Patentability/Literature Research:

1. What other inventions, methods, discoveries, or processes exist (or have been written about or described) that are similar to your invention?

<u>Wavy Serpentine Stretchable Electronics</u>

Chang, Dahl-Young, et al. "A stretchable form of single-crystal silicon for high-performance electronics on rubber substrates." *Science* 311.5758 (2006): 208-212.)

-Stretchable silicon in nanoribbon structures, embedded onto a rubber substrate.

Gray, Darren S., Joe Tien, and Christopher S. Chen. "High-conductivity elastomeric electronics." *Advanced Materials* 16.5 (2004): 393-397

-Study of geometrical serpentine structural parameters that enable large strains of metal traces for elastomeric electronics.

Khang, Dahl-Young, et al. "A stretchable form of single-crystal silicon for high-performance electronics on rubber substrates." Science 311.5758 (2006): 208-212.

-Fabrication methods of wavy single crystal silicon devices, and transfer processes onto compliant substrates to enable stretchability within the semiconductor.

Khang, Dahl-Young, John A. Rogers, and Hong H. Lee. "Mechanical buckling: mechanics, metrology, and stretchable electronics." *Advanced Functional Materials* 19.10 (2009)

-Methods to fabricate thin-film wavy single crystal silicon and transferring to a PET substrate

Kim et al. "Stretchable and foldable silicon integrated circuits." *Science* 320.5875 (2008)

-Demonstration of foldable and stretchable single crystal silicon nanoribbons on ultra-thin plastic substrates. Demonstration of integrated stretchable electronic circuit components (CMOS) and

Kim, Dae-Hyeong, et al. "Epidermal electronics." science 333.6044 (2011): 838-843.

-Stretchable and flexible devices that can be printed directly onto human skin. Demonstration of wavy lateral p-n junction diode. This structure inspired our initial lateral photovoltaic structure.

Lazarus, Nathan, Chris D. Meyer, and Sarah S. Bedair. "Stretchable Inductor Design." *IEEE Transactions on Electron Devices* 62.7 (2015): 2270-2277.

-Modeling of geometrical parameters of wavy serpentine structures, used to fabricate stretchable inductors. Serpentine geometries used for photovoltaic device construction are from this paper.

Lu, Nanshu, and Dae-Hyeong Kim. "Flexible and stretchable electronics paving the way for soft robotics." *Soft Robotics* 1.1 (2014): 53-62.

-Review article on flexible and stretchable electronics. Sets needs for development of stretchable energy harvesting and power generation devices.

Rogers, John A., Takao Someya, and Yonggang Huang. "Materials and mechanics for stretchable electronics." *Science* 327.5973 (2010): 1603-1607.

-Review paper on the mechanics of stretchable structures, and the materials commonly used for stretchable device fabrication.

<u>Stretchable Silicon Patents:</u>

Nuzzo, Ralph G., et al. "Methods and devices for fabricating and assembling printable semiconductor elements." U.S. Patent No. 9,450,043. 20 Sep. 2016.

-Stretchable semiconductors ribbon/plate structures and devices that achieve good performance in stretched state.

Rogers, John A., Dahl-Young Khang, and Yugang Sun. "Stretchable form of single crystal silicon for high performance electronics on rubber substrates." U.S. Patent No. 7,521,292. 21 Apr. 2009.

-Fabrication procedure of ‘bent’ geometries to enable stretchable semiconductors, embedded into paper or polymer substrates.

Rogers, John A., et al. "Release strategies for making transferable semiconductor structures, devices and device components." U.S. Patent No. 7,932,123. 26 Apr. 2011.

-Release of multilayered electronic devices; specifically mentions application to photovoltaics.

Rogers, John A., et al. "Controlled buckling structures in semiconductor interconnects and nanomembranes for stretchable electronics." U.S. Patent No. 9,324,733. 26 Apr. 2016.

-Stretchable geometries using nanoribbon structures that buckle out of plane to relieve stress, embedded into an elastomer.

<u>Stretchable Solar Cells</u>

Bozzola, A., P. Kowalczewski, and L. C. Andreani. "Towards high efficiency thin-film crystalline silicon solar cells: the roles of light trapping and non-radiative recombinations." *Journal of Applied Physics* 115.9 (2014): 094501.”.

-Methods for improving thin-film crystalline solar cells efficiency using layers such as light trapping and non-radiative recombinations.

Lee, Jongho, et al. "Stretchable GaAs photovoltaics with designs that enable high areal coverage." *Advanced Materials* 23.8 (2011): 986-991.

-Fabricated a traditional GaAs inorganic solar cell, with stretchable metal interconnects, embedded within a prestrained substrate. Overall system that can undergo stretching of up to ~123% strain.

Lipomi, Darren J., and Zhenan Bao. "Stretchable, elastic materials and devices for solar energy conversion." *Energy & Environmental Science* 4.9 (2011): 3314-3328

-Review article on methods and materials to enable stretchable solar cell devices. Emphasis on organic materials over inorganic materials such as silicon.

Lipomi, Darren J., et al. "Stretchable organic solar cells." *Advanced Materials* 23.15 (2011): 1771-1775.

-Demonstration of a stretchable organic solar cell with no change in electrical performance while in the stretched and unstretched state.

Yu, Ki Jun. "Ultrathin Mono-crystalline Silicon Photovoltaic Cells with Mechanically Flexible and Stretchable Designs, and Light-Trapping Structures". 2012, University of Illinois at Urbana-Champaign.

-Fabrication methods and designs to enable stretchable structures for thin-film silicon. Methods for improving thin-film flexible single-crystalline silicon photovoltaic devices.

X. R. Varache, C. Leendertz, M. E. Gueunier-Farret, J. Haschke, D. Muñoz, and L. Korte. "Investigation of Selective Junctions Using a Newly Developed Tunnel Current Model for Solar Cell Applications." *Solar Energy Materials and Solar Cells* **141** (2015) 14–23. doi:10.1016/j.solmat.2015.05.014.

-AFORS-HET simulation solar cell modeling reference.

Stretchable Solar Cell Patents:

Frolov, Sergey V., Michael Cyrus, and Allan J. Bruce. "Formation of stretchable photovoltaic devices and carriers." U.S. Patent No. 7,923,282. 12 Apr. 2011.

-Fabrication of stretchable solar cells, using metal or plastic carrier as substrate for the solar cell.

Wang, Deli, et al. "Vertical group III-V nanowires on si, heterostructures, flexible arrays and fabrication." U.S. Patent No. 8,932,940. 13 Jan. 2015.

-Fabrication of III-V heterostructure solar cells for flexible and stretchable applications.

Mechanical Modeling of Stretchable Structures

Khang, Dahl-Young, John A. Rogers, and Hong H. Lee. "Mechanical buckling: mechanics, metrology, and stretchable electronics." *Advanced Functional Materials* 19.10 (2009)

-Theoretical calculations and finite element modeling used to explore influence of geometrical parameters such as amplitude, wavelength, and width on buckling mechanics of wavy silicon nanoribbons, on prestrained compliant substrates.

-Buckling-based mechanical investigation of organic materials used for flexible photovoltaics.

Lee, Jongho, et al. "Stretchable GaAs photovoltaics with designs that enable high areal coverage." *Advanced Materials* 23.8 (2011): 986-991.

-Finite element analysis paired with calculations to determine strain contributions of GaAs rigid device islands, stretchable metal interconnections, and substrates. Shows substrate enables stretchability within the system, rather stretching the rigid solar cell itself.

Tompkins, Randy P., et al. "Mechanical Analysis of Stretchable AlGaN/GaN High Electron Mobility Transistors." *ECS Transactions* 72.5 (2016): 89-95.

-FEM modeling of the mechanics of serpentine structures with a 30% strain parallel to the trace.

Zhang, Yihui, et al. "Experimental and theoretical studies of serpentine microstructures bonded to prestrained elastomers for stretchable electronics." *Advanced Functional Materials* 24.14 (2014): 2028-2037.

-FEM and experimental study of serpentine structures bonded to pre-strained elastomeric substrates.

2. How does your invention differ from those other inventions, methods, discoveries, or processes; specifically, what makes your invention different, unique, or an advancement over existing inventions, processes, discoveries, or methods?

Section one is a detailed list of the relevant journals, patents, and conference proceedings of research and innovation on stretchable forms of silicon and stretchable photovoltaic devices. These previous inventions have focused on fabrication methods that use alternative geometric set ups that enable stretchability within silicon: one such method is using interconnected patterned nanoribbons that enable stretchable electronic devices such as diodes or MOSFETs. Many of the referenced journals exploit methods, modeling, and theory for fabricating stretchable silicon Finite element modeling and theoretical calculations performed on our serpentine geometries were very similar to the corresponding methods reported in the referenced publications, making our results directly comparable to other serpentine inventions. The main difference in our design is our utilization of brittle, inorganic semiconducting material versus the use of organic materials in current innovations on stretchable solar cells. The reported materials utilized in stretchable solar cells focus on using organic materials and III-V hetero-structures. Our invention is one of the first investigations of using silicon for a stretchable photovoltaic device.

To the best of our knowledge, none of the aforementioned journals or patents apply the concepts of the wavy, serpentine geometries into the fabrication of single crystal silicon photovoltaic devices. Furthermore, our design demonstrates a cheap, easily reproducible and efficient fabrication process that enables a silicon photovoltaic to maintain its electrical and mechanical performance while undergoing extreme amounts of tensile strain. Further research and development using our methods and proposed processing techniques can allow more flexibility and higher efficiency within the design, enabling *Stretchable Silicon Photovoltaics* as wearable, renewable energy-harvesting devices.