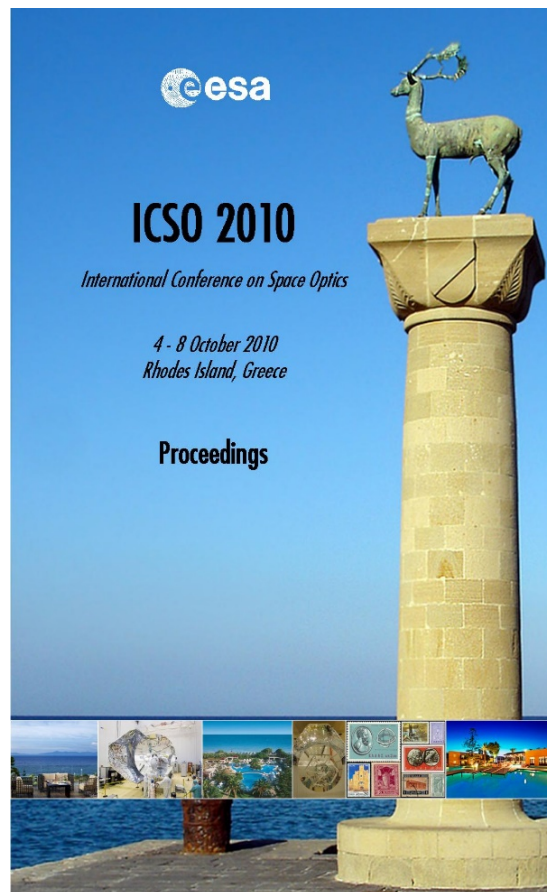


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D. Dumas, M. Fendler, F. Berger, G. Lasfargues



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CURVING MONOLITHIC INFRARED DETECTORS: APPLICATIONS TO LARGE FIELD OF VIEW TELESCOPE AND SPECTROMETRY

D.Dumas^{1*}, M.Fendler¹, F.Berger¹, G. Lasfargues¹, F.Marion¹, C. Vialle¹, V. Goudon¹, J.Primot², E.Le Coarer³, H.Ribot¹

¹ CEA Minatec – Léti Grenoble DOPT; ² ONERA – DOTA/CIO Saclay France, ³ LAOG – UJF Grenoble France

* 17 rue des Martyrs – 38054 Grenoble cedex 9, delphine.dumas@cea.fr – (33) 04-38-78-13-27

I. INTRODUCTION

Spatial applications have several challenges. In ground based astronomy, wide survey telescopes are built with larger field of view in order to observe larger part of the sky. The requirement is to increase the field of view as well as the sensibility in order to detect even smaller objects or light (meteorites, debris from human activities, and light from exoplanets or supernovae). Telescopes with large field of view and high resolution need large aperture diameter and so a very fast camera is needed. However, in these cameras the main difficulty is to correct aberrations of curvature. In spatial astronomy for instance star trackers, spatial telescopes and spectrometers, a larger field of view and a better resolution are also needed. However, the main requirement is given by the necessity to launch these instruments and this step is particularly expensive. So the specific requirement is to decrease the volume and weight of these systems in order to decrease the launched price and to increase the number of systems launched. The key point is thus the miniaturization of these systems. However by scaling down the system, the detector becomes closer to the optical element and so less space could be dedicated to correct aberrations.

Wide survey telescopes and spatial instruments are looking for high resolution cameras, and each of them are facing specific requirement, respectively large field of view and small sized systems. Nevertheless, they both face with a main difficulty: the correction of aberrations. Usually the main solution is to add optical lenses in the system design. However this solution becomes more complex, especially for large aperture telescopes and the system size is increased [1], so miniaturization can not be achieved. Thus the design of miniature spectrometers or cameras must be done by a novel system design. An interesting look in nature shows us that these key points have been already solved. Indeed, most animals have larger field of view and higher resolution; and especially small insects have few space dedicated to the visual system but they do have good resolution and large field of view. In all eye architecture, the focal plane is curved (fig. 1). Curving the focal plane allows to enlarge the field of view and to decrease some aberrations, especially aberrations of curvature.

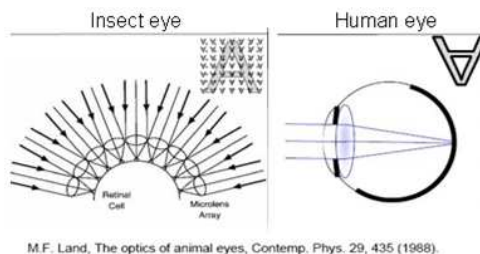


Fig.1. Insect and human eye: curved focal planes

The suppression of aberrations could be illustrated by fig.2 and 3 on a simple optical design. With a planar focal plane (fig. 2) light off axis is not well focus, in contrast to on axis light. This slight difference induces aberrations which decrease the modulation transfer function (MTF) off axis. These aberrations are usually corrected by adding lenses. By curving the focal plane, as nature does (fig. 3), both lights on and off axis are focused on the same surface; aberrations of curvature are suppressed and the MTF is then better.

So the curved focal plane has several advantages: the field of view is increased and aberrations are suppressed. The system is then simplified and miniaturized (no correcting lenses added). The curved focal plane answers the previous spatial requirements. And we could see in the state of the art that curved detectors are more and more needed [1] [2]. However, all detectors are manufactured in a planar shape; so curving the focal plane leads to a breakthrough in the camera design and manufacturing.

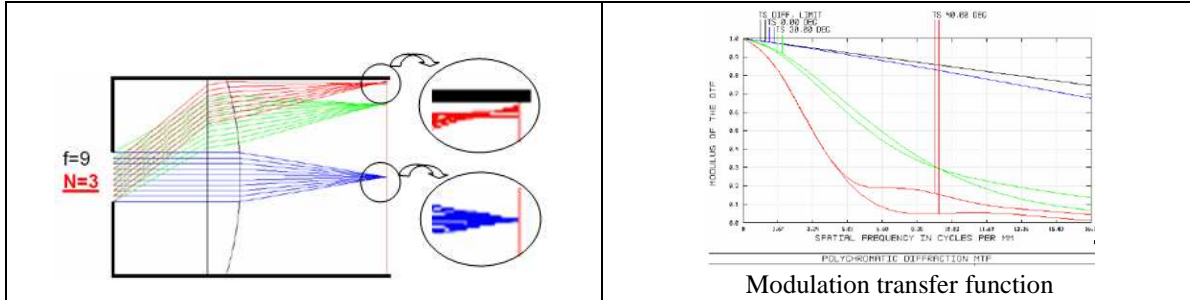


Fig.2. System with planar focal plane

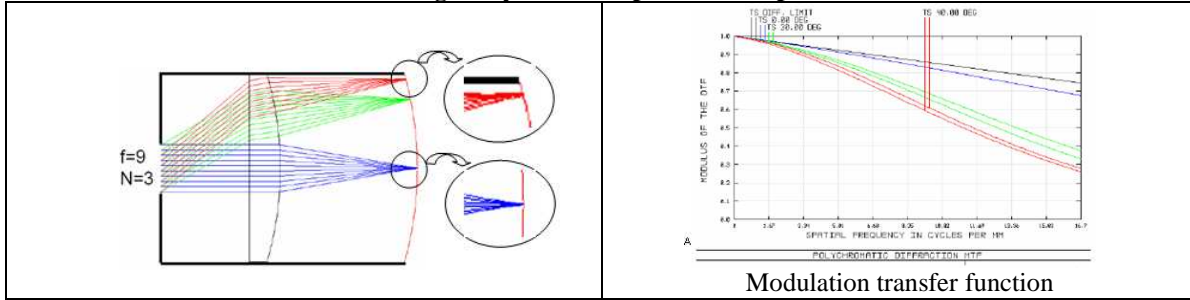


Fig.3. System with curved focal plane

II. STATE OF THE ART SOLUTIONS TO CURVE A RETINA

Only few articles focus on the spherical bending of detectors. More articles can be found from the soft electronic research, but they are dedicated to realize stretchable and flexible systems.

The state of art presents two kinds of solution to realize the spherical curvature. The first one (fig. 4 and 5) consists in patterning the device into small separated islands of devices connected to each other by a metallic line. This technique comes from the soft electronic research; Ko et al [4] has realized the first hemispherical eye camera. However, with this technique the fill factor is lower than 100% and the detector flowchart must be modified.

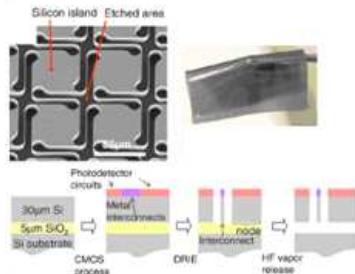


Fig.4. Curving focal plane by SOI wafer in [3]

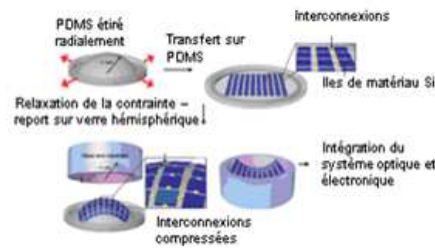


Fig.5. Curving focal plane in [4]

The second solution consists in thinning the device in order to curve it. Different solutions to thin exist [1], however few articles could be found in the public area. These articles present studies on curved silicon or CCD [5]. However, few electronics results have been presented and no work on curved infrared detectors can be found.

III. BENDING PROCESS CHARACTERISTICS

The work presented in this paper is focused on the spherical bending of curved infrared sensors. To do so, we choose to thin the device, by grinding and polishing. In contrast to the first kind of solution presented, thinning allows us to curve the whole device without structuring it; the flowchart of the component is not modified. By decreasing the thickness, the component becomes more flexible and a cylindrical deformation could be easily achieved. The specific spherical shape is more complicated, because the device must be both stretch and strain. In our process, we use a holder, with an appropriate radius of curvature, on which the device is reported. The spherical shape is given by applying a pressure onto the thinned device; as a result the device reproduces the holder curvature and is bonded using a conventional epoxy. Both concave and convex shapes can be performed. Firstly, our process has been developed to curve silicon samples before being transferred on infrared sensors. In

this part, we will present the results obtained on silicon samples before focusing on our first electrical results achieved on real devices.

The same process is able to curve both concave and convex shapes. By thinning the silicon down to 25 or 50 μm , the spherical shape could be achieved without mechanical damage. To characterize the result, the curved surface is scanned (first column of fig. 6), the second column is the perfect sphere deduced, and the last one is the defect to the perfect sphere. For a 46mm bending radius, fig. 6 compares the convex and concave silicon surfaces obtained. For a concave curvature, the defect to the perfect sphere picture shows no distortion: the curvature is then perfectly spherical. On the contrary, the convex silicon is more deformed: four folds, with a height between 118 μm and 53 μm , can be seen on the defect to the perfect sphere picture. This deformation is the characteristic defect of convex silicon: in this configuration, the sample edges are raised up and form folds.

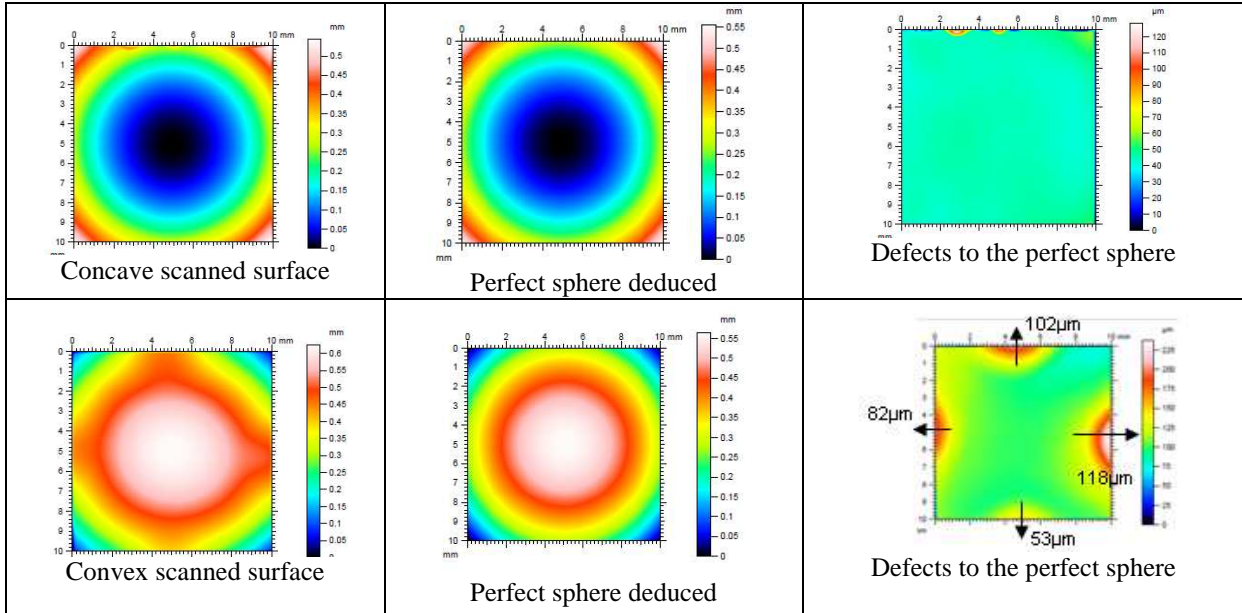


Fig.6. Concave and convex silicon – radius of curvature 46mm (10x10mm² thickness 50 μm)

So the trend is to have better results in the concave curvature. The difference between convex and concave configuration may be explained by two assumptions:

- the process: to realize a convex shape it seems necessary to apply a higher pressure at the boundary of the silicon (where the folds appear), whereas in concave configuration a pressure applied in the middle of the silicon is sufficient.
- the convex silicon seems more sensitive to the holder's shape. Indeed, the present holders are not perfectly spherical; the radius dispersion along the holder surface is between 0 to 9mm. In some cases (fig. 7) the holder defects are reproduced on the silicon surface.

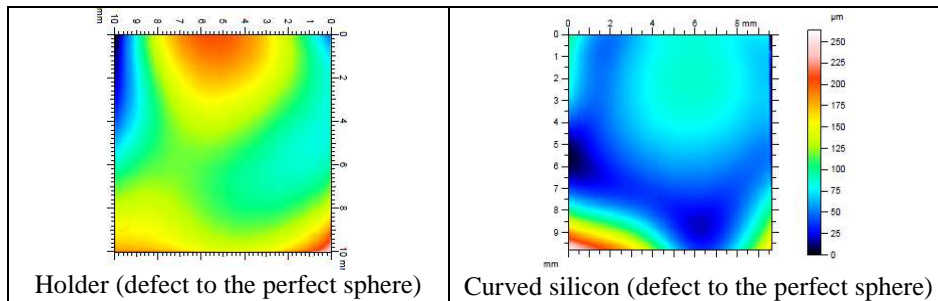


Fig.7. Defect of the holder reproduced onto the silicon

To characterize the spherical surface obtained, we compare the radius of the perfect sphere measured on the holder and then on the silicon. The table 1 shows that there is gap between the holder radius and the silicon radius either for 25 and 50 μm thick sample. The radius deviation is between 0 to 8mm for 50 μm silicon and between 0 to 4mm for 25 μm . This deviation can be explained by the surface holder and the glue thickness. Despite this slight radius deviation, the silicon is well spherically bent, with a radius achieved really close to the holder radius.

Table.1. Radius deviation between holder and silicon

Radius holder (mm)	Radius Silicon (mm)	Deviation in radius (mm)
77,8	74,6	3,2
50,9	48,7	2,2
44,7	45,7	-0,9
39,6	38,9	0,7

Thickness 25 μ m

Radius Holder (mm)	Radius silicon (mm)	Deviation in radius (mm)
39,5	40,2	-0,8
40,2	44,5	-4,3
44,2	44,2	0,1
44,9	45,3	-0,4
45,6	39,5	6,1
45,9	54,0	-8,1
47,6	43,3	4,3

Thickness 50 μ m

As we present previously (fig. 6) the convex silicon presents folds in the middle of the sample edges when it is spherically bent. The number of folds increases while the radius of curvature decreases. Figure 8 presents the number of folds for two thickness samples: 25 μ m and 50 μ m. For a same radius of curvature, a sample of 50 μ m thick has fewer folds than a 25 μ m thick sample, and even smaller radius of curvature could be achieved.

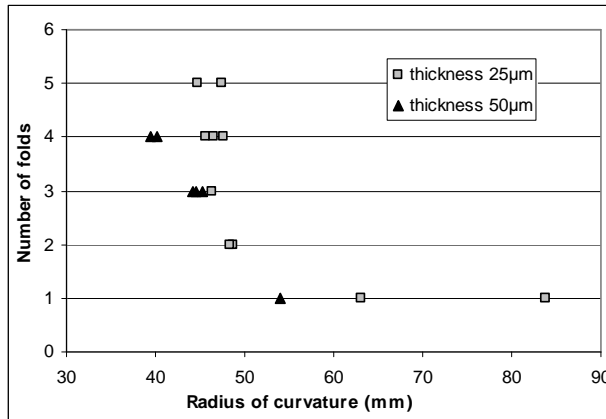


Fig.8. Number of folds versus radius of curvature

Only the edges of the sample are degraded by the folds; the large central area is still perfectly spherical and forms the suitable surface. To illustrate this, the perfect spherical surface called “surface free of folds” can be measured. Fig.9 shows that the surface decreases while the radius is smaller; this is explained by the increase number of folds. Comparing the thickness behaviour, a 50 μ m thick sample has a larger surface free of folds than a 25 μ m thick measured at the same radius of curvature. Depending on the thickness, the folds expand along the periphery or inside the sample. So the thickness of the sample is an important parameter related to the spherical shape obtained; thinner sample could be more easily bent, however the sample must be rigid enough to keep a spherical shape.

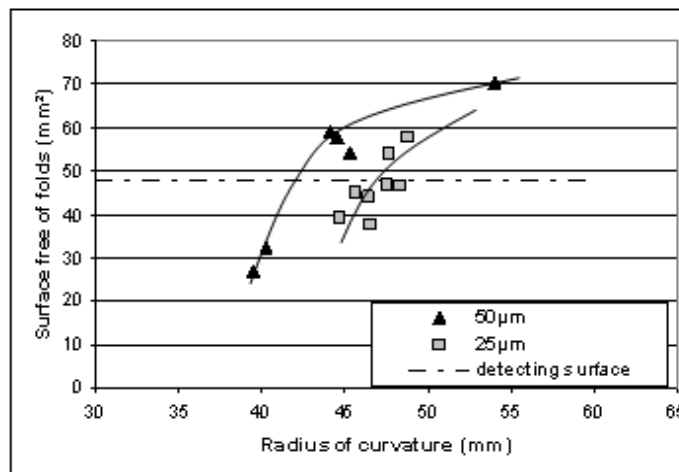


Fig.9. Surface free of folds

IV. APPLICATIONS TO INFRARED DETECTORS

Now we will focus on uncooled infrared detectors; these components are mainly processed with silicon (fig. 10). The pixels matrix is smaller than the detector size, and we can see on fig. 9 that the detecting matrix could be perfectly spherical with a thickness decreased down to 50µm and a radius down to 43mm, following the previous results. Thanks to our technique, the flowchart of the device is not modified. The thinning is made after the sensor process; and then the sensor is curved in convex or concave shapes and characterized mechanically and electrically.

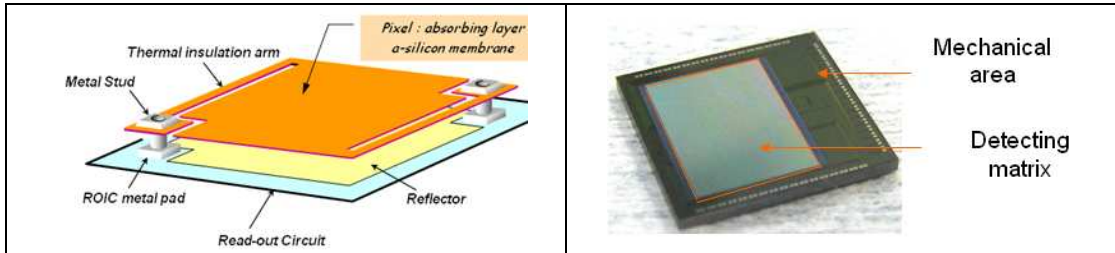


Fig.10. Uncooled infrared pixel and overview of the sensor (bolometer)

Four uncooled detectors have been curved, the radius achieved is between 47mm and 53mm. No mechanical damage has been observed; folds are mainly out of the detecting matrix and so electrically the folds do not modify the resistance measured [6].

Uncooled infrared sensors have been curved in both concave and convex shape. The surface achieved is presented in fig. 11. The radius of the convex sensor is 52.7mm, the radius deviation with the holder is 6.06mm, and two folds appear with a height of 58.6µm and 48.3µm. The radius of the concave sensor is 50.5mm and the radius deviation is 0.83mm; no fold can be measured. Sensors have a similar behaviour than the silicon studied in the first part.

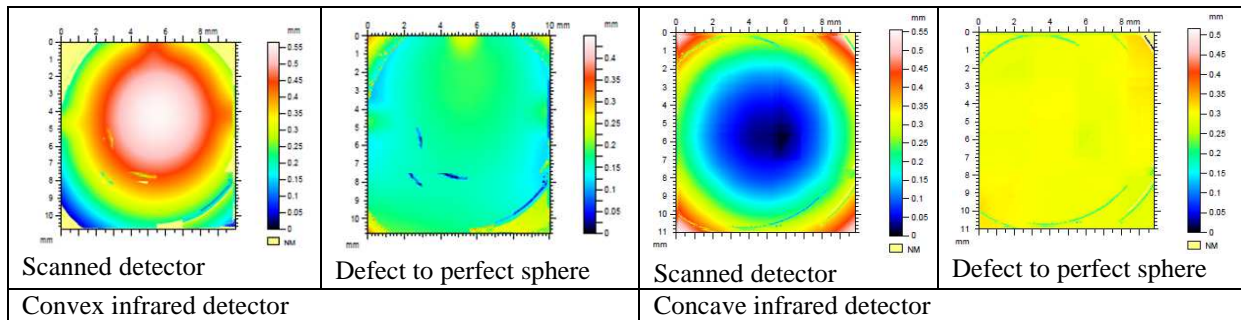


Fig.11. Comparison between concave and convex curved silicon

These components have been electrically tested allowing the comparison between the concave and convex shape; the read out circuit is an interconnexion network, the electrical test is made on several individual pixels.

Table.2. Electrical comparison between planar, concave and convex shape

	Δ plan / concave	Δ plan / convex	Δ concave / convex
Resistance	12.12%	11.14%	11.18%
1/f noise parameter	5.16%	6.72%	1.48%
Thermal resistance	20.5%	14.3%	7.7%

The variation of the electrical performances between the planar and curved detectors is small; the gap measured is part of the dispersion between detectors manufacturing. Concave and convex sensors have a similar behaviour through the spherical strain. To conclude on this part, pixels are not mechanically and electrically damaged by the spherical bending. The difference between the previous sensor and the functional bolometer is the read out circuit which is respectively an interconnexion network and a CMOS.

Four uncooled infrared sensors have been curved. The radius is 65mm, 70mm and 75mm in concave and convex shape. Figure 12 illustrates one of these detectors. Mechanically these sensors are not damaged by the curvature,

the electrical tests are presently ongoing. This is the last step before the achievement of the first image captured by a curved focal plane.

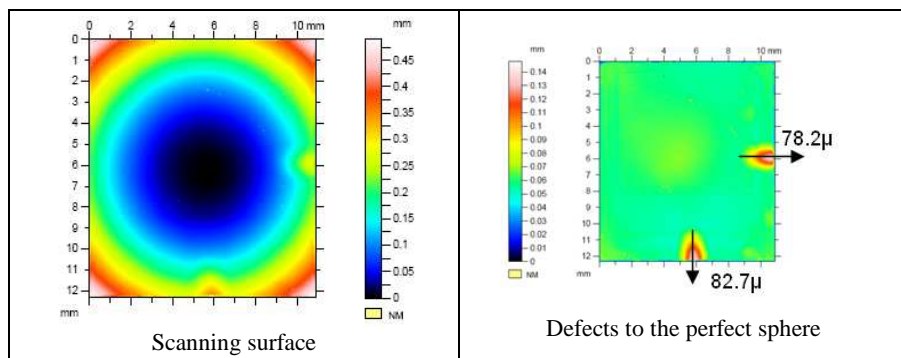


Fig.12. Functional infrared detector – curvature radius 67.3mm

V. CONCLUSIONS

In astronomy, projects as wide survey telescopes and miniaturization of spatial instruments need a novel camera design. Correction of aberrations is one of the challenging points; nature gives us a solution by curving the focal plane of the human and insect eyes. Indeed, the curved shape suppresses aberration of curvature and then leads to a simplification and a miniaturization of the camera design. We have developed a process to curve in both convex and concave shapes the infrared detectors. The process uses substrate thinning and allows curving the whole detector without modifying the flowchart. The development has been made by curving thin silicon and has been successfully transferred to uncooled infrared sensors. Infrared pixels did not suffer from mechanical and electrical damages after the spherical bending. The electrical test of the functional infrared detector is presently made and would allow the optical test of this new kind of detector.

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