35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Non-Planar and Flexible Chip Technology for Biomedical Applications

Ching-Yu Liu, Hsiao-Chen Lin, Chih-Chiao Teng, and Long-Sheng Fan

Abstract—**We report a novel non-planar flexible silicon chip technology by means of patterning thin films of high residual stress on top of shaped thin silicon substrate. High residual stresses of thin films make thin chip deform into designed three-dimensional shapes. In this study, a series of patterned stress films and "petal-like" chips were fabricated and analyzed. Large curvatures can also be formed and maintained by the packaging process bonding the chips to constraining elements such as thin-film polymer ring structures. As a demonstration, a CMOS image-sensing retina chip is made into a contact-lens shape conforming to a human eyeball 12.5mm in radius. This non-planar and flexible chip technology provides a desirable device surface interface to soft or non-planar bio surfaces and opens up possibilities for many biomedical applications.**

I. Introduction

Silicon is the common material used for making many sensors, transducers and IC (Integrated Circuit) and finds its way into biomedical applications that require signal sensing, transduction and processing; however, silicon is a stiff and brittle material, and most silicon chips are fabricated in a planar shape after the planar manufacturing process. On the other hand, most of biological tissues evolve into three-dimensional non-planar shapes. Besides making these chips biocompatible through appropriate packaging technology, the capability of the sensing and transduction might also be limited due to the mismatch of the shape and stiffness when organic tissues are interfaced to these planar and stiff chips. We previously reported a flexible CMOS (Complementary Metal Oxide Semiconductor transistor) technology based on a standard 0.18μm 1P6M mixed-signal /RF CMOS process for medical implant applications [1-2], and a functional flexible electronic chip sandwiched between layers of passivation material can be curled and fitted into a small capillary tube a few mm in size as shown in Fig. 1.

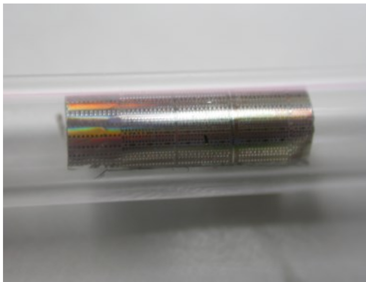

Figure 1. A curled flexible CMOS wafer piece inserted into a 4mm diameter glass capillary

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A biological body is composed of many tissues with different shapes and stiffness; therefore, to better conform to these organism characteristics, flexible and non-planar geometric structures are frequently needed for many biomedical applications. One example is for artificial retina that closely interfaced to retina tissue on the backside of an eyeball. A conforming surface with minimum separation between device and the soft & quasi-spherical retina tissue is a necessary condition for the high visual acuity and large field of view [3-4]. The required radius of curvature is 12.5mm.

Three-dimensional geometric shapes can be made through instabilities such as swelling-induced bucking of tubular gel [5], or by using the thermal loading to create creep and stress relaxation in thin film bi-layer cantilever, and leading to structure warping [6], or soft-spring-connected islands to conform to non-planar surface [7]. In this research, we report a novel non-planar flexible silicon chip technology by combination of patterning high residual stress thin films on top of shaped thin silicon substrate. A CMOS image-sensing retina chip is made into a contact-lens shape conforming to a human eyeball 25mm in diameter. The curvature is maintained through bonding the flexible chip to constraining polymer ring.

II. Strategies for Non-Planar Silicon Surfaces

We use two strategies to make non-planar silicon chip: 1. Depositing and shaping stress thin films on thin silicon chips into various patterns for various evolvable geometric deformations of the chips. 2. Etching the thinned silicon chips into particular shapes such as "petal-like" shapes, or round shapes partially separated into a number of lobes with the deposited stress films on top of the chips to induce large curvature of deformations. Large curvatures can also be formed and maintained by the packaging process bonding the flexible chips to constraining elements such as thin-film polymer ring structures.

A. Patterned stress film

As an example for the 1st strategy, we deposited silicon nitride or amorphous silicon thin films as the "stress films" by PECVD processes on thin silicon chips with a round shape 3mm in diameter. The residual stresses of the thin films create bending moments and make the thin substrates curl into non-planar shapes. In particular, we deposit PECVD silicon nitride thin films, which can have high tensile stresses of a few hundreds of mega Pascal to Giga Pascal, on thin silicon chips and induce geometric deformation such that the thin silicon substrates will be concave as illustrated in Fig. 2.

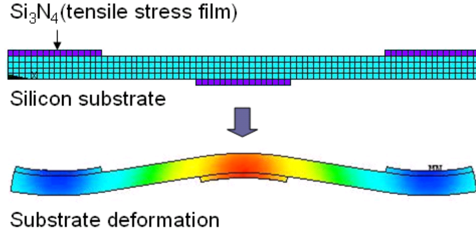

Figure 2. FEM simulation result of substrate deformation due to patterned stress films

We make our chips into a disk shape with patterned stress films as shown in Fig. 3 with (a) strip, (b) radiation, or (c) & (d) annular to make specific three-dimensional geometrical deformation from the original planar disk-shaped thin chips.

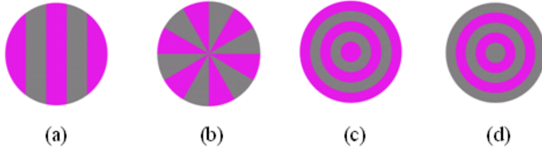

Figure 3. Illustration of patterned stress films (purplish areas are silicon nitride films)

B. Patterned substrate and constraining elements

Many 3D surface shapes with non-zero Gaussian curvature, such as spherical surfaces, are not developable from planar disks, which have zero Gaussian curvature, and extensive stresses on certain locations might be needed to achieve the target deformation. To minimize this issue in the demonstration of a non-planar surface approximately conforming to a sphere, we remove the excess areas by etching through the substrate some wedge opening into the circular disks, or petal-like chip, as shown in Fig. 4. The minimum width of the opening is designed such that the edges will be butting each other when the disk is deformed into the desirable radius of curvature, and the length of opening is set at 2/3 and 1/2 of the radius from the edge toward the center of the disk with stress-relieve endings. Full stress films are deposited on one side to create the bending moments.

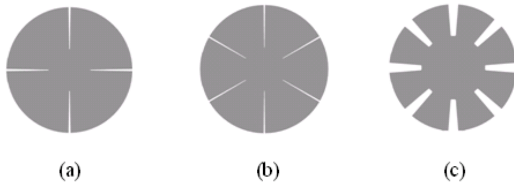

Figure 4. Illustration of some petal-like disks: (a) 4 petals, (b) 6 petals and (c) 8 petals with opening width intentionally larger than forming butting lobes after deformation

In the application of an artificial retina conforming to the spherical surface of an eyeball 25mm in diameter, a 3mm chip will have a bow (vertical displacement from center to edge) of ~90μm. As will be shown by the simulation and experiment results, the stress-induced bending of the flexible chip is not adequate to achieve the target displacement by stress films alone. We use a thin polymer ring to bond to the chip as illustrated in Fig. 5. Through a thermal molding step, the polymer ring bonds with the silicon chip according to the shape of the mold and, acting as a “rubber band”, keeps the silicon in the required curvature.

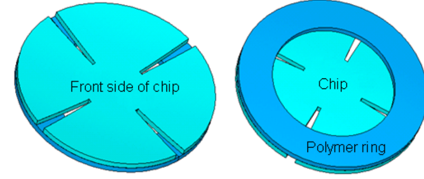

Figure 5. Illustration of a polymer ring bonded to a silicom chip

III. THEORETICAL MODELING

A. Curvature of a composite disk

Stoney formula is frequently used to calculate the residual stress of thin films on silicon substrate [8]. However, the formula assumes that the value of in-plane deformation is much smaller than the substrate thickness and it is not applicable to the larger deformations we target here. We use the energy method [9] to analyze our composite thin disk with a radius R, and the composite disk curvature $1/\rho$ is obtained as the real root of the following equation, and the bow is calculated accordingly.

$$
\begin{aligned}
&A \cdot \rho^3 - B \cdot \rho^2 - C = 0 \\
&where \\
&A = 6(h_s + h_f)^2 (1 - \nu_s)\, h_f^2 \left(\frac{h_f}{h_s} + 1\right)\sigma_f \\
&B = E_s h_s^3 (h_s + h_f)^2 \frac{h_f}{h_s} \\
&C = 0.28\, E_s h_s^3 \left(\frac{E_f}{E_s}\right)^{\frac{1}{5}} \left(\frac{h_f}{h_s}\right)^{\frac{4}{3}} R^4
\end{aligned}
\tag{1}
$$

, where σ is the stress, E is the Young’s modulus, v is the Poisson’s ratio, h is the thickness and ρ is the radius of curvature, and the subscript s and f mean substrate and film respectively.

B. Finite element simulation

As will be described in the follow section, the process uses <100> silicon wafer, and the corresponding layers and material properties used are shown in TABLE I. We assume linear-elastic materials and include large-deflection effects in the static finite element analysis.

TABLE I. MATERIAL PROPERTIES

Material type	***Young’s modulus (GPa)***	***Poisson’s ratio***
Polymer film	3.2	0.4
Silicon nitride	250	0.23
Silicon	179	0.22
Silicon oxide	70	0.17

- The solid model of a 3mm-diameter disk with 1 μm-thick Si_3N_4 and 10 μm-thick Si, stacked vertically is calculated by FEM method. The stress film has an initial tensile stress of 200 MPa and various patterned shapes. As the calculation result shown in Fig. 6, deformation curvature increases at the locations corresponds to the patterned stress films and the deformed chip has apparent wavy buckling shape.

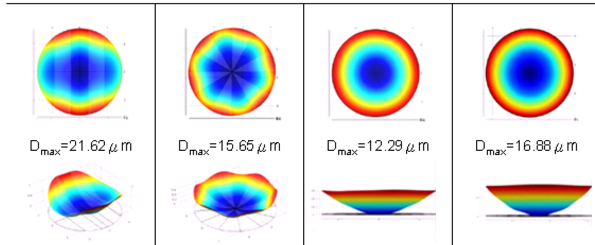

Figure 6. Simulation results of various silicon nitride patterned shapes

- We use SOI wafers to fabricate 4-layer "petal-like" chips and the material and thickness of these layers are as following: polymer film 2.5μm, Si_3N_4 0.38μm, Si 10μm and SiO_2 0.5μm. The boundary conditions are the same as previous paragraph. Fig. 7 compares the FEM-calculated vertical displacements of the chip. Increasing the number of petals, both opening length and opening width increases the curvature of chip.

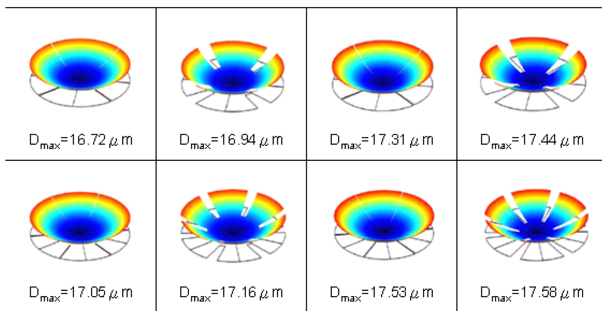

Figure 7. Simulation results of various petal-like chips

- We compare the theoretical values of bows from the analytical calculation, Stoney formula and the FEM calculation in Fig. 8 & Fig. 9. Fig. 8 shows the calculated bows with a fixed initial stress of nitride layer (200 MPa), a fixed silicon thickness (10 μm), and varying nitride thickness from 0.33 μm to 1 μm. Fig. 9 shows the calculated bows for a fixed thickness of nitride (0.33 μm) and silicon and varying stress of the nitride layer from 200 MPa to 300 MPa. The analytical solution is within 5% of the FEM result. Stoney's formula overestimates the bows.

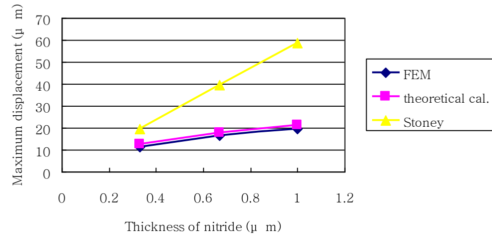

Figure 8. Theoretical values of the bow of a round silicon chip due to fixed nitride stress with variable nitride thickness

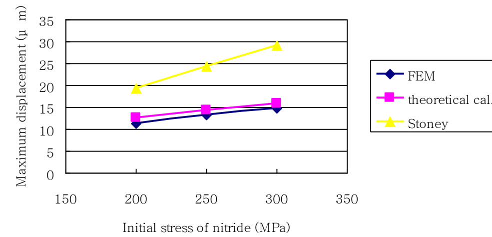

Figure 9. Theoretical values of the bow of a round silicon chip due to variable nitride stress with fixed nitride thickness

IV. Sample Preparation

We use SOI wafers to make the "petal-like" chips, and the process flow is as in Fig.10. The SiO2 layer is the etch stop layer in the backside thinning etch step.

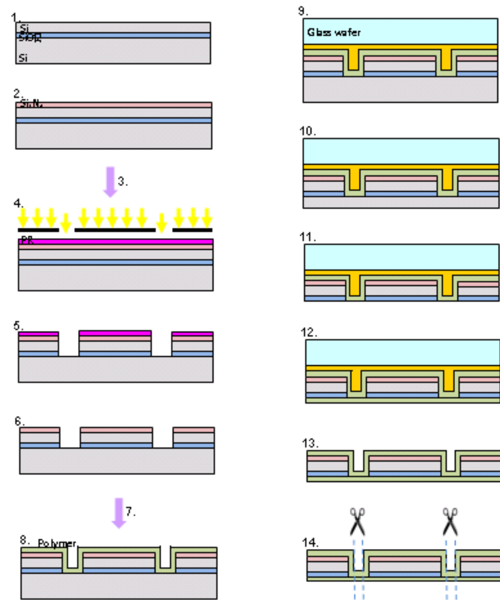

Figure 10. Process flow of SOI wafer for petal-like chips. 1.starting SOI wafer 2.PECVD deposit of silicon nitride film 4.photolithography 5.RIE top side 6.strip photoresist 8.deposition of polymer film 9.bond wafer piece to a carrier wafer 10.lapping down to ~50 μ m 11.RIE rear side of silicon substrate 12.deposition of polymer film 13.wafer release 14.punch through polymer film to separate chips

Radius of curvature is measured before and after PECVD film deposition for calculating residual stress of stress film. Trenches are first etched to define the chips and stopped at the buried oxide layer. A polymer layer 2.5µm thick is deposited on top of the surface. After bonding to the carrier substrate, we mechanically thinned the backside Si to the thickness about 50µm. A dry etch such as XeF2 or RIE (Reactive Ion Etching) is used to remove the surface micro-crack damages induced during the lapping process and etch the Si substrate down to 10µm in thickness. We then deposit another polymer film 2.5µm in thickness as the backside passivation of the chip. Finally, we release the thinned wafer from the carrier wafer, and individual chips can be separated by punching through the polymer layers.

V. Non-Planar Chip Implementation and Profile Measurement

A. Silicon spherical chips

As shown in Fig. 11, the final thin silicon chip, with a total thickness of ~16µm, curls due to the residual stress of the stress films. Fig. 11(a) shows the wafer from the silicon oxide side (left) and the rear side of nitride (right). Fig. 11(b) shows examples of the petal-like chips after releasing from the carrier wafer. The planar disks deforms into a non-planar shapes that can conform to a spherical surface. The transparent polymer films are visible at the edges.

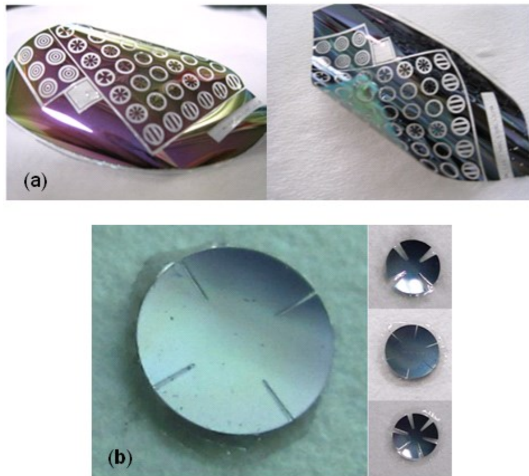

Figure 11. Non-planar flexible silicon chips

Fig. 12(a) is the photograph of a deformed chip and Fig. 12(b) shows the 3D image. We use a 3D laser confocal microscope (OLS LEXT 3000) to measure the surface profile of the 4-petal spherical chips and the film-stress-curled round disks, and the measurement results together with FEM results are summarized in TABLE II. The wedge opening length to form the petals is 1/2 of the radius of the silicon disks, and the wedge opening angles are 18° and 0.18^{o}. The measured results correspond to a minimum radius of curvature of ~40mm. The average bows of pedal-like chips are larger than that of simple round disks.

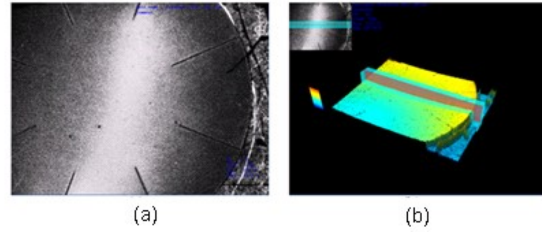

Figure 12. Measuring the surface profile by confocal microscope

TABLE II. FEM and Measured Bows of 4-Petal Disks and Round Disk Samples

Max. D (µ m)	*4-petal and R/2*		***Round disk***
	θ=18°	***θ=0.18°***	
FEM	26.566	25.764	18.077
Avg. of meas.	28.085	25.641	17.105

B. CMOS spherical retina chips

A spherical CMOS image-sensing retina chip is made using this same approach [10]. This chip is 6mm in size and contains 16,384 active imaging pixels and neural interface. The chip is conforming to a silicate sphere (12.5mm in radius) as shown in Fig. 13(a). The chip is formed and maintained in a contact-lens shape with the polymer-ring backing, and the front side of the packaged chip is shown in Fig. 13(b).

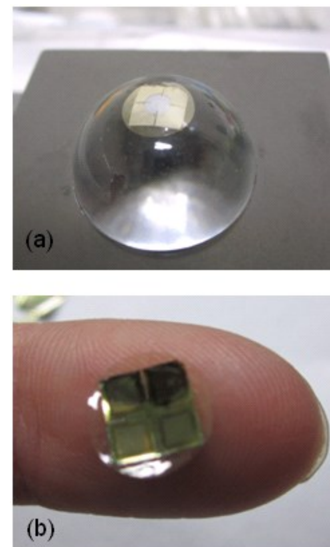

Figure 13. A spherical flexible CMOS retina chip (a) conforms to the surface of glass sphere 25mm in diameter, and (b) the front side of the packaged chip

The profiles of a 4-petal, stress-curved spherical silicon chip and the spherical CMOS retina chip constrained by a

polymer ring were measured by using a confocal microscope within a 3mm range and curve fitted to have the ρ of 40mm and 10mm respectively as shown in Fig. 14. The corresponding maximum stresses in the spherical silicon chip ρ = 10mm are ±160 MPa, an order of magnitude smaller than the ultimate strength of silicon.

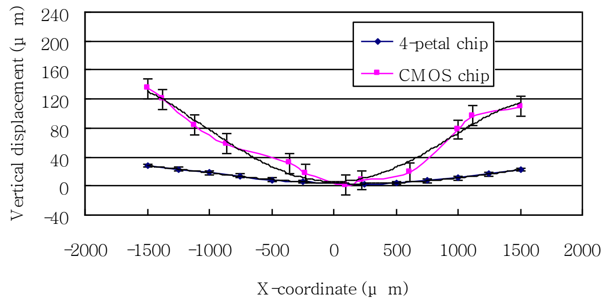

Figure 14. Measured profiles for a 4-petal chip curled by thin-film stress and a CMOS retina chip constrained by a polymer ring

We previously reported the electrical characteristics of these flexible CMOS transistors [2]. The primary effect of bending stresses on the transistor characteristics is the variation of transconductances. The transconductance variations per 100 MPa are 2.7% in longitudinal direction and and 1.3% in transverse direction for NMOS. They are -0.7% in longitudinal direction and 0.5% in transverse direction for PMOS. Circuit was designed pre-compensated.

VI. CONCLUSION

We have demonstrated a non-planar flexible silicon chip technology. The deformation of planar chips has been achieved by means of patterned stress films of high residual stress on top of shaped thin silicon substrate. High residual stresses of thin films make thin chip deform into designed three-dimensional shapes. Both thin disks and "petal-like" chips were fabricated and analyzed, and deformations into shapes that can conform to spherical surfaces down to a 10mm radius of curvature have been demonstrated. This non-planar and flexible chip technology provides devices with a desirable interface to soft or non-planar bio surfaces in many biomedical applications.

ACKNOWLEDGMENT

The authors acknowledge C-C Yang, Z-H Yang, C-H Chung, M-Y Chang and F-M Wang in NTHU for valuable discussions and supports. We thank tsmc for supporting the CMOS image sensor fabrication. The research is funded by grants from NTHU and IMTC.

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