The challenge of highly curved monolithic imaging detectors

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ABSTRACT

In a recent optical design study of CODEX – a visible spectrograph planned for the European Extremely Large Telescope (E-ELT) - it was determined that a significant simplification of the optical design – accompanied by an improvement of the image quality - could be achieved through the application of large format (90mm square) concave spherically curved detectors with a low radius of curvature (500 to 250mm).

Current assemblies of image sensors and optics rely on the optics to project a corrected image onto a flat detector. While scientific large-size CCDs (49mm square) have been produced unintentionally with a spherical radius of convex curvature of around 5m, in the past most efforts have concentrated onto flattening the light-sensitive detector silicon area as best as possible for both scientific state-of-the-art systems, as well as commercial low-cost consumer products. In some cases curved focal planes are mosaicked out of individual flat detectors, but a standard method to derive individual spherically curved large size detectors has not been demonstrated.

This paper summarizes important developments in the area of curved detectors in the past and their different technical approaches mostly linked to specific thinning processes. ESO’s specifications for an ongoing feasibility study are presented. First results of the latter are described with a link to theoretical and practical examinations of currently available technology to implement curved CCD and CMOS detectors for scientific applications.

Keywords: CCD, CMOS, curvature, E-ELT, focal plane, mosaic, curved silicon, thinning

1. EVOLUTION OF NATURE STILL BEATS TECHNOLOGY

Many features of the human eye have been emulated by detector technology. Most of them are routinely used - except the curvature of the retina (Figure 1). Following the analogies of other technologies derived from the eye, reason enough to study the advantages of a curved detector.

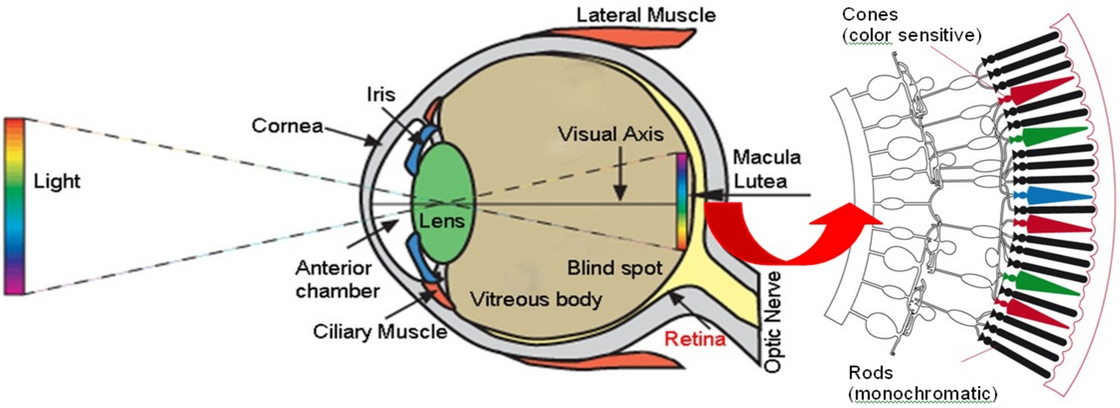

Figure 1. Picture of a human eyeball (left) and detail of its curved retina (right)[1]. Reproduced with permission from authors.

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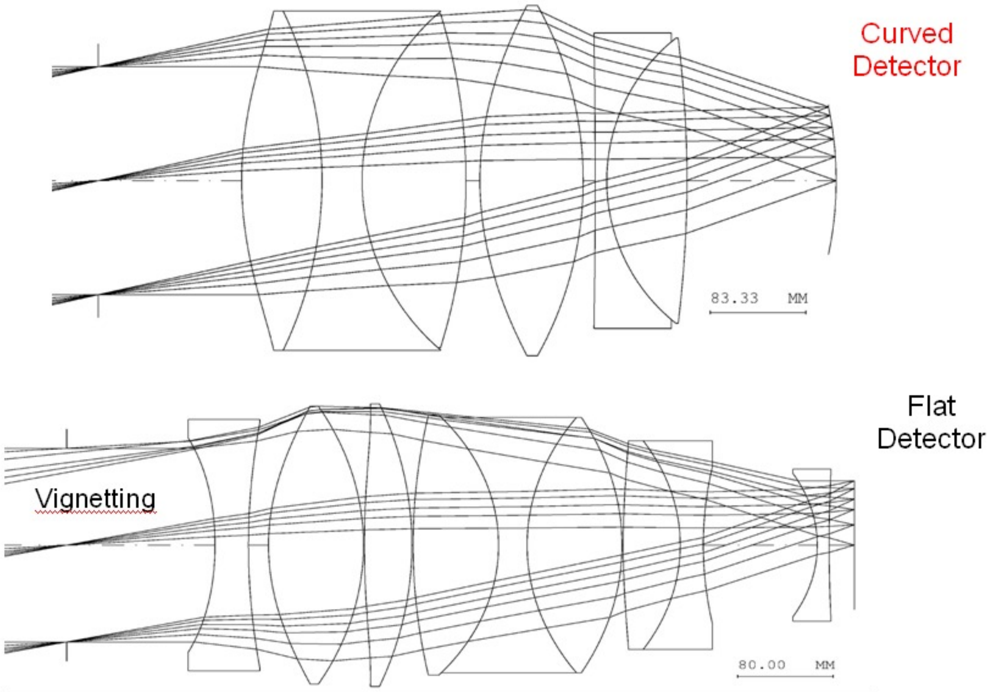
2. WHY A CURVED DETECTOR FOR THE E-ELT ?

Figure 2 shows a typical optical design under study for E-ELT instrumentation – comparing a curved (top) and a flat detector (bottom). The correction of the field curvature is a major problem for fast cameras with large field of view. The combination of diverging and converging elements leads to very high incidence angles on some optical surfaces. Very often vignetting has to be introduced to limit this effect.

A curved monolithic detector with 90 x 90 mm with curvature radius of 310 mm, would enable the optical designer to:

- Design a very fast camera of F 1.5 with fewer optical elements, thereby increasing the throughput by ~15 %
- Eliminate the vignetting and optimize the image quality through fewer optical elements and fewer air / glass surfaces
- Eliminate field flattening elements, necessitating to introduce other lenses for their correction
- Introduce cost savings on the optics side



Optical characteristics (both cameras):
Focal length: 300 mm
F/Number: 1.50
Entrance pupil diameter: 200 mm
Entrance pupil location:
125 mm in front of 1st lens
Angular field of view: 25 °
Detector: up to 100 x 100 mm

Figure 2. Comparison of optical design with curved detector (top) and flat detector (bottom). The optical characteristics of both cameras are given in the table (below).

With a flat detector often *no* camera design with an affordable number of lenses can be found with equivalent transmission and identical field of view.

3. PUBLISHED TECHNIQUES FOR CURVED DETECTORS, FILL FACTOR << 100 %

Rogers et al.[2] developed a CMOS detector (silicon) on a curved rubber substrate, mainly for applications of artificial seeing (Figure 3).

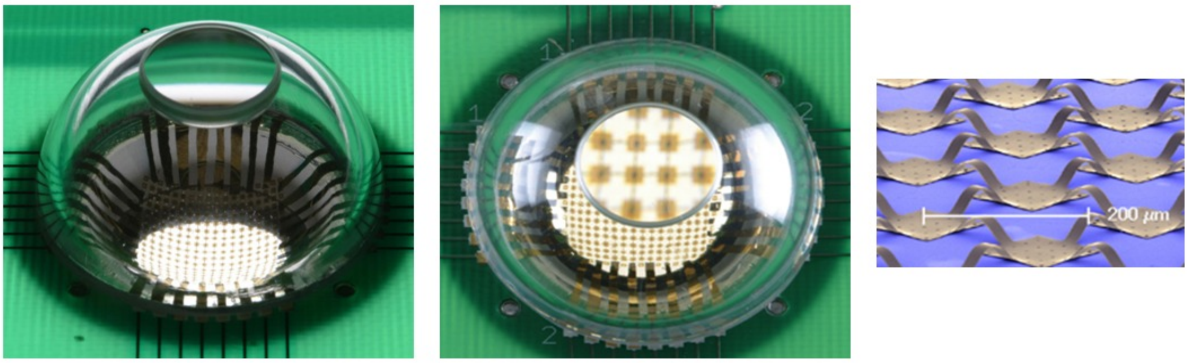


Figure 3. (Left) Curved CMOS detector on a curved rubber substrate, with optics; (Middle) Individual pixel cells (silicon) on curved rubber substrate; (Right) Magnified view of deformable ribbon metal cables between silicon islands. Reproduced with permission from authors[2].

Several mosaics of CCDs have been assembled on a curved substrate. One of them is the mosaic of Kepler, as shown in Figure 4. The individual flat CCDs are mounted on a curved substrate and are fitted with individual field flattener optics.

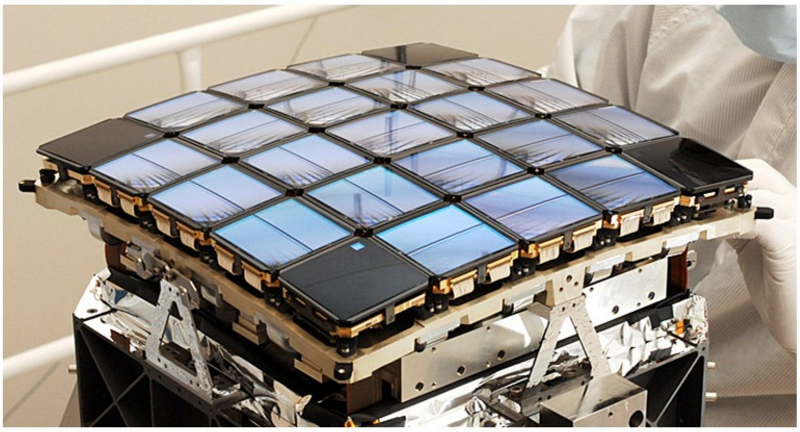


Figure 4. Image of Kepler focal plane, employing a CCD detector mosaic on a curved spherical substrate[3]. Reproduced with permission from authors[3].

4. PUBLISHED TECHNIQUES FOR CURVED DETECTORS, FILL FACTOR = 100 %

Method A: Curving silicon, then processing the curved silicon:
Jin[4] and Buchhoeft[5] describe techniques to first curve the silicon on a spherical glass substrate and then deposit the imager structures via soft lithography. To date no results of this approach are known to produce a working test imager with fill factor 100%.

Method B: Processing of flat silicon, followed by thinning, then curving:

I. Dinyari et al.[6] and Rim et al.[7] (Figure 5): The silicon is structured such as to introduce silicon springs between individual pixel islands, increasing its flexibility. Due to these structures this technology is better suitable for backside-illuminated CMOS detectors. Curved silicon (without detector) has been produced with size 1cm x 1cm and curvature radius 1cm.

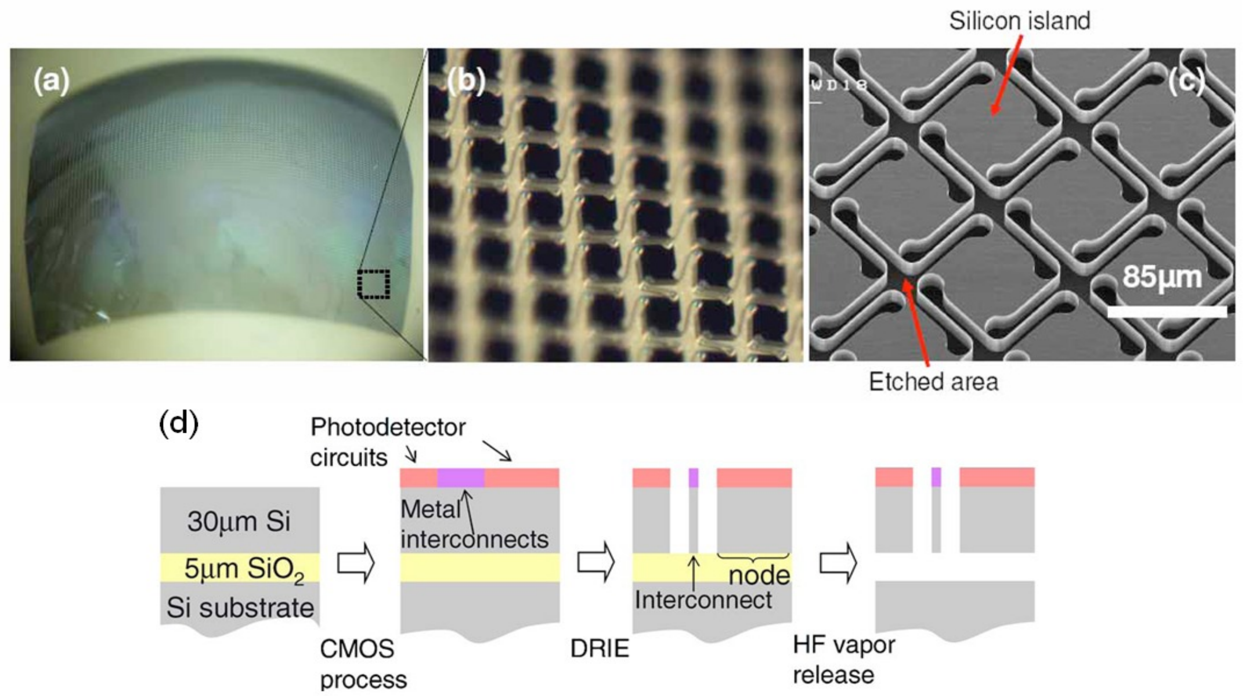


Figure 5. Silicon processed to increase its flexibility: (a) curved die, (b) detail of curved die at off-axis location,(c) SEM picture of undeformed die, (d) Silicon springs combined with electrical contacts. Reproduced with permission from authors[6].

All following techniques deposit first a CCD on flat silicon, then thin it with different backside thinning technologies in order to curve it:

II. Sarnoff process[8]: Figure 6 shows frame thinning at wafer scale without substrate, then bending the center 10…30 µm thin membrane. Advantages: Handling through monolithic frame, stressfree wet etching. The produced device with curvature radius ~ 500 mm was DC tested only.

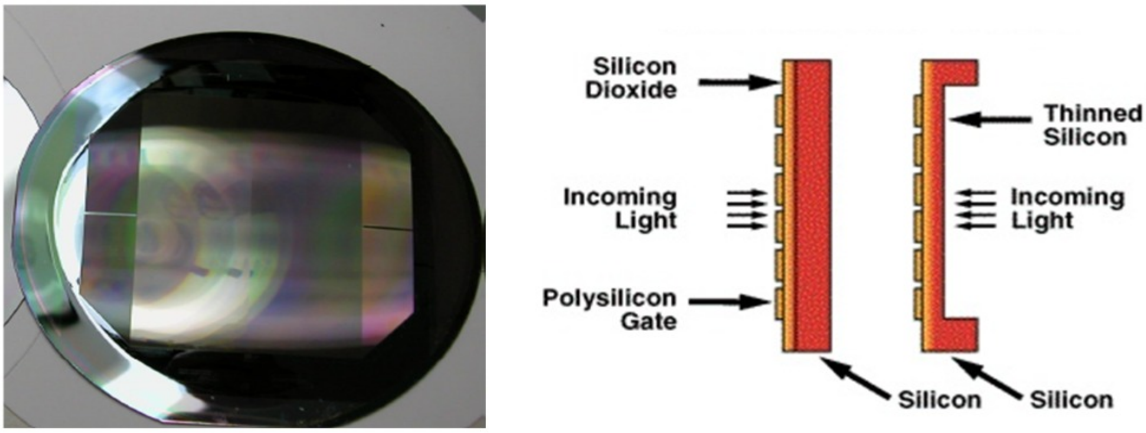


Figure 6. (Left) Spherical curved CCD wafer 4 inch, frame thinned; (Right) Principle of frame thinning. Reproduced with permission from authors[8].

Figure 6 illustrates the principle of frame thinning: This technique utilises the monolithic wafer as natural stabilisation frame with the thinned membrane inside. No substrate is required. For the curvature the device is then laminated with a curved glass layer.

III. ITL/University of Arizona[9]: Figure 7 shows the basic thinning sequence used. A key point for curving the device is the optimum thickness of the substrate supported device.

Main Backside Process Steps, ITL, University of Arizona

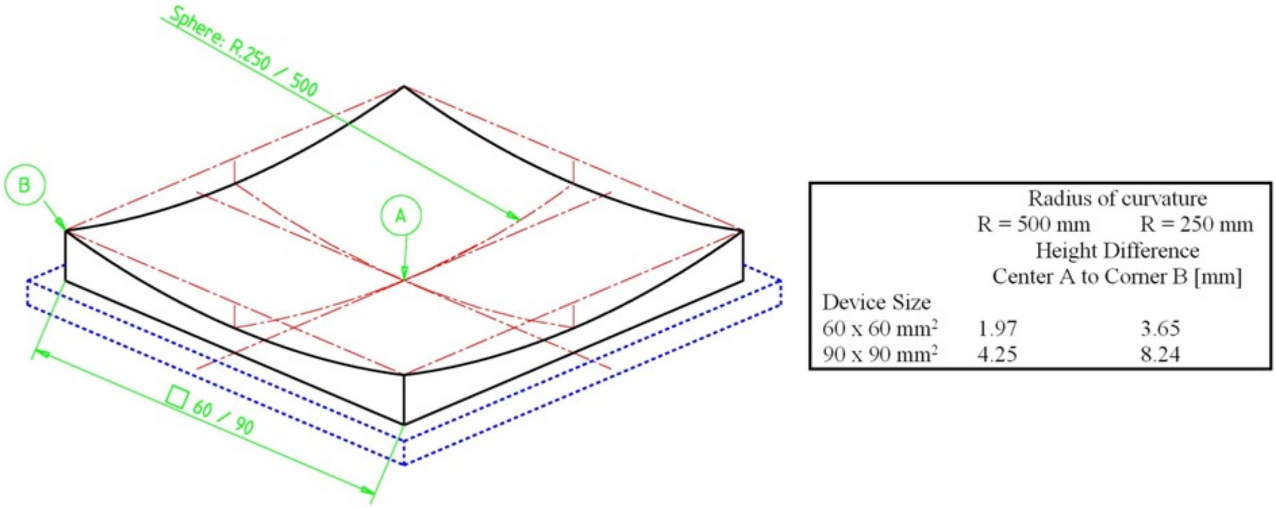
1. Wafer backside grind (vendor)
2. Stud bump application
3. Dice
4. Hybridize with substrate wafer
5. Epoxy underfill
6. Acid protection
7. Selective acid etch
8. Epitaxial acid etch
9. Oxidize back surface
10. Chemisorption/AR coating

Figure 7. Backside Process steps at ITL/University of Arizona. Reproduced with permission from authors[9].

IV. JPL process[10]:
Curved test devices (cylindrical and spherical) have been produced:
a.) Standard silicon: Similar to the ITL/University of Arizona process, but using a variety of techniques including attached or removable substrate, enabling to handle & curve the unsupported detector membrane, applying JPL molecular beam epitaxy (MBE) delta doping process.
b.) Thick fully depleted silicon: Polishing the thick wafer into curved shape from backside, growth of thin electrode at ultra low temperature, JPL MBE delta doping.

5. ESO'S SPECIFICATION & FEASIBILITY STUDY

ESO has a long-term interest in curved large monolithic detectors for E-ELT. After developing a specification, a feasibility study was started, aiming at curved detectors with a detector size between 60 x 60 and 90 x 90 mm^2.
The feasibility study leaves freedom for demonstration samples of smaller size, but focuses onto the final radius of curvature between 500 and 250 mm (Figure 8).



	Radius of curvature	
	R = 500 mm	R = 250 mm
	Height Difference Center A to Corner B [mm]	
Device Size		
60 x 60 mm^2	1.97	3.65
90 x 90 mm^2	4.25	8.24

Figure 8. (Left) Drawing of curved detector sphere, following ESO specification (Right) Associated height difference

The technical specification for the feasibility study separates the detector parameters into a.) physical properties and b.) electrical properties. Whereas a.) contains the main parameters for size, curvature radius and two dimensional concave shape, b.) states that the curved CCD in the end should not differ in its performance from a flat state-of-the-art detector of existing technology with 100% fill factor.

The specification summarized all performances for a potential curved end product and assumed that the thinning of the detector is mandatory in order to reach the specified curvature radius, while leaving ample options for the demonstration of the curvature possibilities either on non-working curved silicon die, or on a smaller size working CCD. The latter approach invited suppliers to take into account the projection and scaleability to larger device size.

In August 2009 the specifications were submitted to a wide variety of research institutions and all leading CCD manufacturers in order to attract potentially interested parties. The corresponding discussions and received proposals enabled to crosscheck the interest in end-to-end manufacturing or partial work packages, as well as to assign a ROM cost to the related activities.

6. LESSONS LEARNT DURING THE ESO FEASIBILITY STUDY

Internal to ESO the extraction of spectral information recorded with flat and curved detectors was studied[11]. The simulations show that the extraction of data from observations made with a curved detector does not imply a loss of quality or information.

The following points surfaced in more detail during discussions with interested parties:

- The vast majority of responses agreed that the bending should be done starting from a conventionally processed CCD structure on flat silicon without further design changes.
- Frame thinning technology seems to be the preferred approach to prepare detectors for curvature, ‘integrating’ the handling provisions ‘into’ the wafer.
- Chip internal strain: Theoretical simulation of bended silicon and empirical tests show limited agreement. It is not possible to model reliably the behavior of the internal silicon strain, due to its local crystalline imperfections. Laboratory tests are necessary to determine the level at which specifically processed Silicon cleaves.
- Scaleability: It is questionable whether scaling relations based on actual curvature of small devices give dependable forecasts for larger devices at identical curvature radius. Tests should be made as close as possible to the full scale of the specified device.
- The permanent support of the curved device needs to be studied together with the packaging materials to enable cryogenic operation.
- Bending the thinned surface is the first proof of concept. However, to enhance the curved backside surface, the bending step needs to be preceded (better still an integrated process) by a surface treatment that removes any resultant dangling bonds.

There is a principal tradeoff between two fundamental questions:

a.) Can the required curvature be demonstrated on a large-size (thinned) CCD ?
b.) How well will the (thinned) CCD perform after the bending process electro-optically ?

Some CCD manufacturers were initially very interested in this topic, but following their evaluation, based on theoretical simulation, were not convinced that there is a technique to curve thinned silicon such as to overcome the required size / curvature quotient, despite application possibilities in commercial products. The following section demonstrates that there is a realization potential even without thinning the silicon.

7. HIGHLIGHTS OF EXPERIMENTAL CURVATURE RESULTS

From a number of interesting results the following results are depicted exemplarily due to their direct impact on the fundamental points as outlined in Section 6:

JPL[10] demonstrated a number of theoretical calculations for thinned detectors, based on the mechanical deformation limit of Silicon of 1%, indicating a provisional limit at 45 mm device size and 325 mm radius of curvature with existing technology. Besides mounting thinned detectors to curved substrates using various approaches, techniques to curve thinned detectors unsupported were demonstrated. The curvature was modified on the fly by applying air pressure to the thinned membrane and also during readout of the detector. Figure 9 shows the principle of the used set-up and an unsupported thinned detector at different curvature radii.

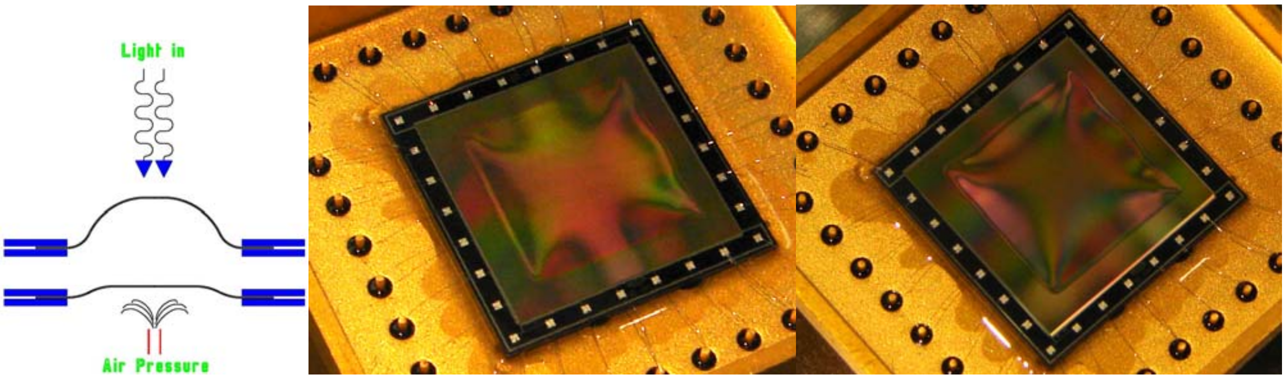


Figure 9. (Left) Principle of curvature modulation for thinned detector. (Middle & Right) Device curvature modulation at different radii from convex to concave on the fly. Reproduced with permission from authors[10].

The typical device size utilized was 1k x 1k with 12 µm pixelsize at a radius of curvature down to -250 (convex), respectively +250 mm (concave). The devices were operated without mechanical damage at room temperature and air pressures up to 22 psi. A qualitative and partially quantitative analysis of the device behaviour did not reveal significant performance changes for operating parameters such as output sensitivity and readout characteristics.
Furthermore, a different method of using thick full-depletion of devices has also been devised and demonstrated with 200 mm radius of curvature.

ITL/University of Arizona[9] demonstrated a spherical convex curvature of 500 mm on a non-working 500 µm thick frontside-illuminated CCD of 60 x 60 mm^2 size, permanently supporting it on a curved substrate and package. Figure 10 shows the curved frontside-illuminated detector mounted in its package.

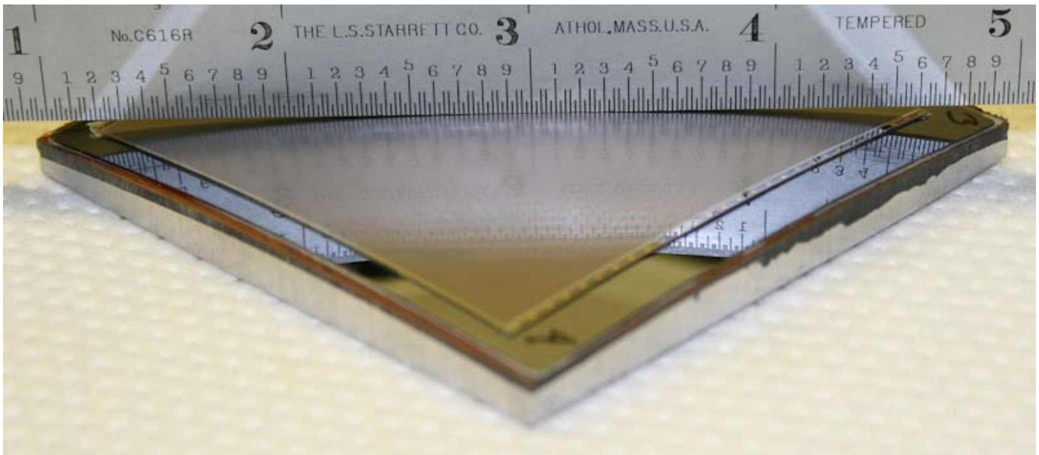


Figure 10. Photograph of convex curved frontside-illuminated ITL detector (thickness 500 µm) with size of 60 x 60 mm^2, curvature radius 500 mm. Reproduced with permission from authors[9].

As this test was deliberately done with a non-functional device, performance results are not available. Also the packaging materials have not yet been studied for cryogenic operation of the curved fully supported device. The convex curvature of the frontside device is an analogy to the concave curvature of a potential backside device.

8. TOWARDS CONCLUSIVE EXPERIMENTAL TESTS

ESO received a number of interesting proposals from different parties. Naturally the scope, experience and ROM cost varied greatly.

Taking all points into consideration, as highlighted in Section 6, ESO decided especially in view of the experimental results outlined in Section 7 to launch a first study contract, envisaging the following goals:

a.) curve working non-thinned frontside-illuminated devices with a size of 60 x 60 mm^2 with a curvature radius between 500 and 250 mm
b.) support the devices permanently and characterize the curvature cold
c.) characterize the curved detectors at cryogenic operating temperature in a test dewar and compare to cooled wafer-probe test results of the original flat devices for most of the typical device parameters for astronomical application (e.g., CTE, RON, dark current, cosmetic defects)
d.) keep in mind the scaleability of this process to 90 x 90 mm^2 devices and the required changes if done with a backside-illuminated device for improved quantum efficiency.

Provided the results of the upcoming phase are successful, an extension to thinned devices may be considered.

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