The challenge of highly curved monolithic imaging detectors

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ABSTRACT

Current assemblies of image sensors and optics rely on the optics to project a corrected image onto a flat detector surface. In the optical design study of instrumentation 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 (90 mm square) concave curved detectors, with a low radius of curvature (500 - 250 mm). This paper summarizes important developments in the area of curved detectors in the past, their different approaches, and ESO's specifications for an on-going feasibility study.

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.

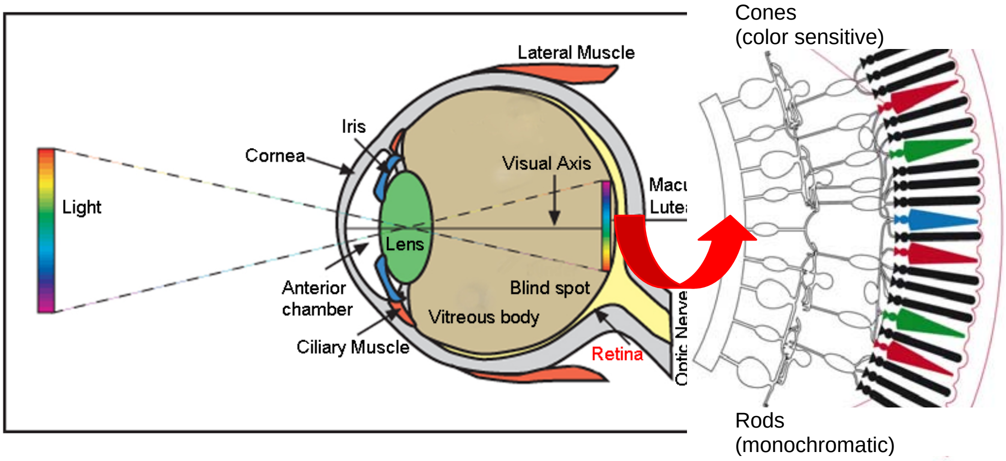

Figure 1: Picture of a human eyeball (left) and detail of its curved retina (right) ***[1]***
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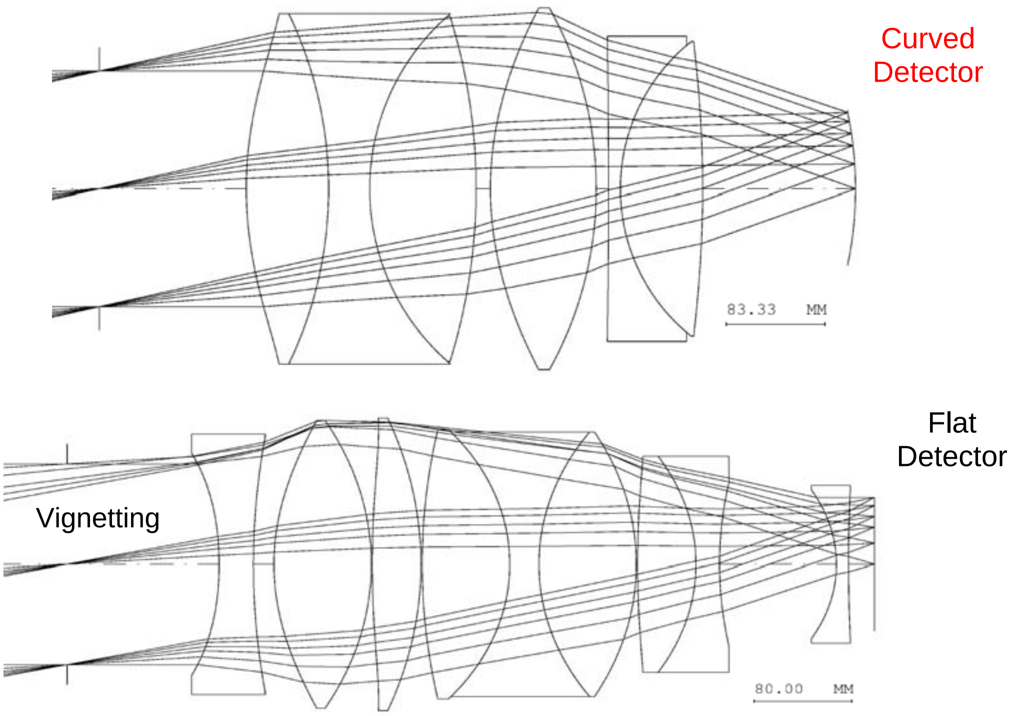
2. WHY A CURVED DETECTOR FOR E-ELT ?

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 incident 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 to:

- Design a very fast camera of F 1.5 with fewer optical elements, herewith 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 º	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 identical 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).

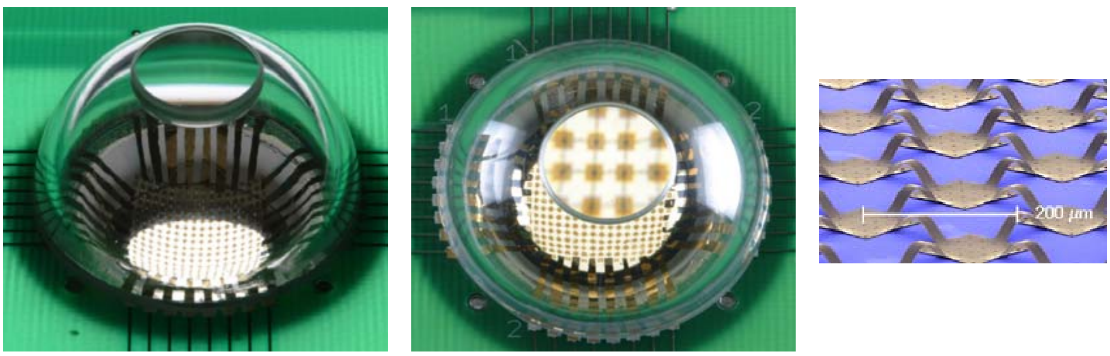


Figure 3: (Left) Curved CMOS detector on a curved rubber substrate, with optics;
(Middle) Individual pixel cells (silicon) on curved rubber substrate;
(Right) Magnified view of deformable ribbon metal cables between silicon islands
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Several mosaics of CCDs have been assembled on a curved substrate. One of them is the mosaic of Kepler, as shown in (Figure 4).

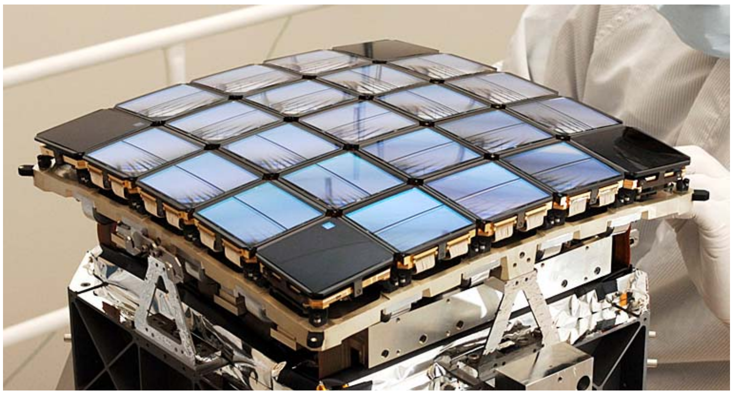

Figure 4: Image of Kepler focal plane, employing a CCD detector mosaic on a curved spherical substrate ***[3]***
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4. PUBLISHED TECHNIQUES FOR CURVED DETECTORS, FILL FACTOR = 100 %

Method A: Curving silicon, then processing the curved silicon:
Jin **[4]** & Buchhoeft **[5]** describe techniques to first curve the silicon on a spherically curved 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. Rim & Peumanns **[6]**, **[7]** (Figure 5): The silicon is structured such as to introduce silicon springs between individual pixels 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.

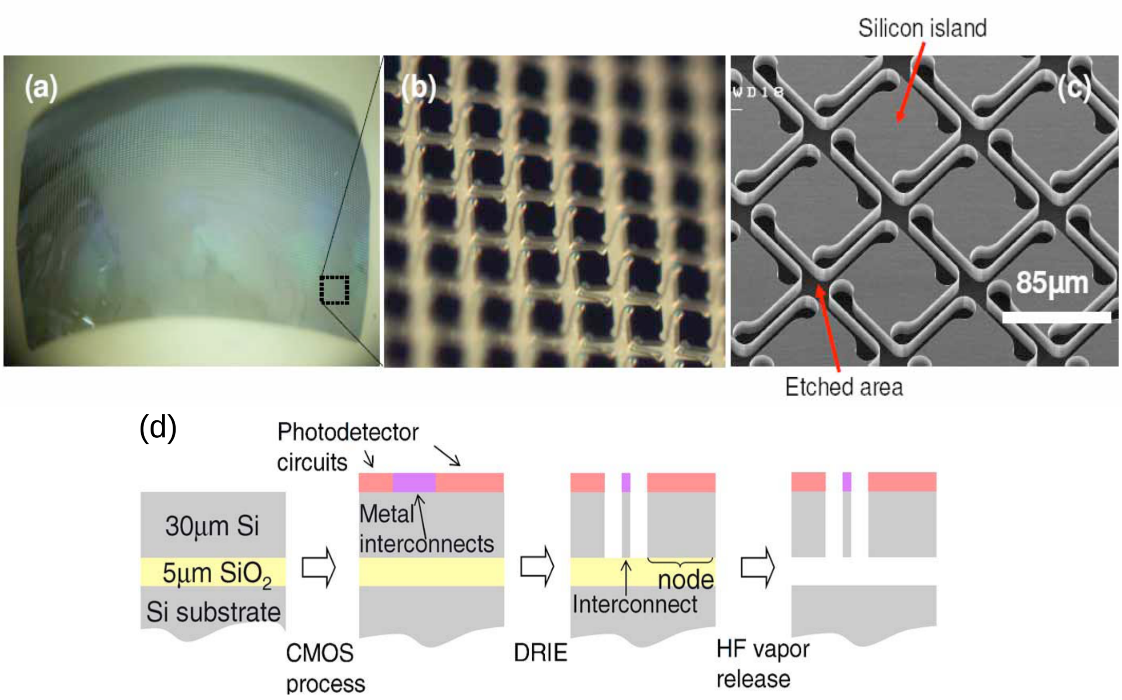

Figure 5: Silicon processed to increase its flexibility: (a) curved die, (b) detail of curved die at off-axis location,(c) SEM picture of undeformed die, (d) Silicon springs combined with electrical contacts
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All following techniques deposit first a 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.

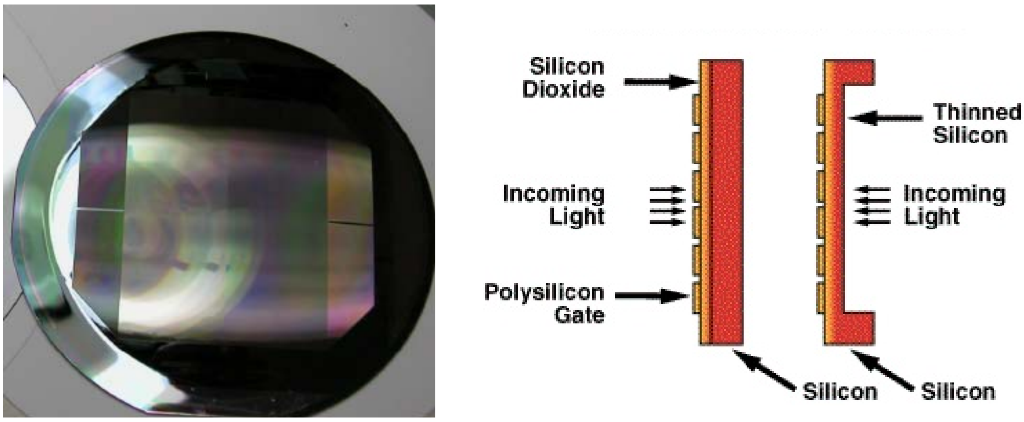

Figure 6: (Left): Spherical curved CCD wafer 4 inch, frame thinned.   (Right): Principle of frame thinning
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Figure 6 illustrates the principle of frame thinning: The frame thinning utilises the monolithic wafer as natural stabilisation frame with the thinned membrane inside. No substrate is required. For the curvature the device is then laminated with a curved glass layer.

III. ITL/Lesser process **[9]**: Figure 7 shows the basic thinning sequence used by M. Lesser. 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
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IV. JPL process **[10]**:
Curved test devices (mainly cylindrical) have been produced:
a.) Standard silicon: Similar to the Lesser process, but using a removable substrate, enabling to handle & curve the unsupported detector membrane, applying JPL 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 of 90 mm x 90 mm.
The latter leaves freedom for demonstration samples of smaller size, but focuses onto the final radius of curvature between 500 and 250 mm (Figure 8).

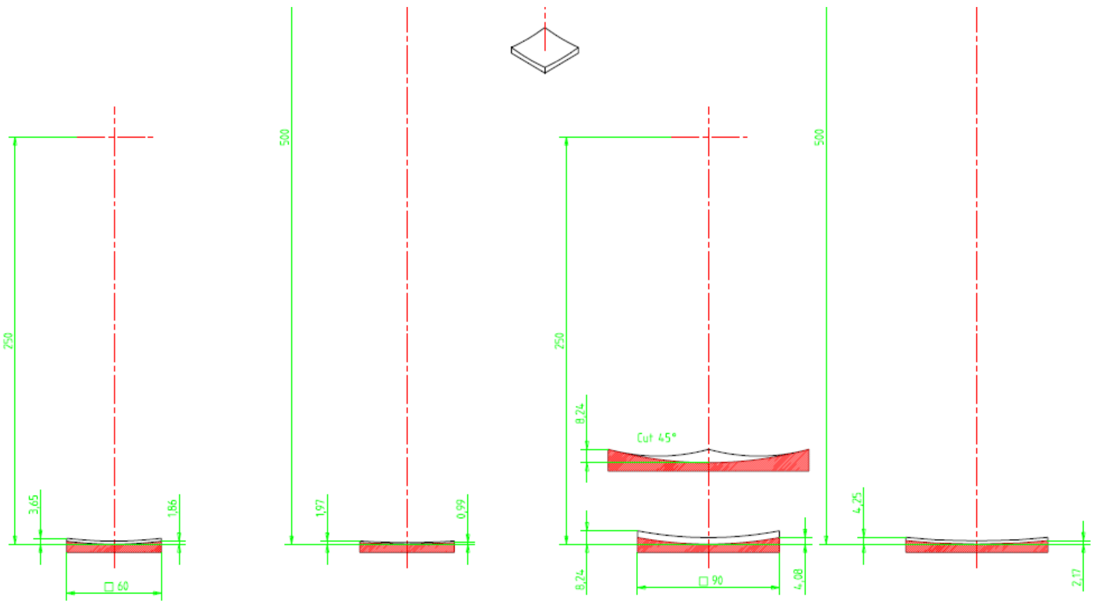

Figure 8: Drawing of curved 60 x 60 mm detector (left), respectively 90 x 90 mm (right). The height difference between center and corners of both detectors are shown for curvature radii of 500 mm, respectively 250 mm.

STATUS / NEXT STEPS OF ESO FEASIBILITY STUDY

The following points outline findings and current status of ESO’s feasibility study:

- Simulation of spectral extraction shows a good match between flat & curved detectors.
- August 09: Draft Specification was sent out to a wide variety of companies and research institutions
- Ongoing: Informal discussions with potential partners to define feasibility of study / scope of work and ROM cost per phase
- Q4/2009 Update of specifications, Q1/2010 Formal call for tender procedure

6. IS IT FEASIBLE ?: OPEN ITEMS

In the current phase the following items have been identified, which will require a follow-up during the next phases of the feasibility study:

- Is an existing detector construction suitable for curving?
- How well will an existing detector perform after bending (fields, shift charge, noise...)?
- Will the optical PSF be as before?
- Which features will the crystal structure exhibit after bending (increased dark current / defects)?
- What is the most promising approach to curve thinned silicon (supported / unsupported)?
- What is the optimum thickness before curving the (thinned) detector?
- Is backside thinning really a requirement for curved silicon?
- How well is the curving process scaleable after testing small samples (at identical radius of curvature)?

REFERENCES

[1] http://www.studentenlabor.de/seminar1/Photorezeptoren.htm

[2] John Rogers, 7. August 2008, University of Illinois, Urbana Champaign, Nature Vol. 454, pages 748-753

[3] Ball Aerospace http://www.ballaerospace.com/gallery/kepler/

[4] H. C. Jin, J. R. Abelson, M. Erhardt, R. Nuzzo, 2004, “Soft lithographic fabrication of an image sensor array on a curved susbstrate”, Journal of vacuum science and & technology 22

[5] P. Ruchhoeft, M. Colbum and B. Choi et al, 1999, “Patterning curved surfaces: Template generation by ion beam proximity lithography and relief transfer by step and flash imprint lithography”, Journal of vacuum science and technology 17

[6] Rostam Dinyari, Seung Bum Rim, Kevin Huang, Peter B. Catrysse, Peter Peumans, 2008, “Curving monolithic silicon for nonplanar focal plane array applications” Applied Physics Letter 92

[7] Seung-Bum Rim, Peter B. Catrysse, Rostam Dinyari, Kevin Huang, and Peter Peumans, 2008, “The optical advantages of curved focal plane arrays”, Optics Express, Vol. 16, Issue 7, pp. 4965-4971

[8] P. K. Swain, D. J. Channin, G. C. Taylor, S. A. Lipp and D. S. Mark, 2004, "Curved CCDs and their application with astronomical telescopes and stereo panoramic cameras", Proc. SPIE 5301, 109-129

[9] M. Lesser, private communication at IISW Symposium on Backside Illumination of Solid-Sate Image Sensors, 2009 Bergen, Norway

[10] S. Nikzad, private communication at IISW Symposium on Backside Illumination of Solid-Sate Image Sensors, 2009 Bergen, Norway