First results from a novel curving process for large area scientific imagers

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ABSTRACT

Observations in seeing limited imaging conditions with an extremely large telescope - such as the European Extremely Large Telescope (E-ELT) - will require large detectors and very fast cameras (around F/1.0). The correction of field curvature is a complex task, requiring numerous optical elements operating with high incidence angles. Large format (60 to 90 mm square) concave detectors with a curvature radius between 500 and 250 mm would considerably simplify the optical design, while improving image quality and cutting cost of optical components. Potential applications are not limited to astronomy exclusively. The associated advantages of curved image sensors inside (mosaicked) focal planes have been described in our paper "The challenge of highly curved monolithic imaging detectors", presented at SPIE 2010 [1].
This paper compares in a first step important developments in the area of curving CCD and CMOS detectors using different technical approaches linked to specific thinning processes with a novel approach followed after ESO's initial feasibility study: First results of the latter are described with a report on the chosen curving technology aimed at producing 500 to 250 mm radius of curvature silicon detectors of approximately 60 mm square format (typical astronomical 4k x 4k CCDs). The curvature technique has been developed for front-illuminated devices with the goal of extending the process to back-illuminated sensors in the near future. We will discuss the fabrication process of curving the devices as well as the difficulties encountered during development. Characterization results from a curved detector, including metrology, and electrical performance before and after curvature are presented.

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

1. OPTICS IMPROVEMENTS THROUGH CURVED DETECTORS

Figure 1 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^2 with curvature radius of 310 mm in both dimensions, 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 other aspects of image quality through fewer optical elements and fewer air / glass surfaces
- Increase back focal distance / dismiss field flattening elements, necessitating to introduce other lenses for their correction
- Introduce cost savings on the optics side

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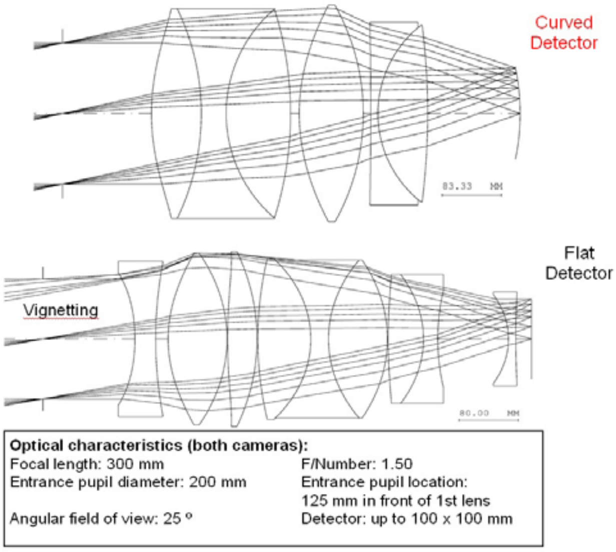

Figure 1. Comparison of optical design with curved detector in two dimensions (top) and flat detector (bottom). The optical characteristics of both cameras are given in the table.

Another example - more related to the overall achievable camera system performance - is shown in Figure 2, where both sketches on the top show an optics design with a curved detector of up to 153 x 153 mm^2 size with 400 mm radius of detector curvature for 20 and 30 degrees field of view:

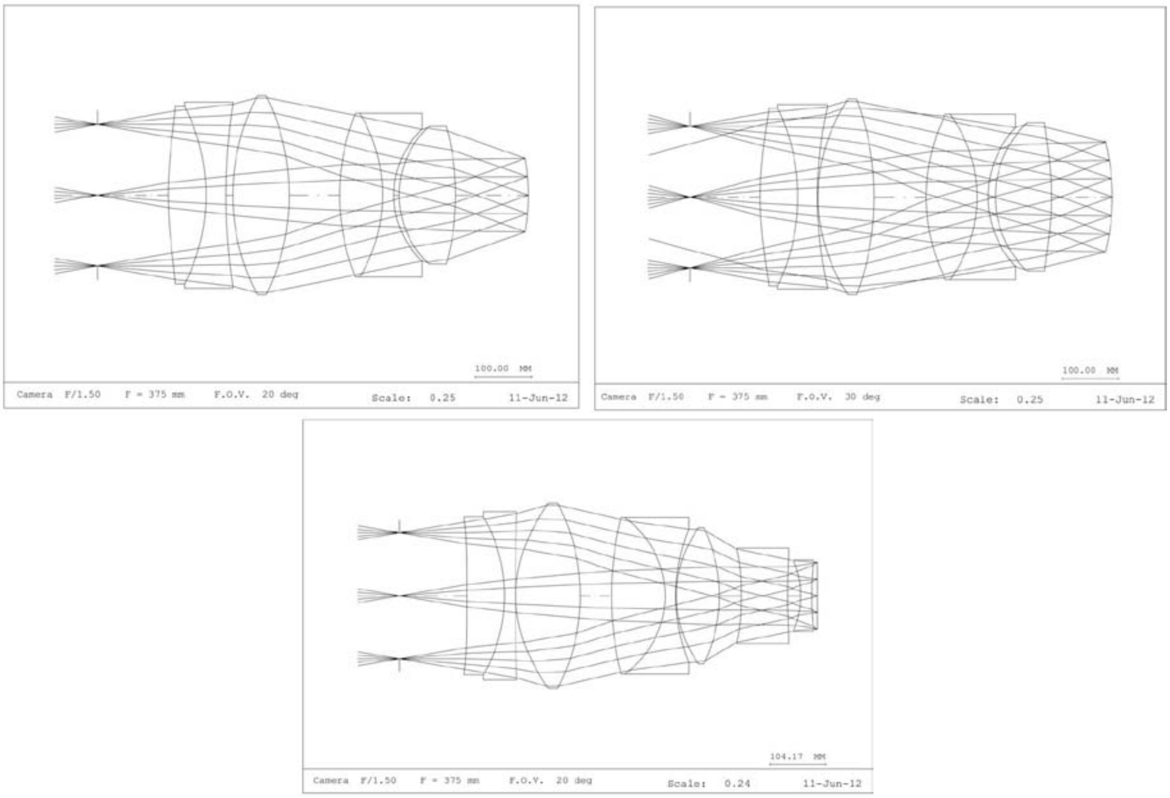

Figure 2. Comparison of optical design with curved detector in two dimensions (top two) for 20 and 30 degree field, and flat detector (bottom) with lower image quality

All three optics designs shown in Figure 2 have the same characteristics:

F = 375 mm
Pupil: 250 mm located 125 mm in front of the 1st surface
F/1.50
Wavelength range 480 – 1000 nm

The camera with the curved detector in Figure 2 has a better image quality (spot diameter of 15 µm over the complete field of view for 80% geometrical energy) than the camera with the flat detector (spot diameter ~ 22 µm). The latter has 2 lenses more and also an additional aspheric surface (three instead of two for the camera with the curved detector). The camera for the flat detector also requires much stronger lens curvatures which create severe problems for cementing and alignment. 20 degrees field of view is near the limit for a camera with a flat detector with this kind of fast F number. This is not the case for the camera with the curved detector, which can accommodate a much higher field of view of up to 30 degrees with the same vignetting at the edge of the field as shown in Figure 2.

In summary there are several main advantages of curved detectors versus flat detectors with respect to the optics design:

a.) Simplification and cost saving
b.) Best image quality
c.) Achieve a large back focal distance

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.

2. CONTEXT AND REQUIREMENTS OF CURVED DETECTOR DEVOLOPMENT

Several approaches for curved detectors in different forms (e.g., mosaics, distributed detectors, patterned silicon) have been tried in the past. The developments in the area of curved detectors have been reviewed in [1].

Due to the complex challenges in E-ELT instrumentation (see Section 1) and the obvious benefits of curved detectors from an optical point of view, ESO launched a feasibility study in 2009/2010 to explore the potential of curved detectors in connection with required detector properties. The main specifications for the required curvature properties based on optical design were to achieve a curvature radius of 500 to 250 mm with a device size of 60 x 60 mm^2 to 90 x 90 mm^2. These numbers correspond to a height difference of the silicon from center to corner between ~ 2 up to ~ 8 mm in the extreme case of an 90 x 90 mm^2 device with 250 mm curvature radius.
Although several techniques have been demonstrated on an experimental level for curved monolithic detectors, the feasibility study showed that most approaches could not conclusively demonstrate the full potential of curved detectors, because:

a.) the experimentally explored detector size was often small (e.g., 1 cm^2)
b.) the limits of the curvature radius with respect to large device size were not explored
c.) the question whether curvature results of a small device with high curvature radius can be scaled to a large device with smaller curvature radius pointed into the direction that experimental results must be collected for the actual device size and curvature radius required
d.) results of theoretical studies of chip internal strain inside the silicon prevented main commercial players to invest into curving technology. Theoretical simulations of bended silicon and empirical tests show however limited agreement. Experimental tests are required to determine the level at which specifically processed Silicon cleaves.
e.) devices have not been cryogenically tested after curvature for (potential loss of) typical CCD performance data and reliability of curved silicon
f.) previous curving techniques mostly relied on the expensive thinning process as a prerequisite. Frame thinning was a preferred approach 'integrating' the handling provisions 'into' the wafer.

In order to exploit the potential of curved detectors - and to overcome at least some of the above listed shortcomings - ESO decided after the outcome of the feasibility study to fund experimental development of curved detectors on R&D basis. The Imaging Technology Laboratory (ITL) [2] at the University of Arizona was chosen due to their early experience in curving thick CCDs cylindrically (Section 3) and in particular their two dimensionally thick curved prototype, as described in Section 4.

3. EARLY WORK AT ITL, CURVING THICK SILICON DETECTORS ONE DIMENSIONAL

Initial detector curving work was performed at ITL in the late 1990s using detectors attached to flex circuits and curved in one dimension only, to achieve a cylindrical shape. This effort resulted several years ago in cylindrical front-illuminated non-functional devices such as the STA 0520 2688x512 CCD [3] shown in Figure 3 with high curvature radius of ~ 25 mm (thickness 50 µm).

Silicon material can undergo a high cylindrical curvature, as shown in Figure 3, which cannot be achieved easily when curving the detector in two dimensions. In the latter case the introduced stresses into the silicon material can be modeled as a function of thickness and detector size and lead to predictions, which are not really promising to start such an undertaking. In particular those predictions point to the fact that the silicon detectors would need to be quite thin in order to reduce silicon internal strain and achieve an acceptable curvature. As shown in Section 1, the requirements of optical designers are clearly focused onto curved detectors in two dimensions, preferably spherical.

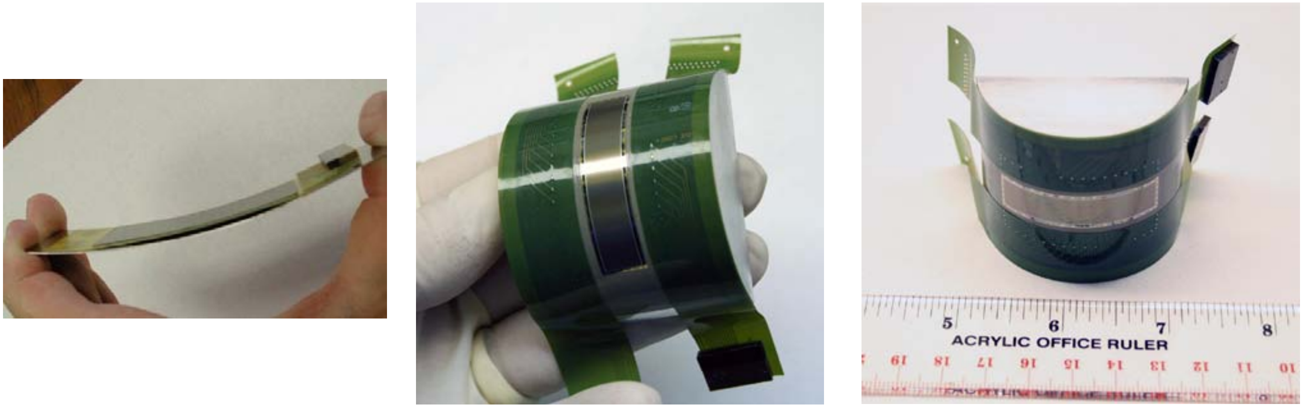

Figure 3. (Left) Early ITL cylindrically curved 2k x 4k CCD with low curvature radius,
(Middle and Right) Cylindrical STA0520 2688 x 512 CCD with ~ 25 mm radius of curvature

4. ESO / ITL APPROACH TO CURVE LARGE SIZE MONLITHIC THICK FRONTSIDE DETECTORS TWO DIMENSIONAL

In parallel to the search for a suitable R&D partner to further explore the potential of curved detectors, as described in Section 2, ITL had manufactured a non-functional sample with a spherical convex curvature of 500 mm with a 500 µm thick frontside-illuminated CCD of 60 x 60 mm^2 size, permanently supported on a curved substrate and package. Figure 4 shows the curved frontside-illuminated detector mounted in its package.

This was a non-functional device and was not cryogenically cooled, but its size and curvature radius matched well with the envisaged range of ESO's requirements.

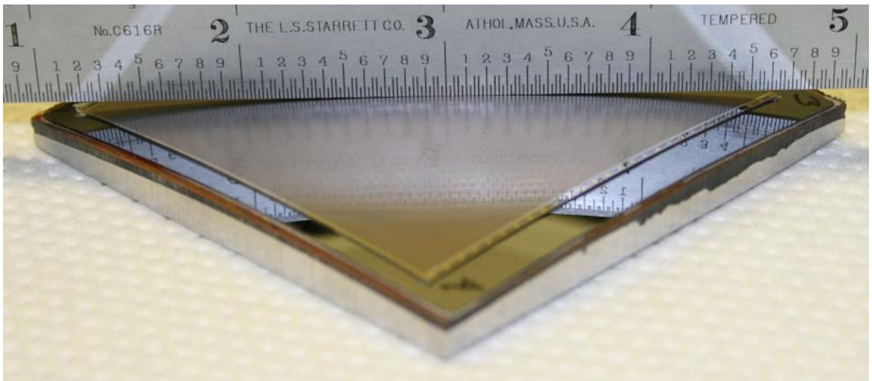

Figure 4. Photograph of convex curved frontside-illuminated ITL detector (thickness 500 µm) with size of 60 x 60 mm^2, curvature radius ~ 500 mm.

Due to ITL's success in curving frontside-illuminated detectors in cylindrical and spherical shape of rather high thickness, ESO and ITL agreed in 2010 on an R&D contract with the following main objectives for the developed hardware:

- Characterize flat dies of functional CCDs to be curved before curvature for CCD performance parameters
- Develop a repeatable process to curve large size front-illuminated devices of high thickness with a possibility to extend this process to backside-illuminated thinned devices in the long term
- Initially curve dead silicon large format devices concave in spherical curvature
- Exploit the limits of curvature radius with respect to large device size
- Manufacture functional unthinned large size (60 x 60 mm^2) frontside-illuminated curved devices with a curvature radius between 500 and 250 mm
- Permanently support curved devices with a fixed curvature inside a curved package
- Cryogenically cool the developed devices for characterization and test the reliability of the curved devices in cold operation
- Characterize devices after curvature and compare with results prior to curvature to enable a decision about the potential of large size curved detectors before investing into thinned devices and their curvature. If possible, eliminate doubts about performance shortcomings (e.g., potential increase of dark current, cosmetic defects, etc.) by testing the devices cryogenically, close to astronomical use.
- Provide a number of functional curved devices to ESO

ESO's interest in this work led to focusing on a development effort to spherically curve 4k x 4k (60 x 60 mm^2) STA 2900 CCDs with a radius of 500 - 250 mm through a novel "Double Vacuum Process". The developed technique and some failures on its way to success are illustrated in Section 5 and 6. Section 7 shows the findings when characterizing the curved devices and Section 8 discusses the possible extension of this process to thinned devices.

5. DEVELOPMENT OF NEW ESO / ITL "DOUBLE VACUUM PROCESS"

Several curving experiments with different ideas (compare Section 6) led to the development of the so called "Double Vacuum Process". Figure 5 shows the individual components of this process in simplified form.

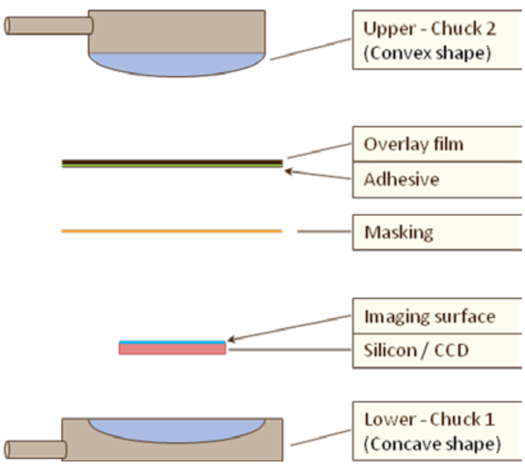

Figure 5. Individual components of "Double Vacuum Curving Process"

Figure 6 shows the basic process steps involved in the "Double Vacuum Curving Process" for a frontside-illuminated thick device.

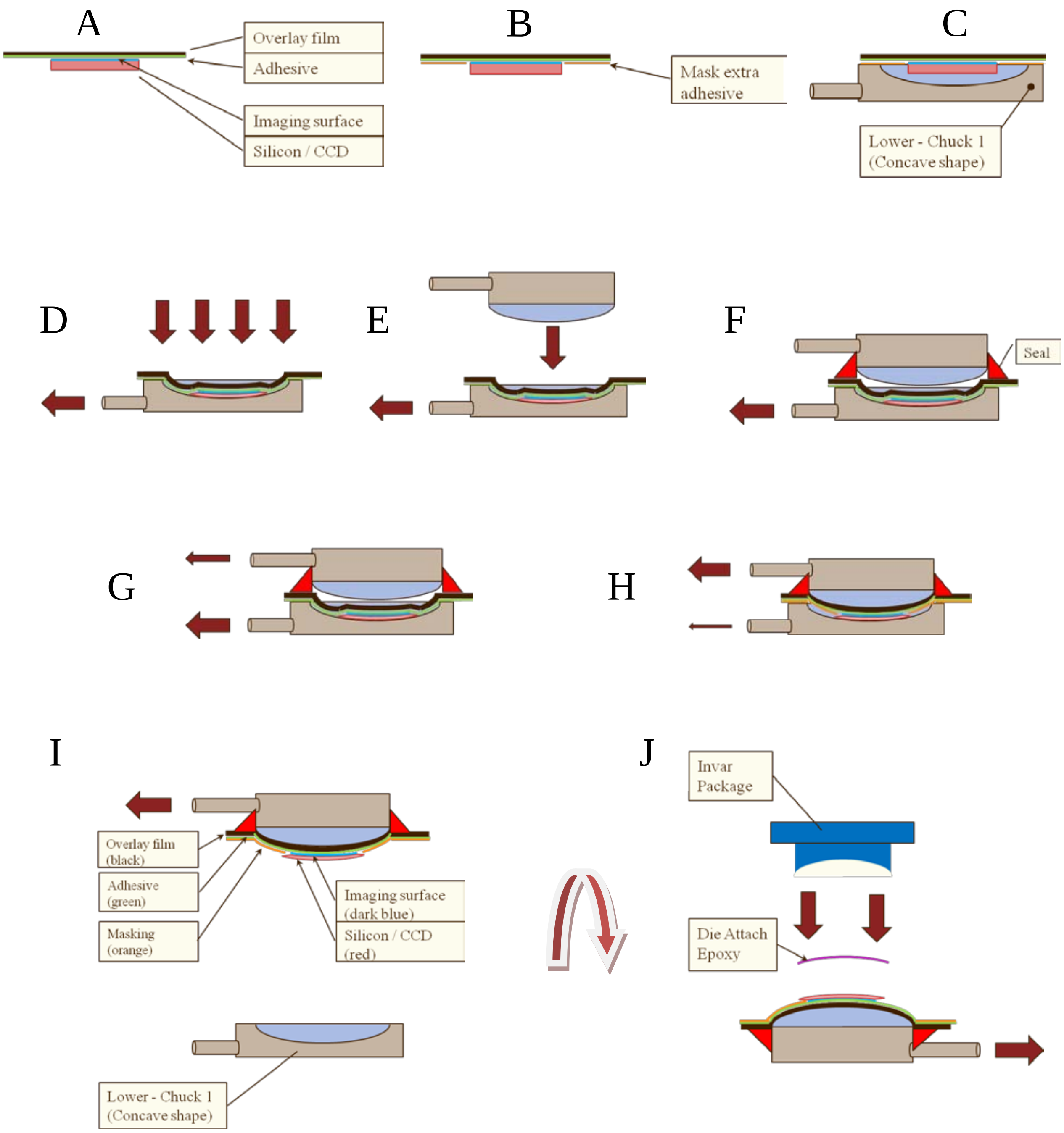

Figure 6. "Double Vacuum Process" illustrated in basic steps A to J in simplified form (compare Figure 5 and the text of this section for explanation)

The “Double Vacuum Process” shown in Figure 6 consists of the following steps in simplified form:

A: Apply silicon CCD to adhesive overlay film adhesive.

B: Mask off any unnecessary adhesive areas.

C: Place mounted silicon CCD and film onto lower vacuum chuck.

D: Open vacuum valve and evacuate lower chuck. (Masking not shown.)

E: Place upper chuck onto stack. Note that vacuum is still applied to lower chuck.

F: Apply adhesive sealant to outside of upper chuck and onto overlay film.

G: Apply vacuum to upper chuck while maintaining lower chuck vacuum.

H: Continue process of “crossing over” the vacuum. Eventually, upper chuck will be at full vacuum, and lower chuck will be vented to atmosphere, causing the silicon to transfer onto the upper chuck. The imaging surface is protected by the overlay film. Note that the overlay film’s adhesive must have very high strength, but also be easily removed.

I: The upper chuck and stack is removed from the lower chuck. The function of the masking (shown again here) is to allow easy release of the unit from the lower chuck.

J: The upper chuck is under vacuum. It is flipped over onto the bench. The “die attach” side of the CCD is now exposed, ready for packaging:
Epoxy and Invar package are applied. The epoxy is cured.
After the die attach epoxy is fully cured, the vacuum is shut off. The adhesive seal (red) is peeled away.
The overlay film is removed from the packaged curved CCD, exposing the imaging surface.
Wirebonding and other processing follows.

The associated hardware developed for this process is shown together with respective labelling in the photograph of Figure 7.

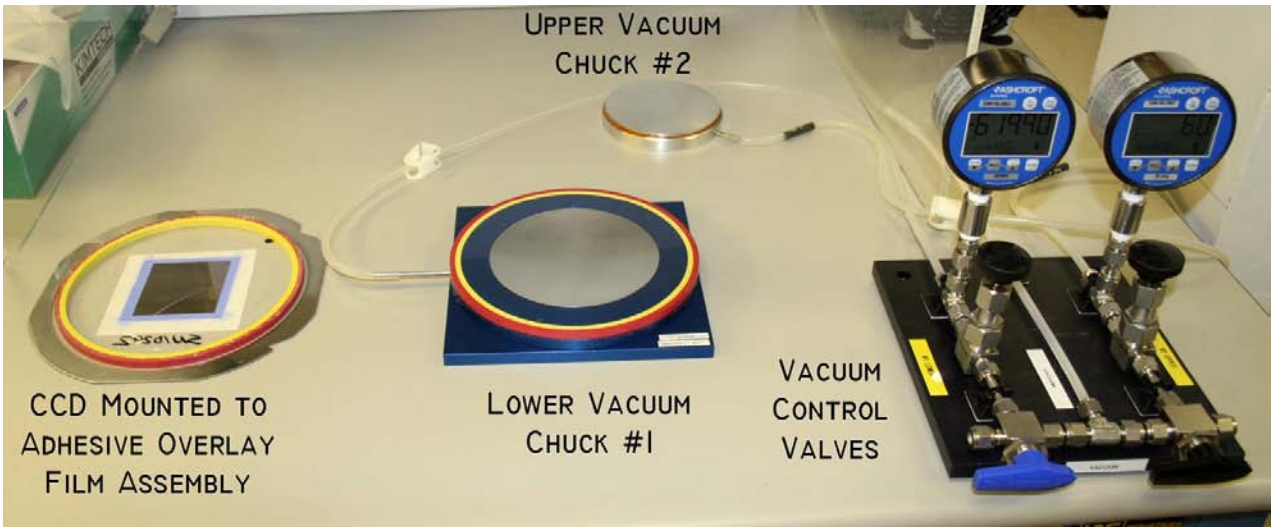

Figure 7. The process hardware to curve devices (compare Figures 5 and 6 for the different parts and process steps)

Figure 8 shows one of three working STA 2900 devices curved in two dimensions with this process. The devices are of 4k x 4k format with 15 µm pixelsize. The curvature radius is about 500 mm. The device performance for mechanical and electro-optical parameters is described in Section 7.

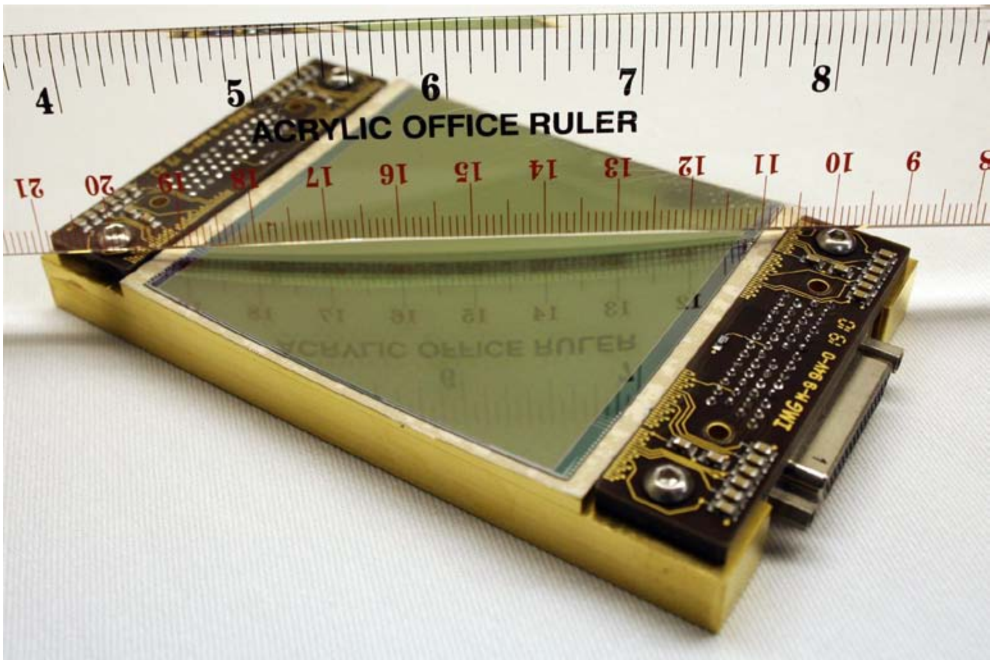

Figure 8. One of three working curved frontside-illuminated devices with 4k x 4k, 15 µm pixelsize, 60 x 60 mm^2, curvature radius ~ 500 mm in two dimensions. Starting point was an STA 2900 device.

6. PROCESS STEPS WHICH DID NOT WORK AS PLANNED

Initially there were many failures due to silicon stress, as can be seen in Figure 9.

Figure 9. (Left) Successful spherical curvature before (Right) self destruction due to stress

D. Ouellette: "At least they take some minutes now before they explode – that's progress..."

A key component for all testing with CCD and substrate silicon material was to obey the crystal orientation and to always use a <100> orientation for repeatable results.

Amongst many interesting items studied during the course of this R&D effort, the following fields of work with suboptimal results deserve to be mentioned, leading in the end to the successful "Double Vacuum Process":

a.) Initially the planned method was to only employ a single vacuum chuck and relying onto the cast transfer moulding to maintain the shape of the curved detector, after the vacuum pressure had been released from the vacuum chuck in the following sequence:

1. Bond CCD sensor to silicon support substrate.
2. Mount imaging-side up to overlay film with temporary adhesive.
3. Fixture to vacuum chuck. Induce curvature per process recipe.
4. Cast transfer molding onto overlay film. Allow to cure.
5. Release vacuum. Detector is held to shape by transfer molding compound.
6. Attach curved sensor stack to package top-unit with room-temperature curing epoxy.
7. Remove transfer molding compound.
8. Remove overlay film.
9. Align sensor stack including package top unit to package bottom-unit
10. Wire bond and test.

Unfortunately stress cracking of the silicon substrate due to shrinkage of the transfer moulding compound was observed.

b.) Importance of material selection: Physical properties of the transfer moulding in connection with the overlay film are important. In addition to meeting temperature requirements of the process, the shrinkage of the compound itself should be well behaved. It must form a sufficiently strong bond to the overlay film so that it does not delaminate when vacuum is released, yet removes easily. High stress materials lead to wafer cracking, even with wafers 500 µm thick. There was a great span of materials tested from window putty to high tech materials. This also applies to the adhesive overlay film materials, the masking material of adhesive / non-adhesive zones and their exact dimensioning, and the vacuum chucks.

c.) Vacuum chuck materials and shape are key items in the curving process for both vacuum porosity and CCD curvature profile: The vacuum chuck is constructed from Metapor, a commercially available easily machinable composite of aluminum and epoxy, which has good porosity for its function as vacuum chuck, but it cannot be polished as is possible with porous ceramics, which is still to be tried. Possibly the sharp edges of silicon tend to grab into the chuck material, especially for 125 µm thick wafers. Once the silicon can no longer slide during the vacuum draw-down step, it breaks. Test trials of etching CE6 (Aluminum–silicon composite material) on the other hand did not achieve the necessary porosity. An obvious step would be to fabricate the CCD package top from a porous material so that it can simultaneously serve as the vacuum chuck for inducing the curvature, but metaphor is not suitable as it presents a severe outgassing risk, lacks sufficient mechanical integrity on its own, and would retain large amounts of water vapor due to its large internal area. There are other porous chuck materials, and even different grades of Metapor to be investigated in the future.

Initial tests indicated that the chuck should be shaped concave no matter which curvature (convex/concave) is to be achieved on the CCD. This way pressure is applied more uniformly over the circumference of the detector as the chuck is evacuated. By comparison, bending silicon over a convex chuck can result in high concentration of stress at the center, and shattering at the point of contact was often experienced. The hardest part was the compliance of the CCD center to the spherical curvature of the vacuum chuck. As a countermeasure the chuck center was machined to different non-spherical shape to compensate for the divergence of device curvature versus chuck curvature. In the "Double Vacuum Process" a different curvature radius was used for lower and upper vacuum chucks.

d.) 100 mm wafer bending results versus bending diced rectangular devices:
Bending complete 100 mm wafers during initial experiments proved to be easier than bending rectangular diced CCDs mounted to an overlay film. Even when bending whole wafers with 125 µm thickness the influence of the primary and secondary wafer flats became apparent when they broke. When bending diced CCDs the stress form the corners of the CCDs introduced a characteristic X shape. An alternative method to circumvent this may be to laser-core the wafer such as to create a minimum diameter circular die, encapsulating the rectangular CCD. This way during the vacuum draw-down process all edges would be fully supported, possibly leading to less risk of breakage and better uniformity of shape.

e) Stack height / material thickness choices:
Wafers thinner than 200 µm cracked during the bending process. The cracks propagate from where the wafer flat meets the wafer curved edge in nearly all instances observed. (Initial failure rate of 125 µm thick wafers was 100%.) Wafers in the 200 to 500 µm range bend relatively easily, however their ability to match the curve of the vacuum chuck decreases as thickness increases. Although first curving experiments with stacked material (CCD plus silicon support substrate, as used in preparations for thinning CCDs) were successful, later experiments concentrated provisionally onto an optimum thickness of ~ 200 µm in monolithic material in the interest of first concluding on the electro-optical characterization of functional curved devices to exploit their potential. After more experience and successful curvature results with the "Double Vacuum Process" the idea of stacking was successfully re-introduced for the first thinning experiments (see Section 8).

The above items led to the successful implementation of the "Double Vacuum Process", as described in Section 5.
Figure 10 shows a number of experiments carried out with the "Double Vacuum Process" in which e.g., the way the raw material was attached to the overlay film differed. It can clearly be seen that many details matter in connection with the used materials (see b and c above) and the base material thickness (see d and e above). The same thickness of material in one case breaks and in the other case can be curved. Due to the fact that the results achieved in this paper are only a couple of weeks old, there is still room for process improvements.

This Breaks	**This Does Not Break**
Stock Ø100 mm unlapped blank wafers (~580 µm thick) machine-mounted to overlay film.	These wafers <u>not bonded</u> to the film, but pressed using the non-adhesive side.
Ø100 mm device (processed) wafers lapped 254 µm thick, machine-mounted to overlay film with grind-side toward chuck.	• These wafers machine-mounted to overlay film with grind-side <u>away</u> from chuck. • These wafers with grind-side toward chuck, but manually mounted to "looser" overlay film.
Ø100 mm device (processed) wafers lapped 125 µm thick, mounted to overlay film in any manner, with grind-side toward chuck.	These wafers <u>not bonded</u> to the film, but pressed using the non-adhesive side. • Variable results (50%) with grind-side toward chuck. • Highly successful with grind-side away from chuck.
62 mm x 66 mm x 200 µm CCD die not bonded to the overlay film, grind-side toward chuck.	• 62 mm x 66 mm x 200 µm CCD die <u>bonded</u> to the overlay film, grind-side toward chuck. *(Note- Did not attempt grind-side away, so no result.)* • 62 mm x 63 mm x 254 µm CCD die - either bonded or not bonded to overlay film, and - either grind-side toward or away from chuck. *(Note- May not be in full contact with chuck.)*

Figure 10. Different curving methods tried with the "Double Vacuum Process"

7. MECHANICAL AND ELECTRO-OPTICAL CHARACTERIZATION RESULTS OF CURVED CCDs

Cryogenic stress testing of curved device: The first curved device (similar to the one shown in Figure 8) underwent ~ 10 dunk cycles into liquid nitrogen without breakage (Figure 11). The subsequent devices were cooled down to -120° C for characterization tests, as described below.

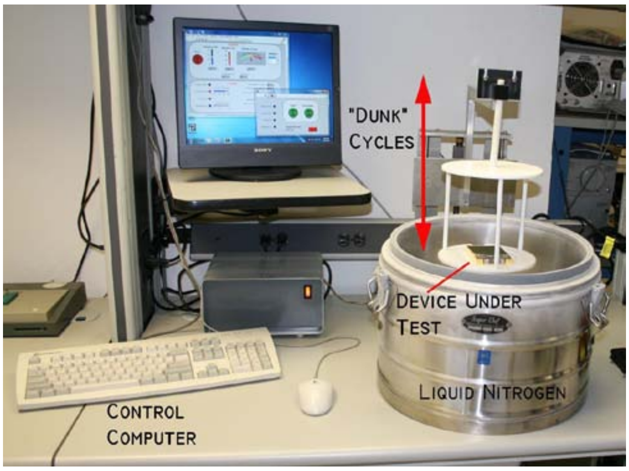

Figure 11. Setup for cryogenic stress testing of curved device

Curvature radius and shape: In order to complete the study project, most experiments concentrated on achieving a reproducible curvature radius of ~ 500 mm on the 60 x 60 mm^2 CCDs. A curvature radius down to 250 mm was tried, but requires more optimization in the interplay between top and bottom vacuum chuck materials, their optimized curvatures, the material thickness and the "Double Vacuum Process", as discussed in Section 6. Achieved exemplary results of one of the three curved devices are shown in Figure 12 for surface profile and curvature radius measurements. These have been corrected for tilt.

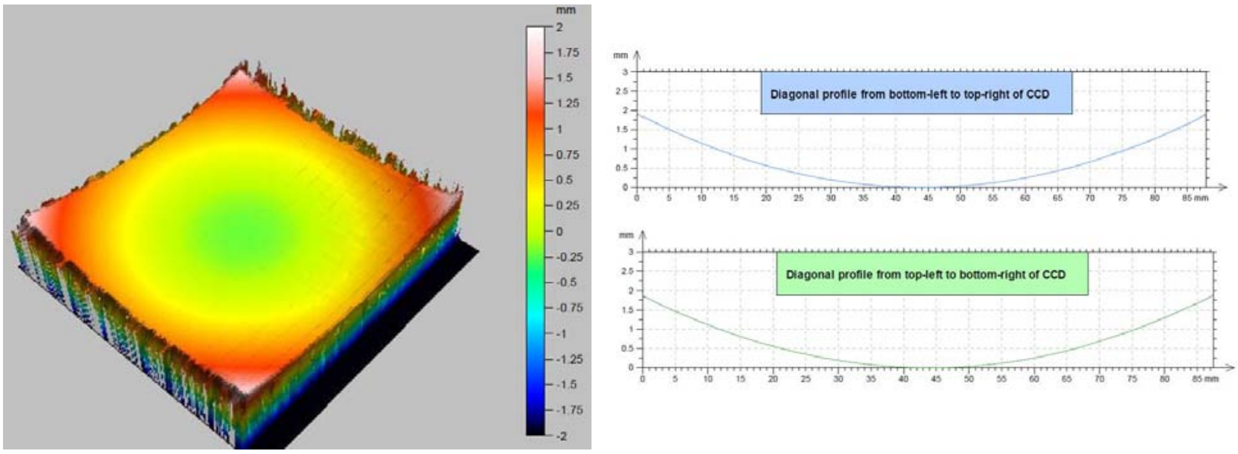

Figure 12. (Left) 3D surface profile (Right) Curvature radius measurements across device

Repeatability of curvature shape:

The three curved functional detectors differ slightly in curvature radius and shape. All show a curvature radius of ~ 500 mm. The repeatability of the curvature shape and radius is believed to be improved by a better centering of the device with respect to lower and upper vacuum chucks during the "Double Vacuum Process", together with improved process tooling for precise positioning, reference templates and guide pins.

Electro-Optical Tests: The three functional devices were tested prior to curvature on a cooled wafer probe station to - 60° C and after curvature in a test cryostat allowing to operate at -120° C. Comparison of test results before and after curvature show no significant performance differences:
Figure 13 shows exemplary main parameters of cryogenic characterization after device curvature of one device. The differences between the three devices are not significant. In one device a defect developed, which could also be due to a device internal problem, independent of the curving process. Suspicions about potentially increased dark current or blemishes due to device curvature could not be confirmed. Long dark exposures, cosmetic performance and Fe55 CTE test data, as well as the comparison to performance data of a backside-illuminated flat device of the same type in regular telescope use do not reveal any major differences leading to concerns.

Therefore there is no obstacle from the actual test data point of view to invest further into the process of curving detectors with improved curvature repeatability, larger size, higher curvature and backside illumination.

Operating Conditions				
System	Kadel dewar			
Temperature	-120 C			
Summary				
Amp	0	1	2	3
Notes	OK	OK	OK	OK
Read Noise Fe-55 (e)	5.4	5.5	4.9	4.2
Read Noise PTC (e)	5.4	5.2	5.4	5.1
Fe55 HCTE	0.999997	0.999997	0.999997	0.999997
Fe55 VCTE	0.999999	0.999999	1.000000	1.000000
Fe55 Gain (e/DN)	1.7	1.8	1.7	1.7
PTC Gain (e/DN)	1.8	1.8	1.7	1.7
Ramp Full Well (e)	>120,000 e^-	>120,000 e^-	>120,000 e^-	>120,000 e^-
PTC Full Well (e)	>120,000 e^-	>120,000 e^-	>120,000 e^-	>120,000 e^-
Dark Current (e/pix/hr)	2.4 e/pix/hr @ -120 C			

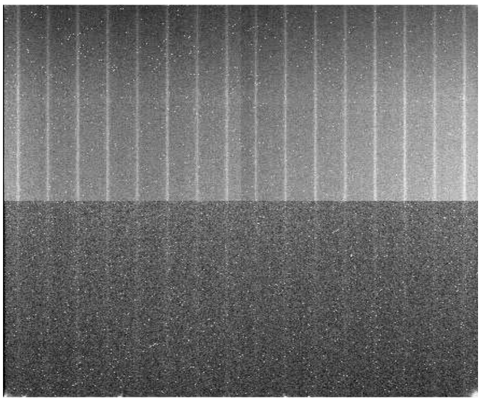

Figure 13. (Left) Exemplary measurement data of main CCD parameters after curvature (Right) Exemplary dark exposure of 600 sec. at -120°C of curved device. Visible stripe patterns are independent of curvature process (metal strapping for high speed clocking on STA2900 devices)

8. EXTENSION OF DOUBLE VACUUM CURVATURE PROCESS TO THINNED DEVICES

The "Double Vacuum Process" demonstrated that large size devices can be curved with a thickness around 200 µm, opposite to most other processes curving a thinned device of considerably lower thickness. Performance results in cryogenic testing indicated no obvious shortcomings. A logical next step is therefore the question whether the "Double Vacuum Process" can also be used to produce thinned devices, leading to state-of-the-art detector performance available for flat devices.

In order to keep the same process recipe for the curvature and to extend this process to thinned devices, first thinning experiments have been carried out with a wafer carrying a non-functional monolithic 2 x 2 mosaic of 2k x 2k sized CCDs, imitating a single 4k x 4k sized die. This enabled to test the basic thinning step through acid etching after device curvature with the "Double Vacuum Process" at the same scale with the least risk and financial budget. Figure 14 shows the die and its frontside mounting to an acid resistant ceramics.
The silicon was curved to a curvature radius of about 500 mm, through the (standard) "Double Vacuum Process", starting at a thickness of 125 µm after initial lapping, to demonstrate also the feasibility of this thickness with this process (compare Section 6).

Instead of bonding to a curved Invar package as done for front-side operation, this unit was epoxied onto a curved ceramic holder. The perimeter of the part was protected with acid-resistant wax as shown in Figure 14. Since this was an initial trial, there was no effort spent in trying to provide for a uniform waxing border or optimizing the holder at this point.

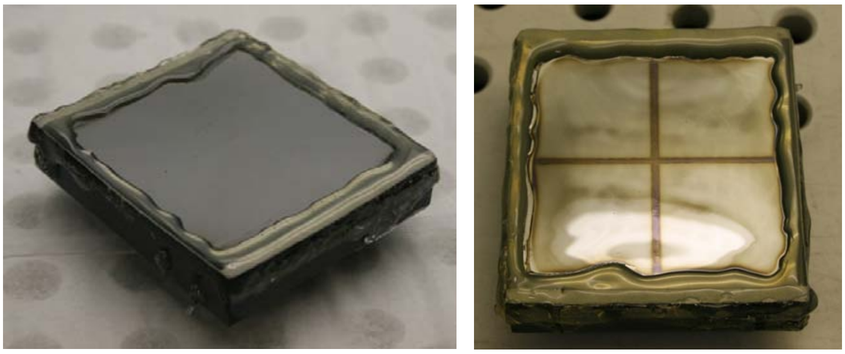

Figure 14. (Left) The curved mosaic part mounted backside-upward onto the curved, acid-resistant ceramic. An expedient wax border protects critical edges from attack. (Right) The successfully etched part. The dark lines relate to the space between the dies.

A critical question in this step was whether a uniform device thickness in etching could be achieved for curved devices. After successful etching a thickness between 20.5 and 21 µm was achieved across the thinned curved die. This result is generally consistent with historical results on flat devices. There does not appear to be significant deviation based on curvature.
Further development work is required with functional devices, but these first results are very encouraging and demonstrate the compliance of the thinning process with the “Double Vacuum Process” to obtain device curvature.

9. CONCLUSIONS AND OUTLOOK

In commercial applications - e.g., in mobile phones - the use of small curved detectors would simplify the cost of the optics in the first place. In the high-end area, such as astronomical instrumentation for E-ELT, the main benefits are partially on the cost side and simplification of the optics, but mainly on the significant better image quality achievable by crossing new frontiers for overall camera performance parameters, which are simply not achievable with flat detectors.

In the described research and development project all set objectives were fulfilled to demonstrate that the potential of curved detectors has not yet been fully explored in practical system implementation, although it is feasible to produce them.
To our knowledge this is the first time ever that:

- Several devices with a thickness of 200 µm and a size of 60 x 60 mm^2 have been curved concave with R ~ 500 mm repeatedly (dies are permanently supported) – in contrast to theoretical models predicting this would fail
- Cryogenic measurements at -120° C of three devices demonstrate no major behavior difference in main CCD parameters after curvature, supported by Fe55 tests and photon transfer curves
- A test device survived cryogenic stress testing with ~ 10 thermal cycles into liquid nitrogen

An extension of this process to even larger devices / stronger curvature and application to thinned devices are under discussion. The basic compatibility and homogeneity of the thinning process after curvature have been tested.
Further improvements in the developed “Double Vacuum Process” will enable a better repeatability and predictability of the curvature shape. New ideas such as active packaging exist, which deserve to be explored.
Additional funding will be required to extend the developed process to a higher radius of curvature, larger format devices (90 x 90 mm^2) and complete thinning and backside treatment after the curvature process.
The authors are looking forward to a new era, in which the fundamental laws of physics cannot be tricked, but the curved detectors might revolutionize the way in which optics design is applied in the future.

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