Uniformity

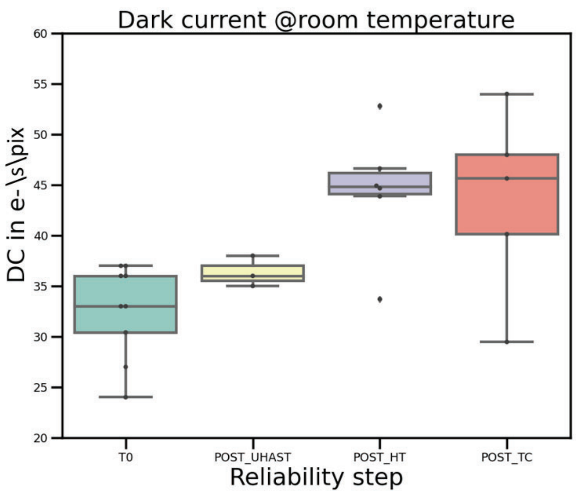


(d) Quantum Efficiency

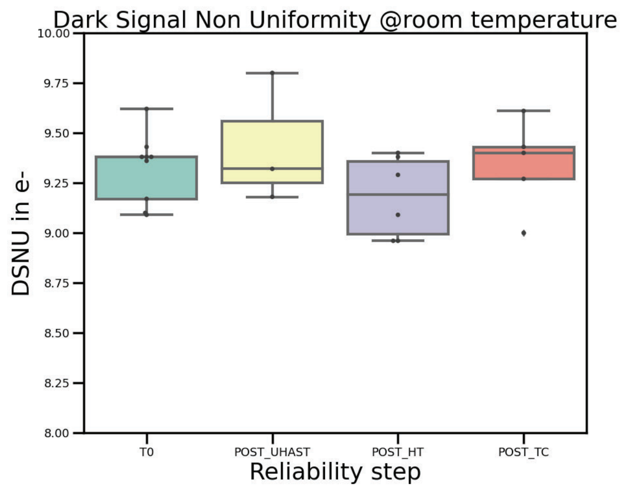


(e) Signal to Noise Ratio

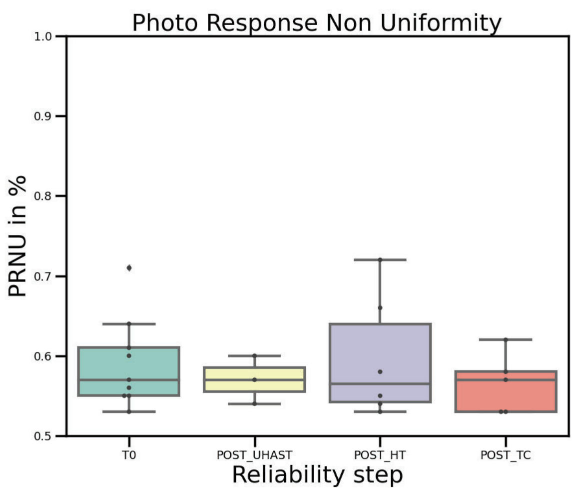
Figure 5. Electro-Optical performance before reliability tests



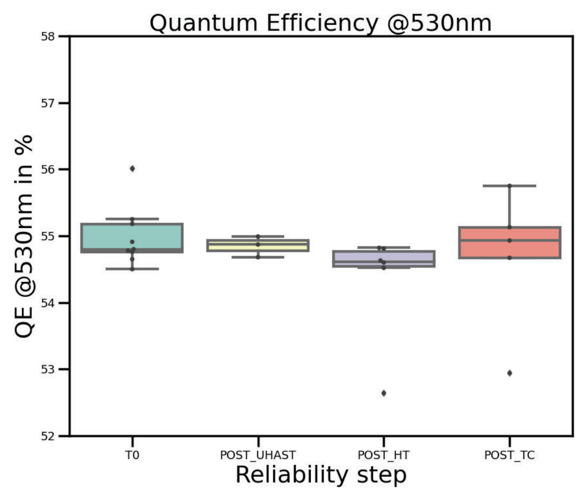
(a) Dark Current



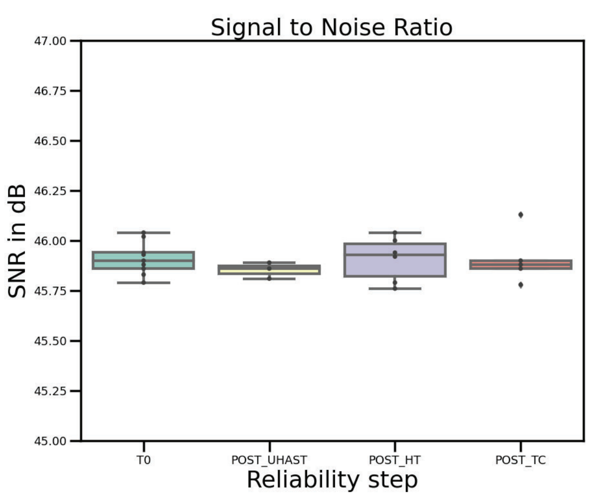
(b) Dark Signal Non Uniformity



(c) Photo Response Non Uniformity



(d) Quantum Efficiency



(e) Signal to Noise Ratio

Figure 6. Electro-Optical performance after reliability tests