2022 21st International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS) | 978-1-6654-9306-2/22/$31.00 ©2022 IEEE | DOI: 10.1109/PowerMEMS56853.2022.10007084

MICROMACHINED FLEXIBLE SILICON SOLAR CELLS AS A POWER SUPPLY FOR SMART CONTACT LENSES

Erfan Pourshaban[1], Mohit U. Karkahnis[1], Adwait Deshpande[1], Md. Rabiul Hasan[1], Nathan D. Rock [2], Aishwaryadev Banerjee[1], Chayanjit Ghosh[1], Hanseup Kim[1], Carlos H. Mastrangelo[1]
[1] Department of Electrical and Computer Engineering, University of Utah, Salt Lake City Utah 84112, USA
[2] Department of Materials Science and Engineering, University of Utah, Salt Lake City Utah 84112, USA

ABSTRACT
This article reports the fabrication, characterization, implementation, and microsystem integration of micromachined flexible silicon solar cells to supply electric power to smart contact lenses. Single silicon solar cell shows the open circuit voltage (V_{oc}) of 0.5 and 0.55 V Under indoor and outdoor lighting conditions, respectively. The V_{oc} enhanced to 1.25 and 1.65 V after making series connections between three cells. The maximum power output of 50 µW and 2.7 mW are recorded under indoor and outdoor lighting conditions. Furthermore, a power management IC is used to boost up the voltage to 3.3 V and efficiently store or use the generated energy.

KEYWORDS
Silicon Solar Cells, Flexibility, Smart Contact Lenses, Microsystems, Power Management

INTRODUCTION
An ever-increasing need for smart health monitoring and disease diagnosis [1], together with the advent of the metaverse [2], has significantly attracted scientific and industrial attention to make a user-friendly smart contact lens. The development of an efficient, standalone, and sustainable electric power supply is one of the most important factors for the commercialization of smart contact lenses. Although several different strategies, including wireless power transfer [3], [4], micro batteries [5], and electrostatic energy generations [6], [7] were used as an energy supply, all of them suffer from serious shortcomings. Wireless power transfer has a very limited reading range of less than 10 cm, and the output power (~0.1 $\mu W.cm^{-2}$) is much less than the required power for smart contact lenses. The presence of toxic materials in conventional Li-ion batteries makes it questionable to be used for wearable devices. In addition, the irregular outputs, together with low generated energy, cancel out the electrostatic generators.

On the other hand, photovoltaic devices demonstrate sufficient power output and can be safely mounted on smart contact lenses. Solar cells can deliver 10 $mW.cm^{-2}$ and 100 $\mu W.cm^{-2}$ under outdoor and indoor lighting conditions. Flexibility, biocompatibility, and efficiency are the most important parameters to define the solar cell's materials. L. Yuan et al. [8] have used different bromine concentrations in the methylammonium lead iodide ($MAPbI_{x-3}Br_x$) perovskite absorber to control the transparency of the photovoltaic device. They achieved a power conversion efficiency (PCE) of 8.8% at the average visible transmittance (AVT) of 41%. G. Eperon et al. [9] also reported a semi-transparent perovskite solar cell based on formamidine lead iodide absorber, which has the PCE of 5.2% at the AVT of 28%. Although perovskite solar cells demonstrate these promising values, the presence of lead in the light absorber structure puts biocompatibility in question. Besides, the low stability of the perovskite absorber against humidity is another discouraging factor [10]. On the other hand, C-C Chen et al. [11] have used a polymer mixture that is capable of absorbing ultraviolet (UV) and near-infrared range of the light spectrum. Their novel material has resulted in a PCE of 4% at AVT of 68%. Besides, T-T Nguyen et al. [12] have fabricated a TiO_2-NiO p-n junction UV absorbing solar cell with the PCE of 2.1% at 57% visible light transmission. However, these types of solar cells stop working in indoor conditions where most wearable electronics require a power supply to operate. Accordingly, we have decided to make flexible silicon solar cells for our wearable application, which require a long lifetime and biocompatibility.

Optoelectronic results show the open circuit voltage of 0.55 V and 0.5 V for the single silicon solar cell under outdoor one sun lighting and indoor lighting condition, respectively. The short circuit current density is 12.1 $mA.cm^{-2}$ and 324 $\mu A.cm^{-2}$ under outdoor and indoor conditions. Making series connection between three individual cells enhances the open circuit voltage to 1.65, and 1.2 V. Results demonstrate the maximum power output of 50 µW and 2.7 mW under indoor and outdoor lighting conditions, respectively. TPS 61094 power management IC is used to boost up the generated voltage to 3.3 V, supply energy to different system loads, and store the generated energy in power storage units while the system load is light.

EXPERIMENTAL
As shown in Fig. 1 (a), the fabrication process of the flexible silicon solar cells starts with oxidizing and low-pressure chemical vapor deposition (LPCVD) of low-stress silicon nitride (Si_xN_y) on a boron-doped silicon wafer. The wafers are photolithographically patterned, SiO_2 and Si_xN_y were dry etched, and phosphorous diffusion was done at 1000 °C for 1 hr to make a pn junction (Fig. 1 (b)). Next, 30 µm thick dies were fabricated using Deep reactive ion etching (DRIE). The top surface of the wafer was totally covered with low-stress Si_xN_y, and the wafer was placed in KOH solution to perform backside etching and release 30 µm thick pn junctions from the silicon wafer (Fig. 1 (d, e, and f)). Then, 200 nm Aluminum (Al) was sputtered as a

back contact using Denton Discovery 635. Annealing was done at 500 °C for 15 min to make p+ region at the contact area between boron-doped silicon and Al contact. The passivating Si_xN_y was etched using CF_4/O_2 gases, and Ti/Au was deposited as the top contacts (Fig. 1(g)). As shown in Fig. 1(h), Wire bonding was used to make a series connection between individual cells. The silicon solar cells were tested under indoor lighting condition, which was simulated using white LED (1000 lx) with a power density of 1 $mW.cm^{-2}$. The Oriel Sol3A is also used to replicate outdoor one sun lighting conditions. In addition, the Keithley 4200A and Hewlett-Packard precision parameter analyzer 4145A were used to collect the IV results.

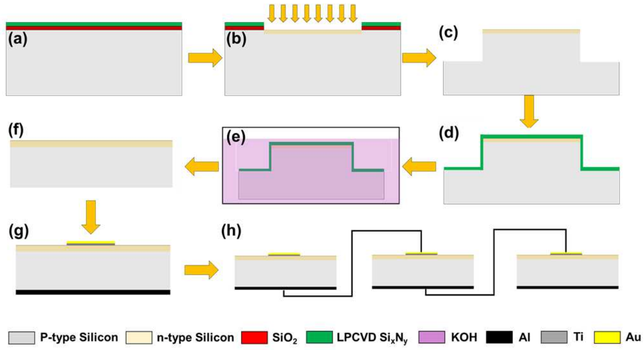

Figure 1: Microfabrication flow of the flexible silicon solar cells; (a) SiO_2 thermal growth and LPCVD Si_xN_y deposition on a p-type silicon wafer, (b) Photolithography, dry etching of the SiO_2 and Si_xN_y layers, and phosphorous diffusion to make the n-type section, (c) Photolithography and DRIE process for 30µm, (d) LPCVD Si_xN_y deposition, (e) KOH etching, (f) Fishing out the thin membrane and etching out the remaining Si_xN_y, (g) Contacts deposition, and (h) Wire bonding to make series connection between individual cell.

RESULTS AND DISCUSSIONS

As shown in Fig 2., IV measurement for single cell and three cells under outdoor one sun and indoor lighting conditions were conducted.

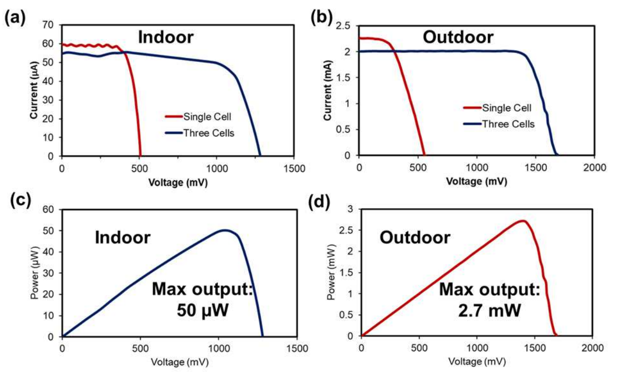

Figure 2: The optoelectrical outputs of the planar and flexible silicon solar cells; (a) IV under one sun lighting condition, (b) IV under indoor lighting condition, (c,d) Load line and power outputs under indoor lighting condition.

Results show the Voc of 0.5 and 0.55V for a single cell under indoor and outdoor lighting conditions, respectively.

As expected, series connection between three individual cells increases the Voc to 1.25 and 1.65V. The short circuit current for a single cell is 60µm and 2mA. The solar cells' current drops slightly due to the power loss within the wiring connections. As shown in Fig 2. (c,d) 50 µW and 2.7 mW are the maximum power output recorded for the cells under indoor and outdoor lighting conditions. To demonstrate the practical application of the cells, the 11 mf off-the-shelf supercapacitor is fully charged after 330 and 5s using photo-generated power. We have also utilized TPS 61094 as the power management IC (PMIC) to boost the solar cells' voltage to 3.3 V, which is the operating voltage of most microcontrollers. Besides, the delivered power at the output of the IC with the clean DC voltage of 3.3 V is measured to be 2.6 mW, while an 11mf supercapacitor is used as the backup energy storage unit. Accordingly, the PMIC's efficiency is 96%, while the solar cells generate electricity under outdoor lighting conditions. Finally, the silicon solar cell and the PMIC which is mounted on a flexible board together with the passive components mounted on a contact lens (Fig. 3(d)).

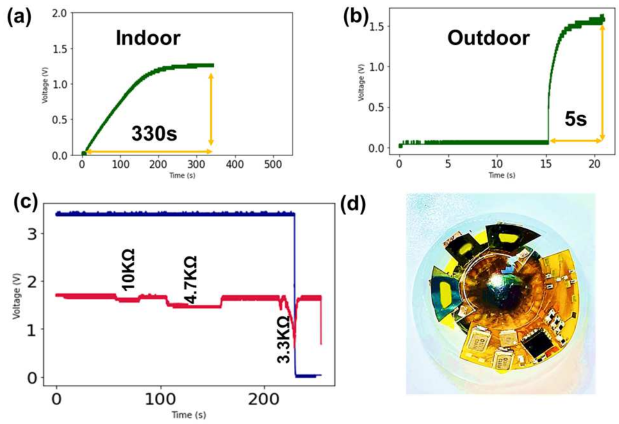

Figure 3: Charging up an 11mf supercapacitor using (a) indoor light, (b) outdoor light, (c) the output of the PMIC and the voltage curve of the backup supercapacitor while having different loads, (d) mounting of the silicon solar cell and the PMIC on a contact lens.

CONCLUSIONS

In the present work, we could be able to successfully microfabricate and characterize a modified version of flexible silicon solar cells to supply electrical power to smart contact lenses. Results show 50 µW and 2.7 mW power output under indoor and outdoor lighting conditions, respectively. Furthermore, we designed and successfully implemented a power management system to boost up the open circuit voltage of the photovoltaic device to 3.3 V, which is a common working voltage of most of microcontrollers. Placing different resistive loads at the output of the power management circuit results in maximum measured power output of 2.6 mW, corresponding to the power efficiency of 96% for the power management IC.

ACKNOWLEDGEMENTS

All the fabrication was performed at the state-of-art Utah Nano Fabrication Facility, Salt Lake City, Utah, USA sponsored under NSF CPS grant 1932606.

REFERENCES

[1] X. Ding, C. Song, and L. Que, “Fabrication of Contact Lens Device with Integrated Microtubes for in Situ Extended Drug Delivery for Ocular Disease Treatment,” in *2019 20th International Conference on Solid-State Sensors, Actuators and Microsystems Eurosensors XXXIII (TRANSDUCERS EUROSENSORS XXXIII)*, Jun. 2019, pp. 306–309. doi: 10.1109/TRANSDUCERS.2019.8808259.

[2] S. Mystakidis, “Metaverse,” *Encyclopedia*, vol. 2, no. 1, Art. no. 1, Mar. 2022, doi: 10.3390/encyclopedia2010031.

[3] J. Park *et al.*, “Soft, smart contact lenses with integrations of wireless circuits, glucose sensors, and displays,” *Sci. Adv.*, vol. 4, no. 1, p. eaap9841, Jan. 2018, doi: 10.1126/sciadv.aap9841.

[4] D. H. Keum *et al.*, “Wireless smart contact lens for diabetic diagnosis and therapy,” *Sci. Adv.*, vol. 6, no. 17, p. eaba3252, Apr. 2020, doi: 10.1126/sciadv.aba3252.

[5] C. Yue, J. Li, and L. Lin, “Fabrication of Si-based three-dimensional microbatteries: A review,” *Front. Mech. Eng.*, vol. 12, no. 4, pp. 459–476, Dec. 2017, doi: 10.1007/s11465-017-0462-x.

[6] E. Pourshaban *et al.*, “A magnetically-coupled micromachined electrostatic energy harvester driven by eye blinking motion,” presented at the 2021 IEEE 21st International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers), Jun. 2021.

[7] E. Pourshaban *et al.*, “Flexible electrostatic energy harvester driven by cyclic eye tear wetting and dewetting,” presented at the 2021 IEEE International Conference on Flexible, Printable Sensors and Systems, Jun. 2021.

[8] L. Yuan *et al.*, “Semi-transparent perovskite solar cells: unveiling the trade-off between transparency and efficiency,” *J. Mater. Chem. A*, vol. 6, no. 40, pp. 19696–19702, Oct. 2018, doi: 10.1039/C8TA07318J.

[9] G. E. Eperon *et al.*, “Efficient, Semitransparent Neutral-Colored Solar Cells Based on Microstructured Formamidinium Lead Trihalide Perovskite,” *J. Phys. Chem. Lett.*, vol. 6, no. 1, pp. 129–138, Jan. 2015, doi: 10.1021/jz502367k.

[10] M. Lira-Cantú, “Perovskite solar cells: Stability lies at interfaces,” *Nat. Energy*, vol. 2, no. 7, Art. no. 7, Jul. 2017, doi: 10.1038/nenergy.2017.115.

[11] C.-C. Chen *et al.*, “Visibly Transparent Polymer Solar Cells Produced by Solution Processing,” *ACS Nano*, vol. 6, no. 8, pp. 7185–7190, Aug. 2012, doi: 10.1021/nn3029327.

[12] T. T. Nguyen *et al.*, “Transparent photovoltaic cells and self-powered photodetectors by TiO2/NiO heterojunction,” *J. Power Sources*, vol. 481, p. 228865, Jan. 2021, doi: 10.1016/j.jpowsour.2020.228865.

CONTACT

Erfan Pourshaban; Erfan.Pourshaban@umail.utah.edu