Curved CMOS Image Sensors Using SOI Layer Transfer Technology

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Abstract

We report the development of curved complementary metal-oxide-semiconductor image sensors (CISs) using silicon-on-insulator (SOI) layer transfer technology. A 11-µm-thick device layer was transferred to a flexible substrate and mounted on a cylindrical concave stage. The curved CISs successfully operated to correct lens aberration, thereby promising next-generation high-quality flexible imaging devices.

Introduction

Mechanical flexibility enhances the applications of image sensors in high-quality imaging, wearable sensing, and implantable devices. Specifically, curving the sensor to match the image formation plane formed by a lens compensates for field curvature aberration without using a large number of lenses (Fig. 1), extremely minimizing camera size. The aberration becomes more pronounced with wider-angle lenses, making the curved sensor especially effective for wide-angle imaging. Although thin-film-transistor-based devices show good bendability [1,2], improving their performance comparable to CISs is challenging. Previous attempts to form curved CISs by thinning silicon (Si) layers have been reported [3,4]; however, the final thinness was insufficient to produce adequate flexibility or a reduced curvature radius. To address these limitations, we propose a flexible CIS using an SOI structure, in which an 11-µm thick Si device layer—thin enough to be flexible—is transferred onto a flexible plastic substrate (Fig. 2) [5,6].

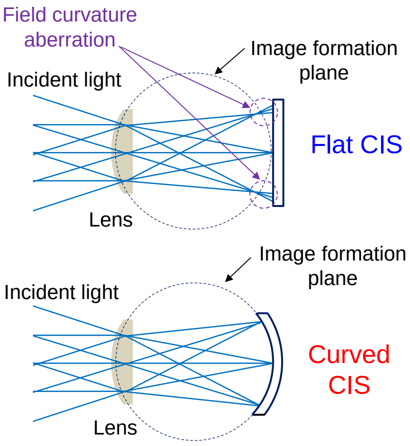


Figure 1: Configurations of flat and curved CISs.

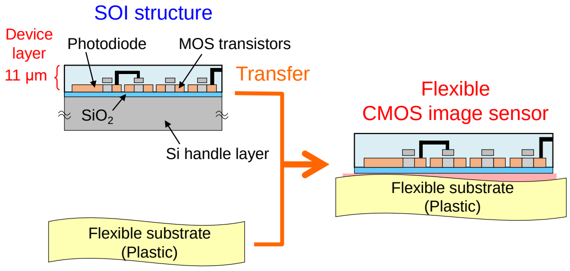


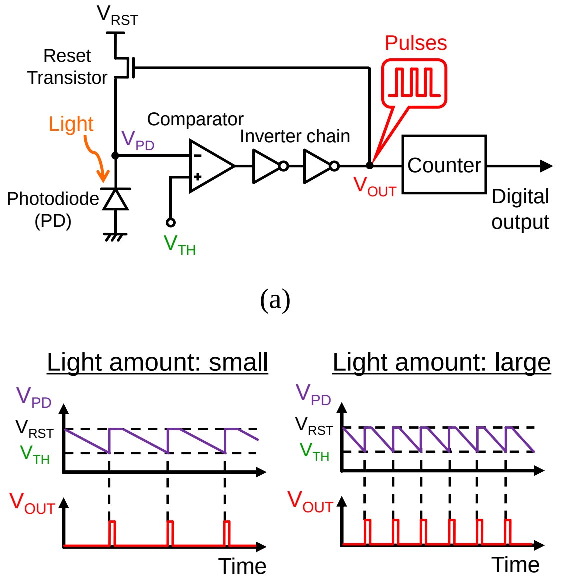
Figure 2: Schematic of flexible CIS.

Design and Implementation

Figure 3 shows the pixel circuit comprising a pixel-parallel A/D converter. Whenever the voltage of the photodiode (PD) reaches the comparator threshold, a pulse is generated and then the PD is reset. The following counter accumulates the number of pulses that corresponds to the incident light intensity [7,8]. As the sensor generates a digital signal for each pixel, it is robust against changes in the wiring resistance when the sensor bends.

Figure 4 details the fabrication process. CISs were fabricated on an SOI wafer, comprising a 725-µm-thick Si handle layer, a 3.5-µm-thick active layer, and an 11-µm-thick device layer, excluding the handle layer (a). Each chip was bonded after dicing to a temporary fixing substrate (b). The handle layer was initially ground (c) and subsequently removed using XeF_2 gas, where Si was selectively etched [9] (d). The chip was bonded to a plastic substrate mediated by an adhesive film (e). After being exposed to ultraviolet rays to weaken the adhesion (f), the temporary fixing substrate was delaminated (g). For the curved image sensor application, the chip was mounted on a cylindrical concave stage and the wiring was formed using a wire bonder (h).

Figure 5 shows the flexibility of the CIS chips after transfer process. The transistor characteristics before and after curving chip show no performance degradation (Fig. 6). Figure 7 shows the CIS chip after dicing (a), curving to 20-mm radius (b), and after packaging (c), including a 320 × 240 pixel array.



(a)

(b)

Figure 3: (a) Pixel circuit and (b) operation timing charts, comprising a pixel-parallel A/D converter.

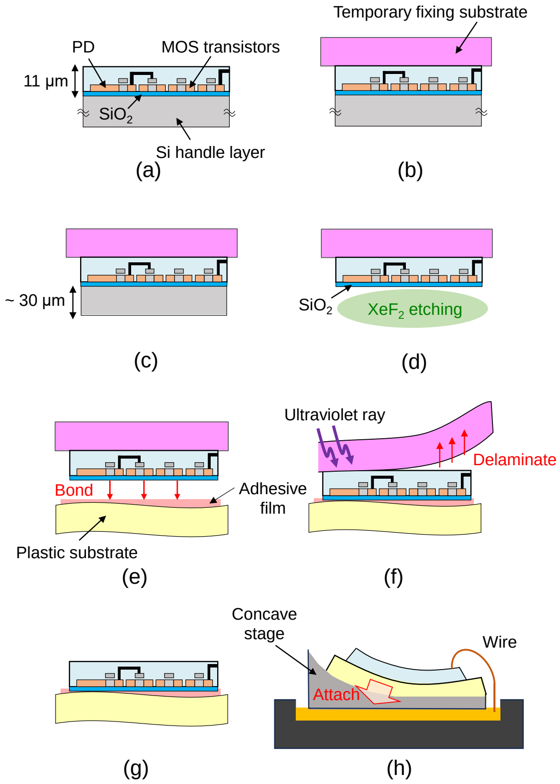


Figure 4: Fabrication process for the curved CIS.

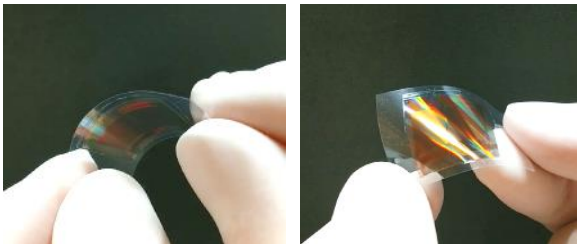


Figure 5: CIS chips being bent (after transfer process).

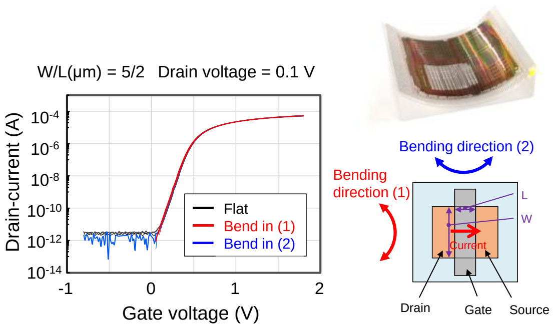
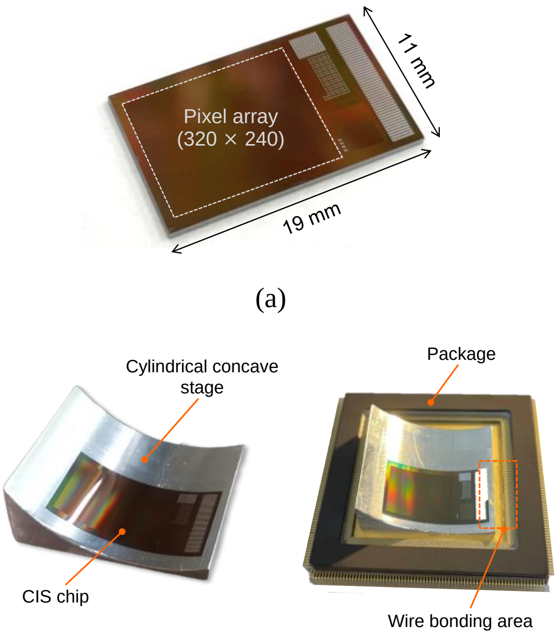


Figure 6: Drain-current–gate-voltage characteristics of n-type MOS transistors before and after bending, where the chip was curved into a cylindrical concave shape with a 15-mm radius (upper right).



(a)

(b) (c)

Figure 7: CIS chips (a) after dicing, (b) curving with a radius of 20 mm, and (c) after packaging.

Measurement Results

Figure 8 shows a measurement setup comparing the curved and flat (before thinning and curving) CISs. Both setups employed identical conditions for the objects, lenses, and lighting. The lens used was an achromatic type—comprising a concave and convex lens bonded together to form a single lens—which corrects only chromatic aberrations and does not address other types of aberrations. Figure 9 shows captured video images at a frame rate of 20 Hz. Both images are focused on the center of the objects. However, the flat CIS occurs peripheral blurring due to field curvature aberration. In contrast, the curved CIS significantly reduces the blurring on the left and right sides of the image, producing a clearer image. Because the CIS is curved cylindrically, some aberration remains in the vertical direction. We are studying on creating a completely concave-shaped CIS to correct aberration in all directions (Fig. 10).

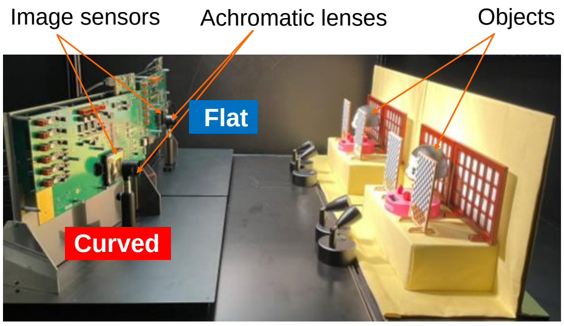


Figure 8: Measurement setup for demonstrating a comparison of a curved CIS and a flat CIS (before thinning and curving).

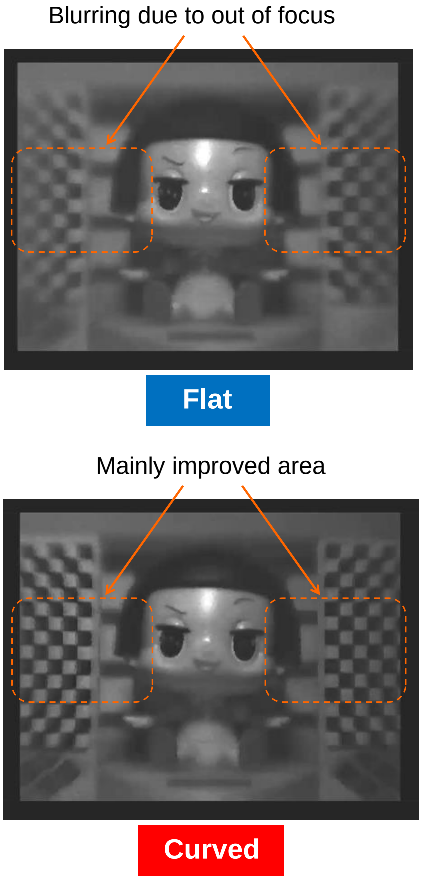


Figure 9: Comparison of captured images. The curved CIS significantly reduces the blurring on the left and right sides of the image.

We have also confirmed the CIS operation at a small curvature radius of 10 mm suitable for wide-angle imaging and on flexible printed circuit packaging to extend flexible applications such as wearable sensors (Fig. 11).

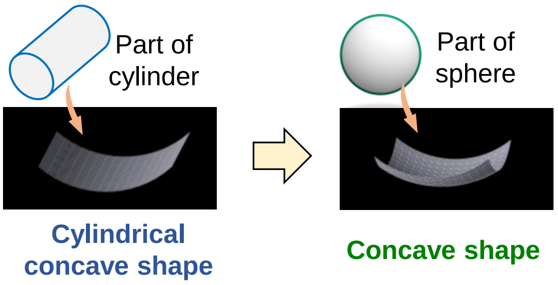
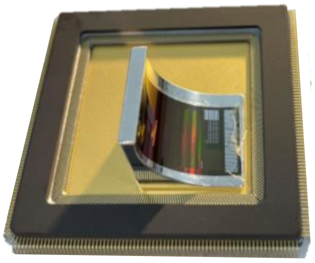
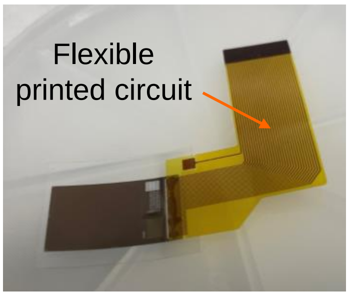


Figure 10: Difference in sensor shape.


(a)



(b)

Figure 11: (a) Cylindrically curved CIS with a radius of 10 mm. (b) Flexible CIS packaged with a flexible printed circuit.

Conclusion

The curved CIS was successfully developed by transferring an SOI layer onto a plastic substrate. The 11-µm-thick CIS device layer was packaged in a curved form with a 20 mm radius. The results confirmed the successful operation of the curved CIS and demonstrated its ability to reduce field curvature aberration using a simple lens system. This achievement shows the potential for high-quality, wide-angle imaging and compact camera systems. The developed process presents promising applications for high-quality flexible CISs and other flexible CMOS devices, including sensors, logic circuits, displays, and memories.

References

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