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Fully spherical stretchable silicon photodiodes array for simultaneous 360 imaging

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Imaging is one of the important wonders of today’s world. While everyday millions of snaps are taken, new advances like panoramic imaging have become increasingly popular. However, as of today an imaging system which can simultaneously capture images from all 360° viewpoints with a single sensor has not been achieved. Here, we show a physically flexible and stretchable version of arrayed silicon photodiodes made from low-cost bulk monocrystalline silicon (100) that can capture simultaneous omnidirectional images. The present report, with multiple wavelength detection, fast photoresponsivity, a wide viewing angle, selective aberration, and dynamic focusing enabled by 3D printed pneumatic actuators (note, today millions of image sensors can be integrated in mm² area), overcomes previous demonstrations of only hemispherical photodetection capability. Such imaging capability will make unmanned air vehicles or self-driven cars safer, affordable augmented and virtual reality and more importantly, in-vivo biomedical imaging will be more effective. Published by AIP Publishing. https://doi.org/10.1063/1.5049233

Imaging and light sensing technologies are at the heart of many different tools that affect our daily lives. Applications such as video imaging, optical communications, high-resolution biomedical imaging, night vision, and motion detection have reached an enhanced level of advancement due to the introduction of different materials, integration techniques, and architectures for photodetection. Nonetheless, with the growth of Internet of Things (IoT) and Internet of Everything (IoE) applications, new form factors are required in electronics and materials underlying photodetection to meet the emerging needs such as portability, processing speed, detectability, visual distance, flexibility, and stretchability. Where, stretchable and flexible are of particular interest for purposes ranging from military applications such as surveillance and unmanned aerial vehicles (UAVs) to consumer electronics and systems such as autonomous driving and robotics. Most of the research in the area of photodetection technologies has focused on obtaining miniaturized devices with high responsivity, large bandwidth, low noise, and high gain. Many of these performance properties are commonly improved by using thick active layers. However, thick active layers hinder the potential of these technologies for emerging applications where free form (flexible and stretchable) electronics are required. For this reason, semiconductor nanowires and nanomembranes and emerging 2D materials have been recently used in the demonstration of high-performance photodetectors and cameras for flexible and stretchable applications. These systems provide several advantages in terms of achieving free form factors and improved fields of view. However, they use complex fabrication techniques and expensive materials, and require the use of intricate micro-lenses to achieve satisfactory results at best. Also, the limited stretchability and the lack of dynamic focus hinder their ability to provide omnidirectional imaging. In recent years, an in-depth mechanical analysis for the use of silicon-on-insulator (SOI) substrates to derive flexible and stretchable structures has been reported to accommodate many different kinds of electronics, including stretchable silicon-based photodetectors. Here, we show a comprehensive integration strategy of materials, designs, and fabrication techniques to produce high-performance photodetectors based on bulk monocrystalline silicon (100). Our fabricated photodetectors are capable of producing foveated images (space variant imaging) due to the intrinsic mechanical stretchability provided by the photosensing platform, allowing higher image processing speeds for applications where real time processing is of imperative importance. We also show a space variant imaging platform capable of producing multiple resolution images that can be advantageous to compactly code images, where the major motivation is that considerably high-frequency information repetition exists in the peripheral regions of the images; thus, more efficient compression can be obtained by removing or reducing such information redundancy.

Figure 1(a) presents a schematic for spiral spring stretchable photodetectors. The platform is based on a heavily doped p-type Si (100) wafer with a resistivity of 0.1 Ω cm. The fabrication is divided into two main steps. The first step creates the active array of silicon-based photodetectors. Each p-n junction photodiode (25 μm × 25 μm) is created with solid-source diffusion of phosphorus (P) into the heavily boron (B) doped wafer. After P diffusion, the carrier concentration was found to be 10^{19} atoms cm^{-3} for n-type carriers and 10^{20} atoms cm^{-3} for p-type carriers. Then, each photodiode is contacted using a self-aligned nickel silicidation process at 450°C to reduce the contact resistance and increase the response currents of the photodiodes under illumination. Finally, the contact pads are created using aluminum (Al) sputtering at room temperature and
Completely reversible due to the mechanical properties of todiodes, while Fig. 1(d) shows the fabricated platform at different flow. Supplementary material Fig. S1 shows the complete fabrication of the freestanding hexagonal islands interconnected by the spiral springs (final substrate thickness after over etch—55 μm). The maximum stretchability of the fabricated platform was found to be 70% (initial length = 2.2 mm—center of a hexagonal island to center of adjacent hexagonal island, final length = 15.4 mm). These results show excellent agreement with previously reported mechanical analysis of the fabricated platform.9 The dimensions of the fabricated platform are as follows: Hexagons: hexagon side = 400 μm; Spirals: spiral inner diameter = 250 μm, spiral outer diameter: 360 μm, arm width = 10 μm, and arm separation = 10 μm.

To better understand the limitations of the system for image sensing purposes, two different characterization methods were applied. The first one consists of flooding the sample with white (800 μW/cm²) and RGB (λR = 650 nm, λG = 520 nm, and λB = 470 nm) light without any focal mechanism. This allows a better understanding about the behavior of the photodiodes under direct illumination with multiple wavelengths of light. Figure 2(a) shows the diode behavior under dark and flood (white) illumination conditions. The saturation and dark current under a 1 V bias were found to be 0.121 μA and 5.4 nA for a 625 μm² photodiode. The rise time (t_rise) was calculated by measuring the time necessary for the current to increase from 10% to 90% of its saturation value, while the fall time (t_fall) was measured as the time necessary for the current to decrease from 90% to 10% of the saturation current. The values for rise and fall times were extracted from Fig. 2(b) and were found to be t_rise = 0.52 ms and t_fall = 0.51 ms. The symmetry between the fall and rise times of the devices shows excellent photoresponsivity and dynamic response. It is to be noted that a current peak appears in each transition between light and dark states of the photodetectors; this was found to be caused by a high intensity pulse produced by the light source in each turn-off cycle where the illumination intensity changes from 800 μW/cm² to 1400 μW/cm². To characterize the sensitivity of the photodiodes under illumination with different wavelengths, RGB light bursts were mounted on top of a constant white light source with the following characteristics: (i) white light intensity = 600 μW/cm²; (ii) consecutive red-green-blue light bursts of 1 ms and an intensity of 400 μW/cm². Figure 2(c) depicts the flood illumination setup used to characterize the photodiodes under direct illumination. Figure 2(d) shows the electrical response of the photodiodes under the RGB illumination conditions confirming multiple wavelength detection due to the use of Si as the active layer. It can be seen that a similar electrical response (saturation current = 0.171 μA) is obtained from the photodiodes for each of the RGB light bursts. This shows the advantage of the fabricated photodetectors to produce multiband light sensing and imaging. It is to be noted that due to the multiple wavelength sensitivity of the fabricated sensors, in order to produce a full color image, filter layers that remove interference from different light wavelengths in the RGB spectrum will be required so that a single color can be detected by each photodiode. The intensity graph obtained from a 10 x 10 matrix can be found in Fig. 2(e). In this case, the grayscale image is obtained from the current matrix acquired from the fabricated photodiodes using a custom MATLAB® algorithm based on the following equation:

\[ I(x, y) = \frac{1}{M \times N} \sum_{i=1}^{M} \sum_{j=1}^{N} I_i \times I_j \]

FIG. 1. (a) Schematic of designed and fabricated stretchable and flexible CMOS Si-based photodetectors. (b) Zoom-out digital image of fabricated Si photodetectors. (c) Zoom-in image of fabricated photodetectors showing device arrays and spiral stretchable joins. (d) Fabricated photodetectors at different strain levels (0%, 50%, 100%, and 200%).

Patterns were patterned using standard lift-off techniques. Due to the state-of-the-art CMOS compatibility, the overall fabrication scheme can be improved further and easily for ultra-large-scale integration (ULSI) to produce more miniaturized diodes with enhanced performance and reliability.

The second step of the fabrication creates the stretchable silicon platform in a single photolithography step. Here, a combination of front and back deep reactive-ion-etching (DRIE) is used to create the freestanding structures. The front etch step creates the initial spiral and hexagonal patterns with a depth of 70 μm on top of the silicon substrate. Then, the sample is flipped and etched from the back, while covering the front surface with thick AZ9260 photoresist, until the complete silicon substrate is consumed leaving only the freestanding hexagonal islands interconnected by the spiral springs (final substrate thickness after over etch—55 μm). The width of the spiral structures is critically important to allow maximum silicon stretchability and flexibility. Finite element analysis (FEA) of the mechanical structures can be found in previously reported work.8 Here, we found that the optimal dimension for the spiral arm width is 10 μm. Supplementary material Fig. S1 shows the complete fabrication flow.

Figures 1(b) and 1(c) show the fabricated stretchable photodiodes, while Fig. 1(d) shows the fabricated platform at different levels of strain. It is to be noted that stretching is completely reversible due to the mechanical properties of crystalline silicon and the stretchable spiral design (Supplementary material Movie S7). The sensitivity of the photodiodes is critical to detect interference from different light wavelengths in the RGB spectrum. The dimensions of the fabricated photodiodes are as follows: Hexagons: hexagon side = 400 μm; Spirals: spiral inner diameter = 250 μm, spiral outer diameter: 360 μm, arm width = 10 μm, and arm separation = 10 μm.

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where $I_{\text{pixel}}$ is the output current of each pixel and $I_{\text{sat}}$ is the saturation current of the photodetectors under constant illumination. The MATLAB™ algorithm yielded a $10 \times 10$ matrix where each pixel’s current is translated into 65536.0 (white) and 0.0 (black). The produced grayscale graph shows the uniform response of the photodiodes under flood illumination, where the maximum deviation was found to be 10% from the median intensity value.

In order to test the compatibility of the fabricated photodetectors with flexible and stretchable electronics, the photodiodes were tested under different bending conditions using the same characterization process. The obtained results (supplementary material Fig. S2) show no change in the electrical characteristics of the photodiodes. The constant results can be attributed to the careful design of the flexible/stretchable platform. Here, although the complete platform is subject to mechanical deformation due to applied strain at different bending radii, localized stress in the hexagonal freestanding structures was found to be negligible, while most of the mechanical stress is concentrated in the spiral interconnecting structures. To ratify this phenomenon, FEA was performed to conduct mechanical simulations where a unit cell composed of two hexagons and a single spiral interconnect was studied (Supplementary material S3–S6).

The second characterization method using a 5 cm focal distance lens was performed in order to test the affinity of the fabricated photodetectors with stretchable electronics. In this case, the photodiodes were placed in an initial planar configuration and a simple image was shined from the top with a distance from the platform of 6 cm, while the lens was kept at a constant distance of 5 cm. The projected image and obtained image from scanning an array of $10 \times 10$ photodiodes under illumination can be seen in Fig. 3(a). Characterization of the fabricated photodetectors in the stretched state was done by changing the distance of the focal lens to 6 cm (unfocused) from the stretchable platform. Then, a 3D printed pneumatic actuator [Fig. 3(b)] is used to lift partial areas of the platform and achieve a distance from the lens of 5 cm (focused). From Fig. 3(c), it can be seen that in the stretched state the platform forms a truncated hexagonal pyramid (frustum). Hence, the effective strain applied to the spiral joints is proportional to the slant height of the hexagonal frustum

$$d = \sqrt{h^2 + (ap_1 - ap_2)^2}.$$  (2)

Using Eq. (2), the obtained expansion applied to the spiral joints of the stretchable platform was calculated to be 8.06 mm. Figure 3(d) depicts the image obtained from scanning the photodetector array at two different focus levels, where the elevated area has an enhanced contrast due to the change in focus with respect to the lens. Also, by scanning finer (smaller footprint) and denser photodiodes in the point of gaze and coarse (bigger footprint) photosensors in the peripheral areas, aberrated or blurred zones can be produced in the resultant image. This way, foveated images can be produced without the need for special hardware or image processing. Equivalent imaging modes are almost impossible to realize using planar photodetector technologies even with sophisticated lenses, mirrors, and their combination due to the lack of multifocal points. In foveated images, the difference between the focused and out of focus currents as well as the difference of scanned diodes in the focal point and its peripherals determines the level of compression that can be achieved with the imaging system. For our fabricated sensors, the ratio $(I_{\text{focused}}/I_{\text{unfocused}})$ was found to be 1.3, and 60% of the scanned sensors are placed in the focal point, while the remaining 40% cover the peripheral area of the resultant image. The final system is given the opportunity of achieving compact imaging by taking advantage of its optimized ordering of visual information in terms of perceptual importance. In space variant-imaging systems, one of the most important characteristics is the determination of foveation points. In our case, the points are statically selected as a proof of concept of the functionality that can be achieved with stretchable
photodetectors. However, depending on the application, this may be done either interactively or automatically based on simple pneumatic or mechanical actuators and a focus feedback.

One of the main attributes provided by stretchable photodetectors is the advantage to produce multiple modes of operation depending on the configuration. In one case, detectors can be positioned in plane to produce either multiple (foveated) or static resolution images (as in commercial imaging systems) depending on the point of gaze, and required compression and image quality. On the other hand, a spherical or tubular configuration can be taken advantage of to produce omnidirectional reconstruction where full 360° in the x-y-z axis images is captured and displayed. Here, the mechanical properties of the fabricated devices ensure that a single integrated sensor can perform overall reconstruction of omnidirectional imaging. In this way, each hexagonal island contributes a single or an array of pixels of different regions of the resultant image. Figure 4(a) shows a schematic of what can be achieved with the use of flexible and stretchable electronic platforms in commercial 360° cameras. It is to be noted that simultaneous 360° imaging will require spherical lenses that are able to focus light on the fabricated photodetector structure. For this reason, at this moment we have not been able to produce a complete 360° image, but instead only partial images can be created at a single time using traditional concave lenses. However, with advances in the area of spherical static lenses, this platform could be used as the main CMOS sensor to produce omnidirectional images. To confirm the advantage of the fabricated stretchable photodiodes for omnidirectional image capture, a second FEA was performed taking into account out-of-plane displacement of the hexagonal structure (Fig. S6). Figure 4(b) shows the stretchable PD mounted on a 3D printed sphere. Due to the spherical shape of the 3D printed platform, it is expected that the spirals experience out-of-plane deformations since the array of hexagons and spirals exist around the whole periphery of sphere. Therefore, to validate the structures’ mechanical robustness for the above-mentioned case, the geometry was also subjected to in-plane and out-of-plane deformations simultaneously (Supplementary material Fig. S3). Supplementary material Fig. S6 shows the distribution of von Mises stresses and strain when the cell was subjected to simultaneous in-plane (along x-axis) and out-of-plane (z-axis) displacements of 1 mm. As expected, the maximum stress was increased from 0.3 GPa to 0.6 GPa and strain was increased from 0.1 to 0.2, respectively. Our previous work shows that the spiral, without experiencing any fracture, provides the higher stretchability i.e., elongation could reach 3 to 4 times higher than that of its initial length.9–32 Although the value of stress and strain increased due to out-of-plane deformation, all the mechanical stress is still concentrated within the spirals, while the hexagons are kept in the stress-free state. Figure 4(b) shows the spherical configuration of the stretchable photodetectors where each hexagonal island contributes an array of pixels of the resultant image. This way, the stretchable platform can be used to create multifocal omnidirectional images with a high level of compression depending on the number of scanned PDs. Finally, Figs. 4(c) and 4(d) show the photodetectors configuration where four different laser sources are directed on a single hexagonal island. This shows the compatibility of the stretchable platform with application where multiple points of focus are required.

Recently, 360° imaging has received increased attention due to its ability to produce high level rendering in applications such as virtual reality (VR), augmented reality (AR), and real time data acquisition for artificial intelligence and

FIG. 3. (a) Projected and scanned imaged obtained from a 10 × 10 photodetector array in focused state. (b) Digital image of stretchable photodetectors mounted on a custom 3D printed holder with pneumatic actuators. (c) Schematic for out-of-plane stretching characterization. (d) Scanned photodetector image comparing focused and out of focus states for foveation achieved with a single photodetector platform due to stretchable properties.
and reliability can be integrated in ultra-dense fashion. The more miniaturized devices with enhanced performance improve material properties and processing precision further, of multiple cameras and processing units. In future, with future-imaging systems could make use of the presented functionality under different mechanical configurations (planar and spherical). For these reasons, we envision that transform CMOS-based photodetectors into flexible and stretchable (700%). The fabricated PDs show reliable characteristics, large-scale-integration density, and multi-functionality under different mechanical configurations (planar and spherical). For these reasons, we envision that future-imaging systems could make use of the presented platform to create omnidirectional images without the need of multiple cameras and processing units. In future, with improved material properties and processing precision further more miniaturized devices with enhanced performance and reliability can be integrated in ultra-dense fashion.

See supplementary material for complete fabrication flow and FEA studies.

8X. Wang, Z. Cheng, K. Xu, H. K. Tsang, and J.-B. Xu, Nat. Photonics 7(11), 888 (2013).

FIG. 4. (a) Schematic image showing achievable consumer electronics omnidirectional cameras by using stretchable multifocal photodetectors. (b) Zoom-in digital image of fabricated photodetectors mounted on a spherical 3D printed platform. (c) Zoom-in digital image of spherical characterization using four different laser sources. (d) Zoom out image of multipoint spherical characterization.