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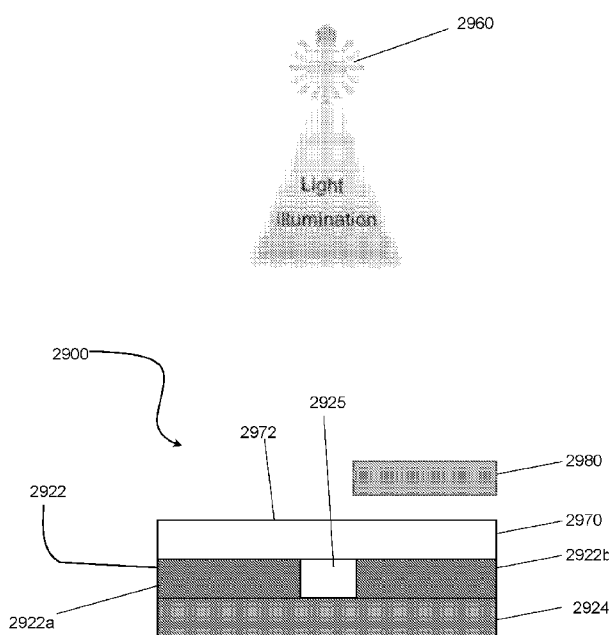


Figure 29

(57) Abstract: A hybrid energy generator 2900,4300,4600 that generates energy based on shadow-effect, and triboelectric effect is disclosed. The hybrid energy generator 2900,4300,4600 includes a semiconductor substrate 2924,4324,4624 a light permeable triboelectric charging element 2970,4370,4670 a metallic element 2922,4322,4622 sandwiched between the light permeable triboelectric charging element 2970,4370,4670 and the semiconductor substrate 2924,4324,4624 and a movable triboelectric charging element 2980,4380,4680 arranged to be movable relative to a surface of the light permeable triboelectric charging element 2970,4370,4670 and exposed to an illumination source 2960,4690 to cast a shadow and to produce an illumination contrast for detection by the metallic element 2922,4322,4622. Energy is generated when the movable triboelectric charging element 2980,4380,4680 is in contact with the surface of the light permeable triboelectric charging element 2970,4370,4670 and from the illumination contrast detected by the metallic element 2922,4322,4622. An energy generator 100,300,2500,2600 that generates energy based on shadow-effect is also disclosed. Methods of generating energy using the energy generators 100,300,2500,2600, 2900,4300,4600 are also disclosed.

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**A SHADOW-EFFECT ENERGY GENERATOR, A HYBRID ENERGY
GENERATOR, AND METHODS OF GENERATING ENERGY USING THE
GENERATORS THEREOF**

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TECHNICAL FIELD

The present application relates to shadow-effect energy generators, triboelectric energy generators, and hybrid energy generators. The present application also relates to methods of generating energy using the shadow-effect energy
10 generator, the triboelectric energy generator and the hybrid energy generator.

BACKGROUND

The energy crisis and environmental concerns associated with the continuous combustion of fossil fuels has spurred the development of clean energy
15 technologies in many industries. However, the adoption of clean energy technologies is often held back by certain shortcomings.

For example, various wearable or portable electronics, especially in small sizes with energy consumption levels in the milli-watt to micro-watt range, have
20 reached many aspects of daily life. One way that clean energy is used is by converting ambient light energy into electricity to offset the reliance of small wearable/portable electronics on conventional energy supplies. However, power outputs of conventional light energy generators, such as photovoltaic cells, drop dramatically in low intensity environment, especially in the presence of shadows,
25 making it difficult to reach the power requirements of most wearable or portable electronics.

In another example, monitoring objects (people or car) is necessary for public security, smart transport system and internet-of-things. Various motion detection
30 methods are employed for monitoring objects passing by. However, the hardware required are usually complex, bulky, expensive, and need an external power source.

Developments have also been made to harness tidal energy. Tidal energy is both a clean and a renewable energy source with tremendous potential to generate electricity globally. If fully exploited, about 40% of the world's power demand could be supplied by this resource, equivalent to about 800 nuclear power plants. One potential method to harness tidal energy is to use the triboelectric nanogenerator (TENG), which offers many potential advantages. However, the small magnitude, pulsed signals, and low power output of TENG may not be suitable as a sustainable energy source.

Therefore, it is desirable to provide a solution that addresses at least one of the problems mentioned in existing prior art, and/or to provide the public with a useful alternative.

SUMMARY

In a first aspect, there is provided a hybrid energy generator comprising a semiconductor substrate; a light permeable triboelectric charging element; a metallic element sandwiched between the light permeable triboelectric charging element and the semiconductor substrate; a movable triboelectric charging element arranged to be movable relative to a surface of the light permeable triboelectric charging element and exposed to an illumination source to cast a shadow and to produce an illumination contrast for detection by the metallic element; wherein energy is generated when the movable triboelectric charging element is in contact with the surface of the light permeable triboelectric charging element, and from the illumination contrast detected by the metallic element.

As described in the preferred embodiments, the hybrid energy generator is able to generate energy based on 'shadow-effect' as well as triboelectric charging effect. Thus, the hybrid energy generator might be an effective solution to harvest solar energy as well as in applications where the hybrid energy generator might be caused to move constantly.

The hybrid energy generator may further include an energy storage element electrically coupled to the metallic element. The energy storage element is arranged to store the energy generated.

- 5 The energy storage element may include at least one fibre-supercapacitor. The at least one fibre-supercapacitor may include a layered molybdenum disulfide. Furthermore, the semiconductor substrate may be an n-doped semiconductor.

10 The metallic element may be made of gold, aluminium or copper. The metallic element may also have a thickness of 15nm. Preferably, the light permeable triboelectric charging element may be made of a polymer. The polymer may be polydimethylsiloxane.

15 The movable triboelectric charging element may be made of aluminium. The movable triboelectric charging element may be movable by gravity along the surface of the light permeable triboelectric charging element. The movable triboelectric charging element may be spherical.

20 In addition, the hybrid energy generator may further include a light permeable exterior shell encapsulating the semiconductor substrate, the metallic element, the light permeable triboelectric charging element, and the movable triboelectric charging element.

25 The movable triboelectric charging element may be movable in a direction that is perpendicular to a surface of the light permeable triboelectric charging element. It is envisaged that the movable triboelectric charging element may be electrically charged liquid droplets, such as water droplets.

30 According to a second aspect, there is provided a method of generating energy using a hybrid energy generator having a semiconductor substrate, a light permeable triboelectric charging element, a metallic element sandwiched between the light permeable triboelectric charging element and the

semiconductor substrate, and a movable triboelectric charging element arranged to be movable relative to a surface of the light permeable triboelectric charging element, the method comprising exposing the movable triboelectric charging element to an illumination source to cast a shadow for producing an illumination contrast for detection by the metallic element; and generating energy when the movable triboelectric charging element is in contact with the surface of the light permeable triboelectric charging element, and from the illumination contrast detected by the metallic element.

10 The method may further include storing the energy generated using an energy storage element electrically coupled to the metallic element.

The energy storage element may include at least one fibre-supercapacitor. The at least one fibre-supercapacitor may include a layered molybdenum disulfide.

15 Furthermore, the semiconductor substrate may be an n-doped semiconductor.

The metallic element may be made of gold, aluminium or copper. The metallic element may also have a thickness of 15nm. Preferably, the light permeable triboelectric charging element may be made of a polymer. The polymer may be polydimethylsiloxane.

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The movable triboelectric charging element may be made of aluminium.

In addition, moving the movable triboelectric charging element relative to a surface of the light permeable triboelectric charging element may further include moving the movable triboelectric charging element by gravity along the surface of the light permeable triboelectric charging element. The movable triboelectric charging element may be spherical.

25

30 The hybrid energy generator may further include a light permeable exterior shell encapsulating the semiconductor substrate, the metallic element, the light

permeable triboelectric charging element, and the movable triboelectric charging element.

Furthermore, moving the movable triboelectric charging element relative to a surface of the light permeable triboelectric charging element may further include moving the movable triboelectric charging element in a direction that is perpendicular to a surface of the light permeable triboelectric charging element. It is envisaged that the movable triboelectric charging element may be electrically charged liquid droplets, such as water droplets.

10

In a third aspect, there is provided an energy generator comprising a plurality of energy generating cells disposed on a substrate and electrically coupled to each other, each energy generating cell including a semiconductor substrate, and a metallic element disposed on the semiconductor substrate, wherein energy is generated when the metallic element detects an illumination contrast produced when a shadow is cast to the metallic element.

The energy generating cells may be electrically coupled in parallel or in series. Additionally, the substrate may be made of a polymer, and the polymer may be polyethylene terephthalate or polytetrafluoroethylene. Preferably, the semiconductor substrate may be an n-doped semiconductor.

20

Furthermore, the metallic element may be made of gold, aluminium or copper. The metallic element may also have a thickness of 15nm.

25

In a fourth aspect, there is provided a motion detection method using an energy generator having a plurality of energy generating cells disposed on a substrate and electrically coupled to each other, each energy generating cell including a semiconductor substrate, and a metallic element disposed on the semiconductor substrate, the method comprising casting a shadow to the metallic element when an object passes between the metallic element and an illumination source to

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produce an illumination contrast; and detecting the object's motion from energy generated from the illumination contrast.

It should be apparent that features relating to one aspect may also be applicable
5 to features of the other aspects.

BRIEF DESCRIPTION OF DRAWINGS

Exemplary embodiments will be described with reference to the accompanying
10 drawings in which:

Figure 1A is a perspective view of an energy generator having ten energy generating cells according to a first embodiment.

Figure 1B is an enlarged cross-sectional view of one of the energy generating cells of Figure 1A.

15 Figure 2A is a top view of the energy generator of Figure 1a bent at a bend angle of 60°.

Figure 2B is a top view of the energy generator of Figure 1a bent at a bend angle of 120°.

Figure 2C is a top view of the energy generator of Figure 1a bent at a bend angle
20 of 180°.

Figure 2D is a top view of the energy generator of Figure 1a bent at a bend angle of 240°.

Figure 3 is a perspective view of an energy generator having four energy generating cells according to a second embodiment.

25 Figure 4A shows a line graph 410 for the short-circuit current (I_{sc}) of the energy generator of Figure 3 at a bend angle of 180°.

Figure 4B shows a line graph for the open-circuit voltage (V_{oc}) of the energy generator of Figure 3 at a bend angle of 180°.

Figure 4C shows two line graphs for the short-circuit current (I_{sc}) and open-circuit
30 voltage (V_{oc}) of the energy generator of Figure 3 respectively varying with the bend angle.

Figure 5 shows five line graphs for the short-circuit current (I_{sc}) of the energy generating cell of Figure 1a having a gold film with five different thicknesses.

Figure 6 shows five line graphs for the open-circuit voltage (V_{oc}) of the energy generating cell of Figure 1a having a gold film with five different thicknesses.

- 5 Figure 7A shows two line graphs for the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) of the energy generating cell of Figure 1a respectively varying with the thickness of the gold film.

Figure 7B shows a line graph of the transmittance of the metallic element varying with the thickness of the gold film.

- 10 Figure 8 shows two line graphs for the IPCE of the energy generating cell of Figure 1a having a gold film thickness of 15nm and 30nm varying with incident photon wavelength, and two line graphs for the transmittance of the gold film having thickness of 15nm and 30nm varying with incident photon wavelength.

- 15 Figure 9 shows two line graphs for the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) of the energy generating cell of Figure 1a respectively varying with the shadow area ratio.

Figure 10A is a perspective view of the energy generating cell of Figure 1a having first and second electrodes connected to the gold film for collecting the excited electrons.

- 20 Figure 10B shows two line graphs for the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) of the energy generating cell of Figure 10A with the first and second electrodes connected at various distances, D_s, D_i on the gold film.

- 25 Figure 11A shows two line graphs for the short-circuit current (I_{sc}) and the power density (P_{HI}) of the energy generating cell of Figure 10A respectively varying with the length of the energy generating cell.

Figure 11B shows a line graph for the open-circuit voltage (V_{oc}) of the energy generating cell of Figure 10A varying with the length of the energy generating cell.

- 30 Figure 12A shows two line graphs for the short-circuit current (I_{sc}) and the power density (P_{HI}) of the energy generating cell of Figure 10A respectively varying with the width of the energy generating cell.

Figure 12B shows a line graph for the open-circuit voltage (V_{oc}) of the energy generating cell of Figure 10A varying with the width of the energy generating cell.

Figure 13 shows two line graphs for the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) of the energy generating cell of Figure 10A with a gold film, an aluminium film, and a copper film respectively.

Figure 14A shows a surface potential map for the work function of the energy
5 generating cell of Figure 10A with the gold film.

Figure 14B is a bar diagram showing the shift in work function of the energy generating cell of Figure 10A with the gold film before and after full illumination.

Figure 15A shows a surface potential map for the work function of the energy generating cell of Figure 10A with the copper film.

10 Figure 15B is a bar diagram showing the shift in work function of the energy generating cell of Figure 10A with the copper film before and after full illumination.

Figure 16A shows a surface potential map for the work function of the energy generating cell of Figure 10A with the aluminium film.

Figure 16B is a bar diagram showing the shift in work function of the energy
15 generating cell of Figure 10A with the aluminium film before and after full illumination.

Figure 17 shows two line graphs for the short-circuit current (I_{sc}), and two line graphs for the open-circuit voltage (V_{oc}), of the energy generating cell of Figure 10A having a planar n-Si and a textured n-Si respectively.

20 Figure 18A is a line graph showing the illumination intensity of the shadow cast on the energy generating cell of Figure 10A varying with the transmittance of the shadow-throwing object.

Figure 18B shows two line graphs for the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) of the energy generating cell of Figure 10A respectively
25 varying with illumination contrast.

Figure 19A is a circuit diagram for determining an optimum matching impedance of the energy generating cell of Figure 10A.

Figure 19B shows two line graphs for peak current and peak power of the energy generating cell of Figure 10A respectively varying with load resistance.

30 Figure 20 shows two line graphs for the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) of the energy generating cell respectively varying with illumination intensity.

Figure 21A shows two line graphs for the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) of the energy generating cell respectively varying with the number of illumination cycles.

Figure 21B shows a bar graph for the short-circuit current (I_{sc}) of the energy
5 generating cell varying with time.

Figure 21C shows a bar graph for the open-circuit voltage (V_{oc}) of the energy generating cell varying with time.

Figure 22 shows three line graphs for the short-circuit current (I_{sc}), and three line
10 graphs for the open-circuit voltage (V_{oc}), of the energy generating cell at three incidence angles of illumination.

Figure 23 shows four line graphs of the current density-to-voltage characteristics of a C-Si cell when fully exposed to five different illumination intensities.

Figure 24A shows two line graphs comparing the open-circuit voltages (V_{oc}) of the C-Si cell to an energy generating cell under low illumination intensity.

15 Figure 24B shows two line graphs comparing the short-circuit current (I_{sc}) of the C-Si cell to an energy generating cell under low illumination intensity.

Figure 25A is a front view of a robot before passing an energy generator having one energy generating cell according to a third embodiment.

Figure 25B is a front view of the robot with a foot on the energy generator of
20 Figure 25A.

Figure 25C is a front view of a remote-controlled car before passing the energy generator of Figure 25A.

Figure 25D is a front view of the remote-controlled car with one wheel 2532 on the energy generator of Figure 25A.

25 Figure 25E is a line graph for the open-circuit voltage (V_{oc}) of the energy generator of Figure 25A varying with time.

Figure 26A is a top view of an electronic watch connected to an energy generator having four energy generating cells connected in series according to a fourth embodiment.

30 Figure 26B is a top view of the electronic watch being powered on after the energy generator of Figure 26A is exposed to an illumination source.

Figure 26C is a circuit schematic showing the electronic watch connected to the energy generator of Figure 26A.

Figure 26D is a line graph for the short-circuit current (I_{sc}) of the energy generator of Figure 26A varying with time.

- 5 Figure 26E is a line graph for the open-circuit voltage (V_{oc}) of the energy generator of Figure 26A varying with time.

Figure 27A is a schematic diagram of a foot casting a shadow on the energy generator of Figure 3.

- 10 Figure 27B is a top view of the foot being placed on the energy generator of Figure 3 encased in a glass box.

Figure 27C is a top view of the foot being removed from the energy generator of Figure 3 encased in the glass box.

Figure 27D is a line graph for the short-circuit current (I_{sc}) of the energy generator of Figure 3 varying with time.

- 15 Figure 27E is a line graph for the open-circuit voltage (V_{oc}) of the energy generator of Figure 3 varying with time.

Figure 28A is a schematic diagram of an arm casting a shadow on the energy generator of Figure 3.

- 20 Figure 28B is a side view of the arm being placed in front of the energy generator of Figure 3.

Figure 28C is a side view of the arm moving away from the energy generator of Figure 3.

Figure 28D is a line graph for the short-circuit current (I_{sc}) of the energy generator of Figure 3 varying with time.

- 25 Figure 28E is a line graph for the open-circuit voltage (V_{oc}) of the energy generator of Figure 3 varying with time.

Figure 29 is a schematic diagram of a hybrid energy generator according to a fifth embodiment.

- 30 Figure 30 is a flow diagram illustrating a method for generating energy through the triboelectric effect using the hybrid energy generator of Figure 29.

Figure 31 is a flow diagram illustrating a method for generating energy through the shadow-effect using the hybrid energy generator of Figure 29.

Figure 32 is a circuit diagram of the hybrid energy generator of Figure 29.

Figure 33A is a line graph for the short-circuit current density (J_{sc}) of the hybrid energy generator of Figure 29 varying with time.

Figure 33B is a line graph showing a magnified waveform for the short-circuit current density (J_{sc}) of the hybrid energy generator of Figure 29 without illumination.

Figure 33C is a line graph showing a magnified waveform for the short-circuit current density (J_{sc}) of the hybrid energy generator of Figure 29 with illumination.

Figure 34A shows two line graphs for the transmittance of glass and PDMS-on-glass varying with wavelength of transmitted light.

Figure 34B shows two line graphs for the short-circuit current density (J_{sc}) of the S-TENG of Figure 29 with the PDMS film, and with the PDMS film removed.

Figure 34C shows two line graphs for the open-circuit voltage (V_{oc}) of the hybrid energy generator of Figure 29 with the PDMS film, and with the PDMS film removed.

Figure 35 is a data plot for an electrical resistance of the gold film of the hybrid energy generator of Figure 29 varying with its thickness.

Figure 36 is a schematic diagram of a hybrid energy generator having a gold film with no gap according to a sixth embodiment.

Figure 37A shows two line graphs for the transmittance of glass and black-paper-on-glass varying with wavelength of transmitted light.

Figure 37B is a line graph for the short-circuit current density (J_{sc}) of the hybrid energy generator of Figure 29, (i) with the moving stage removed; (ii) with glass as the moving stage; and (iii) with black-paper-on-glass as the moving stage

Figure 38 is a line graph for the short-circuit current density (J_{sc}) of the hybrid energy generator of Figure 29, (i) with glass as the moving stage; and (ii) with black-paper-on-glass as the moving stage, varying with up-down motion of the moving stage.

Figure 39A shows ten line graphs for the short-circuit current density (J_{sc}) of the hybrid energy generator of Figure 29, with illumination and without illumination, at five contact frequencies of the moving stage.

Figure 39B shows five line graphs for the open-circuit voltage (V_{oc}) of the hybrid energy generator of Figure 29, with illumination, at five contact frequencies of the moving stage.

Figure 40 is a line graph for the short-circuit current density (J_{sc}) of the hybrid energy generator of Figure 29 varying with illumination intensity of the illumination source.

Figure 41 shows two line graphs for the open-circuit voltage (V_{oc}) and charge for a single-electrode hybrid energy generator.

Figure 42 shows two line graphs for the short-circuit current density (J_{sc}) and power density of the hybrid energy generator of Figure 29 varying with load resistance.

Figure 43 is a flow diagram illustrating a method for generating energy using a hybrid energy generator that utilizes water droplets as the movable triboelectric charging element according to a seventh embodiment.

Figure 44A illustrates a line graph for the open-circuit voltage (V_{oc}) of the hybrid energy generator of Figure 43 at various degrees of tilt angle.

Figure 44B illustrates a line graph for the short-circuit current density (J_{sc}) of the hybrid energy generator of Figure 43 at various dripping heights.

Figure 45A is a line graph for the short-circuit current density (J_{sc}) of the hybrid energy generator of Figure 43, with illumination and without illumination.

Figure 45B is a line graph for the open-circuit voltage (V_{oc}) of the hybrid energy generator of Figure 43, with illumination and without illumination.

Figure 45C is a line graph for the charge density ($\Delta\sigma_{sc}$) of the hybrid energy generator of Figure 43, with illumination and without illumination.

Figure 46A is a perspective view of a hybrid energy generator according to an eighth embodiment.

Figure 46B is an enlarged perspective bottom view of a portion of the hybrid energy generator of Figure 46A.

Figure 47 is a flow diagram illustrating the method for generating energy through the triboelectric effect using the hybrid energy generator of Figure 46A.

Figure 48 illustrates a top view of the hybrid energy generator of Figure 46A corresponding to the flow diagram of Figure 47A.

Figure 49A shows three line graphs for the short-circuit current density (J_{sc}) of the hybrid energy generator of Figure 46A at increasing wave intensities.

Figure 49B shows two line graphs for the short-circuit current density (J_{sc}) of the hybrid energy generator of Figure 46A, with the aluminium ball, and with a steel ball.

Figure 49C is a line graph for the short-circuit current density (J_{sc}) of the hybrid energy generator of Figure 46A cycled over a period of 700s.

Figure 49D shows five line graphs for the short-circuit current density (J_{sc}) of the hybrid energy generator of Figure 46A at various incidence angles of illumination.

Figure 49E shows two line graphs for the short-circuit current density (J_{sc}) and peak power density of the hybrid energy generator of Figure 46A varying with load resistance.

Figure 50A shows three line graphs for the short-circuit current density (J_{sc}) of the hybrid energy generator of Figure 46A with (i) shadow-effect only; (ii) triboelectric effect only; and (iii) both shadow-effect and triboelectric effect, before and after being rectified.

Figure 50B shows three line graphs 5020a, 5020b, 5020c for the open-circuit voltage (V_{oc}) of the hybrid energy generator of Figure 46A with (i) shadow-effect only; (ii) triboelectric effect only; and (iii) both shadow-effect and triboelectric effect, before and after being rectified.

Figure 50C illustrates a circuit diagram of the hybrid energy generator of Figure 46A used in a self-charging power system.

Figure 50D shows two line graphs for the open-circuit voltage (V_{oc}) of the hybrid energy generator of Figure 46A used in the self-charging power system with (i) shadow-effect only; (ii) triboelectric effect only; and (iii) both shadow-effect and triboelectric effect.

Figure 51A shows two line graphs for the X-ray diffraction pattern of a few-layered MoS_2 used to fabricate the fiber supercapacitor of the hybrid energy generator of Figure 46A, and a bulk MoS_2 respectively.

Figure 51B shows two line graphs for the Raman spectra of the few-layered MoS_2 referred to in Figure 51A, and the bulk MoS_2 respectively.

Figure 51C is a scanning electron microscopy (SEM) image of a carbon fiber electrode coated with the few-layered MoS₂ referred to in Figure 51A.

Figure 51D is a cross-sectional view of the SEM image of Figure 51C.

Figure 51E shows two cyclic voltammetry (CV) curves for the short-circuit current (I_{sc}) of the fiber supercapacitor of the hybrid energy generator of Figure 46A varying with potential, with the few-layered MoS₂ and without the few-layered MoS₂ respectively.

Figure 51F shows four cyclic voltammetry (CV) curves for the short-circuit current (I_{sc}) of the fiber supercapacitor of the hybrid energy generator of Figure 46A varying with potential, at different scan rates.

Figure 52A shows four galvanostatic charge-discharge (GCD) curves for the potential of the fiber supercapacitor of the hybrid energy generator of Figure 46A varying with time, under various small input currents.

Figure 52B shows a galvanostatic charge-discharge (GCD) curve for the capacitance retention of the fiber supercapacitor of the hybrid energy generator of Figure 46A across 1200 cycles, and a line graph for the potential of the fiber supercapacitor varying over time.

Figure 52C is a line graph of a specific capacitance of the fiber supercapacitor of the hybrid energy generator of Figure 46A varying with discharge currents of the charge-discharge profiles.

Figure 52D is a Ragone plot for a power density of the fiber supercapacitor of the hybrid energy generator of Figure 46A varying with energy density.

Figure 53A shows four cyclic voltammetry (CV) curves for the short-circuit current (I_{sc}) of five fiber supercapacitors of the hybrid energy generator of Figure 46A connected in series varying with potential, at different scan rates.

Figure 53B is a line graph of a capacitance of the five fiber supercapacitors of Figure 53A varying with discharge currents of the charge-discharge profiles.

Figure 53C shows three galvanostatic charge-discharge (GCD) curves for the potential of the five fiber supercapacitor of Figure 53A varying with time, under various small input currents.

Figure 53D shows three galvanostatic charge-discharge (GCD) curves for the potential of the five fiber supercapacitor of Figure 53A varying with time, under different small input currents.

Figure 53E is an enlarged view of the three galvanostatic charge-discharge (GCD) curves of Figure 53D.

Figure 54A is a circuit diagram for a power harvesting system that utilizes the hybrid energy generator of Figure 46A.

Figure 54B is a line graph showing the change in voltage of the five fiber supercapacitors of the power harvesting system of Figure 54A during charging and discharging.

Figure 55 is a top view of an exemplary 4x4 array of the hybrid energy generator of Figure 46A.

DETAILED DESCRIPTION

The following description includes specific examples for illustrative purposes. The person skilled in the art would appreciate that variations and alterations to the specific examples are possible and within the scope of the present disclosure. The figures and the following description of the particular embodiments therefore should not take away from the generality of the preceding summary.

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Figure 1a illustrates an exemplary energy generator 100 including ten energy generating cells 120 disposed on a substrate 150. The ten energy generating cells 120 are spaced apart and arranged in a single row on the substrate 150. The SEG cells 120 are electrically coupled to each other so that the energy generated by each SEG cell 120 is combined to increase power output of the SEG 100. The energy generating cells 120 have a similar structure and Figure 1b is an enlarged cross-sectional view of one of the energy generating cells 120 (referred to as 120a) is described. As shown in Figure 1b, the energy generating cell 120a includes a metallic element 122 disposed on a semiconductor substrate 124. In this embodiment, the metallic element 122 is a gold thin film 122 having a thickness of 15nm, and the semiconductor substrate 124 is an n-doped silicon

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substrate/wafer 124. A Schottky barrier is formed at an interface 126 of the metallic element 122 and the semiconductor substrate 124.

The energy generating cell 120a generates energy based on 'shadow-effect'. The working principle of shadow-effect energy generation is described in detail in the scientific publication "Ravi, S. K., Sun, W., Nandakumar, D. K., Zhang, Y. and Tan, S. C., Optical manipulation of work function contrasts on metal thin films, Sci. Adv. 4, eaao6050 (2018)". In essence, and using the energy generating cell 120a as an example, when the energy generator 100 is exposed to an illumination source 160, a shadow is cast on the metallic element 122 of the energy generating cell 120a, producing an illumination contrast, i.e., a bright region 130 and a dark/shadow region 140. Notably, work function of metal is lower when illuminated. This can be understood as a shortening of the Schottky barrier height. Photoexcited electrons that overcome the Schottky barrier are injected into the metallic element 122 from the semiconductor substrate 124. Since the photoexcited electrons injected into the metal are at a lower work function in the bright region, the photoexcited electrons are transferred to the dark region which has a higher work function. In effect, the illumination contrast results in a directional flow of electrons from the bright region 130 to the dark region 140, thereby generating energy through the shadow-effect. For this reason, the energy generator 100 is also referred to as a shadow-effect energy generator (SEG) 100, and the energy generating cells 120 are also referred to as a SEG cell 120.

In this embodiment, the substrate 150 is a polyethylene terephthalate (PET) film which is flexible and transparent. This gives the SEG 100 flexibility to be implemented in a variety of electronic applications. For example, the SEG 100 can be attached to clothing and can power wearable electronic devices by continuously converting the shadows cast on the SEG 100 into electricity. The SEG 100 in Figure 1a is shown to be bent at a bend angle of 120°. However, the SEG 100 can also be bent to other bend angles as illustrated in Figures 2A to 2D which depict a top view of the energy generator 100 at bend angles of 60°, 120°, 180°, and 240° respectively.

It should be noted that the substrate 150 may be made of other materials depending on the specific application. The SEG 100 may also be bent at other bend angles such as 90°, 150°, and 210°. Depending on the flexibility of the substrate 150, the SEG 100 may also be bent to 30° or 270°.

The SEG cells 120 may also be electrically coupled in parallel or in series. Furthermore, the shape and arrangement of SEG cells 120 may vary depending on the specific application. In addition, although the SEG 100 is described as including ten SEG cells 120, it is possible for the SEG 100 to include any number of SEG cells 120. For example, Figure 3 illustrates an SEG 300 having four SEG cells 120 arranged in a single row on the substrate 150. In this embodiment, the SEG cells 120 of the SEG 300 are electrically coupled in parallel.

The performance of the SEG 300 in outdoor conditions is described with reference to Figures 4A to 4C. In outdoor conditions, the illumination source 160 is the sun, and the SEG 300 is exposed to an illumination intensity of 1kW/m² (or 1-sun intensity). Figure 4A shows a line graph 410 for the short-circuit current (I_{sc}) of the SEG 300 at a bend angle of 180° in outdoor conditions. Figure 4B shows a line graph 420 for the open-circuit voltage (V_{oc}) of the SEG 300 at a bend angle of 180° in outdoor conditions. The SEG 300 achieves its peak performance when 'half-in-shadow'. The term 'half-in-shadow' (or variants such as 'half-illuminated') refers to the condition when a half portion 330 of the SEG 300 is exposed to the illumination source 160, and the remaining half portion 340 of the SEG 300 is in the shadow to produce an illumination contrast between the two half portions 330,340. The term 'full illumination' (or variants such as 'fully illuminated') then refers to the condition when both half portions 330,340 are fully exposed to the illumination source. Referring to Figures 4A and 4B, the SEG 300 is exposed to the illumination source 160 at time, $t = 10\text{-}20\text{s}$, $30\text{-}40\text{s}$, and $50\text{-}60\text{s}$. Under half-in-shadow conditions, the SEG 300 achieves a short-circuit current (I_{sc}) of 1.2mA, and an open-circuit voltage (V_{oc}) of 500mV. For a remainder of the time, at $t = 0\text{-}10\text{s}$, $20\text{-}30\text{s}$, $40\text{-}50\text{s}$, and $60\text{-}70\text{s}$, the SEG 300 is not exposed to the illumination

source 160, and thus there is negligible short-circuit current ($I_{sc} \approx 0$) and open-circuit voltage ($V_{oc} \approx 0$).

Figure 4C shows two line graphs 430,440 for the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) of the SEG 300 respectively varying with the bend angle of the SEG 300. Both the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) increases with the bend angle from 30° to 180° . The short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) reaches peak values ($I_{sc}=1.2\text{mA}$; $V_{oc}=500\text{mV}$) when the bend angle is 180° . As the bend angle increases from 180° to 240° , the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) decrease from their respective peak values. This decrease is attributable to a decrease in the illumination intensity that the SEG 300 is exposed to as the SEG 300 is bent.

15 PERFORMANCE CHARACTERISTICS OF THE SEG CELL 120

(I) Short-circuit current (I_{sc}) and open-circuit voltage (V_{oc})

Figure 5 shows five line graphs 510,520,530,540,550 for the short-circuit current (I_{sc}) of the SEG cell 120 having a gold film 122 with five different thicknesses. When the short circuit current (I_{sc}) is zero, the SEG cell 120 is not exposed to the illumination source 160. When exposed to an illumination intensity of 1-sun, and with the SEG cell 120 half-in-shadow, the SEG cell 120 having respective gold film thickness of 15nm, 30nm, 60nm, 120nm, and 240nm generated a short-circuit current (I_{sc}) of 134 μA , 98 μA , 17 μA , 2 μA and 1 μA respectively. The SEG cell 120 having the gold film thickness of 15nm yielded the highest short-circuit current (I_{sc}).

Figure 6 shows five line graphs 610,620,630,640,650 for the open-circuit voltage (V_{oc}) of the SEG cell 120 having a gold film 122 with five different thicknesses. When the open-circuit voltage (V_{oc}) is zero, the SEG cell 120 is not exposed to the illumination source 160. When exposed to an illumination intensity of 1-sun, and with the SEG cell 120 half-in-shadow, the SEG cell 120 having respective

gold film thickness of 15nm, 30nm, 60nm, 120nm, and 240nm generated an open-circuit voltage (V_{oc}) of 371mv, 42 mV, 10mV, 0.57 mV and 0.03 mV respectively. The SEG cell 120 having the gold film thickness of 15nm yielded the highest open-circuit voltage (V_{oc}).

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Figure 7A shows two line graphs 710,720 for the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) of the SEG cell 120 respectively varying with the thickness of the gold film 122. In particular, the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) decreases drastically with increasing gold film

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thickness. Figure 7B shows a line graph 730 of the transmittance of the gold film 122 varying with the thickness of the gold film 122. Referring to Figure 7B, by increasing the thickness of the gold film 122, the transparency of the gold film 122 decreases.

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This in turn limits the illumination intensity reaching the n-doped silicon substrate 124. Since the n-doped silicon substrate 124 is the main source of photocarrier generation, limiting the illumination intensity reaching the n-doped silicon substrate 124 reduces the number of photocarriers generated. Thus, the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) decreases drastically with

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(II) Incident Photon-to-electron Conversion Efficiency (IPCE)

Figure 8 shows two line graphs 810,820 for the IPCE of the SEG cell 120 having respective gold film thicknesses of 15nm and 30nm varying with incident photon wavelength, and two line graphs 830,840 for the transmittance of the gold film 122 having respective gold film thicknesses of 15nm and 30nm varying with incident photon wavelength.

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The IPCE is calculated using Equation (1):

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$$IPCE (\%) = \frac{12400 \times I_{sc} (\mu A \text{ cm}^{-2})}{\lambda (nm) \times P_{in} (\mu W \text{ cm}^{-2})} \quad (1)$$

where P_{in} is the power of the incident photon, and λ is the incident photon wavelength.

Referring to line graphs 810,820, the maximum IPCE of the SEG cell 120 observed for both gold film thicknesses of 15nm and 30nm occurs when the incident photon wavelength is approximately 550nm. The maximum IPCE of the SEG cell 120 having a gold film thickness of 15nm is 42% higher than the maximum IPCE of the SEG cell 120 having a gold film thickness of 30nm. Referring to line graphs 830,840, the maximum transmittance of the gold film 122 for both gold film thicknesses of 15nm and 30nm occurs when the incident photon wavelength is approximately 500nm, similar to the results for the maximum IPCE.

(III) Shadow Area Ratio

The shadow area ratio is determined by dividing the area of the dark region by the combined area of the bright region and dark region (see also Figure 1b). The shadow area ratio affects the performance of the SEG cell 120. Figure 9 shows two line graphs 910,920 for the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) of the SEG cell 120 respectively varying with the shadow area ratio. When the shadow area ratio is either 0% (i.e. SEG cell 120 is fully illuminated) or 100% (i.e. SEG cell 120 is fully in shadow), the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) of the SEG cell 120 are at their lowest values. There is no electron flow (i.e. no power output) when the SEG cell 120 is fully in shadow, and there is only a small power output when the SEG cell 120 is fully illuminated. The small power output is a result of minor discrepancies on the surface of the gold film 122 producing an illumination contrast. The short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) of the SEG cell 120 are at their peak values when the SEG cell 120 is half-in-shadow (or the shadow area ratio is 50%) as this provides an optimum surface area for electron generation and electron collection.

(IV) Electrode contact points

Figure 10A is a perspective view of the SEG cell 120 having first and second electrodes 1010,1020 connected to the gold film 122 for collecting the excited electrons. An object (not shown) is positioned above the SEG cell 120 for casting

a shadow on the gold film 122 to produce the illumination contrast (i.e. bright region 130 and dark region 140). In this embodiment, the object casts a shadow on 50% of the gold film 122 such that the SEG cell 120 is half-in-shadow. The first electrode 1010 is connected to the gold film 122 at a distance, D_s from one end 1011 of the SEG cell 120. The second electrode 1020 is connected to the gold film 122 at a distance, D_i from an opposing end 1021 of the gold film. The distances D_s, D_i (where the first and second electrodes 1010, 1020 are connected to the gold film 122) affect the short-circuit current (I_{sc}) of the SEG cell 120. An electric field is formed where the first and second electrodes 1010, 1020 are connected to the gold film 122 which drives the electrons from the bright region 130 to the dark region 140. As the distances D_s, D_i decreases, the first and second electrodes 1010, 1020 move further apart. Since electric field strength decreases further away from the first and second electrodes 1010, 1020, the electrons are driven less strongly by the electric fields created by the first and second electrodes 1010, 1020 as the distances, D_s and D_i decrease.

Figure 10B shows two line graphs 1050, 1060 for the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) of the SEG cell 120 with the first and second electrodes 1010, 1020 connected at various distances, D_s, D_i on the gold film. The short-circuit current (I_{sc}) increases from $104\mu A$ to $200\mu A$ as the distances D_s, D_i approaches 3cm (first and second electrodes 1010, 1020 are placed closer to each other). Conversely, the open-circuit voltage (V_{oc}) does not vary much with the distances D_s, D_i as the open-circuit voltage (V_{oc}) is mainly affected by factors relating to illumination intensity.

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(V) Length and width of the SEG cell

The performance of the SEG cell 120 that is half-in-shadow depends on two factors – electron generation and electron transport from the bright region 130 to the dark region 140 where it is collected by the first electrode 1010. If the position of the first and second electrodes 1010, 1020 are fixed, then the performance of the SEG cell 120 is limited to electron generation. Furthermore, if the illumination intensity is fixed at 1-sun, then electron generation is mainly influenced by the

surface area of the gold film 122 (and n-doped silicon substrate 124) that is exposed to the illumination source 160 since as the area of illumination increases, the number of electrons that is excited also increases.

5 Figure 11A shows two line graphs 1110, 1120 for the short-circuit current (I_{sc}) and the power density (P_{HI}) of the SEG cell 120 respectively varying with the length of the SEG cell 120. Figure 11B shows a line graph 1130 for the open-circuit voltage (V_{oc}) of the SEG cell 120 varying with the length of the SEG cell 120. With the width of the SEG cell 120 fixed at 2cm, the short-circuit current (I_{sc}) of
 10 the SEG cell 120 increases as the length of the SEG cell 120 increases due to the increase in the surface area of the gold film 122 (and n-doped silicon substrate 124) that is exposed to the illumination source 160. On the other hand, the short-circuit voltage (V_{oc}) is influenced by illumination intensity, and thus, it remains fairly constant.

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Figure 12A shows two line graphs 1210, 1220 for the short-circuit current (I_{sc}) and the power density (P_{HI}) of the SEG cell 120 respectively varying with the width of the SEG cell 120. Figure 12B shows a line graph 1130 for the open-circuit voltage (V_{oc}) of the SEG cell 120 varying with the width of the SEG cell 120. With the
 20 length of the SEG cell 120 fixed at 8cm, the short-circuit current (I_{sc}) of the SEG cell 120 likewise increases as the width of the SEG cell 120 increases. On the other hand, the power density (P_{HI}) peaks when the width of the SEG cell 120 is 2cm. Any further increase in the width of the SEG cell 120 decreases the power density (P_{HI}). A width of 2cm for the SEG cell 120 gives the maximum output as
 25 it offers an optimum area of electron generation and energy collection. While larger SEG cells have a greater rate of electron generation, the efficiency of collection is hampered due to the non-uniformity in the electric field that drives the excited electrons towards the dark region 140. On the other hand, with smaller samples, the rate of electron generation is lower owing to a smaller surface area
 30 of the gold film 122 (and n-doped silicon substrate 124) being exposed to the illumination source 160. The short-circuit voltage (V_{oc}) is influenced by illumination intensity, and thus, it remains fairly constant.

(VI) Metal content of metallic element

In the previous embodiments, the metallic element 122 is described to be a gold film 122. However, the metallic element 122 need not be limited to gold. For
5 example, the metallic element 122 may be a copper film or an aluminium film.

Figure 13A shows two line graphs 1310, 1320 for the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) of the SEG cell 120 having the metallic element 122 that is a gold film, an aluminium film, and a copper film respectively. The gold
10 film, aluminium film and copper film have a thickness of 15nm. The SEG cell with the copper film generated the highest open-circuit voltage (V_{oc}) of about 1000mV, while the SEG cell with the aluminium film generated the lowest open-circuit voltage (V_{oc}) of 0.26mV. On the other hand, the short-circuit current (I_{sc}) generated by the SEG cell with the copper film has the lowest value of about
15 0.25 μ A. Due to the poor conductivity and instability of the aluminium film, the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) of the SEG cell with the aluminium film did not reach the same values as that of the SEG cell 120 with the gold film.

20 Figure 14A shows a surface potential map for the work function of the SEG cell 120 with the gold film 122. Figure 14B is a bar diagram showing the shift in work function of the SEG cell 120 with the gold film 122 before and after full illumination.

Figure 15A shows a surface potential map for the work function of the SEG cell
25 with the copper film. Figure 15B is a bar diagram showing the shift in work function of the SEG cell with the copper film before and after full illumination.

Figure 16A shows a surface potential map for the work function of the SEG cell with the aluminium film. Figure 16B is a bar diagram showing the shift in work
30 function of the SEG cell with the aluminium film before and after full illumination.

Referring to Figure 14B, the difference in work function when the SEG cell 120 with the gold film 122 is illuminated compared to when in shadow is calculated to be 0.13eV. Referring to Figure 15B, the difference in work function when the SEG cell with the copper film is illuminated compared to when in shadow is calculated to be 0.11eV. Referring to Figure 16B, the difference in work function when the SEG cell with the aluminium film is illuminated compared to when in shadow is calculated to be 0.03eV. The SEG cell 120 with gold film 122 performed the best since gold has better stability and conductivity compared to copper and aluminium.

(VII) Textured vs planar n-doped silicon substrate

In the previous embodiments, the n-doped silicon substrate (n-Si) 124 is a planar n-Si. However, the n-doped silicon substrate 124 may also be a textured n-Si. A textured n-Si has an increased surface area and reduces reflection of incident light.

Figure 17 shows two line graphs 1710, 1720 for the short-circuit current (I_{sc}), and two line graphs 1730, 1740 for the open-circuit voltage (V_{oc}), of the SEG cell 120 having a planar n-Si and a textured n-Si respectively. The SEG cell 120 with the textured n-Si has a short-circuit current (I_{sc}) of 343 μ A, whereas the SEG cell 120 with the planar n-Si has a short-circuit current (I_{sc}) of 134 μ A which is lower. On the other hand, the open-circuit voltage (V_{oc}) of the SEG cell 120 with the textured n-Si is 78 mV, the open-circuit voltage (V_{oc}) of the SEG cell 120 with the planar n-Si is 371 mV which is higher. Due to the pyramidal shape of the textured n-Si, each side of the pyramid is exposed to different light intensities, thus affecting the open-circuit voltage (V_{oc}). On the other hand, the planar n-Si is exposed to uniform illumination which results in a uniform work function shift.

(VIII) Illumination contrast

The illumination intensity of a shadow is related to the shape, position, and transmittance of the object casting the shadow (or shadow-throwing object). The light intensity of the shadow influences the illumination contrast that is produced

between the bright region 130 and the dark region 140 of the SEG cell 120. Figure 18A is a line graph 1810 showing the illumination intensity of the shadow varying with the transmittance of the shadow-throwing object. In this embodiment, the shadow-throwing object is A4-sized papers. The A4-sized papers are stacked to
 5 decrease its transmittance. As the number of A4-sized papers increases, light from the illumination source 160 is increasingly scattered and absorbed. The average transmittance of the shadow-throwing object decreases with increasing numbers of A4-sized papers. This in turn decreases the illumination intensity of the shadow cast on the dark region 140 of the SEG cell 120, and the dark region
 10 140 becomes darker.

The illumination contrast between the bright region 130 and the dark region 140 of the SEG cell 120 is calculated using Equation (2).

$$\tau = \frac{L_i - L_s}{L_l} \times 100\% \quad (2)$$

15 where τ is the illumination contrast, L_l the illumination intensity of the light source, L_i is the illumination intensity of the bright region 130 of the SEG cell 120, and L_s is the illumination intensity of the dark region 140 of the SEG cell 120. τ is a measure of L_s , and an inverse measure of L_i .

20 Figure 18B shows two line graphs 1820, 1830 for the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) of the SEG cell 120 varying with illumination contrast. Improving the illumination contrast from 96% to 100% leads to an increase in the short-circuit current (I_{sc}) from 131 μ A to 134 μ A, and an increase in the open-circuit voltage (V_{oc}) from 332mV to 371mV.

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(IX) Optimum matching impedance

Figure 19A is a circuit diagram 1910 for determining an optimum matching impedance of the SEG cell 120. The SEG 120 is connected to a variable resistor 1912 (Z_{load}) and an ammeter 1914. The peak current and peak power of the SEG
 30 cell 120 is calculated by varying the load resistance of the variable resistor 1912 and measuring the current I_{OP} from the ammeter 1914. Figure 19B shows two line graphs 1920, 1930 for peak current and peak power of the SEG cell 120

respectively varying with load resistance. The peak current decreases as the load resistance 1912 increases from 30Ω to $6M\Omega$ under an illumination intensity of 1-sun. The peak power reached a maximum value of $4.4\mu W$ when the load resistance 1912 is 120Ω , indicating that the inherent impedance of the SEG cell 120 is 120Ω .

(X) Illumination intensity

Figure 20 shows three line graphs 2010,2020,2030 for the short-circuit current (I_{sc}), the open-circuit voltage (V_{oc}), and the power density (P_{HI}) of the SEG cell 120 respectively varying with illumination intensity of the illumination source 160. The SEG cell 120 is placed half-in-shadow. The short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) are strongly dependent on the illumination intensity of the illumination source 160. As the illumination intensity decreases, the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) of the SEG cell 120 also decreases. On the other hand, the power density (P_{HI}) of the SEG cell 120 is less strongly dependent on the illumination intensity within the range of $1 W/m^2$ to $20W/m^2$. However, as the illumination intensity increases beyond $20W/m^2$, the power density (P_{HI}) of the SEG cell 120 becomes more strongly dependent on the illumination intensity.

(XI) Stability

In real-world applications, the illumination source 160 is often intermittent and unstable. This is simulated by exposing the SEG cell 120 placed half-in-shadow to an intermittent light source having an illumination intensity of 1-sun over 1000 cycles. The performance of the SEG cell 120 is robust and shows no degradation over long periods of exposure to the intermittent light source.

Figure 21A shows two line graphs 2110,2120 for the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) of the SEG cell 120 respectively varying with the number of illumination cycles. The short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) of the SEG cells 120 remain stable regardless of the number of

illumination cycles, with standard deviations of about $1.4\mu\text{A}$ and 1.6mV respectively.

Figure 21B shows a bar graph 2130 for the short-circuit current (I_{sc}) of the SEG cell 120 varying with time. Figure 21C shows a bar graph 2140 for the open-circuit voltage (V_{oc}) of the SEG cell 120 varying with time. The short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) of the SEG cell 120 remained stable in the last fifty illumination cycles.

10 (XII) Incidence angle of illumination

Figure 22 shows three line graphs 2210,2220,2230 for the short-circuit current (I_{sc}), and three line graphs 2240,2250,2260 for the open-circuit voltage (V_{oc}), of the SEG cell 120 at three incidence angles of illumination. In this embodiment, the SEG cell 120 is fully illuminated.

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At an incidence angle of illumination of 0° , the SEG cell 120 is directly under the illumination source 160 ('middle position' in Figure 22). Under full illumination, the SEG cell 120 has a short-circuit current (I_{sc}) of $1.2\mu\text{A}$, and an open-circuit voltage (V_{oc}) of 15mV . This can be attributed to inherent work-function non-uniformity of the gold film 122 arising from surface non-uniformity of the gold film 122, or from the presence of surface impurities which alters the work function of the gold film 122. Any slight gradient in work function (not necessarily light-induced) can drive the short-circuit current (I_{sc}).

25 At an incidence angle of illumination of 60° , the SEG cell 120 is positioned to one side of the middle position ('left position' in Figure 22). Under full illumination, the short-circuit current (I_{sc}) of the SEG cell 120 increases to about $3\mu\text{A}$, while the open-circuit voltage (V_{oc}) of the SEG cell 120 increases to about 75mV .

30 At an incidence angle of illumination of -60° , the SEG cell 120 is positioned to an opposing side of the middle position ('right position' in Figure 22). Under full illumination, the short-circuit current (I_{sc}) of the SEG cell 120 reversed its polarity

to about $-3\mu\text{A}$, while the open-circuit voltage (V_{oc}) of the SEG cell 120 reversed its polarity to about -75mV .

When the incidence angle of illumination is non-zero, an intensity gradient is formed on the gold film 122 of the SEG cell 120 which results in a minor work function gradient, thus driving a small short-circuit current (I_{sc}).

COMPARISON OF SEG CELL 120 WITH COMMERCIAL SILICON-BASED SOLAR CELLS

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(I) Fabrication Cost

The SEG cells 120 are fabricated at a lower cost than commercial silicon-based solar cells (or C-Si cells). Table 1 compares the fabrication cost of one SEG cell 120 to a C-Si cell. The SEG cell 120 and C-Si cell have a similar dimension of 4 cm x 2 cm. Table 1 indicates that the estimated cost to fabricate one SEG cell 120 is US\$31.60 to US\$51.67 per square meter. On the other hand, the estimated cost to fabricate the C-Si cell is considerably higher at about US\$486.76 to US\$676.47 per square meter. Furthermore, existing fabrication processes for C-Si cells involve high temperatures and hazardous chemical, whereas those for the SEG cells 120 are less hazardous.

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Table 1: Comparison of fabrication cost of SEG cell to a commercial Si-based solar cell

	Content/Brand		Cost (US\$/m ²)
	n-Si (US\$/m ²)	Coating 15nm Au film (Approx. gold price: 43.3 US\$/g)	
SEG cell	19.10 (Lower-end supplier)	12.50	31.60
	39.17	12.50	51.67

	(Higher-end supplier)		
C-Si cell	Lower-end supplier		486.76
	Higher-end supplier		676.47

(II) Effective Indoor Performance

The performance of the C-Si cell decreases drastically as the illumination intensity of the illumination source 160 decreases. In indoor conditions, the illumination source 160 is an artificial lighting with an illumination intensity of around 0.001-sun. Figure 23 illustrates four line graphs 2310,2320,2330,2340 of the current density-to-voltage characteristics of the C-Si cell when fully exposed to respective illumination intensities of 1-sun, 0.8-sun, 0.2-sun, and 0.1-sun. Table 2 lists the values for the short-circuit current density (j_{sc}), open-circuit voltage (V_{oc}), efficiency (η) and fill factor (FF) of the C-Si cell when exposed to the respective illumination intensities of 1-sun, 0.8-sun, 0.2-sun, and 0.1-sun. From Figure 23 and Table 2, the short-circuit current density (j_{sc}), open-circuit voltage (V_{oc}), and efficiency (η) significantly decreases as the illumination intensity decreases.

Table 2: Photovoltaic properties of C-Si cell at different illumination intensities

Illumination intensity	j_{sc} (mA/cm ²)	V_{oc} (mV)	η (%)	FF
1 sun	38.10	647	19.59	0.795
0.8 sun	30.52	640	19.48	0.798
0.2 sun	7.70	599	18.45	0.799
0.1 sun	3.82	577	17.51	0.794

In comparison, the effective indoor performance of the SEG cell surpasses that of C-Si cell when operating under low illumination intensity (0.001-sun). Figure 24A shows two line graphs 2410,2420 comparing the respective open-circuit voltages (V_{oc}) of the C-Si cell and the SEG cell 120 under low illumination

intensity (0.001-sun). Figure 24B shows two line graphs 2430,2440 comparing the respective short-circuit current densities (J_{sc}) of the C-Si cell and the SEG cell 120 under low illumination intensity (0.001-sun). At $t = 0s$, the SEG cell 120 and the C-Si cell are fully illuminated by the illumination source 160. At $t = 10s$, the SEG cell 120 and the C-Si cell then placed under half-in-shadow conditions. The open-circuit voltage (V_{oc}) and the short-circuit current density (j_{sc}) of the C-Si cell decreased significantly when shifted from being fully illuminated to half-in-shadow conditions. On the other hand, the open-circuit voltage (V_{oc}) and the short-circuit current density (j_{sc}) increased when shifted from being fully illuminated to half-in-shadow conditions. Referring to Figure 24A, the open-circuit voltage (V_{oc}) of the SEG cell 120 is more than twelve times higher when the SEG cell 120 is operating half-in-shadow compared to when the SEG cell 120 is fully illuminated.

Power density (P) is calculated using Equation (3),

$$P = \frac{IV}{S} \quad (3)$$

where I is the short-circuit current (I_{sc}), V is the open-circuit voltage (V_{oc}), S is the total area of the SEG cell 120 or the C-Si cell.

Table 3 shows the power densities of the SEG cell 120 and the C-Si cell when fully illuminated and when half-in-shadow. According to Table 3, the half-in-shadow power density (P_{hi}) of the SEG cell under low intensity illumination (0.001 sun) is calculated to be 0.14 mW/cm², which is higher than that of the C-Si cell (0.074 mW/cm²). Advantageously, the resolution of the SEG cell 120 is much higher than that of the C-Si cell. Thus, the SEG cell 120 is able to capture illumination contrasts even when operating under low illumination intensities.

Table 3: Power density of SEG cell & C-Si cell under full illumination and half-in-shadow

	P_{fi} ($\mu W/cm^2$)	P_{hi} ($\mu W/cm^2$)
SEG cell	0.02	0.14
C-Si cell	0.24	0.07

APPLICATIONS

(I) Counter/motion sensor

In this embodiment, an SEG 2500 having a single SEG cell 120 is used to monitor
5 movement of an object in an indoor setting (0.001 sun), and record the number
of time the object passes by, irrespective of speed. Figure 25A illustrates a robot
2510 before passing the SEG 2500. Figure 25B illustrates the robot 2510 with a
foot 2512 on the SEG 2500. Figure 25C illustrates a remote-controlled car 2530
before passing the SEG 2500. Figure 25D illustrates the remote-controlled car
10 2530 with one wheel 2532 on the SEG 2500. Figure 25E is a line graph 2550 for
the open-circuit voltage (V_{oc}) of the SEG 2500 varying with time.

Referring to Figure 25B and 25D, a portion of the SEG 2500 that is under the foot
2512 of the robot 2510, or under the wheel 2532 of the remote-controlled car
15 2530, is in shadow, while the remaining portion of the SEG 2500 that is not under
the foot 2512 or wheel 2532 is illuminated. Owing to the shadow-effect, an open-
circuit voltage (V_{oc}) is generated by the SEG 2500. Thus, the SEG 2500 is able
to detect movement of the robot 2510 and the remote-controlled car 2530.
Referring to Figure 25C, the response time of the SEG 2500 is calculated to be
20 91ms. Notably, size of the SEG cell 120 has no impact on the ability of the SEG
2500 to detect movement. If two SEGs 2500 are deployed at a fixed distance
from each other, speed and acceleration of the robot 2510, and the remote-
controlled car 2530 can also be calculated.

(II) Powering wearable electronics

In this embodiment, an SEG 2600 having four SEG cells 120 connected in series
is used to power an electronic watch 2610 under 1-sun illumination. Figure 26A
illustrates an electronic watch 2610 connected to the SEG 2600. Figure 26B
illustrates the electronic watch 2610 being powered on after the SEG 2600 is
30 exposed to an illumination source 160. Figure 26C is a circuit schematic showing
the electronic watch 2610 connected to the SEG 2600. Figure 26D is a line graph
2620 for the short-circuit current (I_{sc}) of the SEG 2600 varying with time. Figure

26E is a line graph 2630 for the open-circuit voltage (V_{oc}) of the SEG 2600 varying with time.

When the SEG 2600 is exposed to the illumination source 160 having an
5 illumination intensity of 1-sun, the SEG 2600 generated a short-circuit current (I_{sc}) of $55\mu A$ and an open-circuit voltage (V_{oc}) of 1.5V. Under low illumination intensity conditions (0.0025 sun), the electronic watch may also be powered by an SEG having eight SEG cells 120 connected in series.

10 (III) Step counter

In this embodiment, the SEG 300 encased in a glass box 2710 is used for counting the number of times a foot 2720 is placed on the glass box 2710. Figure 27A is a schematic diagram of the foot 2720 casting a shadow on the SEG 300. Figure 27B illustrates the foot 2720 being placed on the glass box 2710. Figure
15 27C illustrates the foot 2720 being removed from the glass box 2710. Figure 27D is a line graph 2730 for the short-circuit current (I_{sc}) of the SEG 300 varying with time. Figure 27E is a line graph 2740 for the open-circuit voltage (V_{oc}) of the SEG 300 varying with time.

20 As the SEG 300 is encased in the glass box 2710, the SEG 300 is exposed to an illumination intensity of about 0.844-sun when placed in an outdoor setting. Each pulse in Figures 27D and 27E represents an instance of the foot 2720 being placed on the glass box 2710. The SEG 300 generated a short-circuit current (I_{sc}) of about $630\mu A$ and an open-circuit voltage (V_{oc}) of about 260mV for the first
25 pulse. In comparison, when the SEG 300 encased in the glass box 2710 is operated in an indoor setting with a lamp as the illumination source 160, the SEG 300 generated an short-circuit current (I_{sc}) of about $64\mu A$ and an open-circuit voltage (V_{oc}) of about 113mV. Notably, the output of the SEG 300 can be increased by increasing the number of SEG cells 120 connected. Referring to
30 Figure 27D and 27E, the number of pulses of the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) represents the number of times a foot has stepped on the glass box 2710. The SEG 300 encased in the glass box 2710 has a stable

performance and is able to be deployed on the platform of bus stops, entrances to a playground or a mall where the SEG 300 can estimate the number of people entering or exiting the place.

5 (IV) Power generation from arm swings

In this embodiment, the SEG 300 is attached to a person's clothing where the person's arm swinging action casts a shadow on the SEG 300 periodically. Figure 28A is a schematic diagram of an arm 2820 casting a shadow on the SEG 300. Figure 28B illustrates the arm 2820 being placed in front of the SEG 300. Figure 10 28C illustrates the arm 2820 moving away from the SEG 300. Figure 28D is a line graph 2830 for the short-circuit current (I_{sc}) of the SEG 300 varying with time. Figure 28E is a line graph 2840 for the open-circuit voltage (V_{oc}) of the SEG 300 varying with time.

15 The SEG 300 is exposed to an illumination intensity of about 0.672-sun. Each pulse in Figure 28D and 28E represents an instance of the arm 2820 casting a shadow on the SEG 300. The SEG 300 generated a short-circuit current (I_{sc}) of about 420 μ A and an open-circuit voltage (V_{oc}) of about 160mV for the first pulse. Notably, the SEG 300 generates an alternating current due to the alternating 20 nature of the arm swinging action where the arm 2820 casts the shadow on one half of the SEG 300 as the arm 2820 swings forward in one direction, and casts the shadow on another half of the SEG 300 as the arm 2820 swings backward in the other direction. In comparison, the SEG 300 generates a direct current from the foot 2720 stepping on the glass box 2710 as the foot 2720 always creates a 25 shadow on a same half of the SEG 300.

Advantageously, the SEG 100,300,2500,2600 can be fabricated at low cost and does not involve any harmful chemicals or intricate synthesis protocols. At the same time, the SEG 100,300,2500,2600 has at least twice the efficiency of 30 commercial solar cells when operating under low illumination intensities. The SEG 100,300,2500,2600 also finds its use in various sensor applications.

To further illustrate the scope of the present disclosure, a hybrid energy generator that combines shadow-effect principles with triboelectric principles to generate energy is described. The hybrid energy generator is also referred to as a hybrid shadow-effect and triboelectric nanogenerator (S-TENG). Figure 29 illustrates an S-TENG 2900 according to a second embodiment. Like the SEG 100,300,2500,2600, the S-TENG 2900 includes a metallic element 2922 disposed on a semiconductor substrate 2924 for generating energy through the shadow-effect. In this embodiment, the metallic element 2922 is a gold film 2922, and the semiconductor substrate 2924 is an n-doped silicon (n-Si) wafer/substrate 2924. However, unlike the previous embodiments, instead of a single sheet of gold, the gold film 2922 includes a first sheet 2922a and a second sheet 2922b, spaced apart by a gap 2925. The gap 2925 has a width of 1cm. The significance of the gap 2925 is described in a later section.

The S-TENG 2900 further includes a light permeable triboelectric charging element 2970 disposed on the metallic element 2922 such that the metallic element 2922 is sandwiched between the light permeable triboelectric charging element 2970 and the semiconductor substrate 2924. In this embodiment, the light permeable triboelectric charging element 2970 is a polydimethylsiloxane (PDMS) film 2970. Importantly, the PDMS film 2970 is light permeable to allow light from an illumination source 2960 to pass through the PDMS film 2970 to reach the gold film 2922 (and n-Si substrate 2924).

The S-TENG 2900 further includes a movable triboelectric charging element 2980 that is arranged to move relative to a surface 2972 of the light permeable triboelectric charging element 2970 to generate energy through the triboelectric effect. In this embodiment, the movable triboelectric charging element 2980 is a moving stage 2980 of a force gauge. The moving stage 2980 is made of aluminium. When exposed to an illumination source 2960, the moving stage 2980 casts a shadow on the gold film 2922 thus producing the illumination contrast for generating energy through the shadow-effect. Since PDMS and aluminium are on opposite ends of the triboelectric series, when the aluminium object 2980 is

brought into transient physical contact with the PDMS film 2970, triboelectric charges build up on the PDMS film 2970 and the aluminium object 2980 to generate energy through the triboelectric effect.

- 5 The method for generating energy using the S-TENG 2900 is described next with reference to Figures 30 and 31. Figure 30 is a flow diagram illustrating the method for generating energy through the triboelectric effect using the S-TENG 2900, while Figure 31 is a flow diagram illustrating the method for generating energy through the shadow-effect using the S-TENG 2900.

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Since energy generation through the triboelectric effect is independent of the illumination intensity, when the illumination intensity is low, the S-TENG 2900 relies on the triboelectric effect to generate most of its energy output. An ammeter 3000 is connected to the S-TENG 2900 to measure the current output.

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- At a first stage 3010, the moving stage 2980 is in physical contact with the PDMS film 2970. Through the triboelectric effect, a layer of positive triboelectric charges is induced on the moving stage 2980, while a layer of negative triboelectric charges is induced on the PDMS film 2970. Notably, the layer of positive triboelectric charges and the layer of negative triboelectric charges do not dissipate over an extended period of time. The positive triboelectric charges on the moving stage 2980 screen the negative triboelectric charges on the PDMS film 2970. As a result, positive charges are induced on the first sheet 2922a of the gold film 2922 (see also Figure 29), whereas negative charges are induced on the second sheet 2922b of the gold film 2922.
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- 25

- At a second stage 3020, the moving stage 2980 moves away from the PDMS film 2970 such that the moving stage 2980 is no longer in physical contact with the PDMS film 2970. As the moving stage 2980 moves away from the PDMS film 2970, unbalanced electric potential between the first sheet 2922a and the second sheet 2922b of the gold film 2922 drives free electrons to flow from the second
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sheet 2922b to the first sheet 2922a, thus generating a current which is indicated by a deflection of the ammeter 3000 in one direction.

At a third stage 3030, as the moving stage 2980 moves further away from the PDMS film 2970, free electrons flow from the second sheet 2922b to the first sheet 2922a until an equilibrium is reached.

At a fourth stage 3040, the moving stage 2980 starts to move towards the PDMS film 2970. As the moving stage 2980 gets closer to the PDMS film 2970, the equilibrium is disturbed, and the electric potential becomes unbalanced again which drives the free electrons to flow from the first sheet 2922a to the second sheet 2922b, thus generating a current in an opposite direction to the current in stage 3020 (indicated by a deflection of the ammeter 3000 in an opposite direction). The moving stage 2980 eventually comes into physical contact with the PDMS film 2970, returning back to stage 3010.

By moving the moving stage 2980 towards and away from the PDMS film 2970 periodically, the S-TENG 2900 produces an alternating current output. In this way, the S-TENG 2900 generates energy through the triboelectric effect.

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The method for generating energy through the shadow-effect is described next with reference to Figure 31. Notably, the working principle behind generating energy through the shadow-effect using the SEG 100,300,2500,2600 is the same for the S-TENG 2900.

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At a first stage 3110, the moving stage 2980 is in physically contact with the PDMS film 2970. A shadow is cast by the moving stage 2980 on the gold film 2922 (see also Figure 29). In this embodiment, the moving stage 2980 is positioned directly above the second sheet 2922b of the gold film 2922, and the shadow is cast on the second sheet 2922b. An illumination contrast is produced between the first sheet 2922a and the second sheet 2922b which is detected by the gold film 2922. Specifically, the work function value (ϕ_m^*) of the first sheet

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2922a which is illuminated is lower than the work function value (ϕ_m) of the second sheet 2922b which is in shadow. This contrast in work function drives free electrons to flow from the first sheet 2922a to the second sheet 2922b, thus generating a current as indicated by a large deflection of the ammeter 3000 in one direction.

At a second stage 3120, the moving stage 2980 moves away from the PDMS film 2970 such that the moving stage 2980 is no longer in physical contact with the PDMS film 2970. As the moving stage 2980 moves away from the PDMS film 2970, more light from the illumination source 2960 is able to reach the second sheet 2922b of the gold film 2922. This causes the work function of the second sheet 2922b to decrease from an initial value, ϕ_m to an intermediate value, ϕ_m^* . However, the intermediate value, ϕ_m^* is still higher than the work function value, ϕ_m^* of the first sheet 2922a ($\phi_m^* > \phi_m^*$). Thus, the illumination contrast continues to drive free electrons from the first sheet 2922a to the second sheet 2922. The current generated in the second stage is weaker than the current generated in the first stage, as indicated by a smaller deflection of the ammeter 3000 since the illumination contrast is weaker.

At a third stage 3030, the moving stage 2980 moves further away from the PDMS film 2970, and the moving stage 2980 no longer casts a shadow on the second sheet 2922b of the gold film 2922. At this point, the second sheet 2922b has the same work function value, ϕ_m^* as the first sheet 2922a. No free electrons are driven, and thus no current is generated as indicated by a non-deflection of the ammeter 3000.

At a fourth stage 3140, the moving stage 2980 starts to move towards the PDMS film 2970. As the moving stage 2980 moves closer to the PDMS film 2970, the illumination contrast between the first sheet 2922a and the second sheet 2922b increases, and the free electrons are again driven more strongly to flow from the first sheet 2922a to the second sheet 2922b, thus generating a stronger current as indicated by a larger deflection of the ammeter 3000 in the same direction as

in the second stage 3120. The moving stage 2980 eventually comes into physical contact with the PDMS film 2970 again, returning back to stage 3110.

By moving the moving stage 2980 towards and away from the PDMS film periodically, the S-TENG 2900 produces a direct current output. In this way, the S-TENG 2900 generates energy through the shadow effect. Notably, the direct current produced increases with the illumination intensity of the illumination source 2960.

It should be clear that energy generation through the triboelectric effect and the shadow-effect may occur concurrently unless the illumination intensity is zero in which case energy generation may be solely by triboelectric effect.

Figure 32 is a circuit diagram for the S-TENG 2900. The triboelectric effect circuit is represented by a capacitor, C_T 3210 using a standard capacitor model. The shadow-effect circuit is represented by an open-circuit voltage source 3220 connected to a resistor (R_s) 3230. The triboelectric effect circuit and the shadow-effect circuit are connected in parallel.

The circuit diagram also satisfies Thevenin's Theorem, where output voltage (V_{AB}) is calculated using the Equation (4).

$$V_{AB} = -\frac{Q}{C_T} + V_{TE} = V_{SE} - IR_s \quad (4)$$

where Q is transferred charges, V_{TE} is the open-circuit voltage generated from the triboelectric effect, V_{SE} is the open-circuit voltage generated from the shadow-effect, and I is current in circuit without load.

PERFORMANCE CHARACTERISTICS OF THE S-TENG 2900

(I) Short-circuit current density (J_{sc})

Figure 33A is a line graph 3310 for the short-circuit current density (J_{sc}) of the S-TENG 2900 varying with time. Figure 33B is a line graph 3320 showing a magnified waveform for the short-circuit current density (J_{sc}) of the S-TENG 2900

without illumination. Figure 33C is a line graph 3330 showing a magnified waveform for the short-circuit current density (J_{sc}) of the S-TENG 2900 with illumination.

5 In this embodiment, the illumination source 2960 is a lamp with an illumination intensity of about 90 mW/cm^2 . The S-TENG 2900 is placed in the dark (i.e. no illumination) from time, $t = 0\text{s}$ to 25s , and from time, $t = 40\text{s}$ to 53s . With no illumination, the S-TENG produced a tribo-induced AC signal with a peak short-circuit current density (J_{sc}) of about $0.01 \mu\text{A/cm}^2$. The S-TENG 2900 is exposed
10 to the illumination source 2960 from time, $t = 25\text{s}$ to 40s , and from time, $t = 53\text{s}$ to 70s . With illumination, the S-TENG generated a DC signal with a peak short-circuit current density (J_{sc}) of about $34 \mu\text{A/cm}^2$. Notably, the current generated through the triboelectric effect and the shadow-effect may have opposite signs. However, as the current generated through the shadow-effect is much larger, the
15 overall current generated by the S-TENG 2900 is in the same direction as the current generated through the shadow-effect.

(II) Transmittance of PDMS film

UV-vis spectroscopy is performed on a glass with the PDMS film 2970 (referred
20 to as 'PDMS-on-glass'). UV-vis spectroscopy is also performed on a glass (i.e. without the PDMS film 2970) for comparison. Figure 34A shows two line graphs 3410, 3420 for the transmittance of glass and PDMS-on-glass varying with wavelength of transmitted light. The transmittance of the PDMS-on-glass and glass are similar in the visible and infra-red regions which means that the addition
25 of the PDMS film to a structure does not change the overall transmittance of the structure.

Figure 34B shows two line graphs 3430, 3440 for the short-circuit current density (J_{sc}) of the S-TENG 2900 with the PDMS film 2970, and with the PDMS film 2970
30 removed. Figure 34C shows two line graphs 3450, 3460 for the open-circuit voltage (V_{oc}) of the S-TENG 2900 with the PDMS film 2970, and with the PDMS film 2970 removed. In both cases, the S-TENG 2900 is exposed to an illumination

intensity of $100\text{mW}/\text{cm}^2$ and placed under half-in-shadow conditions. In both cases, the S-TENG 2900 generated a short-circuit current density (J_{sc}) of $8.5\mu\text{A}/\text{cm}^2$ and an open-circuit voltage (V_{oc}) of 359.8mV , meaning that the presence of the PDMS film 2970 does not impact the energy generated through the shadow-effect.

(III) Electrical resistance of gold film

Figure 35 is a data plot for the electrical resistance of the gold film 2922 varying with its thickness. The gold film 2922 has a width of 3cm . The electrical resistance of the gold film 2922 measured is based on a length of 4cm of the gold film 2922. The electrical resistance of the gold film 2922 decreased from 39.1Ω to 18.2Ω to 3.4Ω , with increasing gold film thicknesses of 15nm , 60nm , and 240nm .

(IV) Effect of gap in gold film on performance of S-TENG

An S-TENG 3600 is described herein. Like the S-TENG 2900, the S-TENG 3600 includes a PDMS film 3670, a n-doped silicon substrate 3624, and a gold film 3622 sandwiched between the PDMS film 3670 and the n-doped silicon substrate 3624. Unlike the gold film 2922, the gold film 3622 is a single sheet of gold with no gaps. Using the illumination source 2960, and having the two S-TENGs 2900,3600 half-in-shadow, the S-TENG 3600 generated a short-circuit current density (J_{sc}) of about $8.5\mu\text{A}/\text{cm}^2$. In comparison, the S-TENG 2900 generated a short-circuit current density (J_{sc}) of about $39\mu\text{A}/\text{cm}^2$.

On the other hand, the open-circuit voltage (V_{oc}) generated by the two S-TENGs 2900,3600 did not show any changes. From the working principle of shadow-effect, the illumination intensity causes the excitation of electrons and the work function shift. As there is no change in excitation of electrons and work function shift in the respective gold films 2922,3622, the open-circuit voltage (V_{oc}) generated by the two S-TENGs 2900,3600 is unchanged. On the other hand, the short-circuit current density of the S-TENGs 2900,3600 depends on electron generation and electron transportation. In the S-TENG 3600, some of the free electrons that are excited by the shadow-effect flow from the bright region to the

dark region directly through the gold film 3622, thereby leading to a decline in the short-circuit current density (J_{sc}). In the case of the S-TENG 2900, due to the presence of the gap 2925, free electrons have to flow from the bright region to the dark region through the external circuit which makes the electron transportation more efficient, thus increasing the short-circuit current density (J_{sc}).

(V) Opacity of moving stage

The opacity of the moving stage 2980 has an impact on the performance of the S-TENG 2900 since the opacity of the moving stage 2980 determines the intensity of the illumination contrast. In this embodiment, a black paper attached on a transparent glass (referred to as 'black-paper-on-glass') is used as the moving stage 2980. Figure 37A shows two line graphs 3710, 3720 for the transmittance of glass and black-paper-on-glass over wavelength of transmitted light. The average transmittance of glass and black-paper-on-glass is 80% and 0% respectively.

Figure 37B is a line graph 3730 for the short-circuit current density (J_{sc}) of the S-TENG 2900, (i) with the moving stage 2980 removed; (ii) with glass as the moving stage 2980; and (iii) with black-paper-on-glass as the moving stage 2980.

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Figure 38 is a line graph 3810 for the short-circuit current density (J_{sc}) of the S-TENG 2900, (i) with glass as the moving stage 2980; and (ii) with black-paper-on-glass as the moving stage 2980, varying with up-down motion of the moving stage 2980. The moving stage 2980 and the light permeable triboelectric charging element 2970 has a contact area of 7.5cm^2 . Under dark conditions (with no illumination), the S-TENG 2900 generated a short-circuit current density (J_{sc}) of $0.005\mu\text{A}/\text{cm}^2$. When the S-TENG 2900 is exposed to the illumination source 2960, the S-TENG 2900 generated a short-circuit current density (J_{sc}) of about $8.2\mu\text{A}/\text{cm}^2$ when glass is used as the moving stage 2980, and a short-circuit current density (J_{sc}) of $43\mu\text{A}/\text{cm}^2$ when black-paper-on-glass is used as the moving stage 2980. When the moving stage 2980 is black-paper-on-glass, the S-

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TENG 2900 generated the highest short-circuit current density (J_{sc}) since the transmittance of black-paper-on-glass is the lowest.

(VI) Contact frequency of moving stage

5 Figure 39A shows ten line graphs 3910a,3910b,3920a,3920b,3930a,3930b, 3940a,3940b,3950a,3950b for the short-circuit current density (J_{sc}) of the S-TENG 2900, with illumination and without illumination, at five contact frequencies of the moving stage 2980. Contact frequency of the moving stage 2980 represents the number of times that the moving stage 2980 comes into contact
10 with the PDMS film 2970. The five contact frequencies are 0.1Hz, 0.09Hz, 0.07Hz, 0.05Hz, and 0.02Hz.

When the S-TENG 2900 is operating in the dark (no illumination), the short-circuit current density (J_{sc}) of the S-TENG 2900 increased with increasing contact
15 frequency of the moving stage 2980. Under dark conditions, the S-TENG 2900 generates energy mainly through the triboelectric effect. Thus, the short-circuit current density (J_{sc}) increases with increasing contact frequency of the moving stage 2980. The short-circuit current density (J_{sc}) is calculated using Equation (5).

$$20 \quad J_{sc} = \frac{d\Delta\sigma_{sc}}{dt} = \left(\frac{d\Delta\sigma_{sc}}{dx} \right) v \quad (5)$$

where x is the displacement, v is the variation velocity which is a measure of frequency, $\Delta\sigma_{sc}$ is the short-circuit transferred charges.

Figure 39B shows five line graphs 3960,3970,3980,3990,4000 for the open-
25 circuit voltage (V_{oc}) of the S-TENG 2900, with illumination, at five contact frequencies of the moving stage 2980.

When the S-TENG 2900 is exposed to the illumination source 2960, the short-circuit current density (J_{sc}) and the open-circuit voltage (V_{oc}) of the S-TENG
30 2900 did not change with the contact frequency of the moving stage 2980.

(VII) Illumination intensity

Figure 40 is a line graph 4000 for the short-circuit current density (J_{sc}) of the S-TENG 2900 varying with illumination intensity of the illumination source 2960. With increasing illumination intensity, more photocarriers are generated in the n-Si substrate 2924 which increase the short-circuit current density (J_{sc}) of the S-TENG 2900.

(VII) Single-electrode S-TENG

As the triboelectric effect circuit and the shadow-effect circuit of the S-TENG 2900 are connected in parallel (refer to Figure 32), the short-circuit current density (J_{sc}) generated by the triboelectric effect when the S-TENG 2900 is operating under dark conditions (with no illumination) can be measured. On the other hand, the open-circuit voltage (V_{oc}) cannot be directly measured as the parallel connection of the shadow-effect circuit has a much lower internal resistance than the triboelectric effect circuit. Since the shadow-effect circuit cannot be removed when measuring triboelectric effect, a connection change method is used to measure the output of a single-electrode S-TENG. The result is expected to estimate the output of the single-electrode S-TENG generated through the triboelectric effect. The positive electrode of a Keithley 6514 is connected to the one electrode of the single-electrode S-TENG, and the negative electrode of the Keithley 6514 is grounded. Figure 41 shows two line graphs 4110, 4120 for the open-circuit voltage (V_{oc}) and charge for the single-electrode S-TENG. The single-electrode S-TENG generated an open-circuit voltage (V_{oc}) and charge of 80 V and 34 nC respectively.

(VIII) Load resistance

Figure 42 shows two line graphs 4210, 4220 for the short-circuit current density (J_{sc}) and power density of the S-TENG 2900 varying with load resistance. Notably, the maximum power density of about $0.28 \mu\text{W}/\text{cm}^2$ is achieved when the load resistance is $8 \text{ G}\Omega$.

FURTHER EMBODIMENTS OF THE S-TENG

(I) Liquid droplets as movable triboelectric charging element

An S-TENG 4300 is described as a further embodiment. Like the S-TENG 2900, the S-TENG 4300 includes a PDMS film 4370, a n-doped silicon substrate 4324, and a gold film 4322 sandwiched between the PDMS film 4370 and the n-doped silicon substrate 4324. Unlike the gold film 2922, the gold film 4322 has no gap. Furthermore, instead of the moving stage 2980, the S-TENG 4300 utilizes liquid droplets or specifically, water droplets 4380 as its movable triboelectric charging element and the source of the water droplets may be rain or other environmental sources such as water flowing over a waterfall, similar to how hydropower may be harnessed. The S-TENG 4300 is tilted at an angle to allow the water droplets 4380 to slide along the PDMS film 4370 by gravity.

Figure 43 is a flow diagram illustrating a method for generating energy through the triboelectric effect using the S-TENG 4300. At a first stage 4310, the water droplets 4380 carrying positive charges are falling onto the PDMS film 4370. At a second stage 4320, the water droplets 4380 come into physical contact with the PDMS film 4370. A positive electric potential difference is formed between the charged water droplets 4380 and the ground which causes free electrons to flow from the ground to the gold film 4322. This generates an instantaneously opposite potential to balance the electric field generated by the flow of free electrons. At a third stage 4330, as the charged water droplets 4380 continue to slide down the PDMS film 4370, an equilibrium is reached. At a fourth stage 4340, as the charged water droplets 4380 falls off the PDMS film 4370, a negative electric potential difference is formed, forcing free electrons to flow from the gold film 4322 to the ground, until another equilibrium is reached.

Figure 44A is a line graph for the open-circuit voltage (V_{oc}) of the S-TENG 4300 at tilt angles of 30°, 45°, 60°, and 80° with respect to the ground. The open-circuit voltage (V_{oc}) of the S-TENG 4300 increased from 2V to 7V when the tilt angle increased from 30° to 60°. However, with a further increase of the tilt angle from 60° to 80°, the open-circuit voltage (V_{oc}) of the S-TENG 4300 decreased to 1.5V. When the tilt angle is large, an effective contact surface area between the water

droplets 4380 and the PDMS film 4370. On the other hand, the water droplets 4380 flows down the PDMS film 4370 slowly when the tilt angle is small. The open-circuit voltage (V_{oc}) of the S-TENG 4300 is maximum when the tilt angle is around 60° owing to the trade-off between effective surface contact area and the speed of the sliding water droplets 4380.

Figure 44B is a line graph for the short-circuit current density (J_{sc}) of the S-TENG 4300 at dripping heights of 5 cm, 10 cm, 15 cm, and 20 cm from the PDMS film 4370. With increasing dripping heights, the short-circuit current density of the S-TENG 4300 increases from 9.2nA/cm^2 , 11.8nA/cm^2 , 13.4nA/cm^2 to 19.1nA/cm^2 .

Figure 45A is a line graph for the short-circuit current density (J_{sc}) of the S-TENG 4300, with illumination and without illumination. Figure 45B is a line graph for the open-circuit voltage (V_{oc}) of the S-TENG 4300, with illumination and without illumination. Figure 45C is a line graph for the charge density ($\Delta\sigma_{sc}$) of the S-TENG 4300, with illumination and without illumination. There are no significant changes to the short-circuit current density (J_{sc}) the open-circuit voltage (V_{oc}) and the charge density ($\Delta\sigma_{sc}$) of the S-TENG 4300, with illumination and without illumination. This means that the effect of light illumination on the output performance of the S-TENG 4300 is negligible.

In an alternative embodiment, a triboelectric energy nanogenerator (TENG) is disclosed. The TENG may include the gold film 2922, and the PDMS film 4370 arranged to receive the water droplets 4380 but without energy being generated from the shadow effect. The method for generating energy through the triboelectric effect using the TENG is similar to the method for generating energy using the S-TENG 4300, and is thus not repeated for brevity.

(II) Energy Ball

Figure 46A is a perspective view of an S-TENG 4600 that is deployed at sea to harvest tidal energy and solar energy. Figure 46B is an enlarged perspective bottom view of a portion of the S-TENG 4600. Like the S-TENG 2900, the S-

TENG 4600 includes a PDMS film 4670, a n-doped silicon substrate 4624, and a gold film 4622 sandwiched between the PDMS film 4670 and the n-doped silicon substrate 4624. The gold film 4622 includes a first sheet 4622a and a second sheet 4622b, spaced apart by a gap 4625. The S-TENG 4600 also includes a
5 movable triboelectric charging element 4680 that is arranged to move relative to a surface 4672 of the PDMS film 4670. In this embodiment, the movable triboelectric charging element 4680 is an aluminium ball. The aluminium ball 4680 harnesses tidal energy to roll on the surface 4672 of the PDMS film 4670 to generate energy through the triboelectric effect. Furthermore, when exposed to
10 an illumination source 4660 (e.g. the sun), the aluminium ball 4680 casts a shadow 4682 on the gold film 4622 thus producing the illumination contrast for generating energy through the shadow-effect.

As the S-TENG 4600 is deployed at sea, the S-TENG 4600 further includes an
15 energy storage element 4690 for storing the energy generated through the triboelectric effect and the shadow-effect. The energy storage element 4690 is electrically coupled to the metallic element 4622. In this embodiment, the energy storage element 4690 is fiber supercapacitors (F-SCs). The fiber supercapacitors 4690 is a structure having layered molybdenum disulphide as an active material.

20 The S-TENG 4600 further includes a light permeable exterior shell 4690 encapsulating the gold film 4622, the n-Si substrate 4624, the PDMS film 4670, and the aluminium ball 4680. In this embodiment, the light permeable exterior shell 4690 is made of polyethylene terephthalate (PET) which is a material that
25 is light permeable to allow light from the illumination source 4660 to be transmitted to the gold film 4622 (and the n-Si substrate 4624). The light permeable exterior shell 4690 is spherical in shape.

The fabrication of the S-TENG 4600 is described herein. A cleaned n-type Si
30 wafer (15 cm²) with thickness of 530µm is used as the n-Si substrate 4624. A 15nm gold film is coated on the n-Si substrate by thermal evaporation. A 1cm gap 4625 in the gold film 4622 added by removing a middle portion of the gold film

4622. Then, the PDMS film 4670 is fabricated on the gold film 4622 by a doctor-blade technique, followed by thermal annealing at 60°C for 2h to form a combined substrate. Then, the light permeable exterior shell 4690 (8cm in diameter) is fabricated. The aluminium ball 4680 (with a diameter of 2.5 cm) is placed within
5 the light permeable exterior shell 4690 with the combined substrate. A counterweight is arranged at the bottom of the light permeable exterior shell 4690 to provide balance and stability to the S-TENG 4600 in water. The fiber supercapacitors 4690 are connected under the combined substrate with a small full-wave rectifier. The S-TENG 4600 is then fabricated.

10

The method for generating energy using the S-TENG 4600 is similar to the method for generating energy using the S-TENG 2900. The difference is that instead of the moving stage 2980 moving vertically away and towards the PDMS film 2970, the aluminium ball 4680 moves laterally on the surface of the PDMS
15 film 4680. Figure 47 is a flow diagram illustrating the method for generating energy through the triboelectric effect using the S-TENG 4600. Figure 48 illustrates a top view of the S-TENG 4600 corresponding to the flow diagram of Figure 47A. The ammeter 3000 is connected to the S-TENG 4600 to measure the current output.

20

At a first stage 4710, the aluminium ball 4680 is full physical contact with the PDMS film 4670. Through the triboelectric effect, a layer of positive triboelectric charges is induced on the aluminium ball 4680, while a layer of negative triboelectric charges is induced on the PDMS film 4670. Notably, the layer of
25 positive triboelectric charges and the layer of negative triboelectric charges do not dissipate over an extended period of time. The positive triboelectric charges on the aluminium ball 4680 screen the negative triboelectric charges on the PDMS film 4670. As a result, positive charges are induced on the first sheet 4622a of the gold film 4622, whereas negative charges are induced on the
30 second sheet 4622b of the gold film 4622.

At a second stage 4720, the aluminium ball 4680 moves laterally away from the PDMS film 4670 such that the aluminium ball 4680 is only in partial physical contact with the PDMS film 4670. As the aluminium ball 4680 is not in full physical contact with the PDMS film 4670, the triboelectric effect is weaker and thus unbalanced electric potential between the first sheet 4622a and the second sheet 4622b of the gold film 4622 drives free electrons to flow from the second sheet 4622b to the first sheet 4622a, thus generating a current which is indicated by a deflection of the ammeter 3000 in one direction.

At a third stage 4630, as the aluminium ball 4680 moves completely off the PDMS film 4670, free electrons flow from the second sheet 4622b to the first sheet 4622a until an equilibrium is reached.

At a fourth stage 4640, the aluminium ball 4680 move laterally towards the PDMS film 4670 again. As the aluminium ball 4680 comes into contact with the PDMS film 4670, the equilibrium is disturbed, and the electric potential becomes unbalanced again which drives the free electrons to flow from the first sheet 4622a to the second sheet 4622b, thus generating a current in an opposite direction to the current in stage 4620 (indicated by a deflection of the ammeter 3000 in an opposite direction). The aluminium ball 4680 eventually comes into full physical contact with the PDMS film 4670, returning back to stage 4610.

By harvesting tidal energy to move the aluminium ball 4680 laterally along the PDMS film 4670, the S-TENG 4600 produces an alternating current output. In this way, the S-TENG 4600 harvest tidal energy to generate energy through the triboelectric effect.

The S-TENG 4600 harvests solar energy in a similar way as the S-TENG 2900. The mechanism for generating energy through the shadow-effect using the S-TENG 4600 is not described for brevity. The S-TENG 4600 is sometimes referred to as an energy ball 4600.

PERFORMANCE CHARACTERISTICS OF THE S-TENG 2900

(I) Short-circuit current density (J_{sc})

Figure 49A shows three line graphs 4910a,4910b,4910c for the short-circuit
 5 current density (J_{sc}) of the S-TENG 4600 at increasing wave intensities. The S-TENG 4600 is placed under no illumination. The short-circuit current density (J_{sc}) of the S-TENG 4600 increased with increasing wave intensities.

(II) Material of moveable triboelectric charging element

10 Figure 49B shows two line graphs 4920a,4920b for the short-circuit current density (J_{sc}) of the S-TENG 4600, with the aluminium ball 4680, and with a steel ball. The S-TENG 4600 is placed under no illumination. The S-TENG 4600 with the aluminium ball 4680 has a larger short-circuit current density (J_{sc}) than the S-TENG with the steel ball due to aluminium being a better tribo-positive material
 15 than steel.

(III) Stability

Figure 49C is a line graph 4930 for the short-circuit current density (J_{sc}) of the S-TENG 4600 cycled over a period of 700s. There are slight changes to the short-circuit current density (J_{sc}) due to slight changes in the wave intensity, and
 20 illumination intensity caused by wave-bobbing motions. However, as a whole, the short-circuit current density (J_{sc}) of the S-TENG 4600 showed no signs of degradation over the period of 700s. The S-TENG 4600 has good stability and durability.

25

(IV) Incidence angle of illumination

Figure 49D shows five line graphs 4940a,4940b,4940c,4940d,4940e for the short-circuit current density (J_{sc}) of the S-TENG 4600 at respective incidence angles of illumination of 0° , 45° , 90° , 135° , 180° with respect to the horizon. The
 30 illumination source 4660 is moved to simulate movement of the sun throughout a day. When the incidence angle is 90° , the short-circuit current density (J_{sc}) of the S-TENG 4600 is highest as the shadow area ratio is optimum when the incidence

angle is 90° . Furthermore, the influence of work function non-uniformity of the gold film 4622 on the output of the S-TENG 4600 is larger when the incidence angle is not 90° .

5 (V) Load resistance

Figure 49D shows two line graphs 4950a,4950b for the short-circuit current density (J_{sc}) and peak power density of the S-TENG 4600 varying with load resistance. The S-TENG 4600 is placed under illumination. The short-circuit current density (J_{sc}) of the S-TENG 4600 decreases with increasing load resistance. The short-circuit current density (J_{sc}) of the S-TENG 4600 decreases rapidly up to a load resistance of 1000Ω . The short-circuit current density (J_{sc}) of the S-TENG 4600 decreases at a slower pace with increasing load resistance of more than 1000Ω . The peak power density of the S-TENG 4600 increases to a peak value of $718\mu W/cm^2$ with increasing load resistance up to 100Ω . The peak power density of the S-TENG 4600 starts to decrease rapidly with increasing load resistance between 100Ω to 1000Ω . Similarly, the peak power density of the S-TENG 4600 decreases at a slower pace with increasing load resistance of more than 1000Ω .

20 In comparison with Figure 42, the impedance of the shadow-effect circuit is smaller than that of the triboelectric effect circuit. When connecting the shadow-effect circuit to the triboelectric effect circuit with different internal impedances in parallel, it is difficult to improve power efficiency, thus five fiber supercapacitors 4690 are used in S-TENG 4600 to form a self-charging power system. The results are described with reference to Figures 50A to 50D.

Figure 50A shows three line graphs 5010a,5010b,5010c for the short-circuit current density (J_{sc}) of the S-TENG 4600 with (i) shadow-effect only; (ii) triboelectric effect only; and (iii) both shadow-effect and triboelectric effect, before and after being rectified.

Figure 50B shows three line graphs 5020a,5020b,5020c for the open-circuit voltage (V_{oc}) of the S-TENG 4600 with (i) shadow-effect only; (ii) triboelectric effect only; and (iii) both shadow-effect and triboelectric effect, before and after being rectified.

5

Figure 50C illustrates a circuit diagram of the S-TENG 4600 used in a self-charging power system.

Figure 50D shows two line graphs 5030a,5030b for the open-circuit voltage (V_{oc}) of the S-TENG 4600 used in the self-charging power system with (i) shadow-effect only; (ii) triboelectric effect only; and (iii) both shadow-effect and triboelectric effect.

In a first stage, only switches SW1,SW2 are closed (refer to Figure 50C), and the S-TENG 4600 generates energy based on the shadow-effect only. When placed under illumination, the short-circuit current density (J_{sc}) and the open-circuit voltage (V_{oc}) of the S-TENG 4600 increased sharply from 0 to 0.2V at time = 4s (refer to Figures 50A and 50B). In a second stage, the switches SW1 and SW2 are opened and switch SW3 is closed simultaneously (refer to Figure 50C). A rectifier is connected to the S-TENG 4600 to convert the AC current to a DC current. When stimulated by waves, the S-TENG 4600 generated a higher open-circuit voltage (V_{oc}) which compensates the limitation of energy generated by shadow-effect after being rectified.

Referring to line graphs 5020b,5020c in Figure 50B, the open-circuit voltage (V_{oc}) generated by the S-TENG 4600 after being rectified is about 4.1V. The open-circuit voltage (V_{oc}) generated by the S-TENG 4600 remained at a similar level, with illumination and with no illumination. This is due to a voltage drop in the rectifier of about 0.7V, thus only allowing higher voltages to pass. The output from the shadow-effect circuit is blocked by the rectifier due to its lower voltage of 0.2V. In this way, the short-circuit currents (I_{sc}) from the shadow-effect circuit and the triboelectric effect circuit that are in opposite directions do not influence the self-

charging power system, and the self-charging power system is charged to a higher voltage. The limitation of impedance matching of the S-TENG is avoided in the self-charging power system.

- 5 After the fiber supercapacitors 4690 are charged, the switches SW1, SW2, SW3 are opened, and switch SW4 is closed. Referring to line graph 5030a of Figure 50D, under illumination and without rectification, the fiber supercapacitors 4690 are charged to 0.2V using the energy generated through the shadow-effect. The fiber supercapacitors 4690 are charged to a higher voltage using the energy
10 generated through both the triboelectric effect and the shadow-effect. Referring to line graph 5030b of Figure 50D, when the S-TENG 4600 is stimulated by waves with no illumination, charging the fiber supercapacitors 4690 to 0.3V using only energy generated by the triboelectric effect took 409.4s. Notably, the time taken to charge the fiber-supercapacitors to 0.3V using both energy generated by the
15 triboelectric effect and the shadow-effect shortened to 156.1s. The S-TENG 4600 is able to harvest both solar energy and tidal energy to shorten charging duration of the fiber supercapacitors 4690.

(VI) Fabrication and performance of fiber supercapacitors

- 20 A fabrication process of the fiber supercapacitors is described herein. A carbon fiber is first pre-treated in acetone, then in ethanol and finally in deionized water, for 15 min under ultrasonication. Then the pre-treated carbon fiber is cut into bundles of 1 cm. Next, a solution is prepared by adding 0.04g of a few-layered molybdenum disulphide (MoS_2) into 5ml of ethanol. The pre-treated carbon fiber
25 is soaked in the solution for 24hrs, removed, and then baked at 150°C to produce a coated carbon fiber (electrode). This soak-and-bake process is repeated several times.

- A H_2SO_4 /PVA gel electrolyte is prepared by mixing 6g of Sulfuric acid (H_2SO_4)
30 and 6g of poly (vinyl alcohol), PVA into 60 ml of deionized water, and heating the mixture to 85°C under stirring until the mixture becomes clear. Then, the was prepared.

A fiber supercapacitor 4680 is then assembled by soaking two of the electrodes in the $\text{H}_2\text{SO}_4/\text{PVA}$ gel electrolyte and then assembling the soaked electrodes to produce the fiber supercapacitor. The process is repeated until five fiber
5 supercapacitors are fabricated.

Figure 51A shows two line graphs 5110a, 5110b for the X-ray diffraction pattern of a few-layered MoS_2 and a bulk MoS_2 respectively. The characteristic peaks of the few-layered MoS_2 are observed at 33.69° and 59.51° which corresponds to
10 the (100) and (110) planes, respectively.

Figure 51B shows two line graphs 5120a, 5120b for the Raman spectra of the few-layered MoS_2 and the bulk MoS_2 respectively. The few-layered MoS_2 and the bulk MoS_2 are excited by a 532nm laser in air ambient environment. E_{2g}^1 (~ 383
15 cm^{-1} for bulk MoS_2) and A_{1g}^1 ($\sim 408 \text{ cm}^{-1}$ for bulk MoS_2) modes are observed in both the few-layered MoS_2 and the bulk MoS_2 . The frequency of E_{2g}^1 peak increased for the few-layered MoS_2 with decreasing layer number due to the decrease in interlayer Van der Waals force in MoS_2 as the layer number decreases.

20

Figure 51C is a scanning electron microscopy (SEM) image of a carbon fiber electrode coated with few-layered MoS_2 (i.e. fiber supercapacitor 4690). The fiber supercapacitor 4690 has a uniform diameter of $400\mu\text{m}$. Figure 51D is a cross-sectional view of the SEM image of Figure 51C. An entire surface of the carbon
25 fiber electrode is covered with the few-layered MoS_2 .

Figure 51E shows two cyclic voltammetry (CV) curves 5130a, 5130b for the short-circuit current (I_{sc}) of the fiber supercapacitor 4690 varying with potential, with the few-layered MoS_2 and without the few-layered MoS_2 respectively. In a two-
30 electrode system, a potential window of the fiber supercapacitor 4690 with the few-layered MoS_2 is 1 V. The fiber supercapacitor 4690 with the few-layered MoS_2 achieves a higher capacitive current than the fiber supercapacitor without

the few-layered MoS₂, indicating that the few-layered MoS₂ optimizes the capacitive performance significantly.

Figure 51F shows four cyclic voltammetry (CV) curves
 5 5140a,5140b,5140c,5140d for the short-circuit current (*I*_{sc}) of the fiber supercapacitor 4690 varying with potential, at different scan rates of 10mV/s, 20mV/s, 50 mV/s, and 100mV/s respectively. As the scan rate increases, even up to a high scan rate of 100mV/s, the CV maintains its rectangular shape well, suggesting the fiber supercapacitor 4690 possesses excellent rate capability.

10

Figure 52A shows four galvanostatic charge-discharge (GCD) curves
 5210a,5210b,5210c,5210d for the potential of the fiber supercapacitor 4690 varying with time, under small input current of 20μA, 40 μA, 80μA, 100μA respectively. The GCD curves have linear shapes and nearly symmetric charge
 15 and discharge curves across the small input current.

Figure 52B shows a galvanostatic charge-discharge (GCD) curve 5220a for the capacitance retention of the fiber supercapacitor 4690 across 1200 cycles, and a line graph 5220b for the potential of the fiber supercapacitor 4690 varying over
 20 time. The input current is set to a constant value of 40μA. The fiber supercapacitor 4690 achieved a capacitance retention of nearly 94% which indicates good cyclability. Furthermore, referring to line graph 5220b, the fiber supercapacitor 4690 exhibits good long-term electrochemical stability, which is evident from the stable charge/discharge curves. The charge curves maintain symmetry relative
 25 to the corresponding discharge curves, showing no significant structural change of the electrode during the charge/discharge processes.

Figure 52C is a line graph 5230 of a specific capacitance of the fiber supercapacitor 4690 varying with discharge currents of the charge-discharge
 30 profiles. The specific capacitance (*C*_m) of the F-SC can be calculated from the curves according to Equation (6).

$$C_m = \frac{I\Delta t}{m\Delta V} \quad (6)$$

where I is the discharge current, Δt is the discharge time, ΔV is the potential window during the discharge process, and m is the load mass of the few-layered MoS₂. The fiber supercapacitor 4690 delivered a specific capacitance of 196.4 F/g at a discharge current density of 2 A g⁻¹. The specific capacitance of the fiber supercapacitor 4690 maintained at 50 F/g even when the current density increased to 10 A/g.

The energy density (E) and average power density (P) of the fiber supercapacitor 4690 can be calculated using Equations (7) and (8).

$$E = \frac{0.5 C_m \Delta V^2}{3600} \quad (7)$$

$$P = \frac{3600 E}{\Delta t} \quad (8)$$

Figure 52D is a Ragone plot 5240 for a power density of the fiber supercapacitor 4690 varying with energy density. The fiber supercapacitor 4690 has an energy density of about 27.3 Wh/kg and a corresponding power density of 1 kW/kg, at a discharge current of 20 μA. The energy density decreases from 27.3 to 6.9 Wh/g, and the power density increases from 1 to 5 kW/kg as a result of the increase in discharge current from 20 μA to 100 μA.

Five fiber supercapacitors 4690 are connected in series to provide a tunable operating voltage for storing converted energy generated by the S-TENG 4600. Figure 53A shows four cyclic voltammetry (CV) curves 5310a, 5310b, 5310c, 5310d for the short-circuit current (I_{sc}) of the five fiber supercapacitors 4690 connected in series varying with potential, at different scan rates of 100 mV/s, 500 mV/s, 1 V/s, and 2 V/s respectively. The open-circuit voltage (V_{oc}) reached 5 V for the five fiber supercapacitors 4690 connected in series. The CV curve retains its rectangular shape well even at a high scan rate of 2 V/s, indicating an excellent rate capability.

Figure 53B is a line graph 5320 of a capacitance of the five fiber supercapacitors 4690 connected in series varying with discharge currents of the charge-discharge

profiles. The C of the 5 F-SC connected in series under different current can be calculated from the GCD curves according to Equation (9).

$$C = \frac{I\Delta t}{\Delta V} \quad (10)$$

where I is the discharge current, Δt is the discharge time, ΔV is a potential

5 window during the discharge process. The 5 F-SCs delivered a capacitance of 0.416mF at a discharge current of 20 μ A, and a capacitance of 1.096mF at a discharge current of 200nA.

Figure 53C shows three galvanostatic charge-discharge (GCD) curves
 10 5330a,5330b,5330c for the potential of the five fiber supercapacitor 4690 connected in series varying with time, under small input currents of 1 μ A, 10 μ A, and 20 μ A respectively. Figure 53D shows three galvanostatic charge-discharge (GCD) curves 5340a,5340b,5340c for the potential of the five fiber supercapacitor 4690 connected in series varying with time, under small input current of 200nA,
 15 400nA, and 800nA respectively. Figure 53E is an enlarged view of the three galvanostatic charge-discharge (GCD) curves of Figure 53D over the potential of 0V to 0.3V. The potential of the five fiber supercapacitor 4690 connected in series vary from 0 to 5V. The five fiber supercapacitor 4690 connected in series can be used to efficiently store energy even with small charging currents in the range of
 20 200nA.

(VII) Power harvesting system

An exemplary power harvesting system 5400 for electrolysing sea water to produce hydrogen gas is described. Figure 54A is a circuit diagram for the power
 25 harvesting system 5400. The power harvesting system 5400 includes a plurality of S-TENGs 4600 electrically coupled in series, and an electrolysis device 5410 electrically coupled to the plurality of S-TENGs to receive energy generated by the plurality of S-TENGs. The energy generated by the plurality of S-TENGs 4600 are stored in five fiber supercapacitors 4690 before being discharged to the
 30 electrolysis device 5410. The electrolysis device 5410 include two electrodes 5412 that are made of a carbon fabric and a platinum sheet. Each of the two electrodes have a surface area of 4cm². The electrolysis device 5410 uses the

energy received from the S-TENGs 4600 to electrolyse seawater into hydrogen gas. The power harvesting system 5400 further includes a hydrogen fuel cell coupled to the electrolysis device 5410 to receive and store the hydrogen gas. The hydrogen gas is then supplied based on demand.

5

Figure 54B is a line graph 5420 showing the change in voltage of the five fiber supercapacitors 4690 of the power harvesting system 5400 during charging and discharging. During the day, the fiber supercapacitors 4690 are charged to 1.3V using energy generated by the S-TENGs 4600 through the shadow-effect and the triboelectric effect, and then discharged for seawater electrolysis. During the night, the fiber supercapacitors 4690 can still be charged using energy generated by the S-TENGs 4600 through the triboelectric effect.

10

(VIII) Energy conversion efficiency

Figure 55 illustrate an exemplary 4x4 array 5500 of S-TENGs 4600 that are electrically coupled to each other.

15

The energy conversion efficiency (η) of one of the S-TENG 4600 in a wave generation machine is calculated by Equation (10).

20

$$\eta = \frac{P_{peak}}{P_{light} + P_{wave}} \times 100\% \quad (10)$$

where P_{peak} is the maximum peak power of one S-TENG 4600, P_{wave} is calculated by dividing power output of the wave generation machine by the amount of water in the wave generation machine (15L), multiplied by the volume of one energy ball. P_{wave} is calculated to be 21.4mW. From Figure 49E, P_{peak} of the S-TENG 4600 is 10.8mW. Thus, the efficiency, η of the S-TENG 4600 is calculated to be 0.7%.

25

Referring to Figure 55, four energy balls roughly occupy an area of about 625cm². One S-TENG 4600 occupies an area of about 156.25 cm². An ideal peak power density of the 4x4 array 5500 is 0.69 MW/km², which is calculated by multiplying the peak power density, P_{peak} of one S-TENG 4600 by a number of S-TENGs 4600 per square kilometre.

30

It should be noted that the various embodiments described herein should not be construed as limitative. For example, the light permeable triboelectric charging element 2970,4370,4670 need not be made of polydimethylsiloxane (PDMS).
5 Other triboelectric materials that is also light permeable may be chosen. Similarly, the movable triboelectric charging element 2980,4380,4680 is not be restricted to the specific embodiments described herein. The skilled person will appreciate that other materials that are suitable for the specific application are within the scope of the disclosure. Likewise, the light permeable exterior shell 4690 may be
10 made of other light permeable materials.

CLAIMS

1. A hybrid energy generator, comprising
 - a semiconductor substrate;
 - 5 a light permeable triboelectric charging element;
 - a metallic element sandwiched between the light permeable triboelectric charging element and the semiconductor substrate;
 - a movable triboelectric charging element arranged to be movable relative to a surface of the light permeable triboelectric charging element and exposed to an illumination source to cast a shadow and to produce an illumination contrast for detection by the metallic element; wherein energy is generated when the movable triboelectric charging element is in contact with the surface of the light permeable triboelectric charging element, and from the illumination contrast detected by the metallic element.
- 15 2. A hybrid energy generator according to claim 1, further comprising an energy storage element electrically coupled to the metallic element, and arranged to store the energy generated.
- 20 3. A hybrid energy generator according to claim 2, wherein the energy storage element comprises at least one fibre-supercapacitor.
4. A hybrid energy generator according to claim 3, wherein the at least one fibre-supercapacitor comprises a layered molybdenum disulfide.
- 25 5. A hybrid energy generator according to any preceding claim, wherein the semiconductor substrate is an n-doped semiconductor.
6. A hybrid energy generator according to any preceding claim, wherein the metallic element is made of gold, aluminium or copper.
- 30

7. A hybrid energy generator according to any preceding claim, wherein the metallic element has a thickness of 15nm.
8. A hybrid energy generator according to any preceding claim, wherein the light permeable triboelectric charging element is made of a polymer.
9. A hybrid energy generator according to claim 8, wherein the polymer is polydimethylsiloxane.
10. 10. A hybrid energy generator according to any preceding claim, wherein the movable triboelectric charging element is made of aluminium.
11. A hybrid energy generator according to any preceding claim, wherein the movable triboelectric charging element is movable by gravity along the surface of the light permeable triboelectric charging element.
12. A hybrid energy generator according to claim 11, wherein the movable triboelectric charging element is spherical.
13. A hybrid energy generator according to any preceding claim, further comprising a light permeable exterior shell encapsulating the semiconductor substrate, the metallic element, the light permeable triboelectric charging element, and the movable triboelectric charging element.
14. A hybrid energy generator according to any one of claims 1 to 10, wherein the movable triboelectric charging element is movable in a direction that is perpendicular to a surface of the light permeable triboelectric charging element.
15. A hybrid energy generator according to any one of claims 1 – 9, wherein the movable triboelectric charging element is electrically charged liquid droplets.

16. A method of generating energy using a hybrid energy generator having a semiconductor substrate, a light permeable triboelectric charging element, a metallic element sandwiched between the light permeable triboelectric charging element and the semiconductor substrate, and a movable triboelectric charging element arranged to be movable relative to a surface of the light permeable triboelectric charging element, the method comprising
- 5 exposing the movable triboelectric charging element to an illumination source to cast a shadow for producing an illumination contrast for detection by the metallic element; and
- 10 generating energy when the movable triboelectric charging element is in contact with the surface of the light permeable triboelectric charging element, and from the illumination contrast detected by the metallic element.
17. A method according to claim 16, further comprising storing the energy generated using an energy storage element electrically coupled to the metallic element.
- 15 18. A method according to claim 17, wherein the energy storage element comprises at least one fibre-supercapacitor.
- 20 19. A method according to claim 18, wherein the at least one fibre-supercapacitor comprises a layered molybdenum disulfide.
20. A method according to any one of claims 16 to 19, wherein the semiconductor substrate is an n-doped semiconductor.
- 25 21. A method according to any one of claims 16 to 20, wherein the metallic element is made of gold, aluminium or copper.
- 30 22. A method according to any one of claims 16 to 21, wherein the metallic element has a thickness of 15nm.

23. A method according to any one of claims 16 to 22, wherein the light permeable triboelectric charging element is made of a polymer.

24. A method according to claim 23, wherein the polymer is polydimethylsiloxane.

5

25. A method according to any one of claims 16 to 24, wherein the movable triboelectric charging element is made of aluminium.

10 26. A method according to any one of claims 16 to 25, wherein moving the movable triboelectric charging element relative to a surface of the light permeable triboelectric charging element further comprises moving the movable triboelectric charging element by gravity along the surface of the light permeable triboelectric charging element.

15 27. A method according to claim 26, wherein the movable triboelectric charging element is spherical.

28. A method according to any one of claims 16 to 27, wherein the hybrid energy generator further includes a light permeable exterior shell encapsulating the semiconductor substrate, the metallic element, the light permeable triboelectric charging element, and the movable triboelectric charging element.

25 29. A method according to any one of claims 16 to 25, wherein moving the movable triboelectric charging element relative to a surface of the light permeable triboelectric charging element further comprises moving the movable triboelectric charging element in a direction that is perpendicular to a surface of the light permeable triboelectric charging element.

30 30. A method according to any one of claims 16 – 24, wherein the movable triboelectric charging element is electrically charged liquid droplets.

31. An energy generator, comprising a plurality of energy generating cells disposed on a substrate and electrically coupled to each other, each energy generating cell including a semiconductor substrate, and a metallic element disposed on the semiconductor substrate, wherein energy is generated when the
5 metallic element detects an illumination contrast produced when a shadow is cast to the metallic element.

32. An energy generator according to claim 31, wherein the energy generating cells are electrically coupled in parallel or in series.

10

33. An energy generator according to claim 31 or 32, wherein the substrate is made of a polymer.

34. An energy generator according to claim 33, wherein the polymer is
15 polyethylene terephthalate or polytetrafluoroethylene.

35. An energy generator according to any one of claims 31 to 34, wherein the semiconductor substrate is an n-doped semiconductor.

20 36. An energy generator according to any one of claims 31 to 35, wherein the metallic element is made of gold, aluminium or copper.

37. An energy generator according to any one of claims 31 to 36, wherein the
25 metallic element has a thickness of 15nm.

25

38. A motion detection method using an energy generator having a plurality of energy generating cells disposed on a substrate and electrically coupled to each other, each energy generating cell including a semiconductor substrate, and a metallic element disposed on the semiconductor substrate, the method
30 comprising casting a shadow to the metallic element when an object passes between the metallic element and an illumination source to produce an

illumination contrast; and detecting the object's motion from energy generated from the illumination contrast.

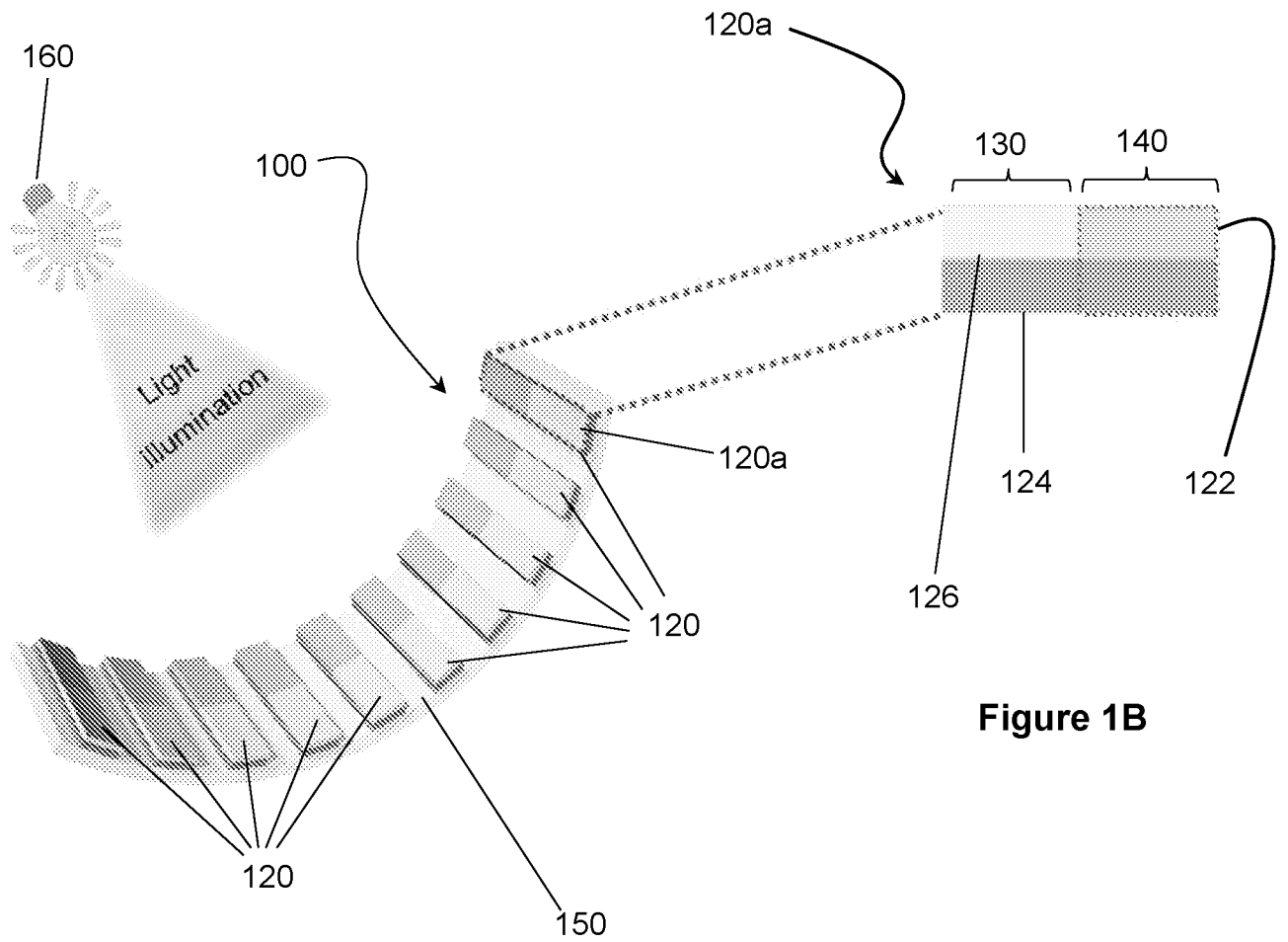


Figure 1A

Figure 1B

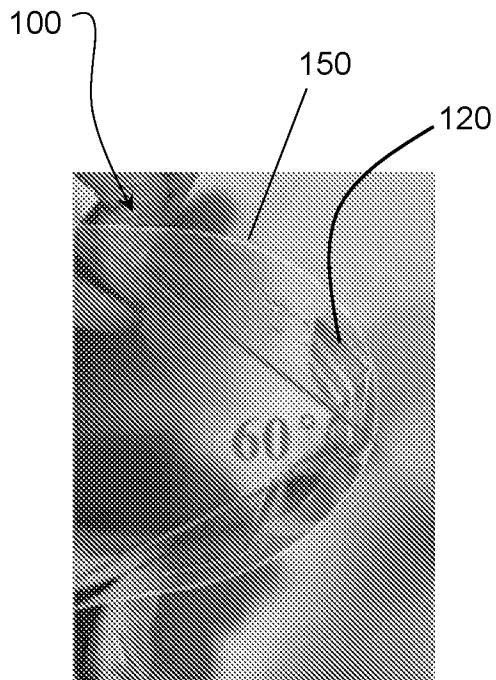


Figure 2A

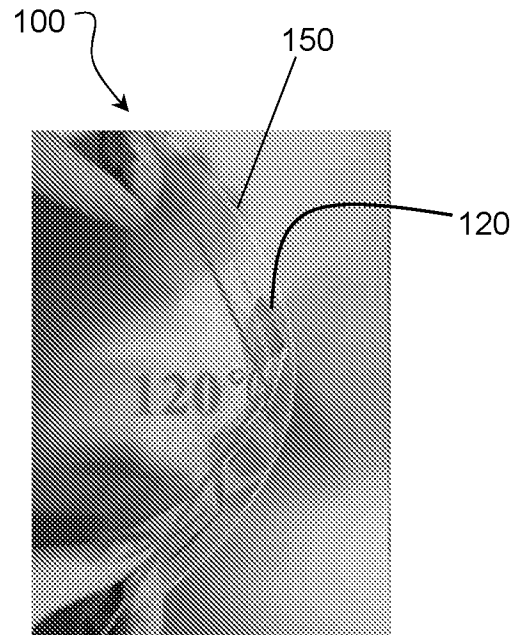


Figure 2B

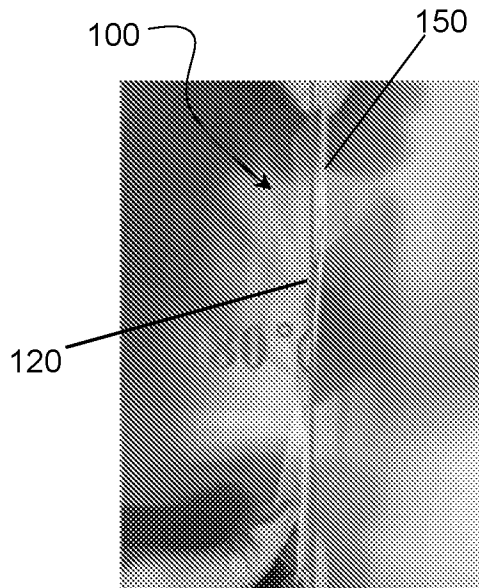


Figure 2C

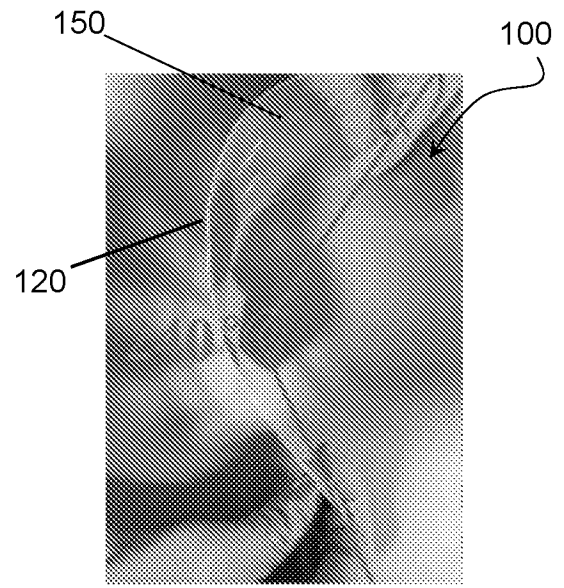


Figure 2D

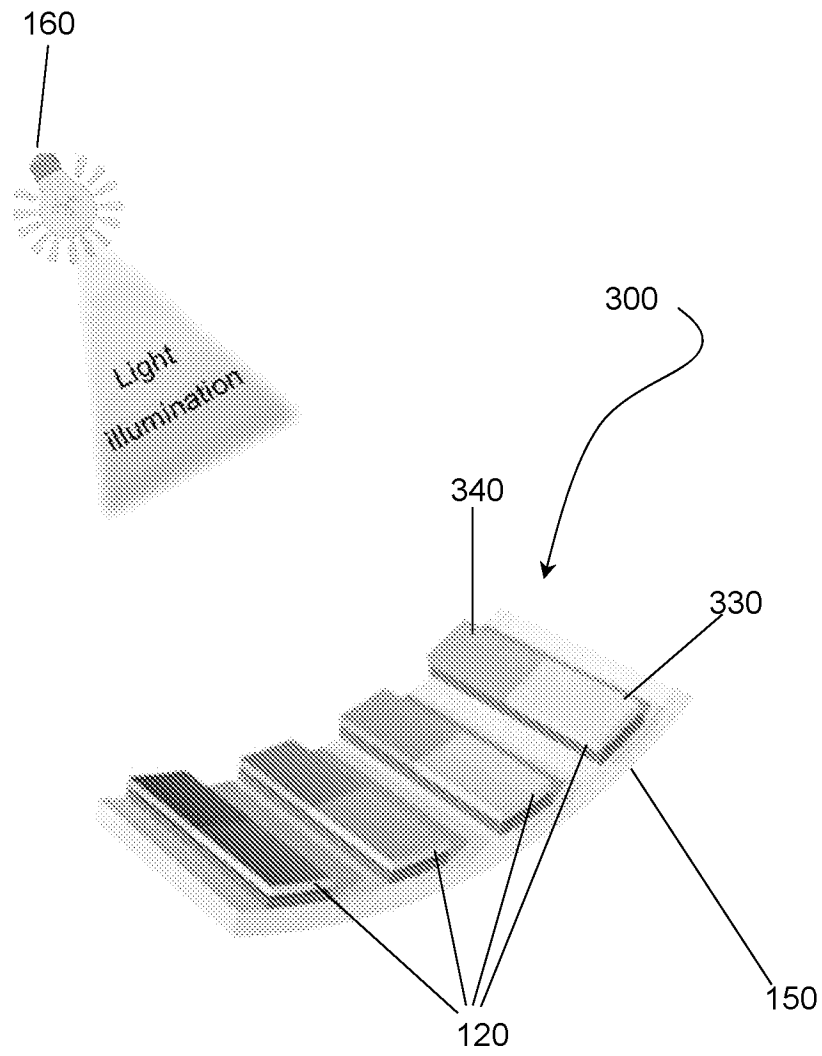


Figure 3

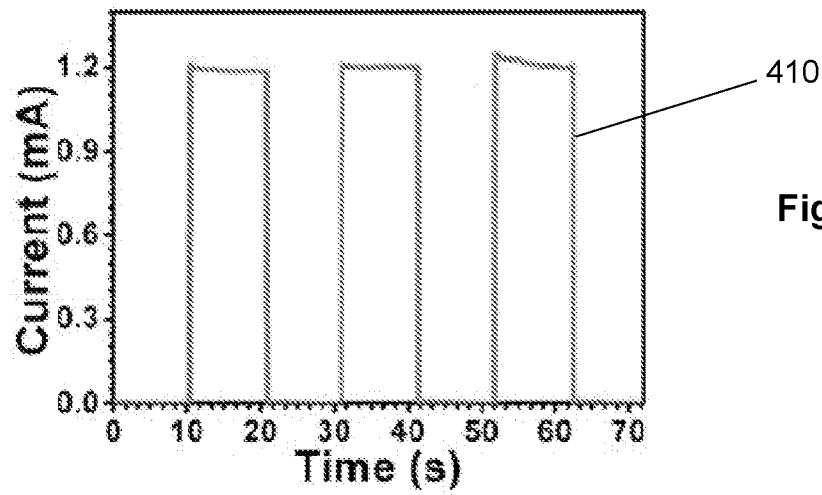


Figure 4A

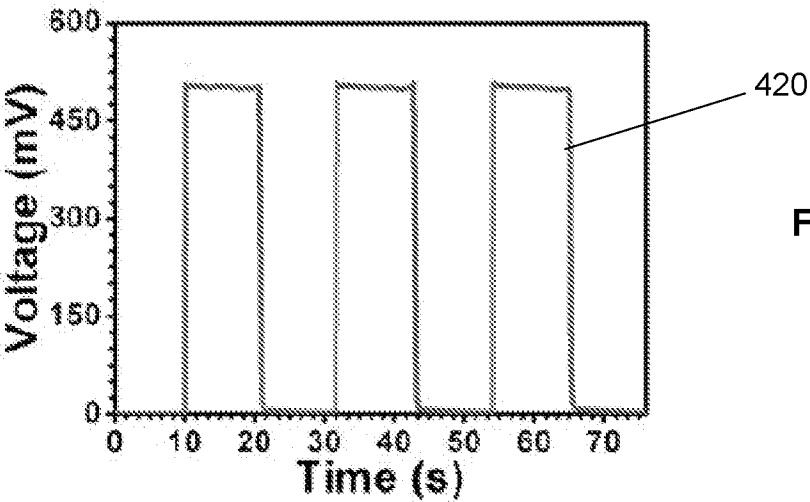


Figure 4B

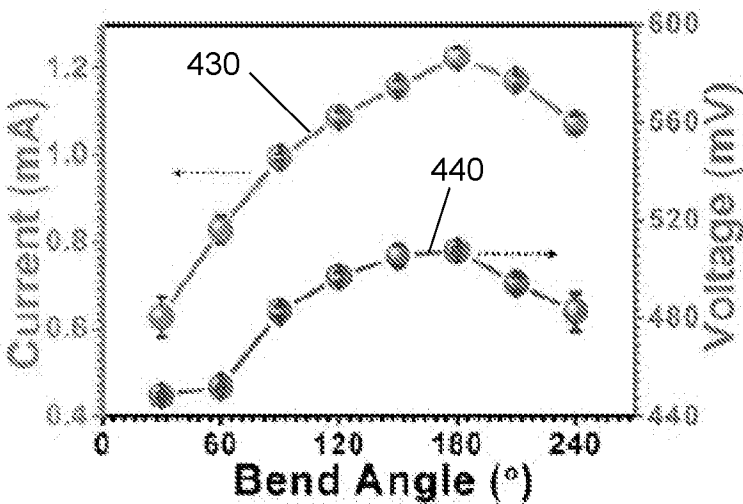


Figure 4C

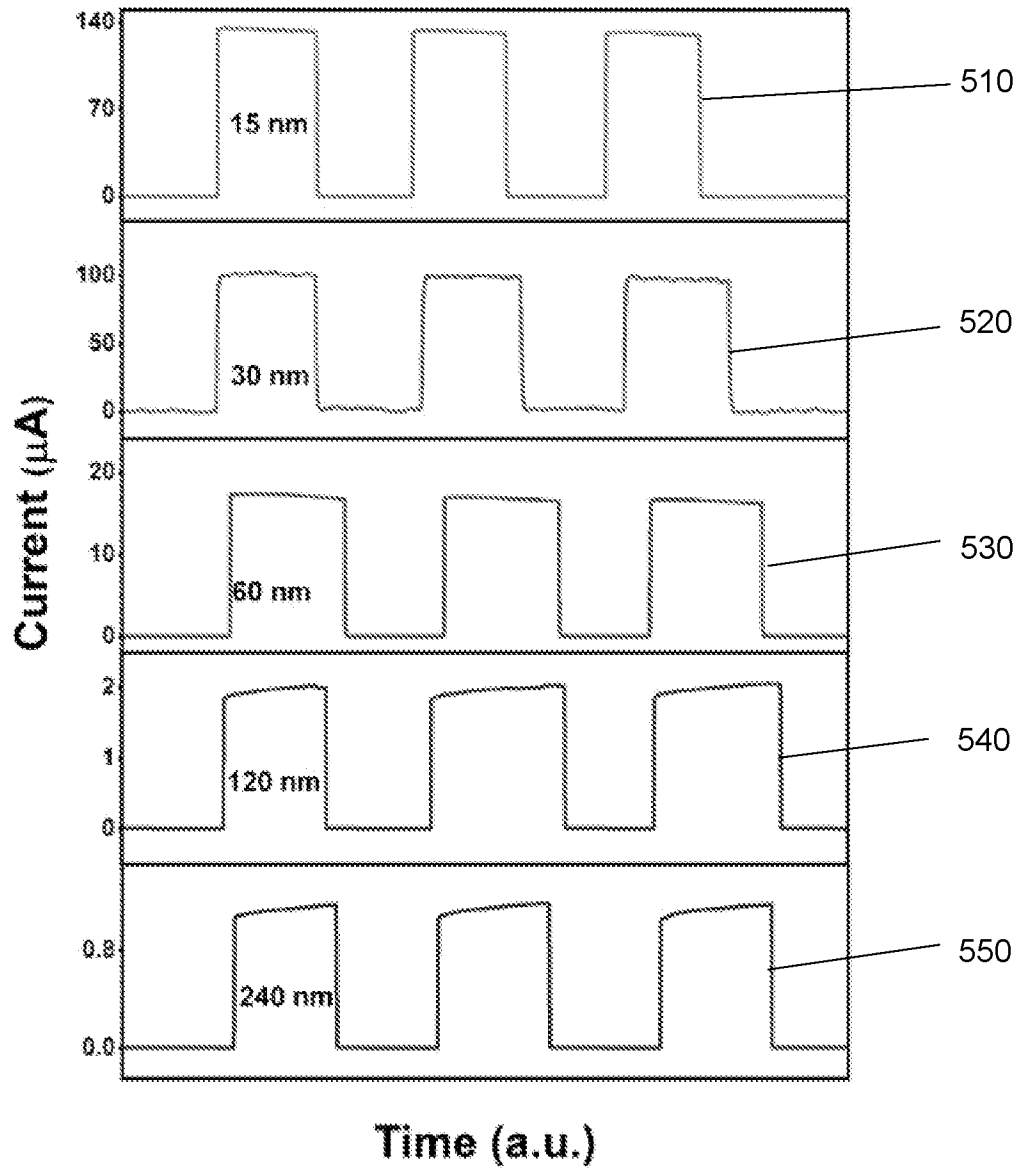


Figure 5

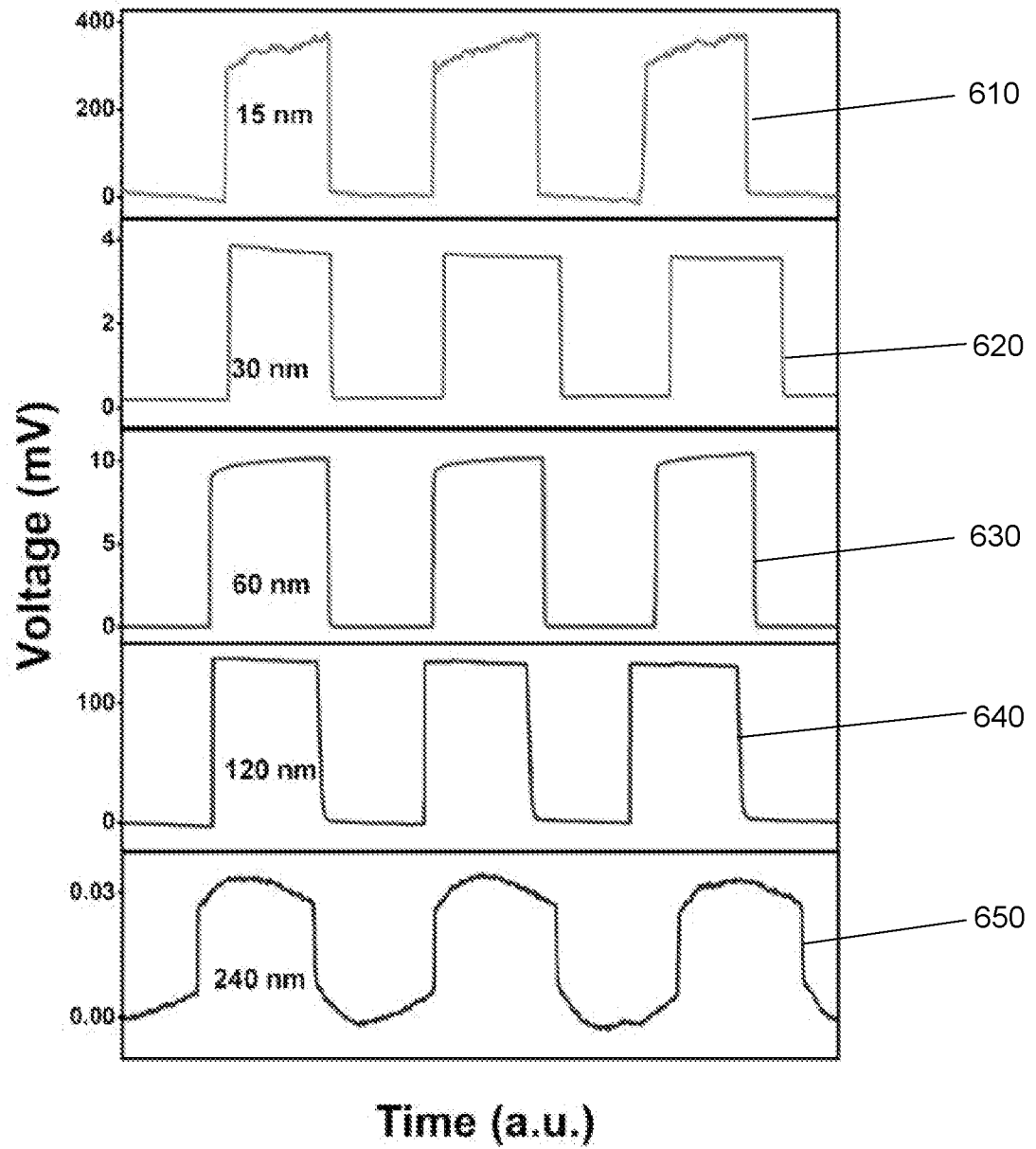


Figure 6

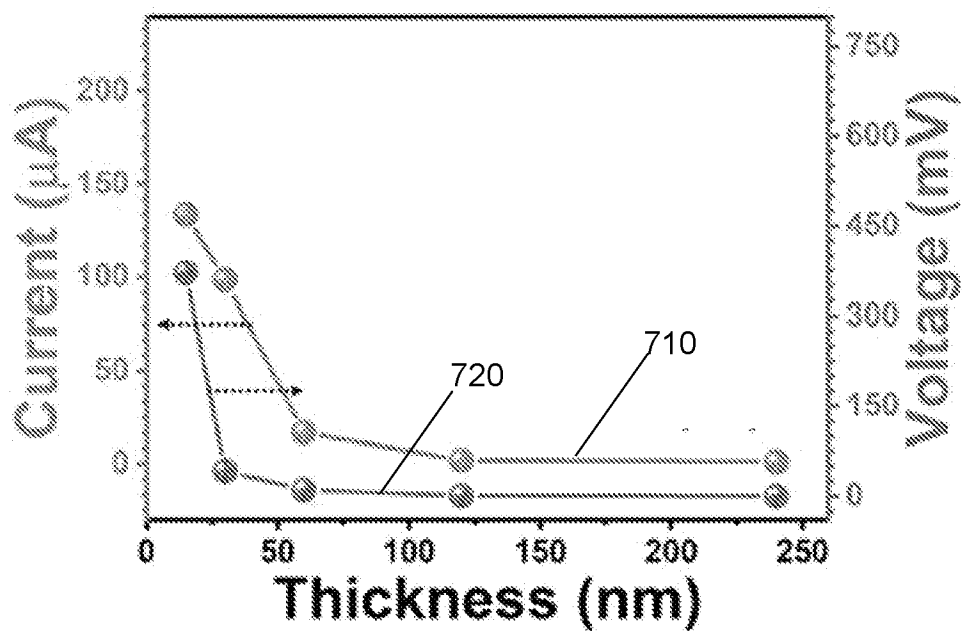


Figure 7A

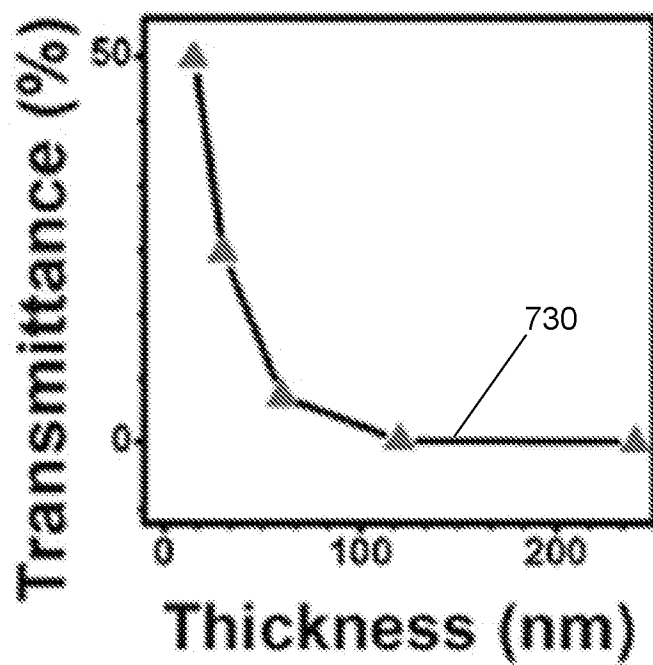


Figure 7B

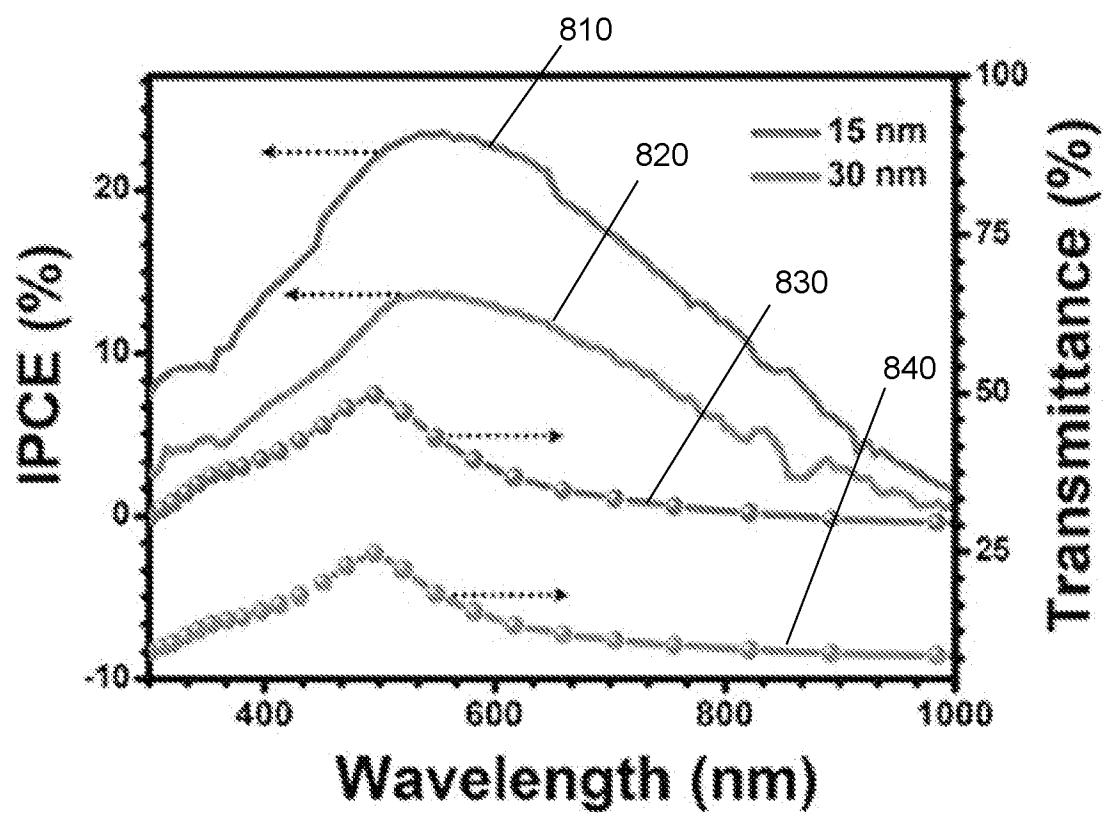


Figure 8

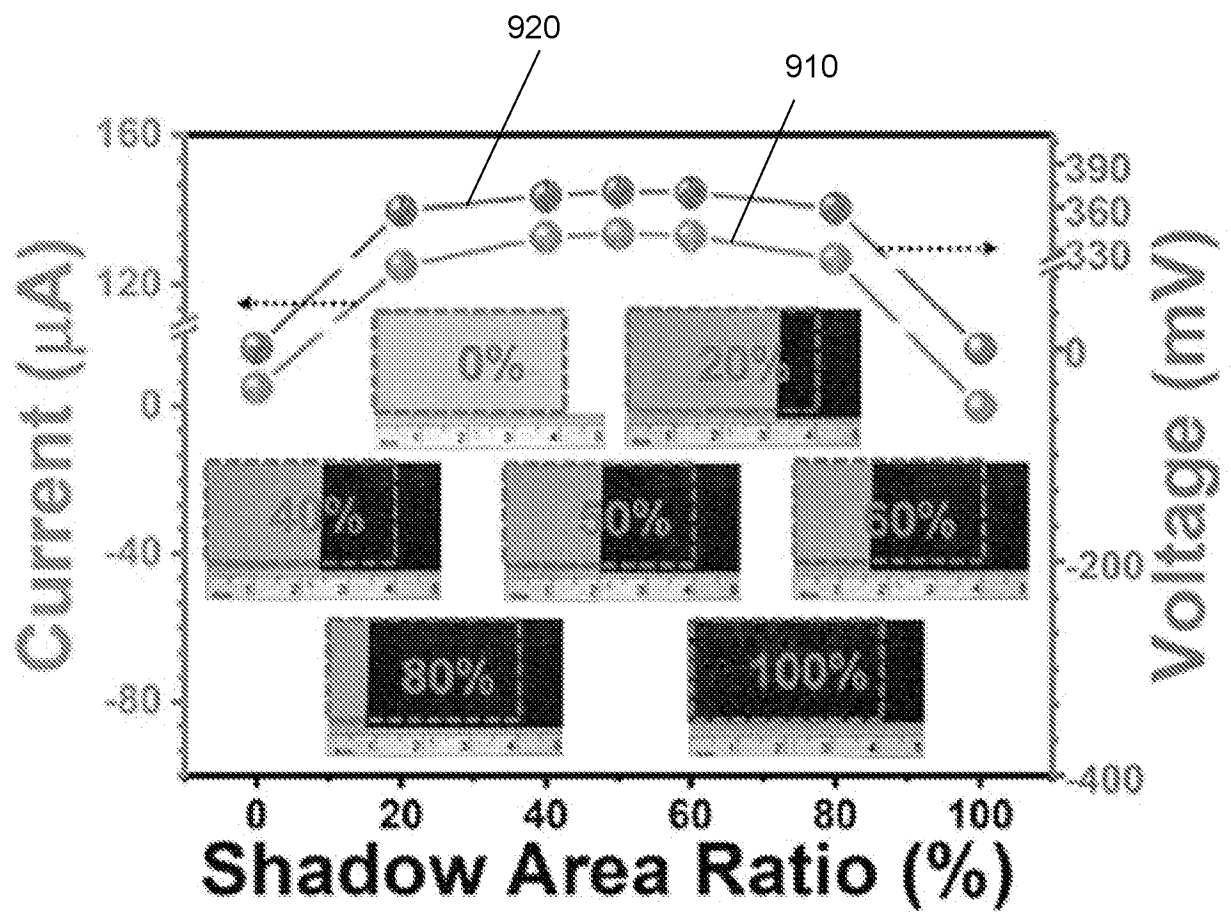


Figure 9

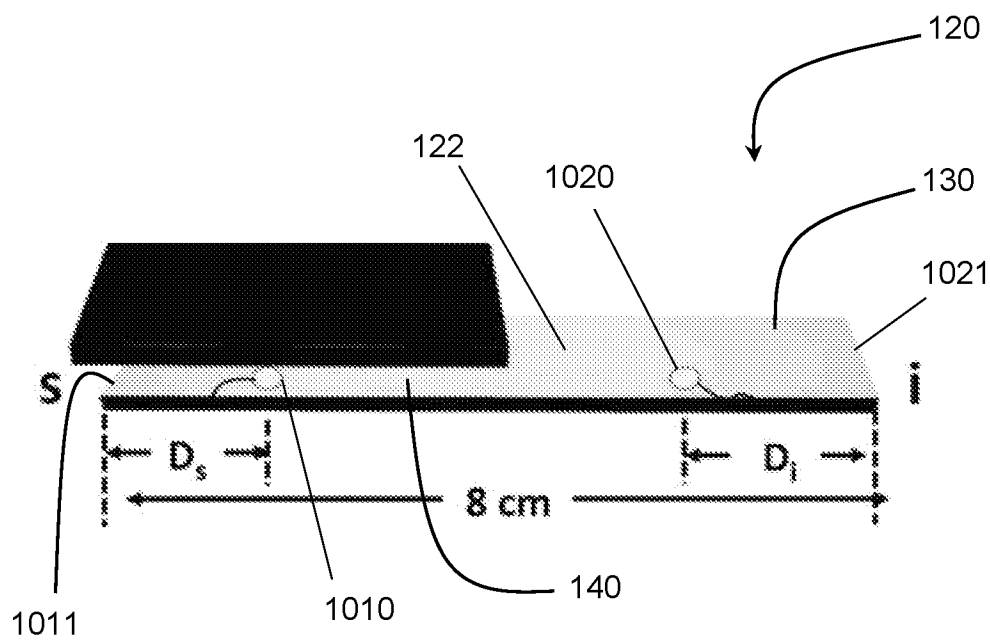


Figure 10A

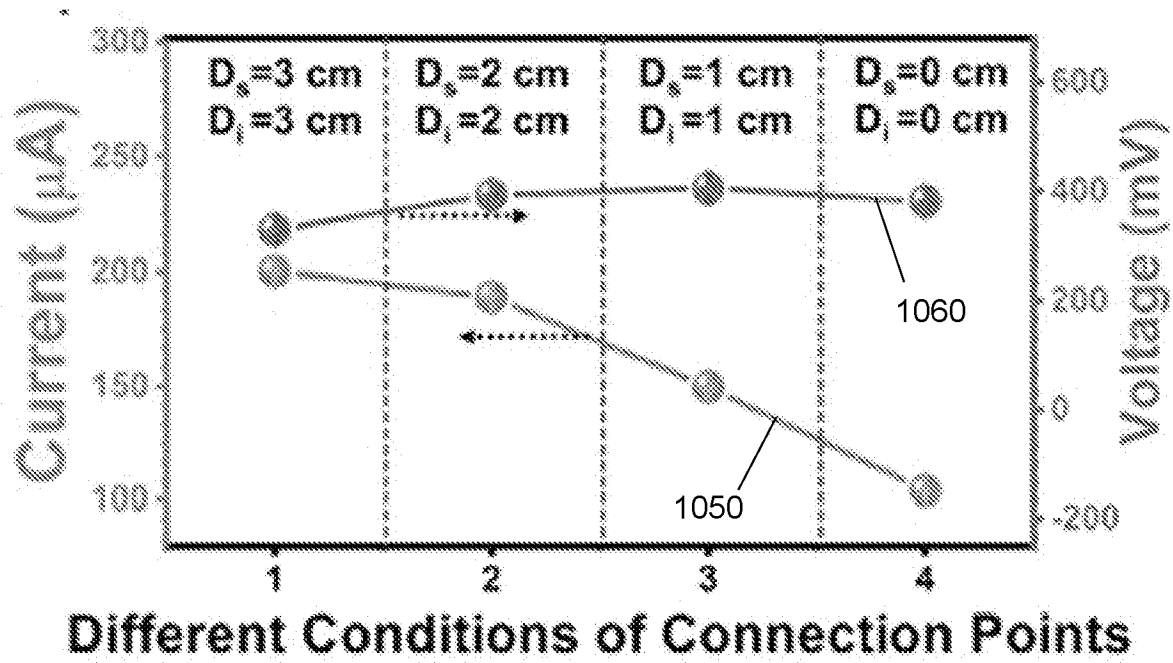


Figure 10B

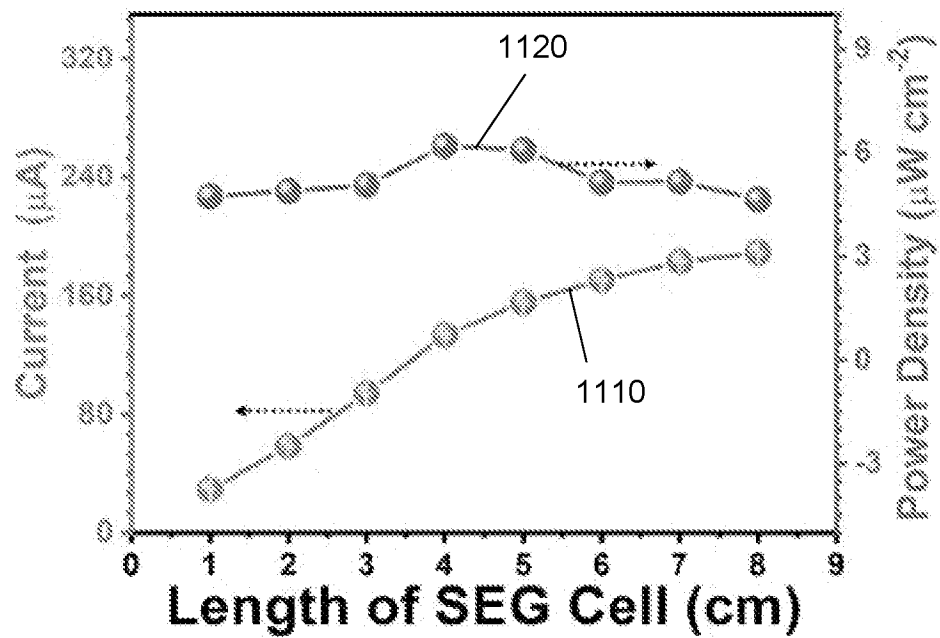


Figure 11A

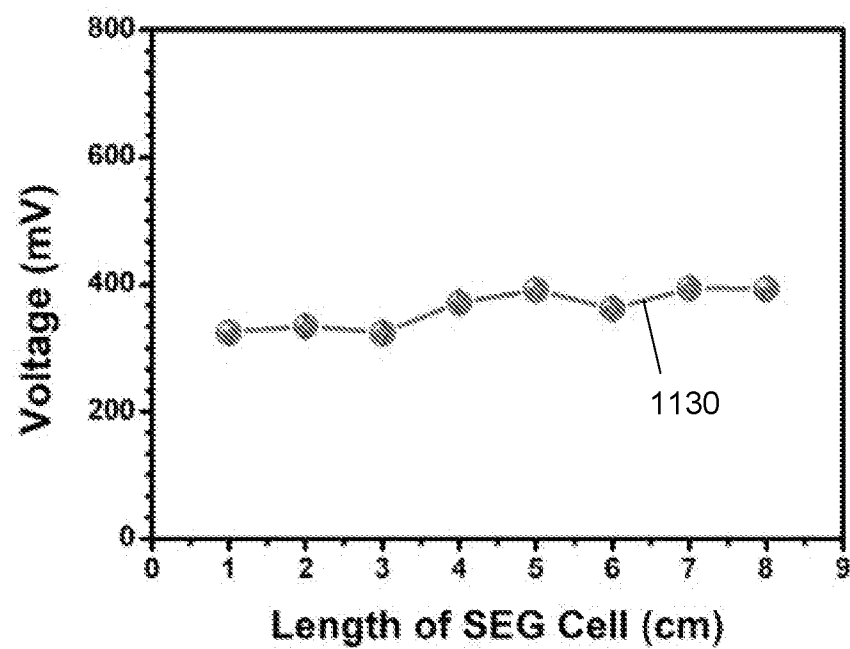


Figure 11B

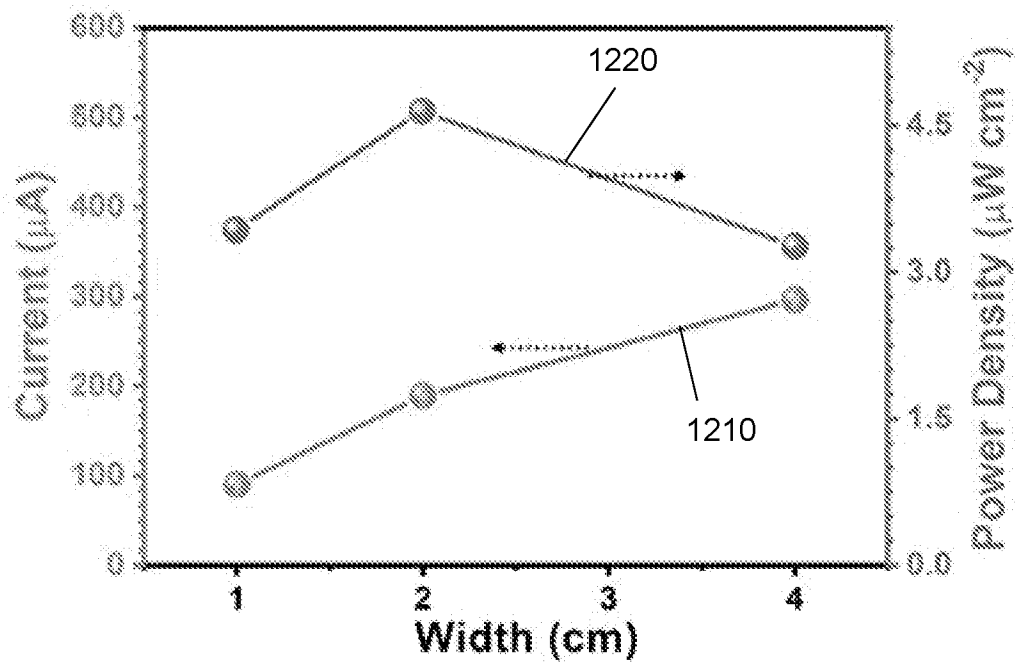


Figure 12A

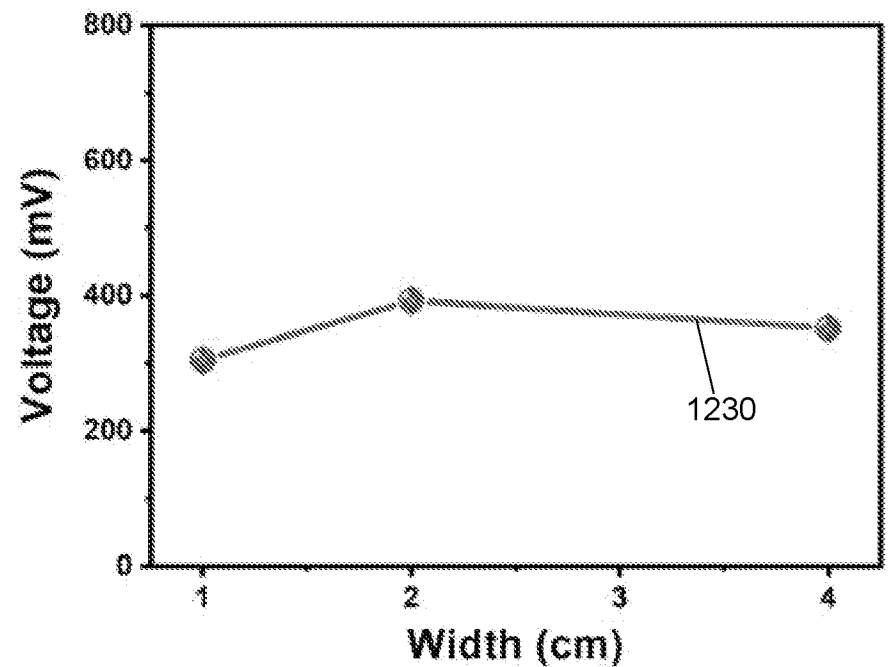


Figure 12B

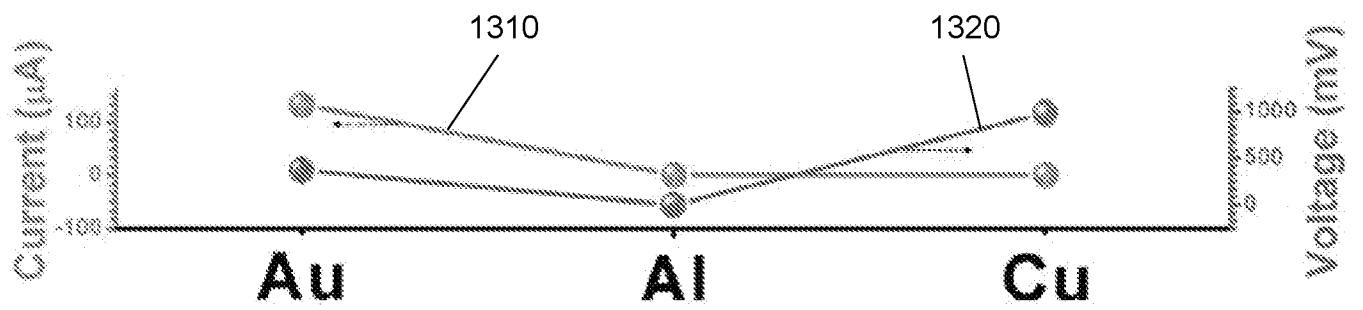


Figure 13

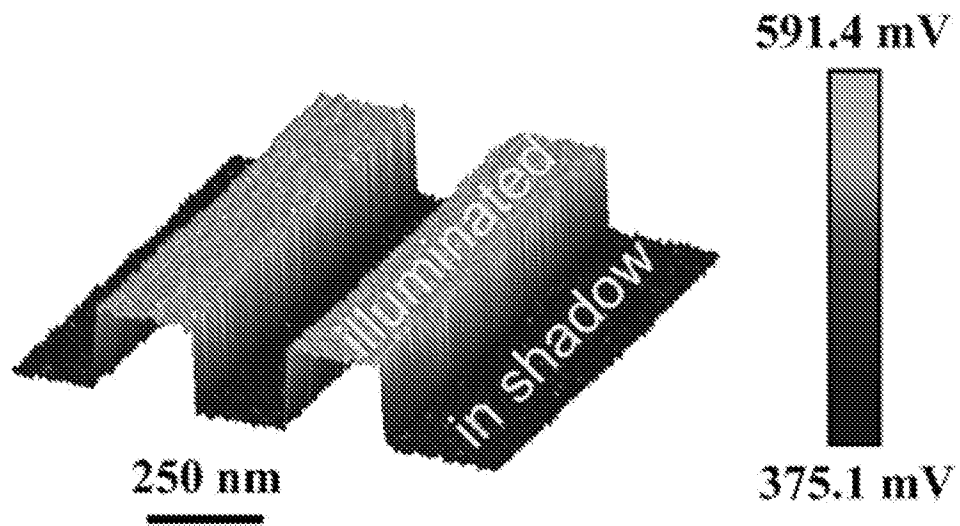


Figure 14A

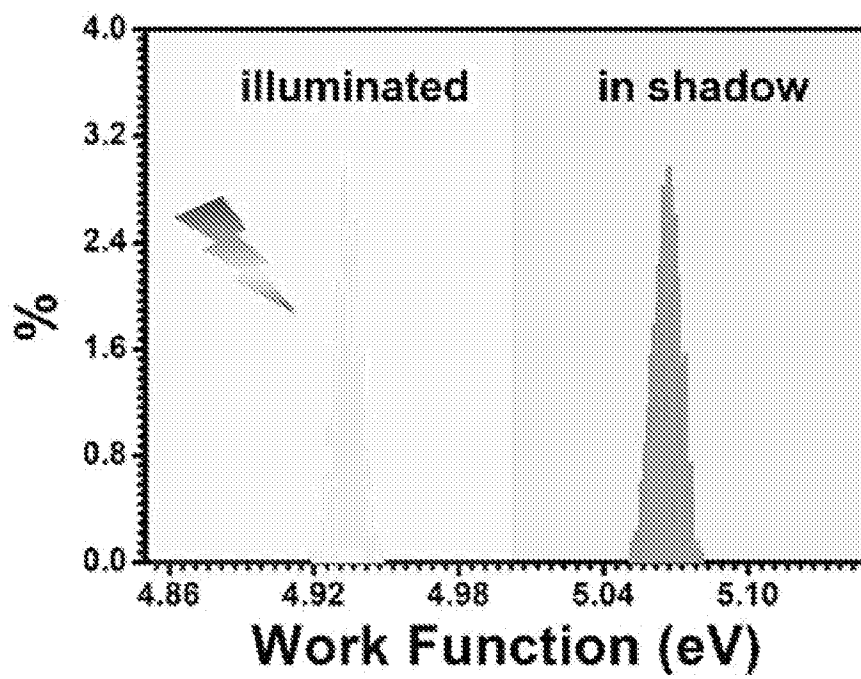


Figure 14B

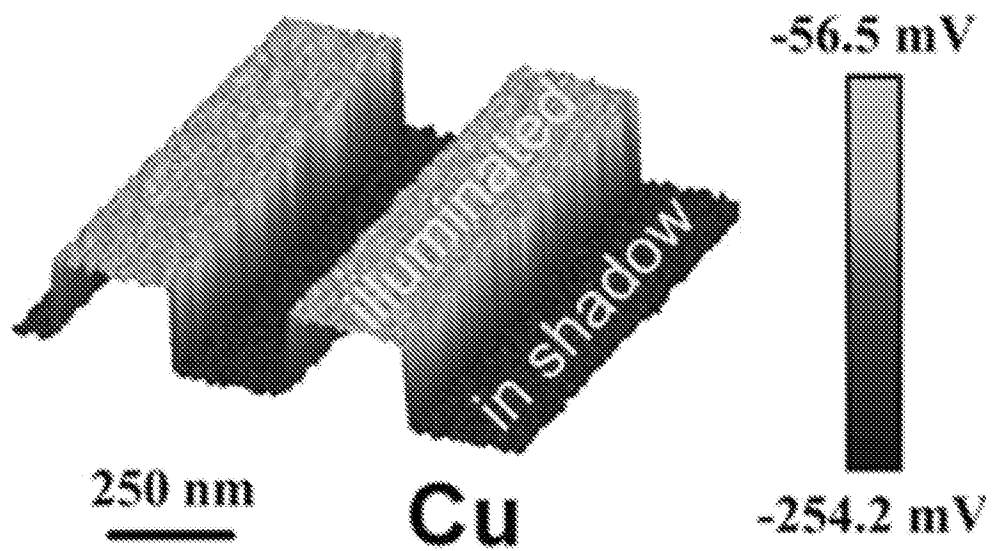


Figure 15A

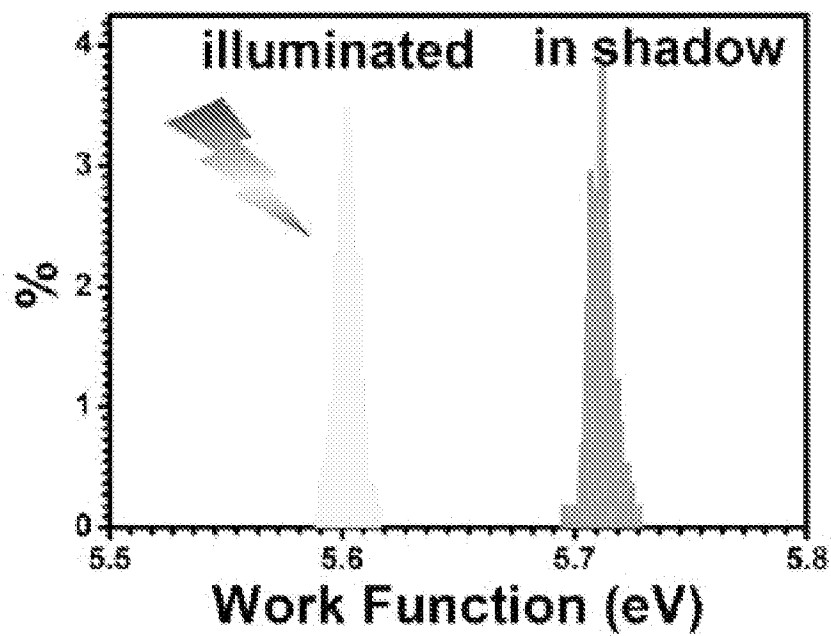


Figure 15B

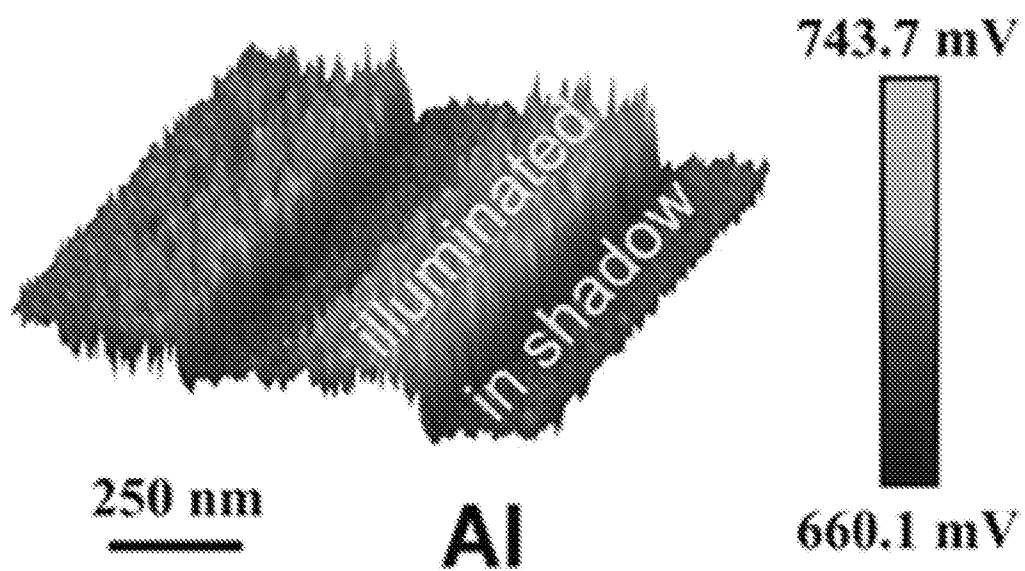


Figure 16A

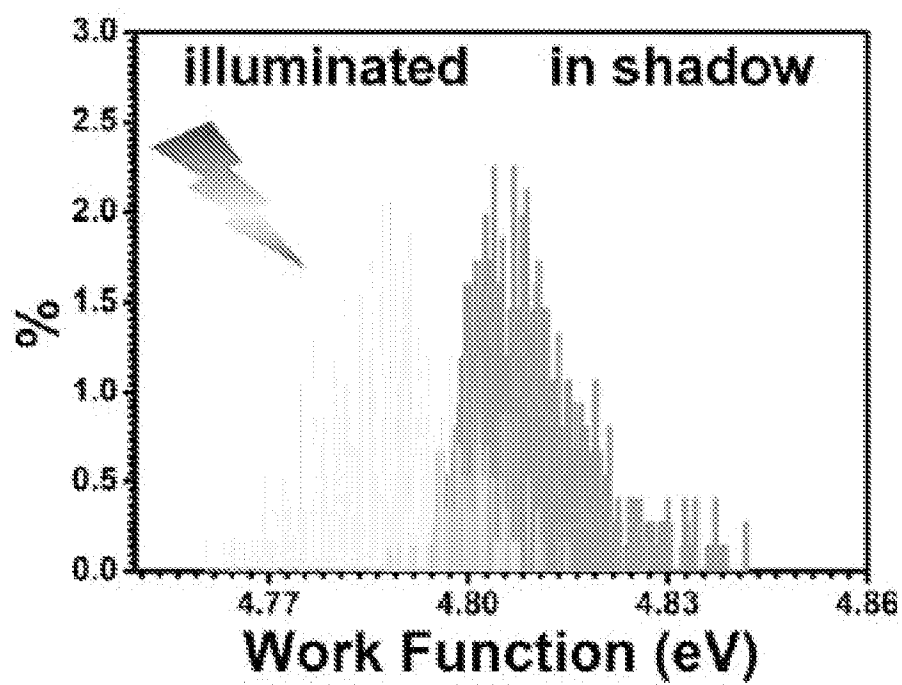


Figure 16B

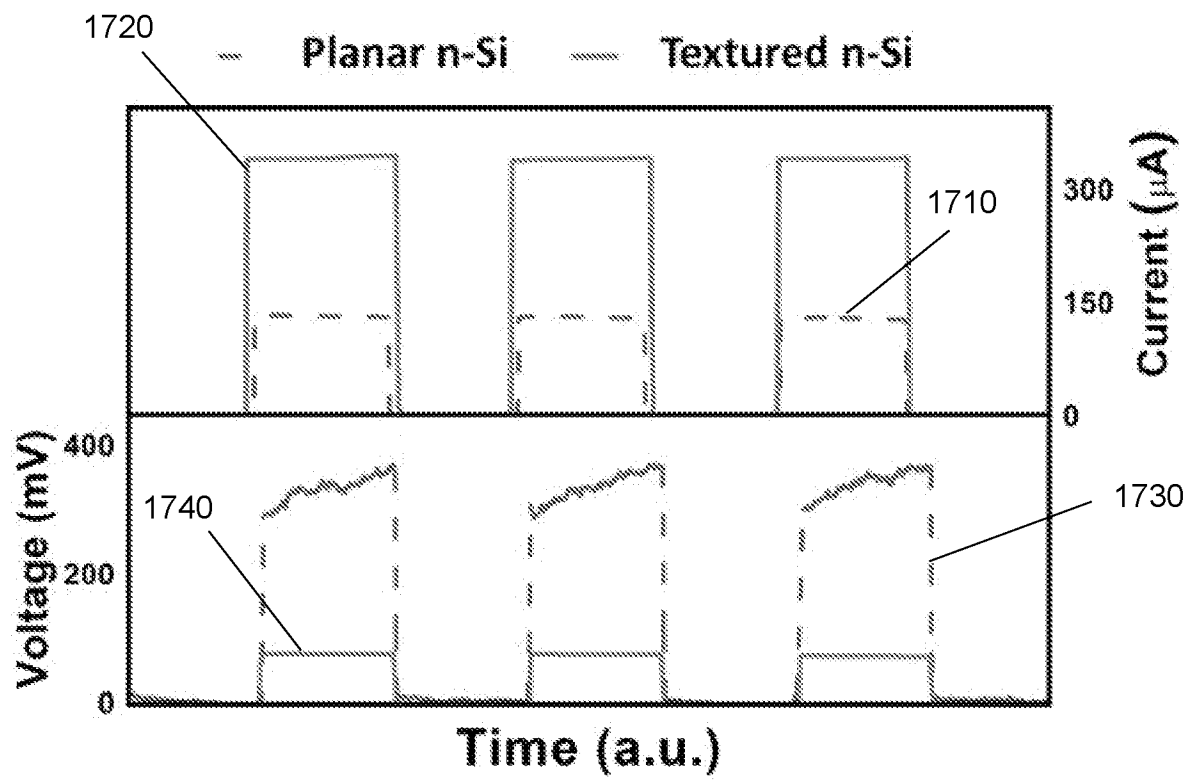


Figure 17

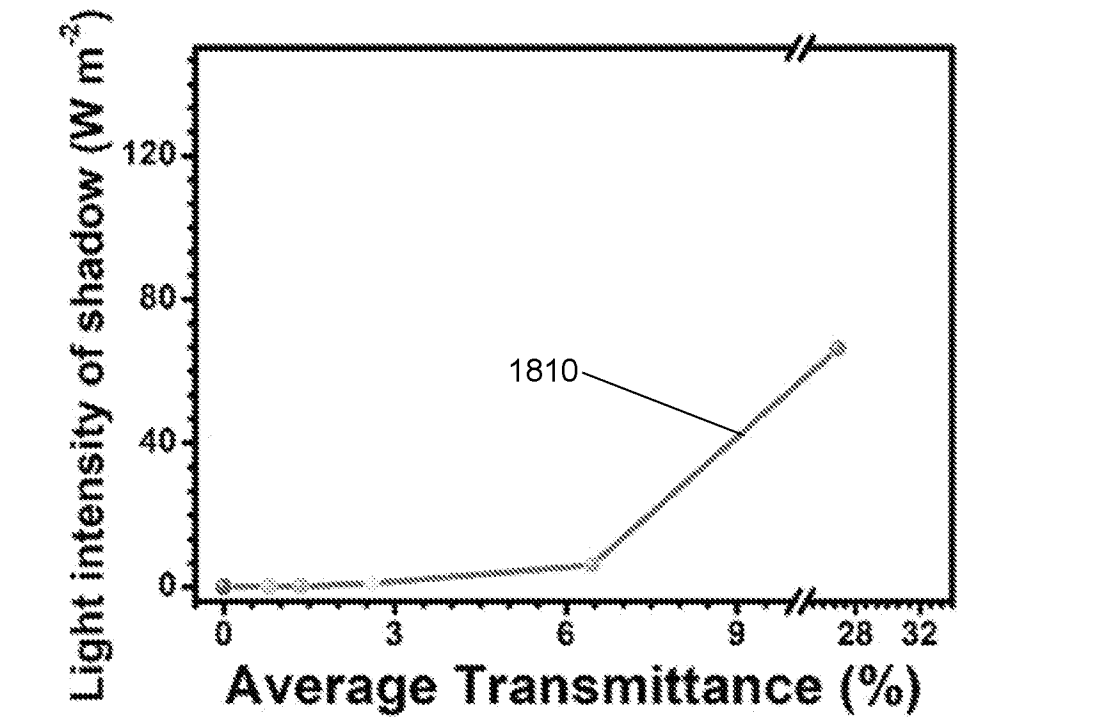


Figure 18A

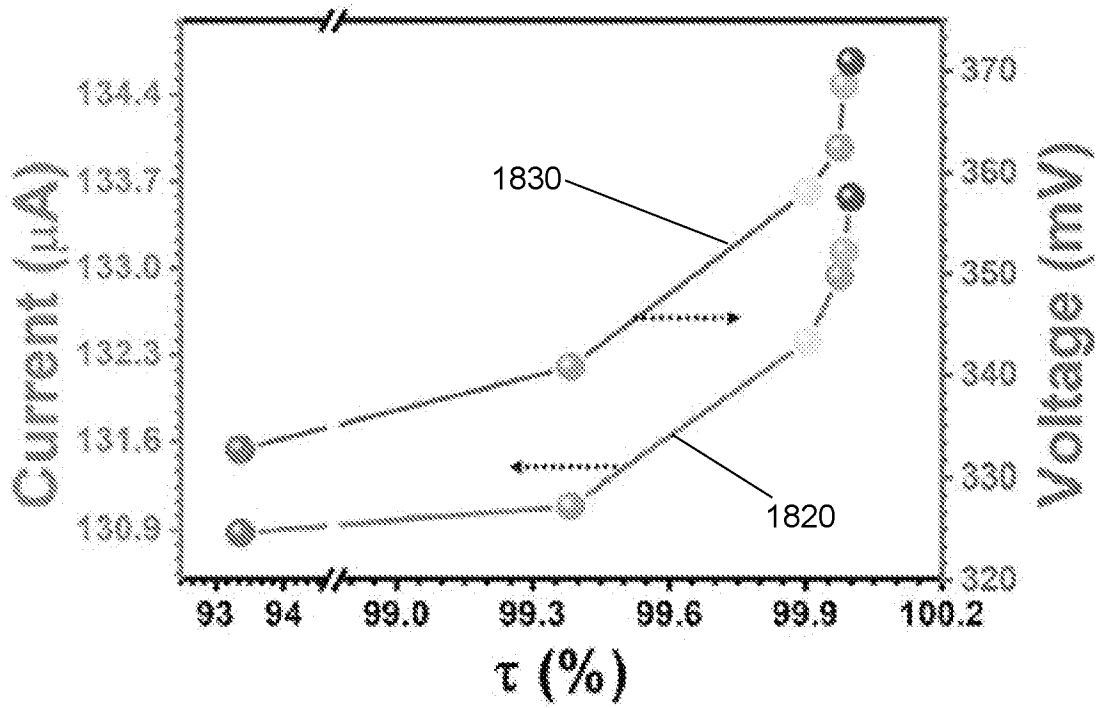


Figure 18B

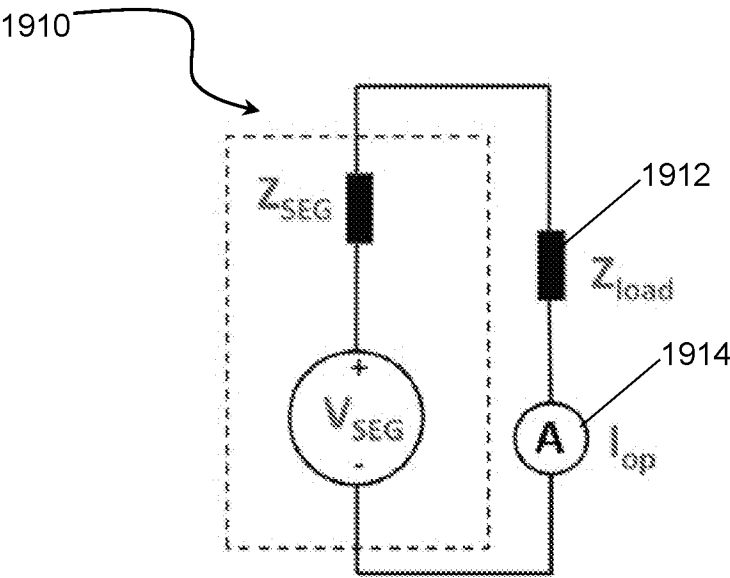


Figure 19A

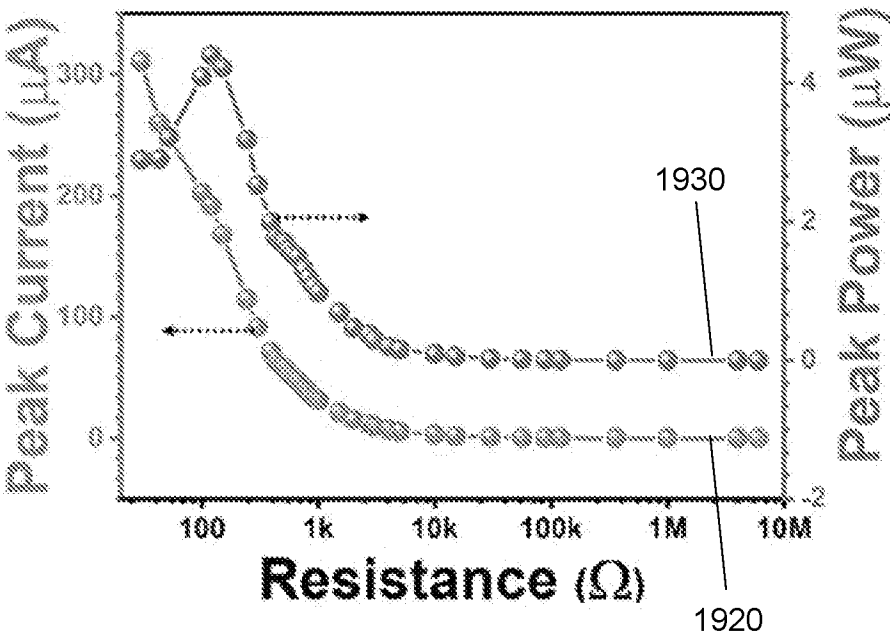


Figure 19B

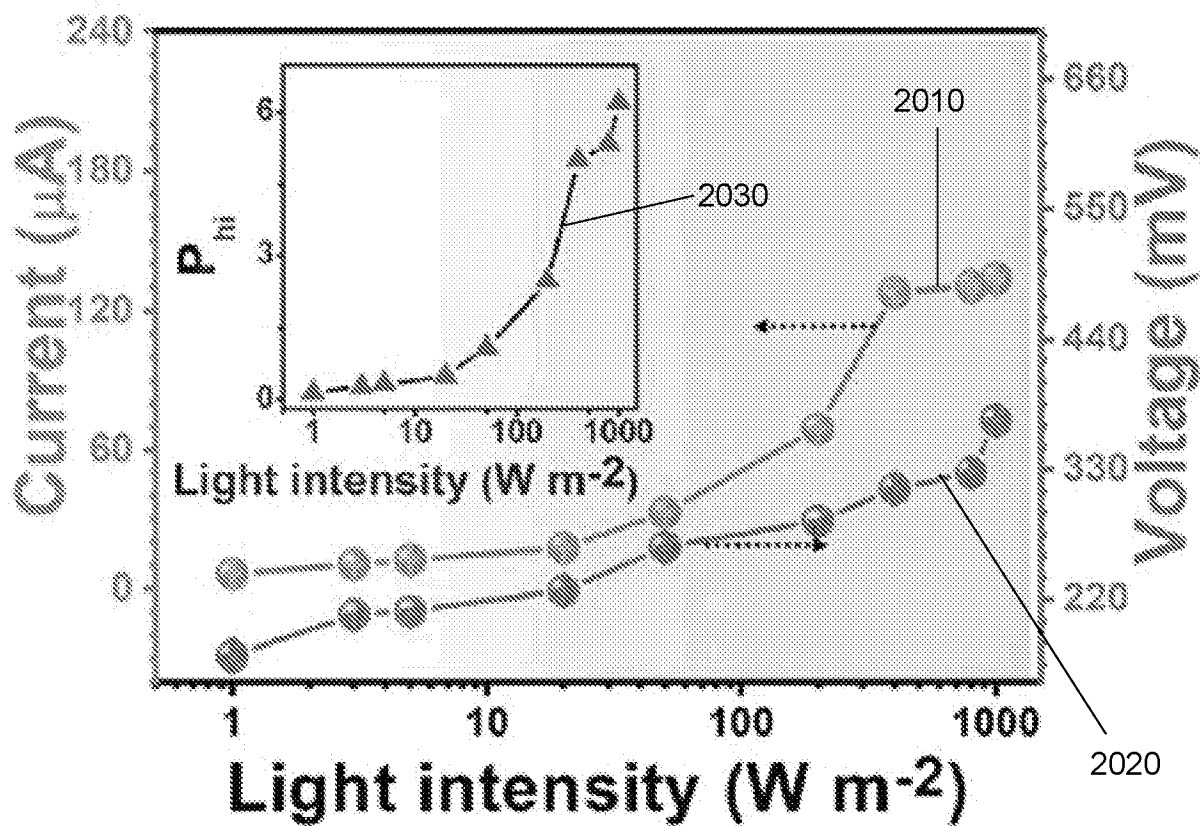


Figure 20

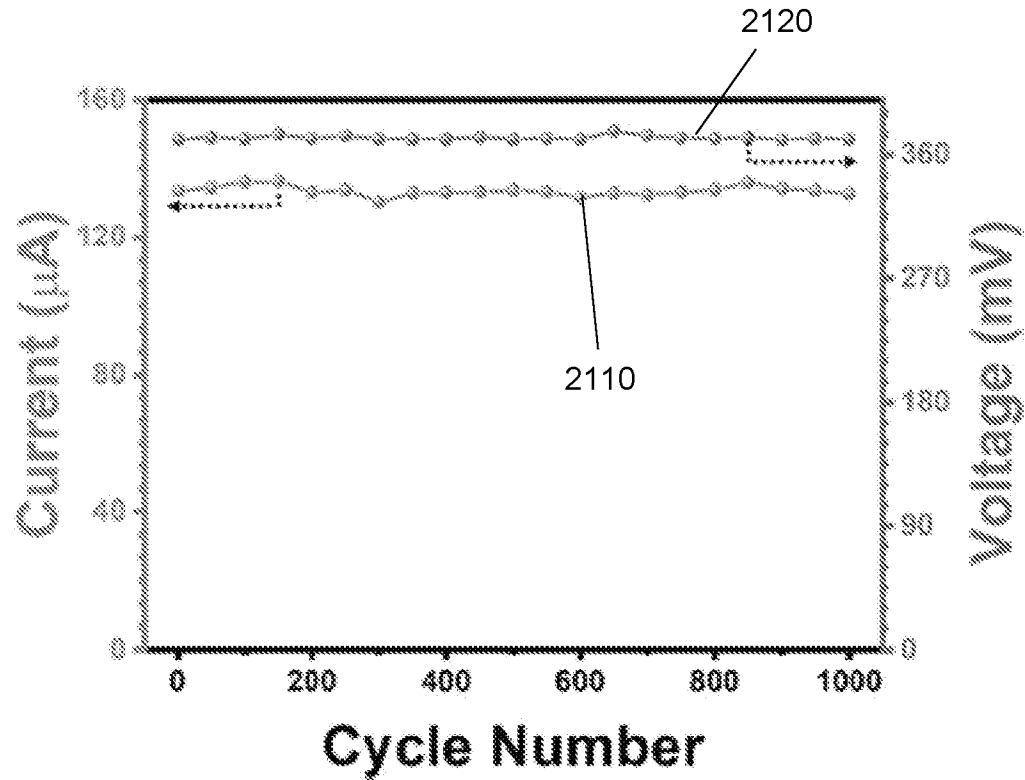


Figure 21A

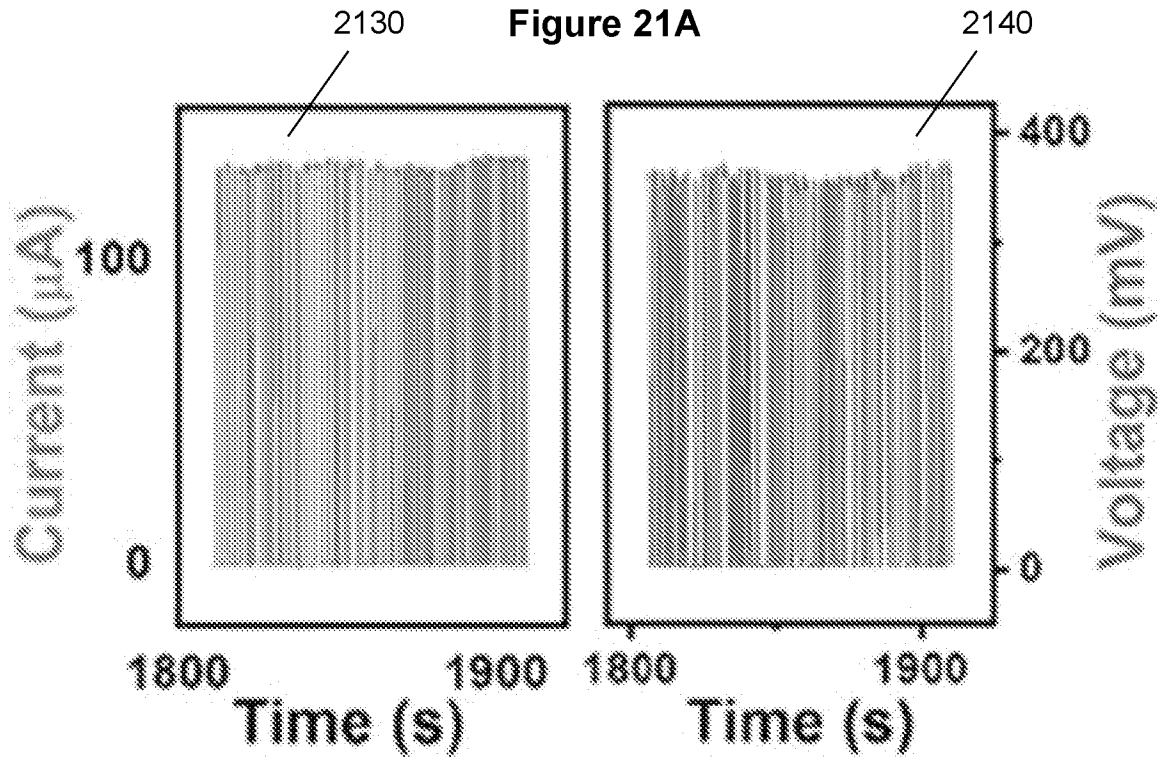


Figure 21B

Figure 21C

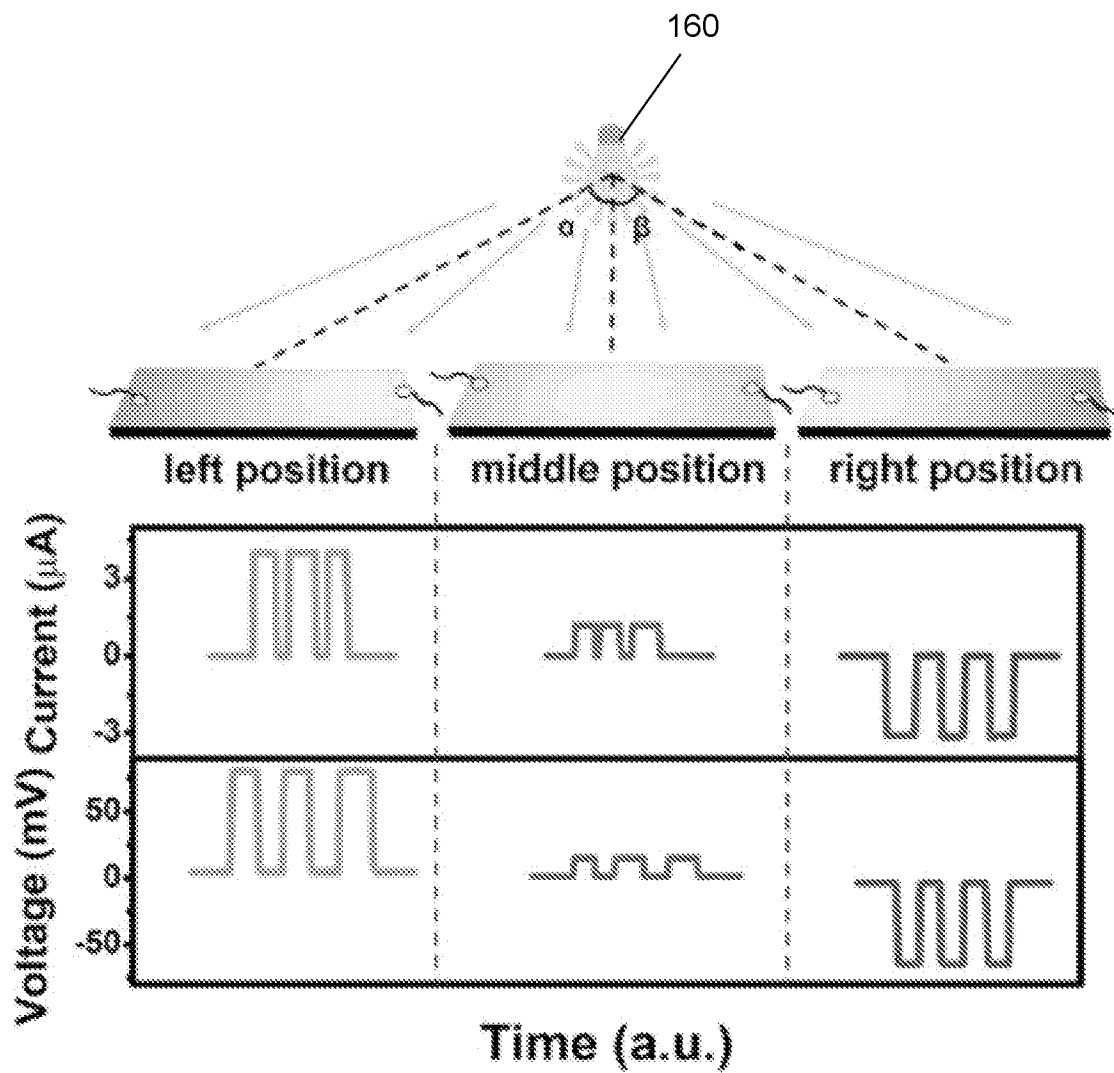


Figure 22

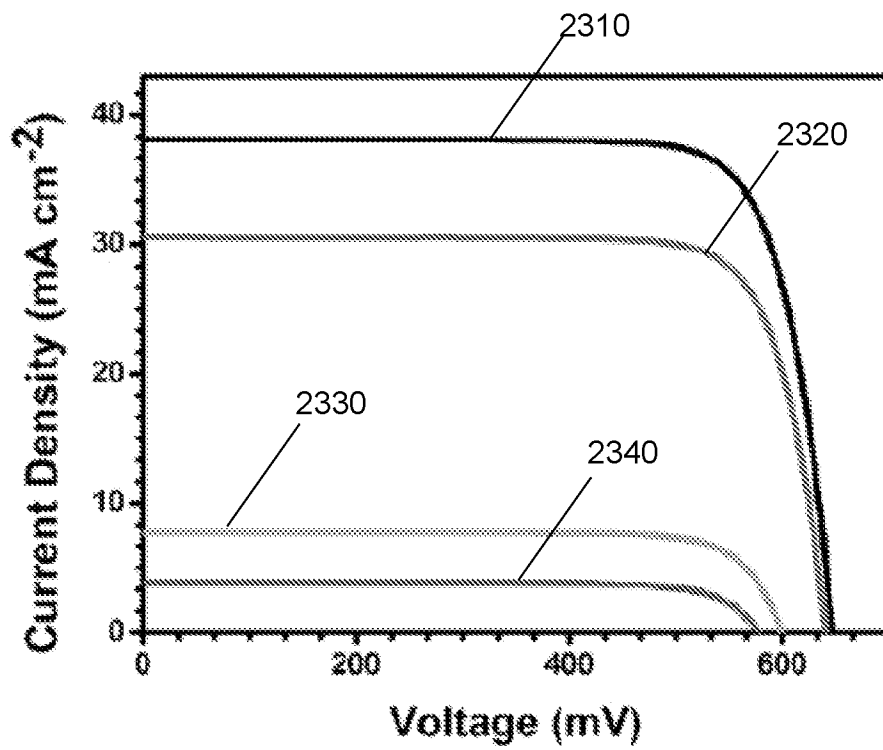


Figure 23

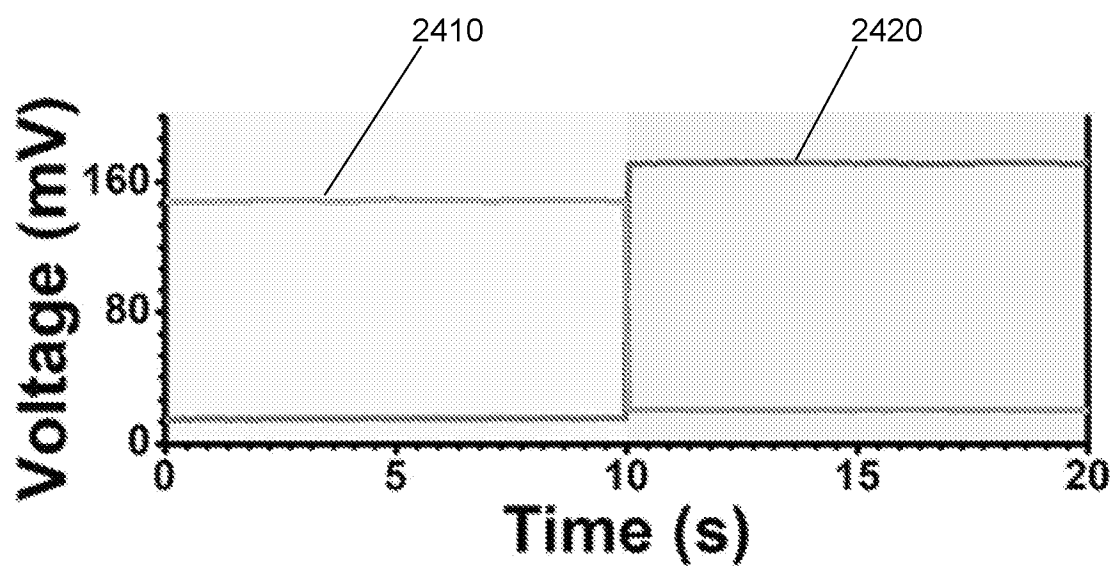


Figure 24A

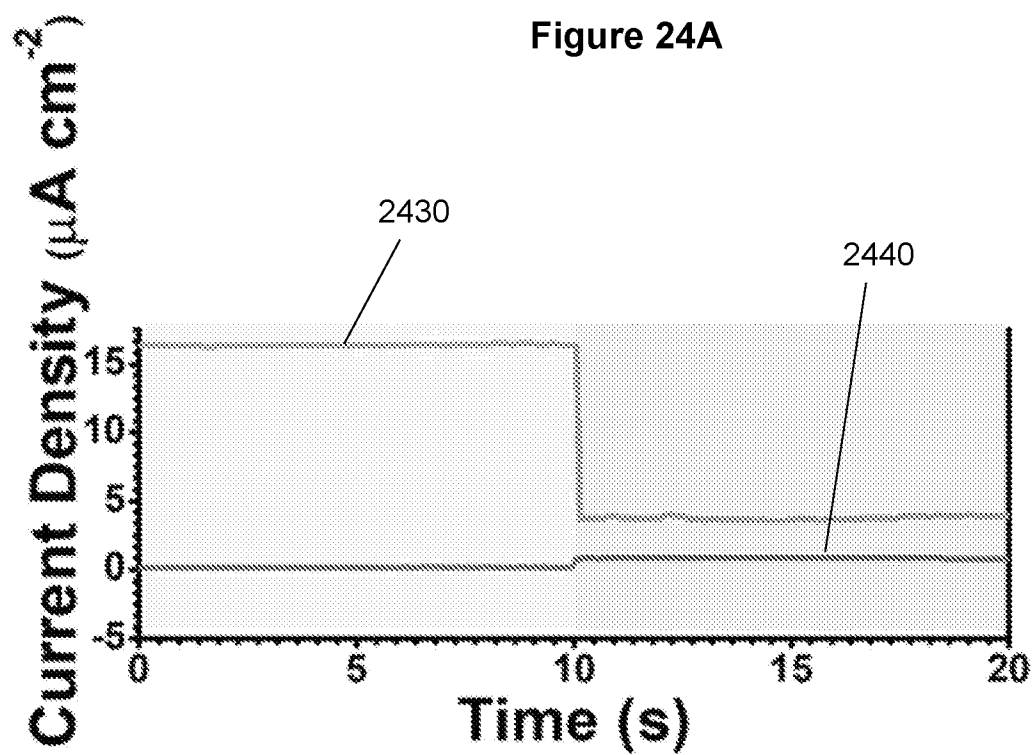


Figure 24B

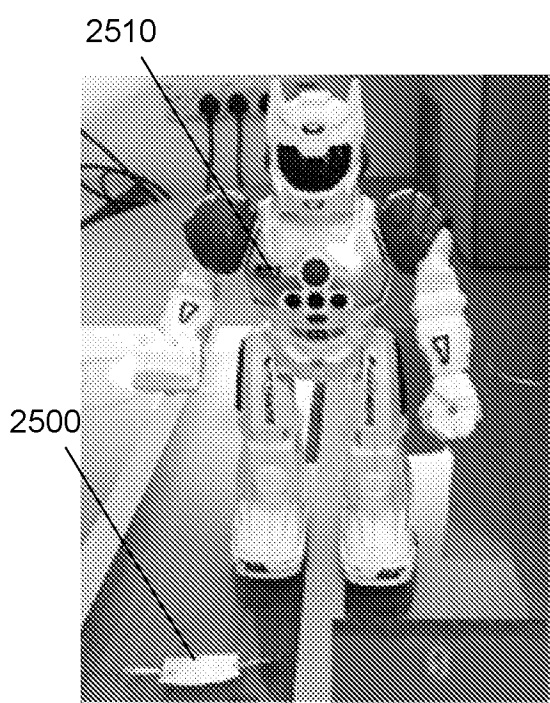


Figure 25A

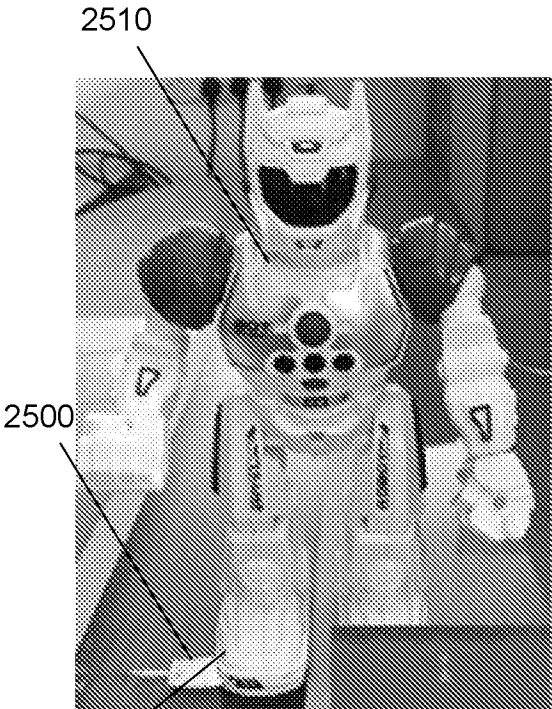


Figure 25B

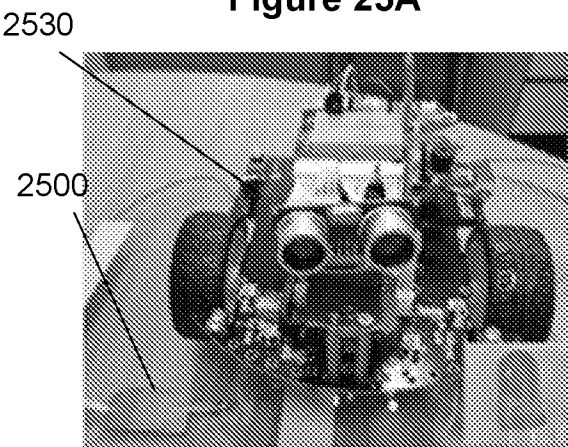


Figure 25C

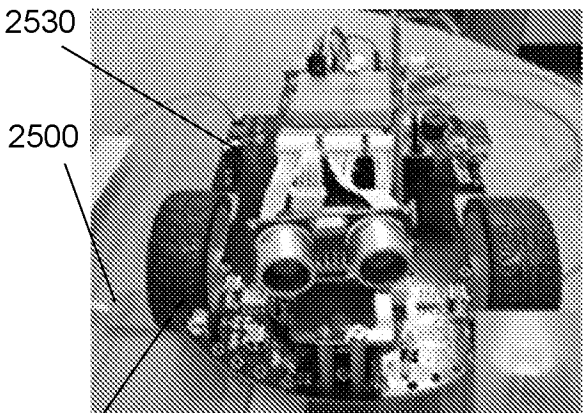


Figure 25D

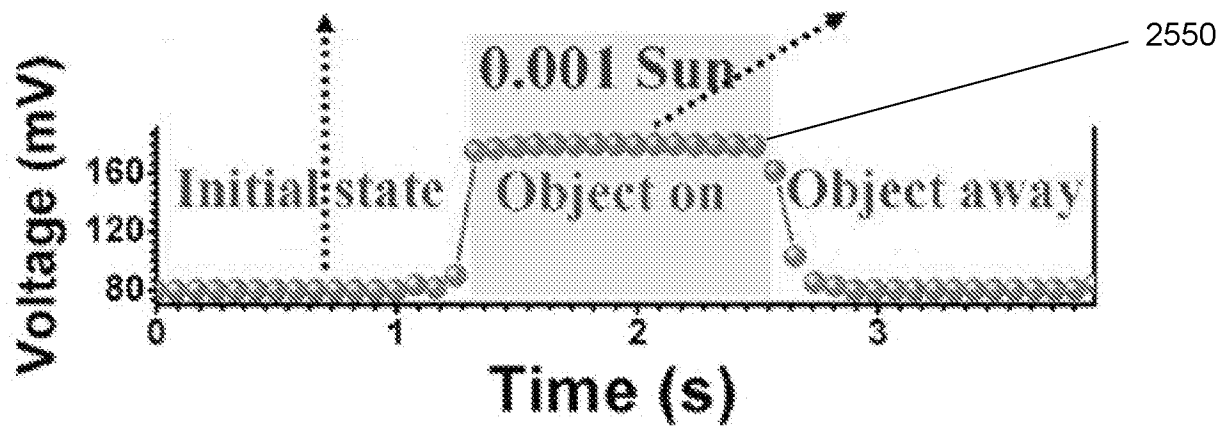


Figure 25E

Figure 26A

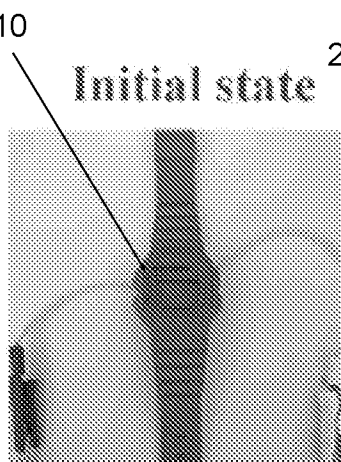


Figure 26B

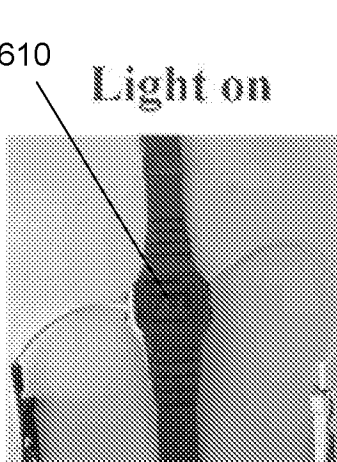


Figure 26C

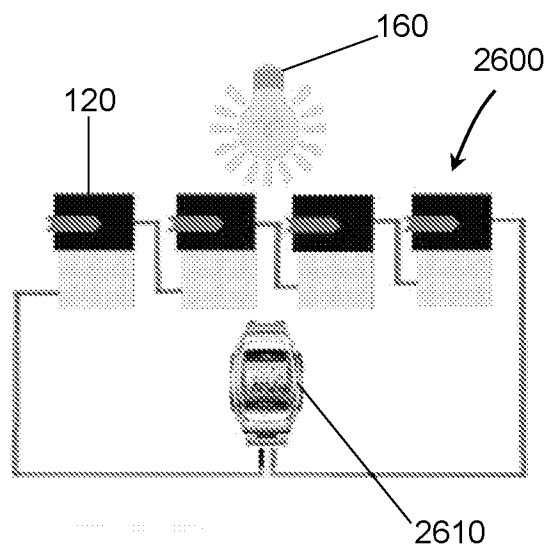


Figure 26D

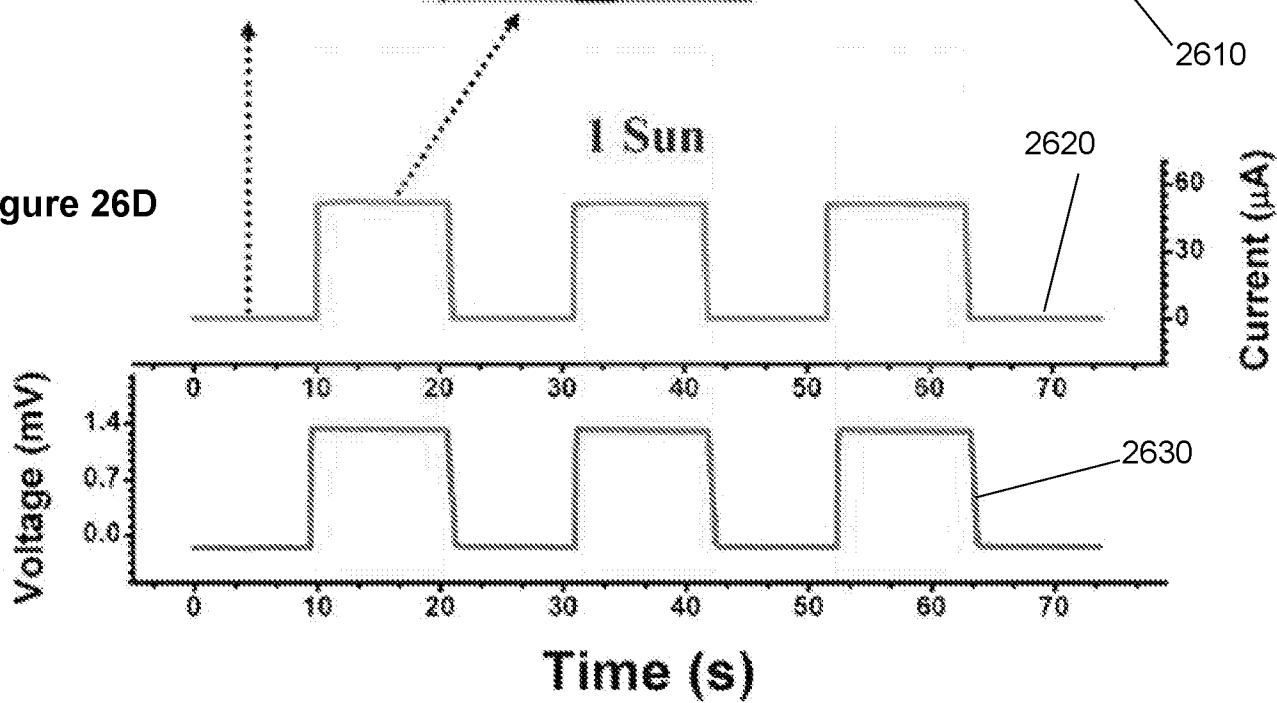


Figure 26E

Figure 27A

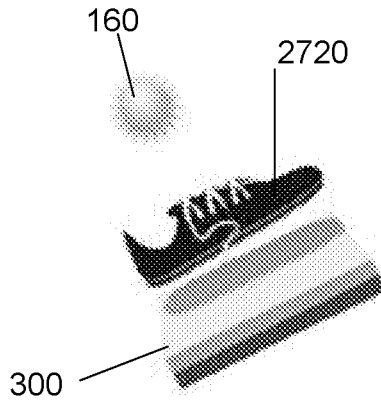


Figure 27B

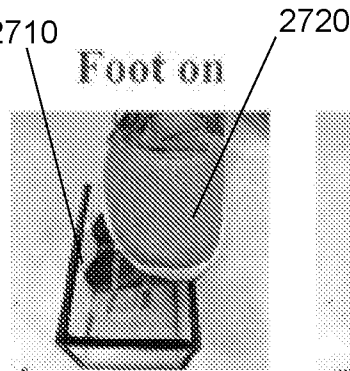


Figure 27C

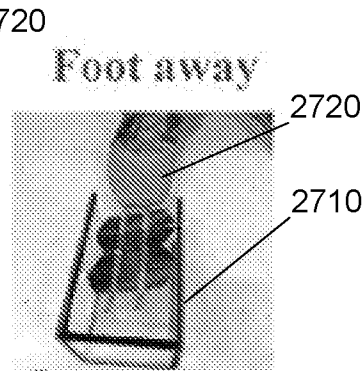


Figure 27D

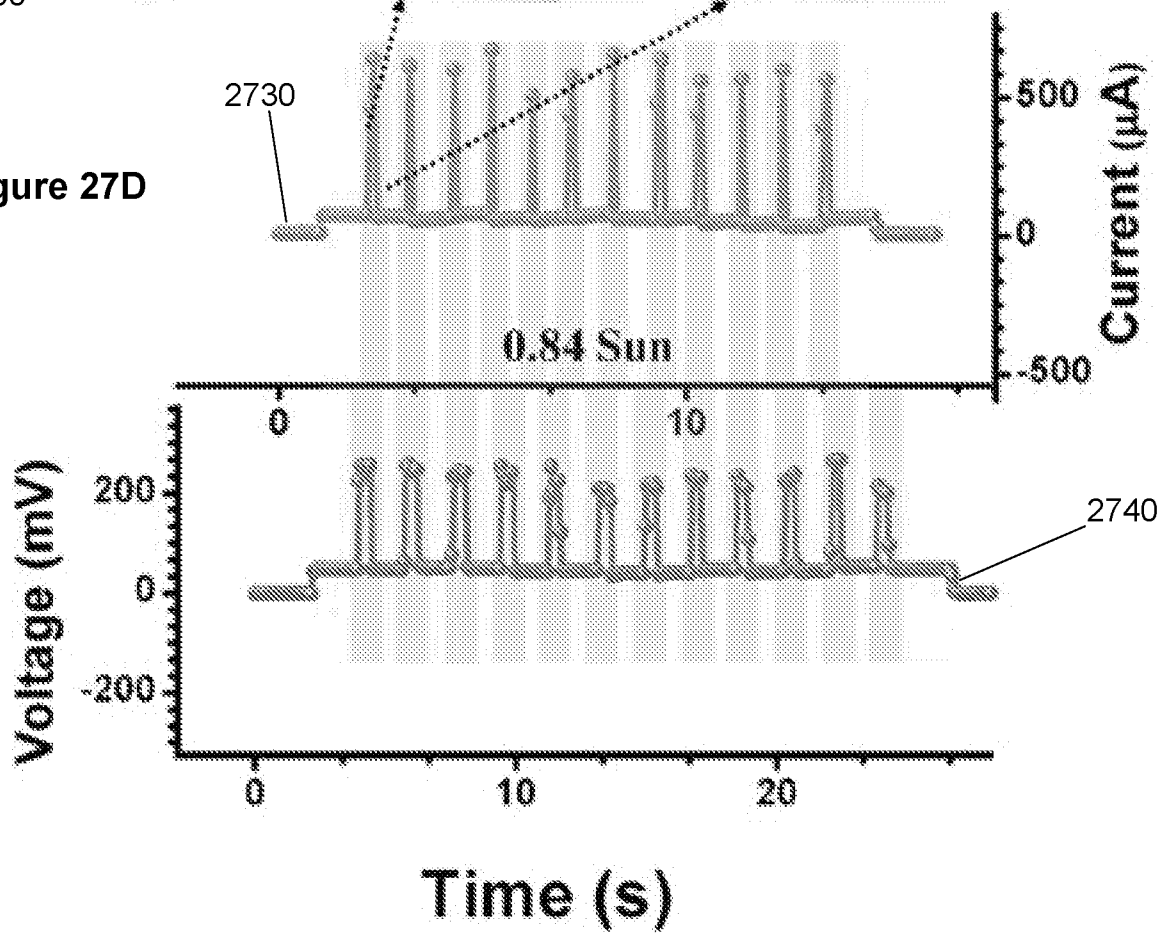


Figure 27E

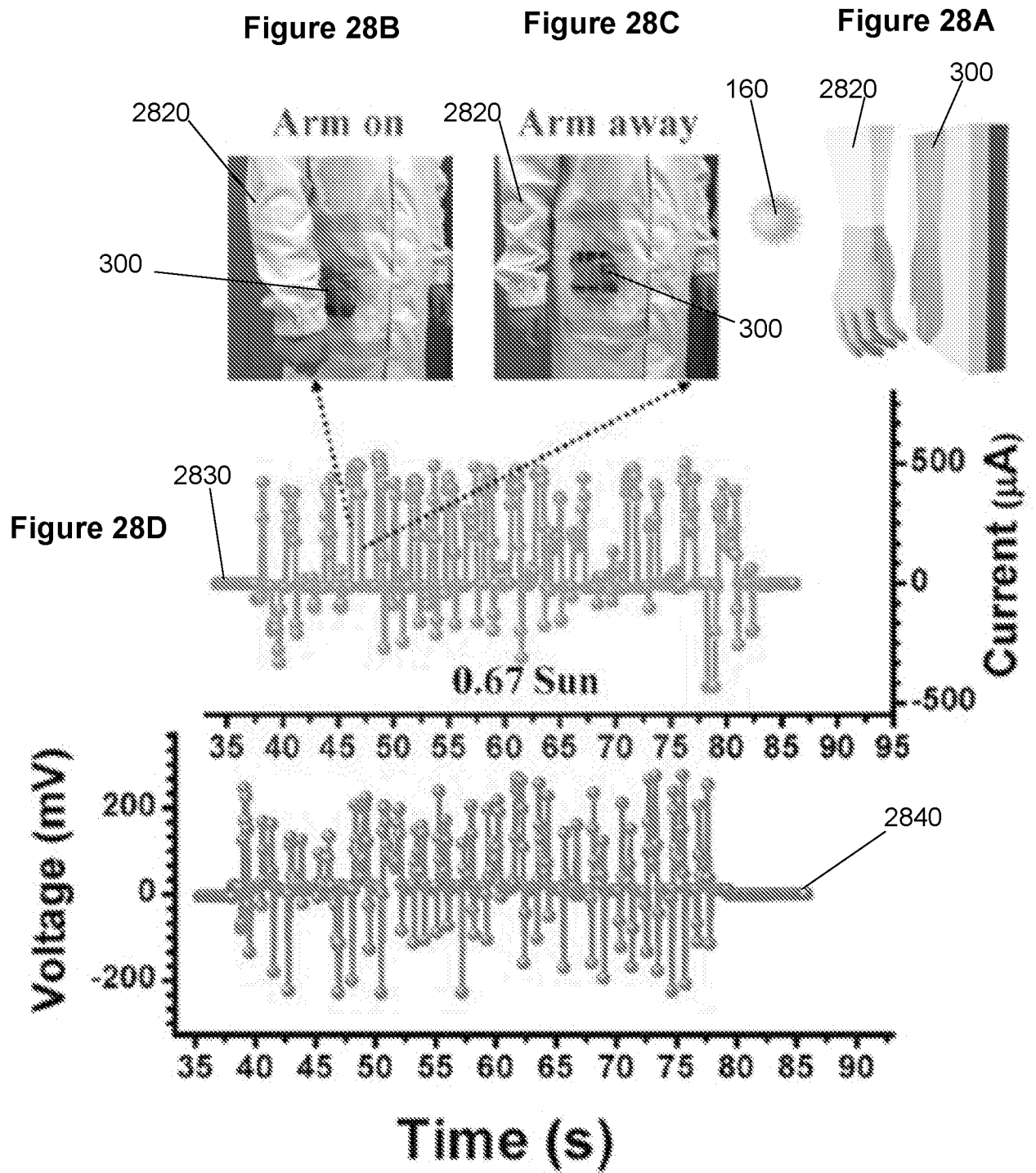


Figure 28E

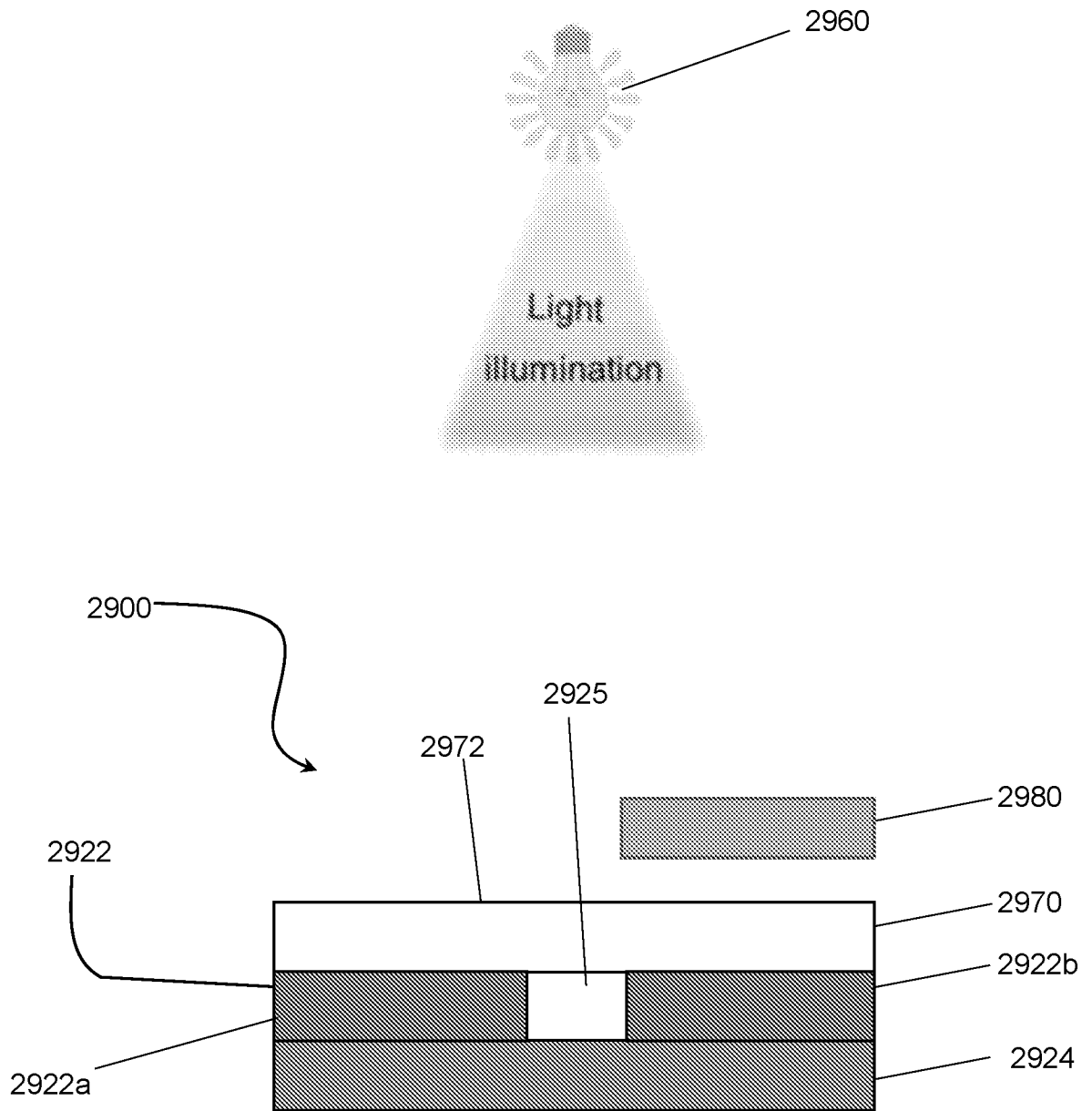


Figure 29

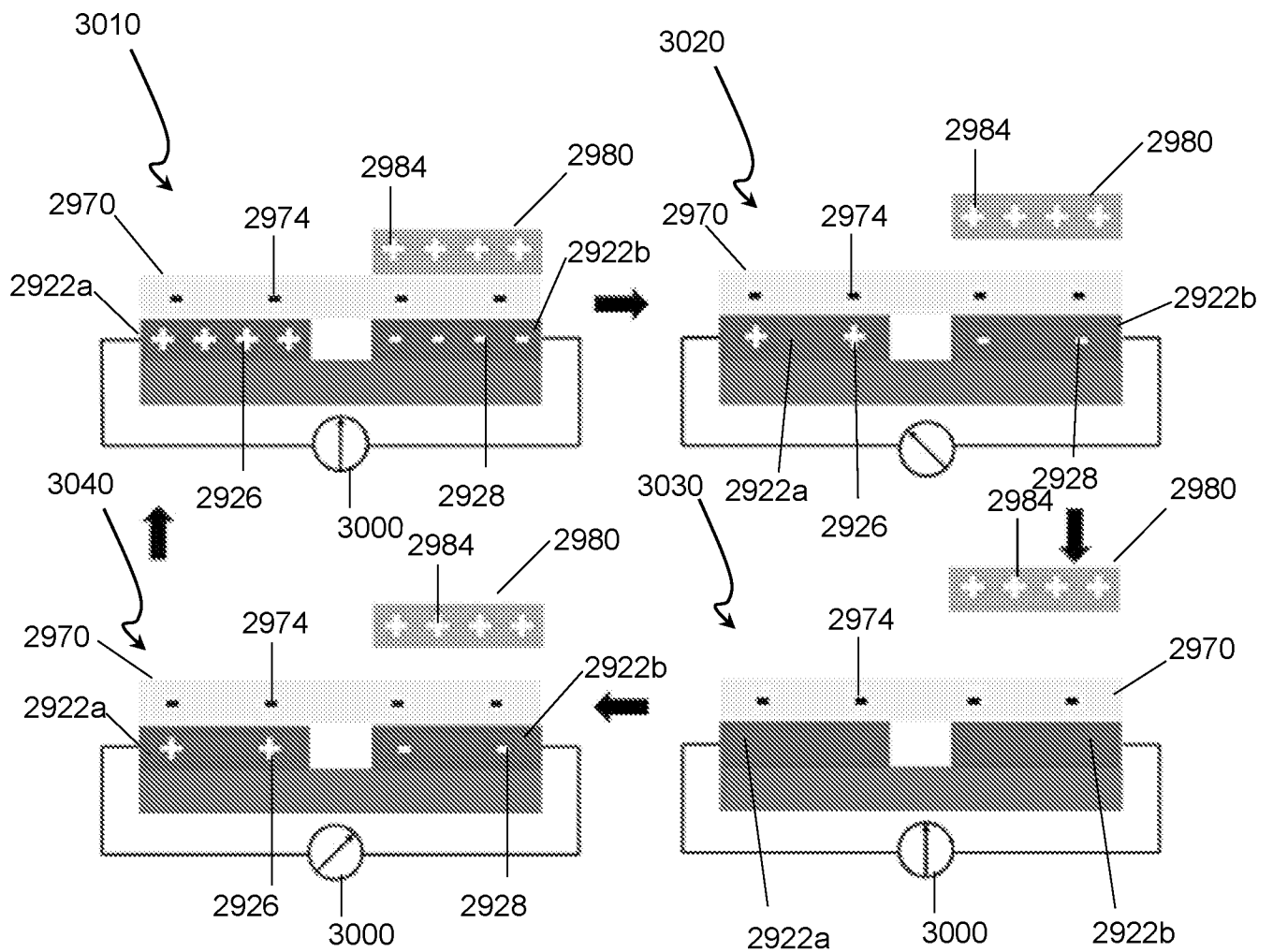


Figure 30

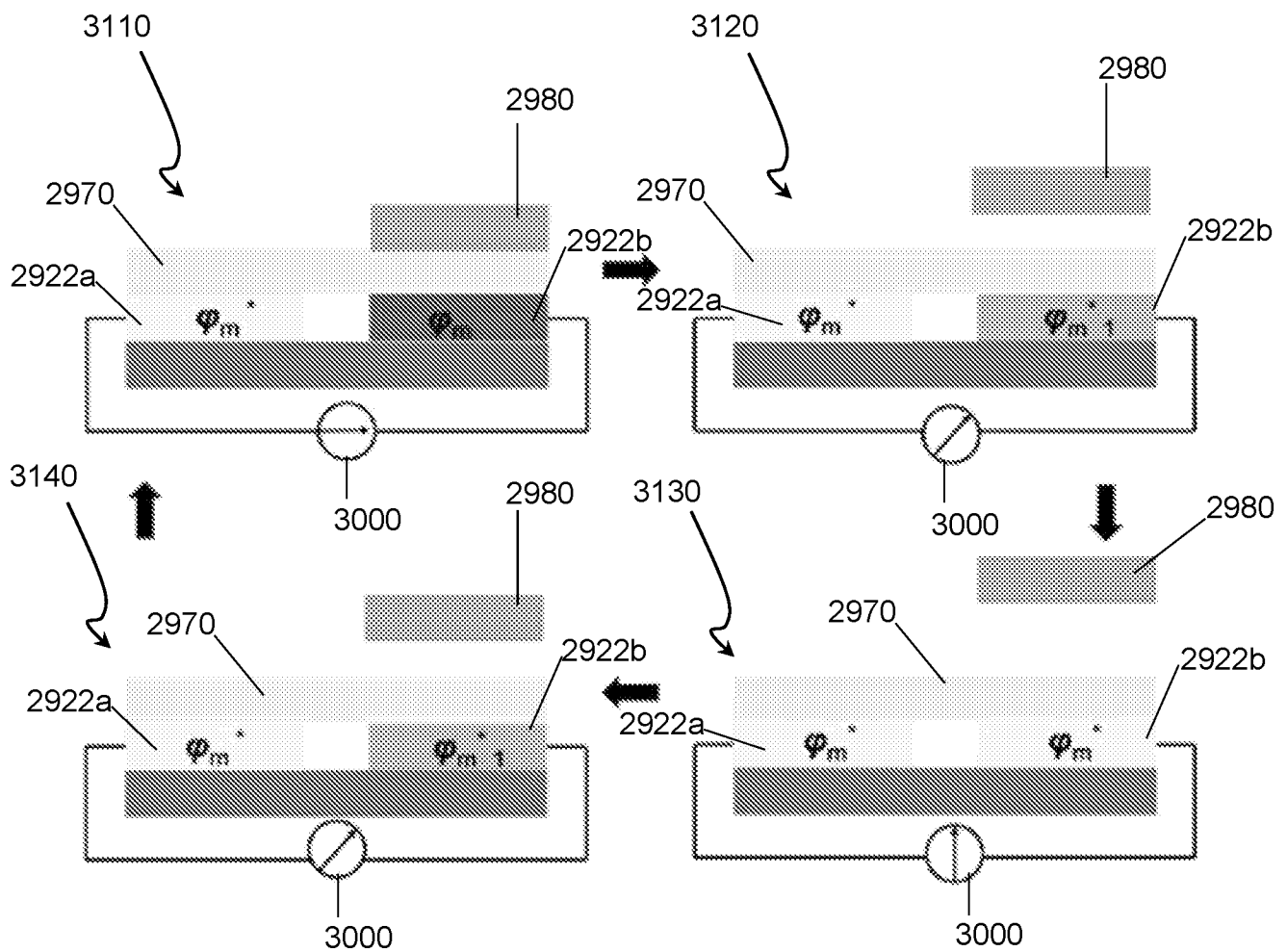


Figure 31

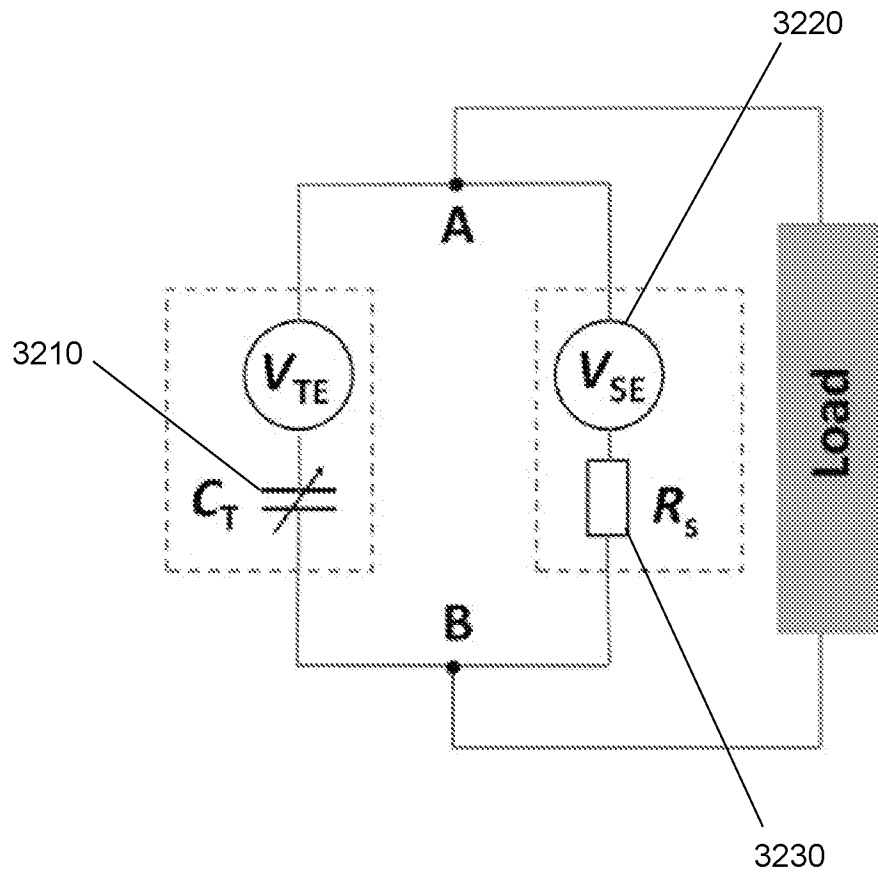


Figure 32

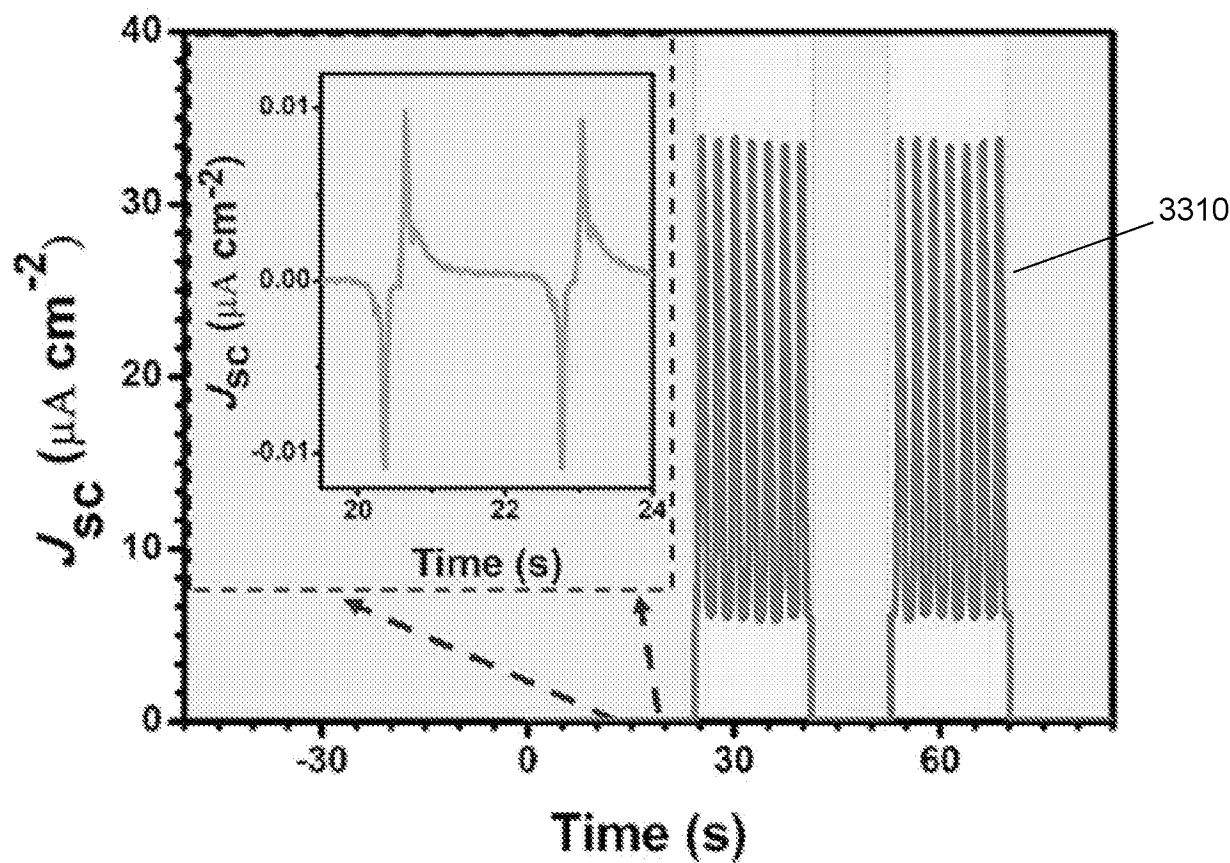


Figure 33A

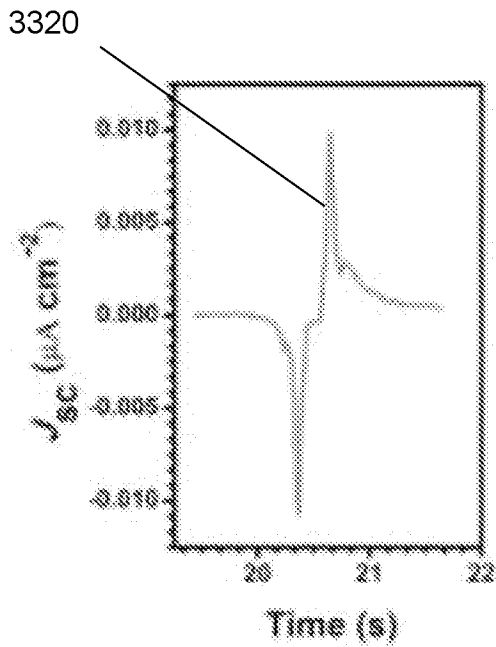


Figure 33B

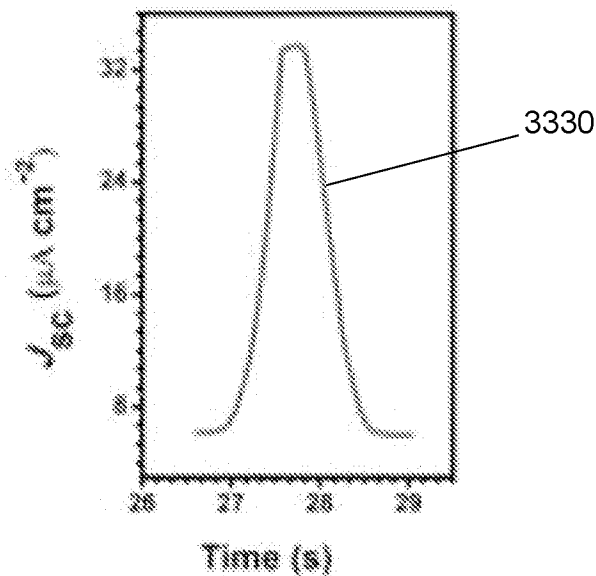


Figure 33C

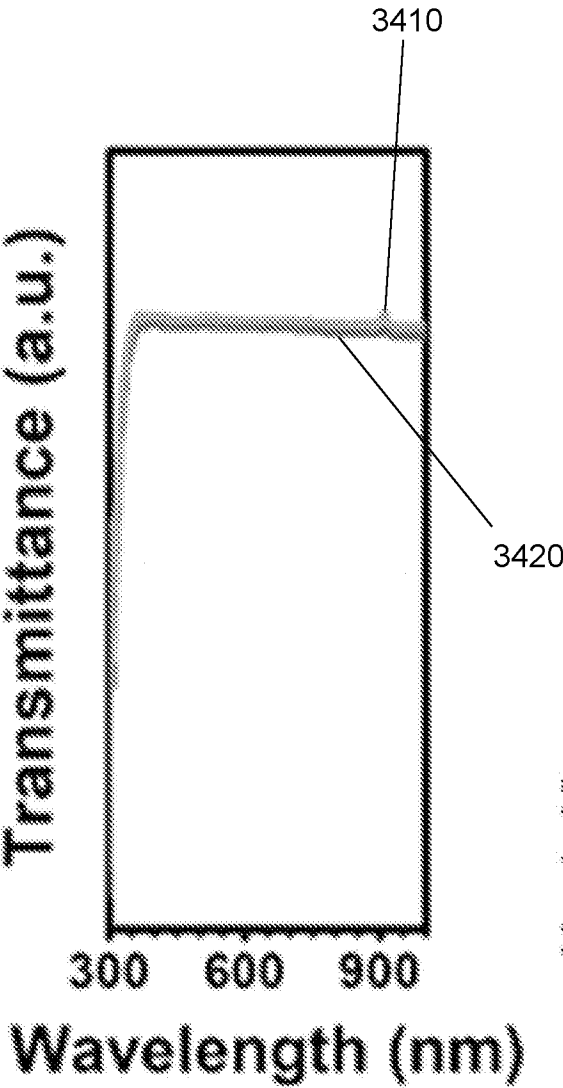


Figure 34A

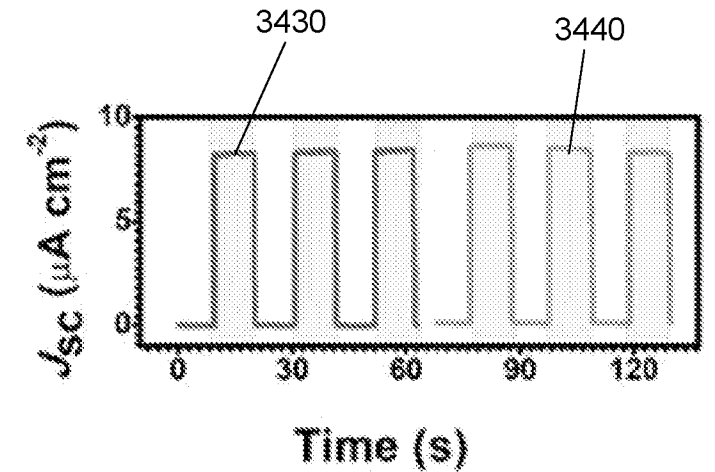


Figure 34B

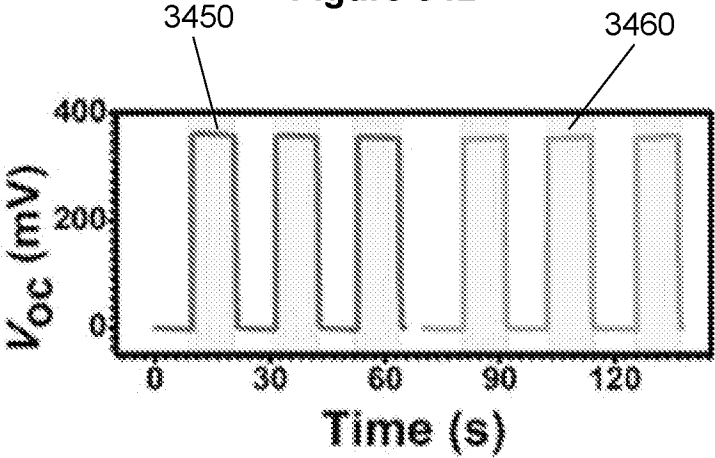


Figure 34C

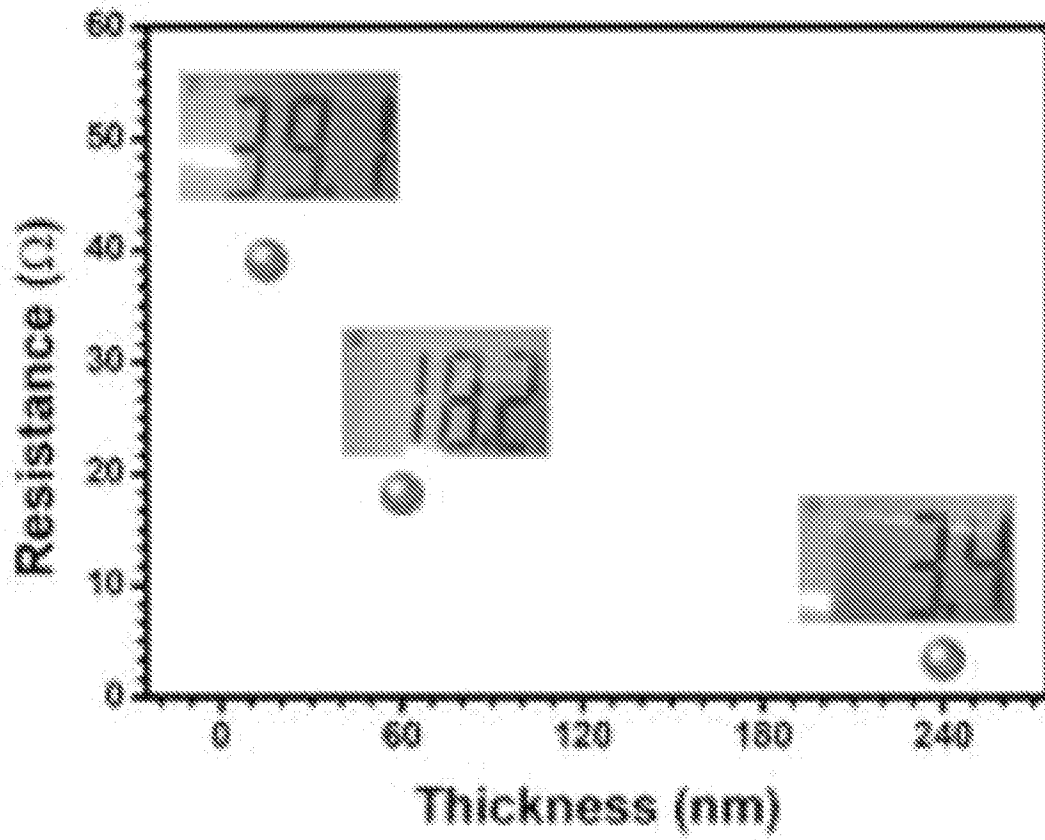


Figure 35

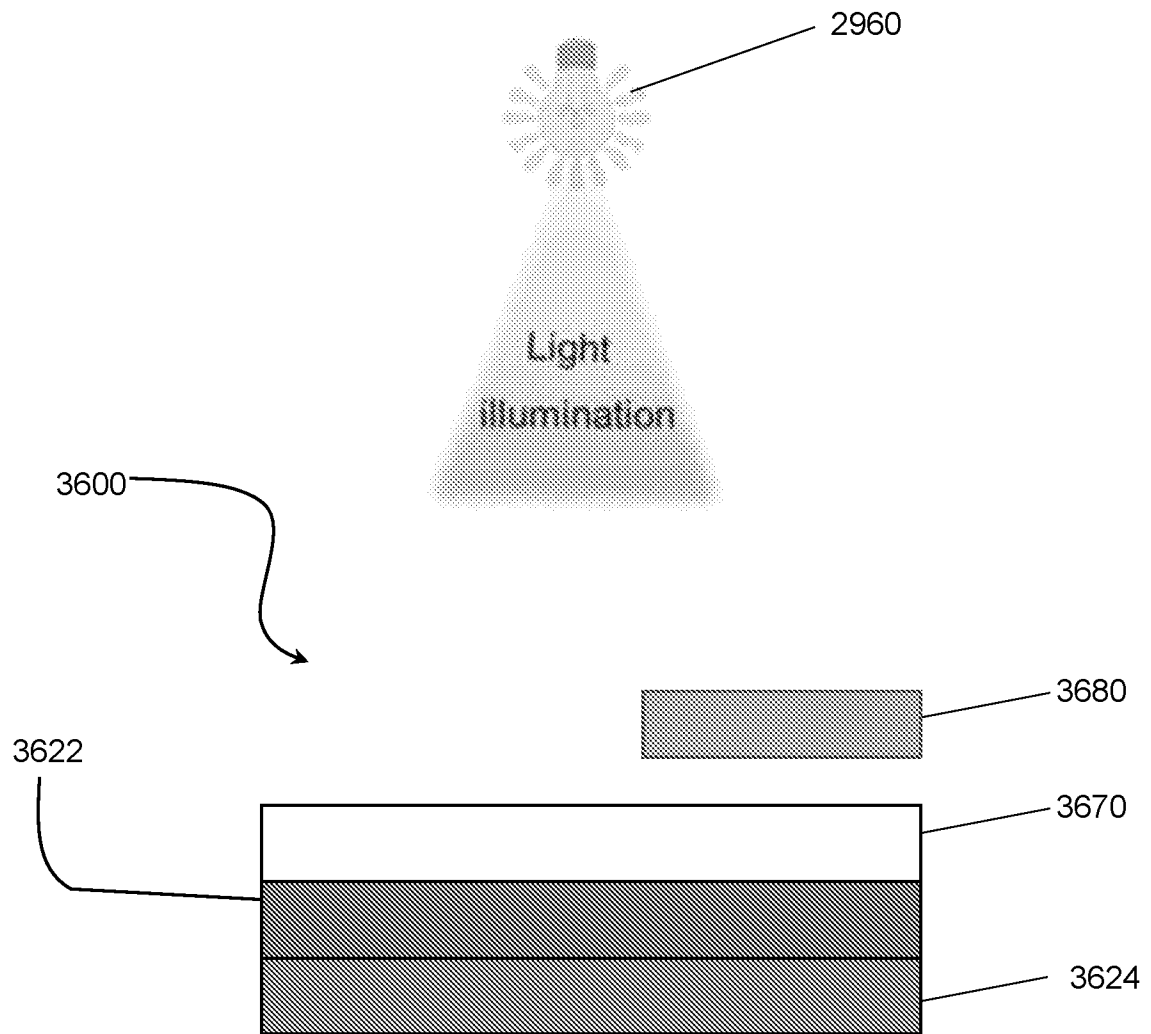


Figure 36

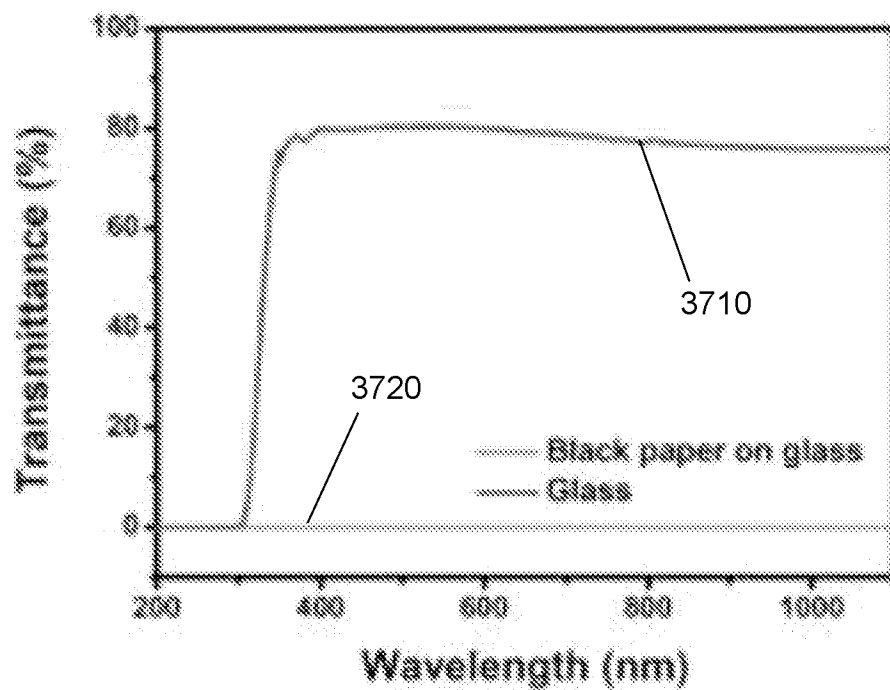


Figure 37A

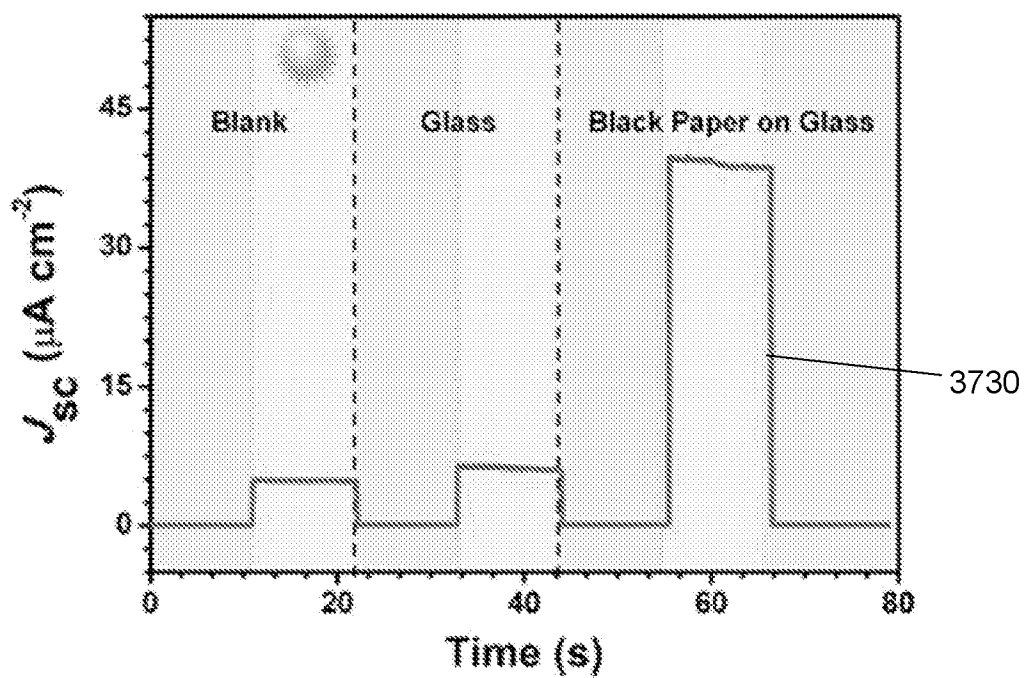
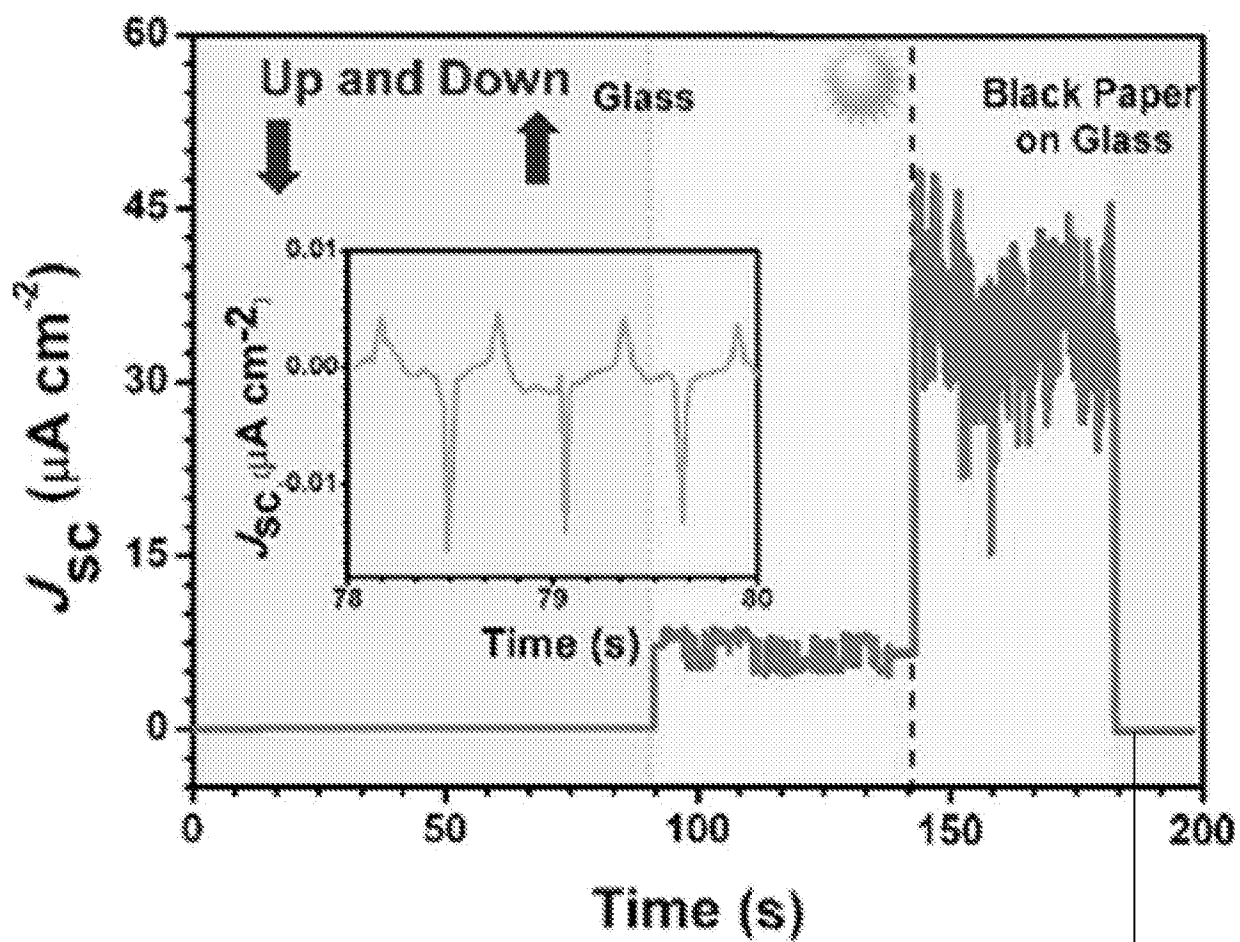


Figure 37B



3810

Figure 38

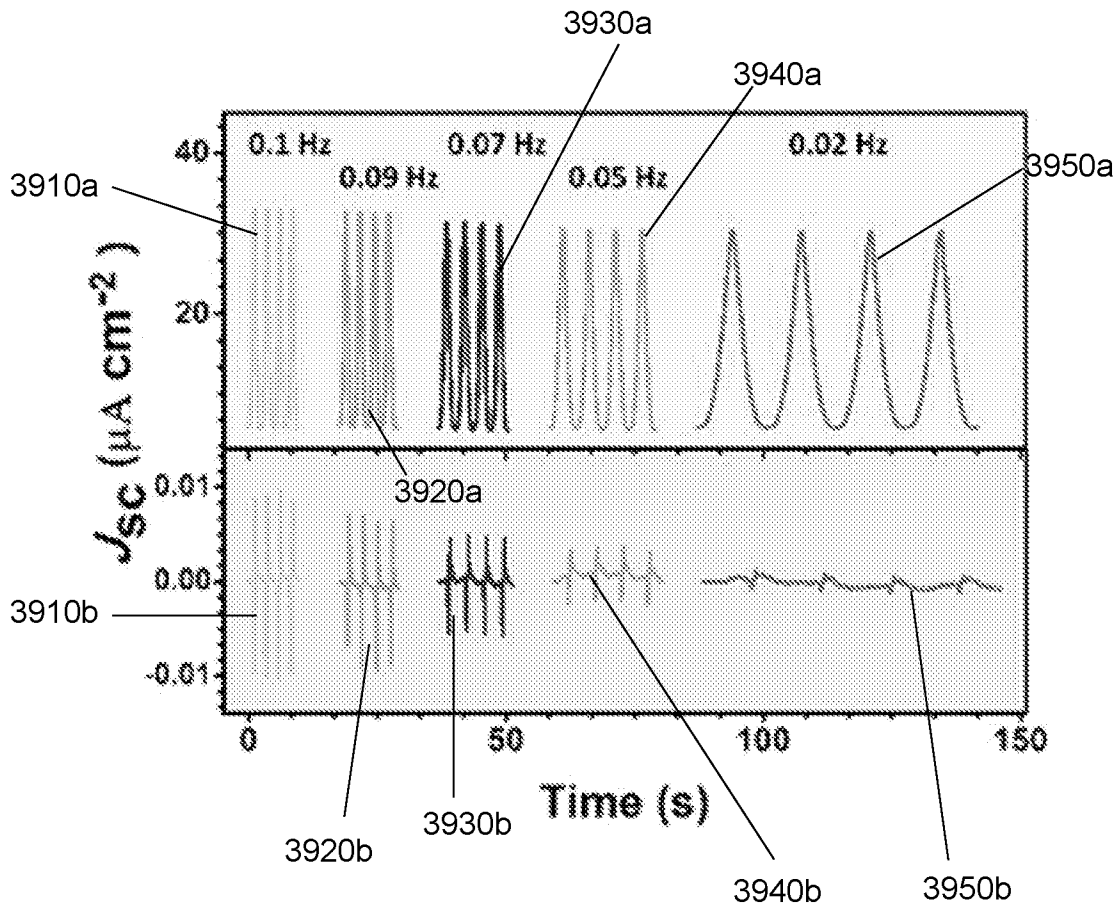


Figure 39A

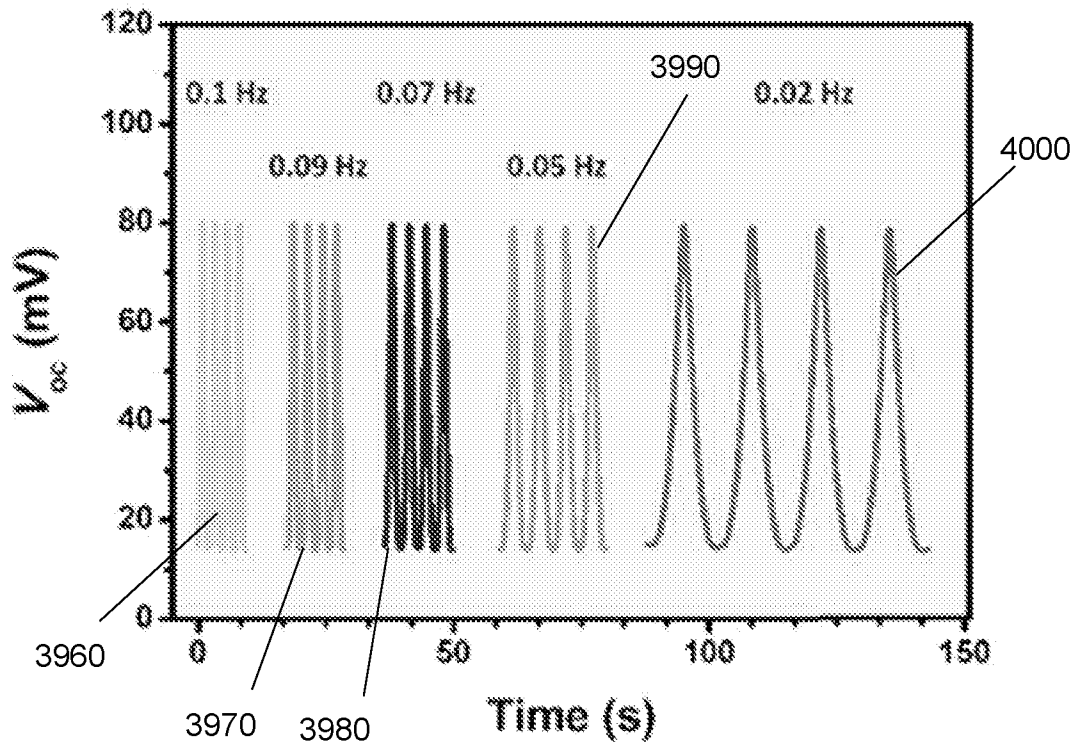


Figure 39B

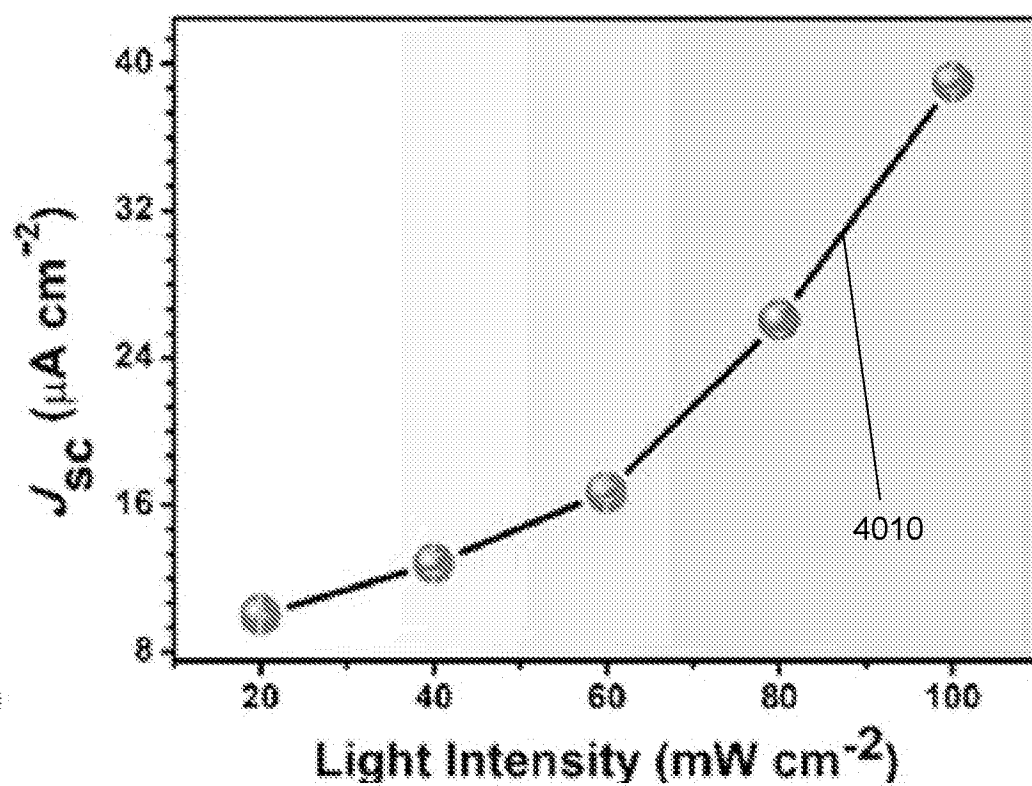


Figure 40

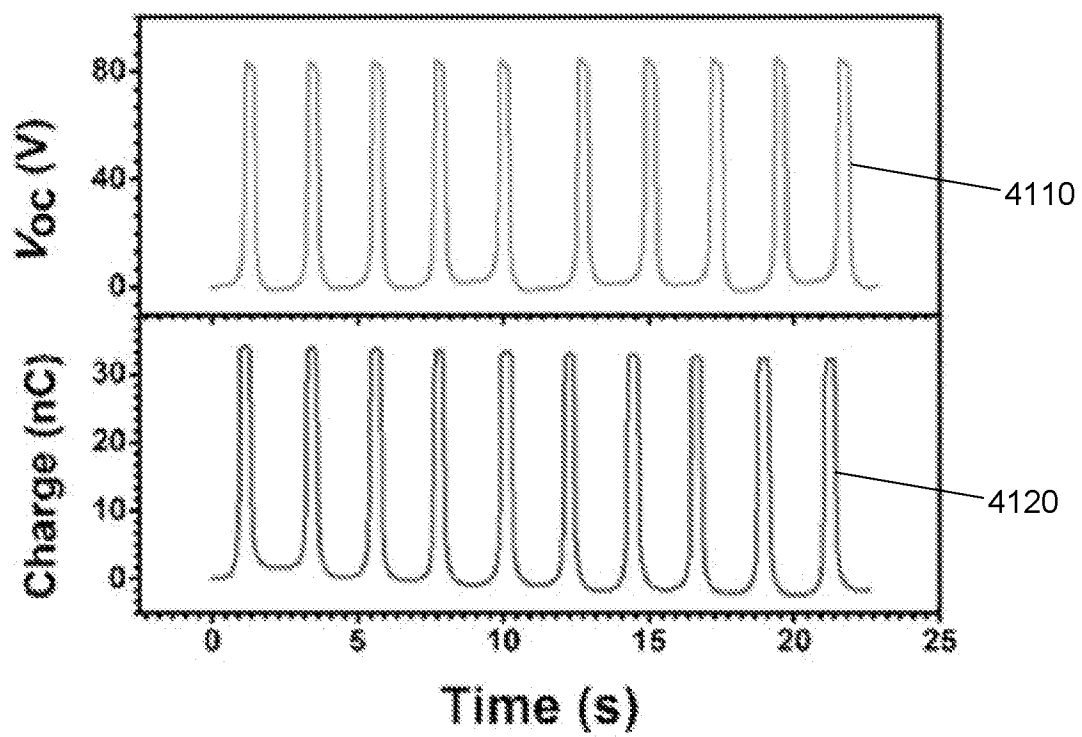


Figure 41

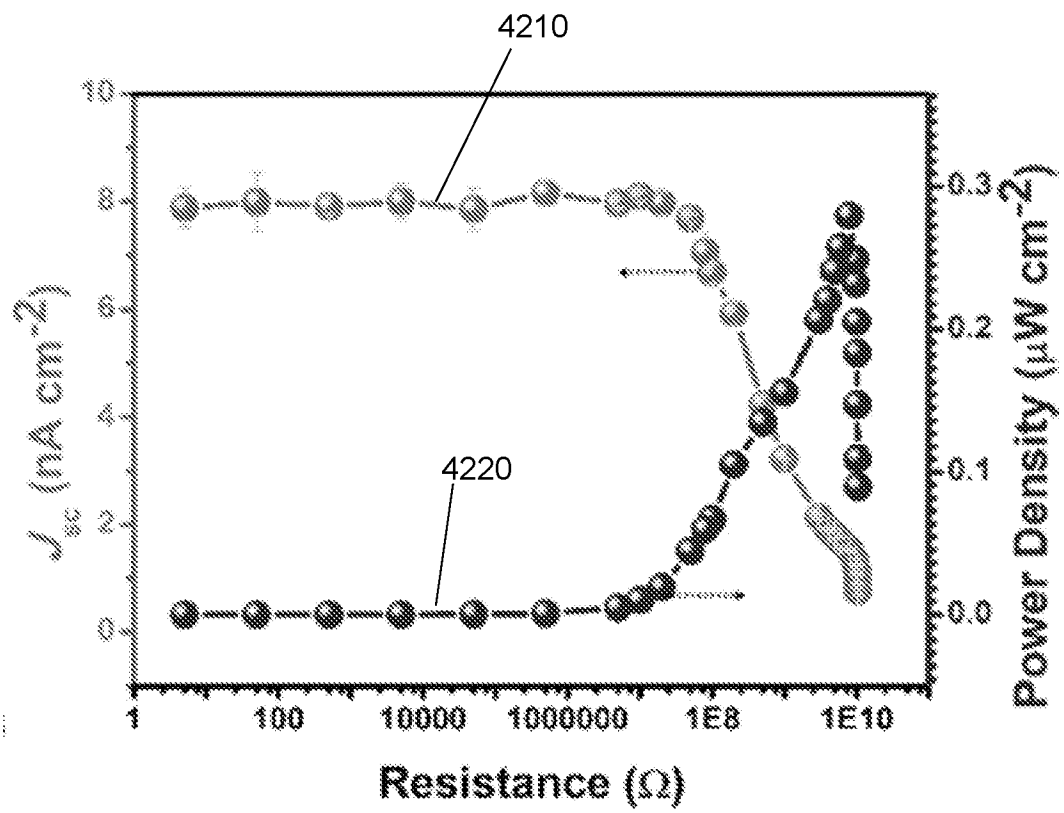


Figure 42

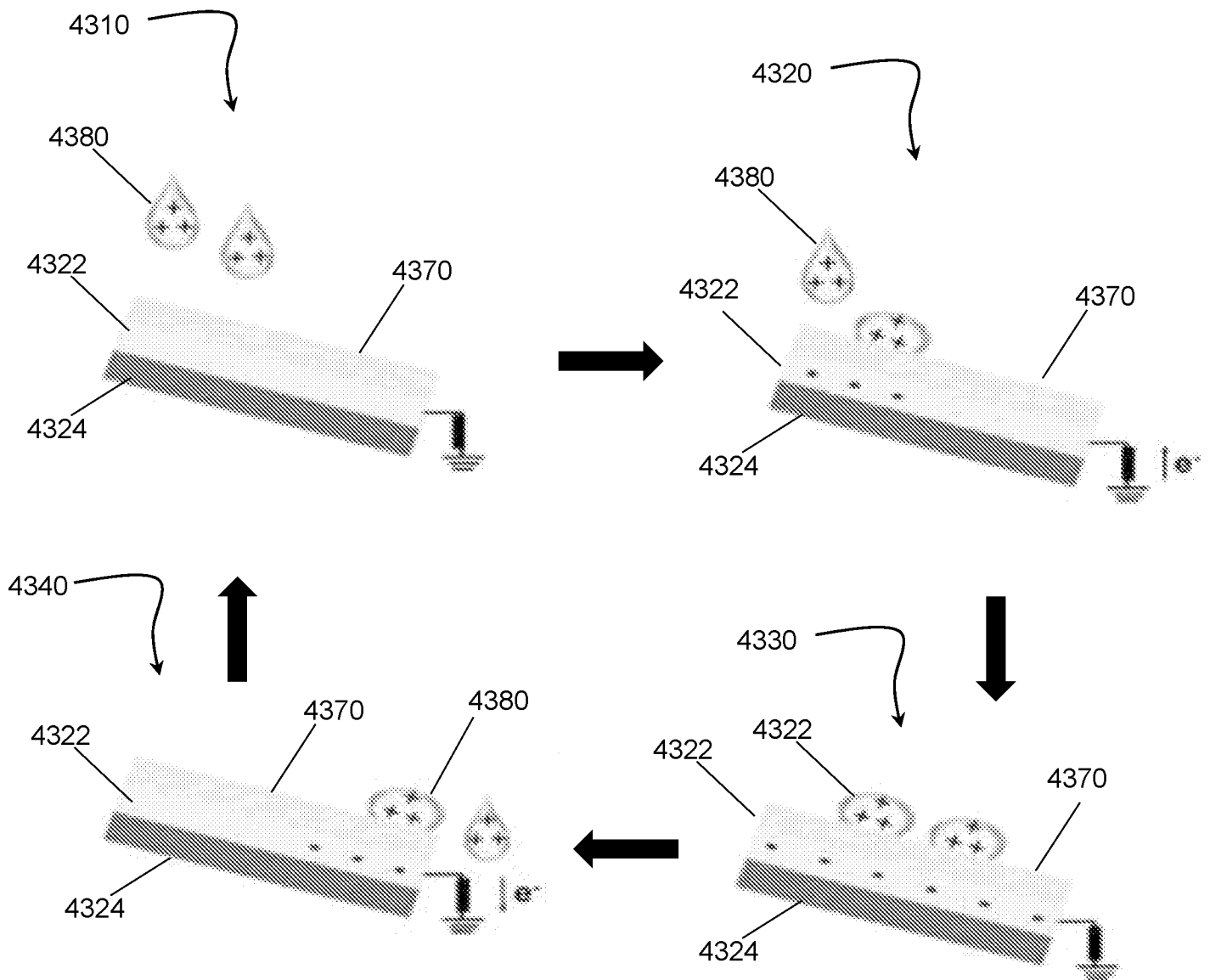


Figure 43

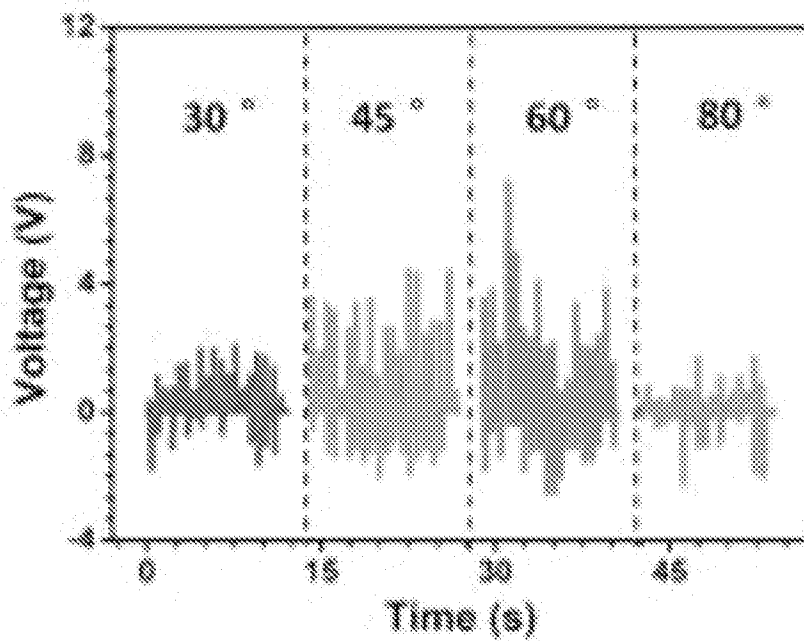


Figure 44A

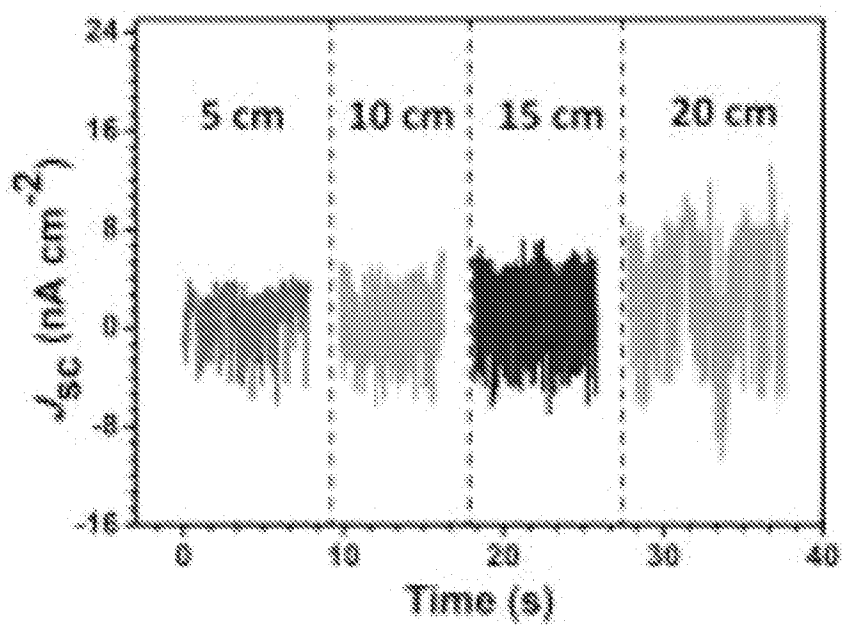


Figure 44B

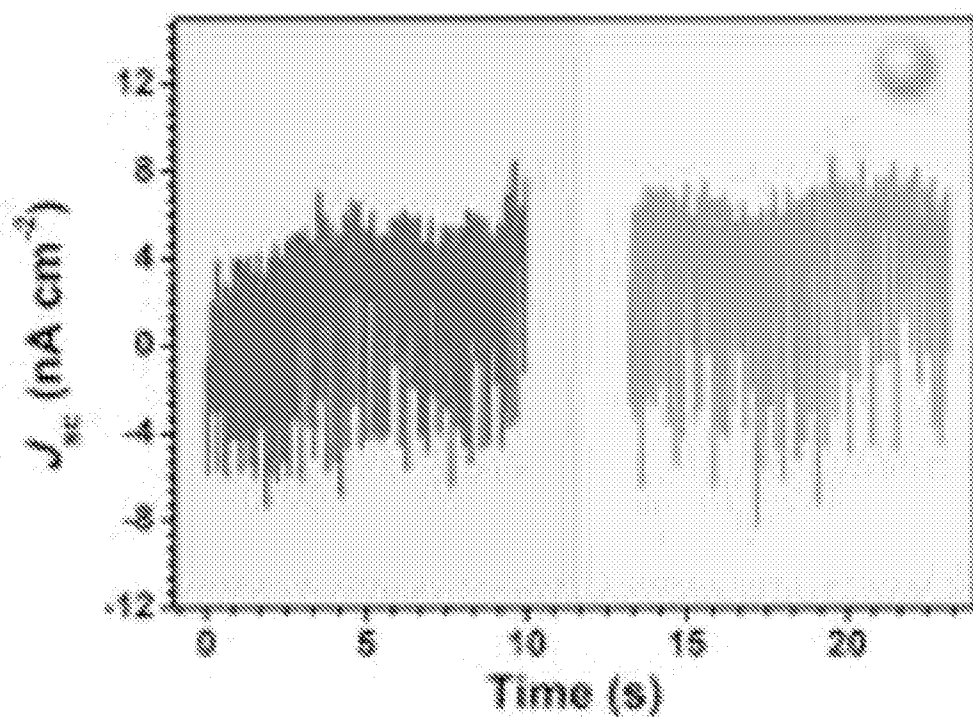


Figure 45A

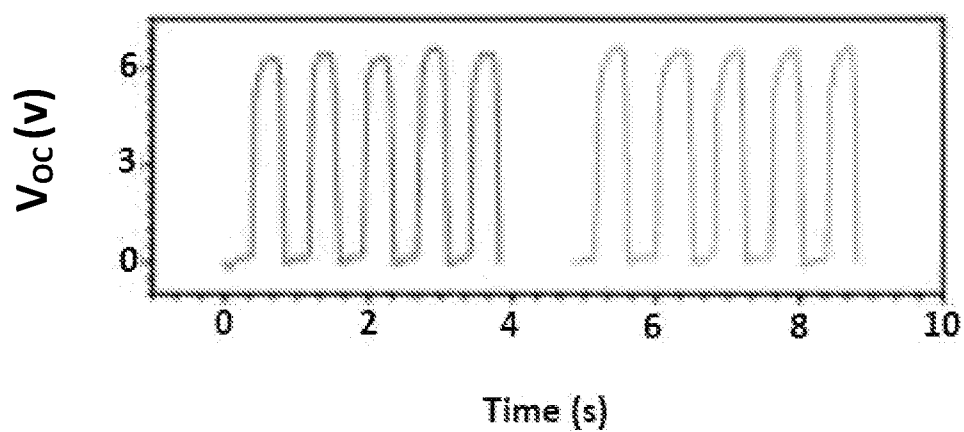


Figure 45B

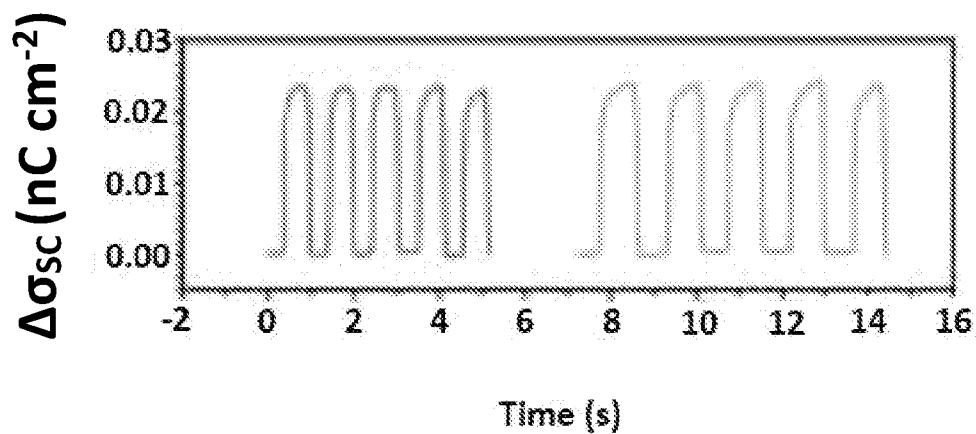
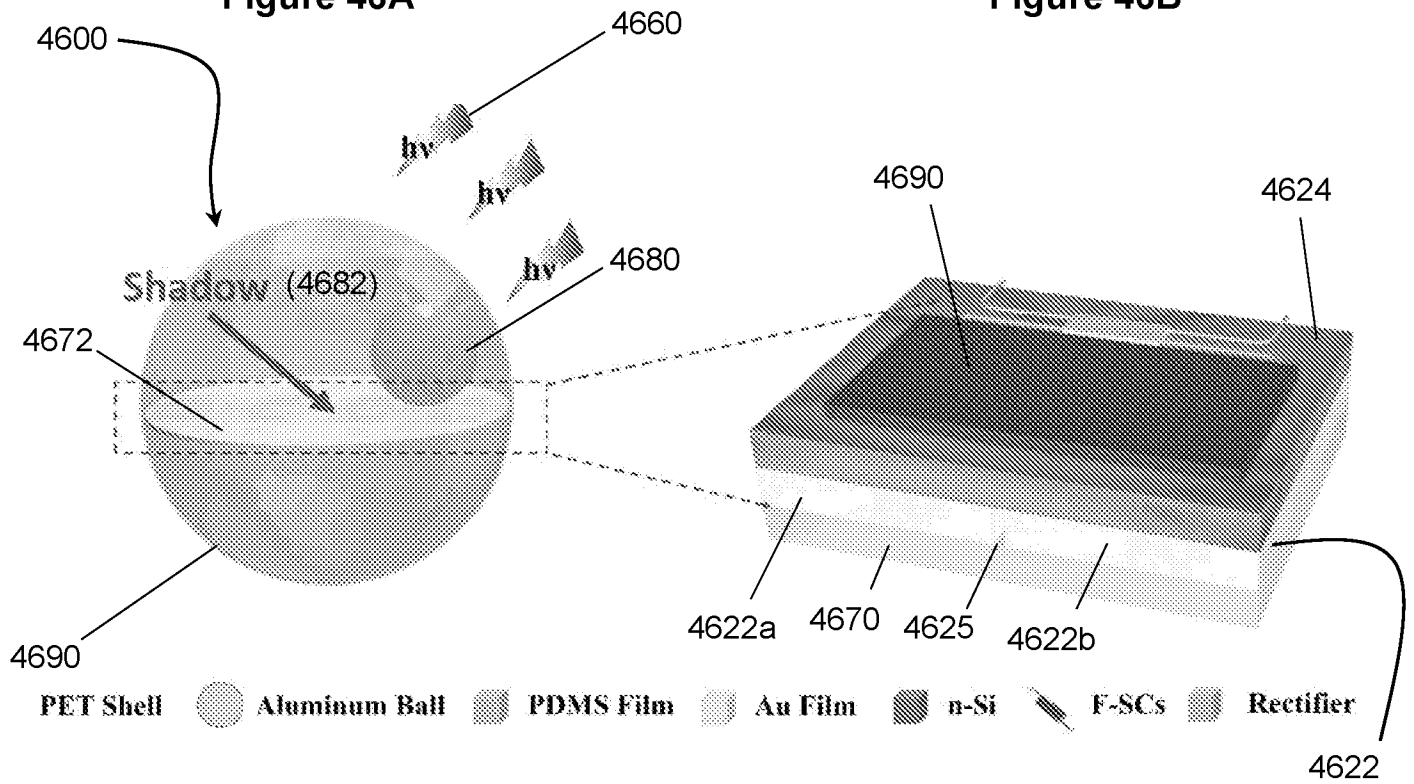


Figure 45C

Figure 46A

Figure 46B



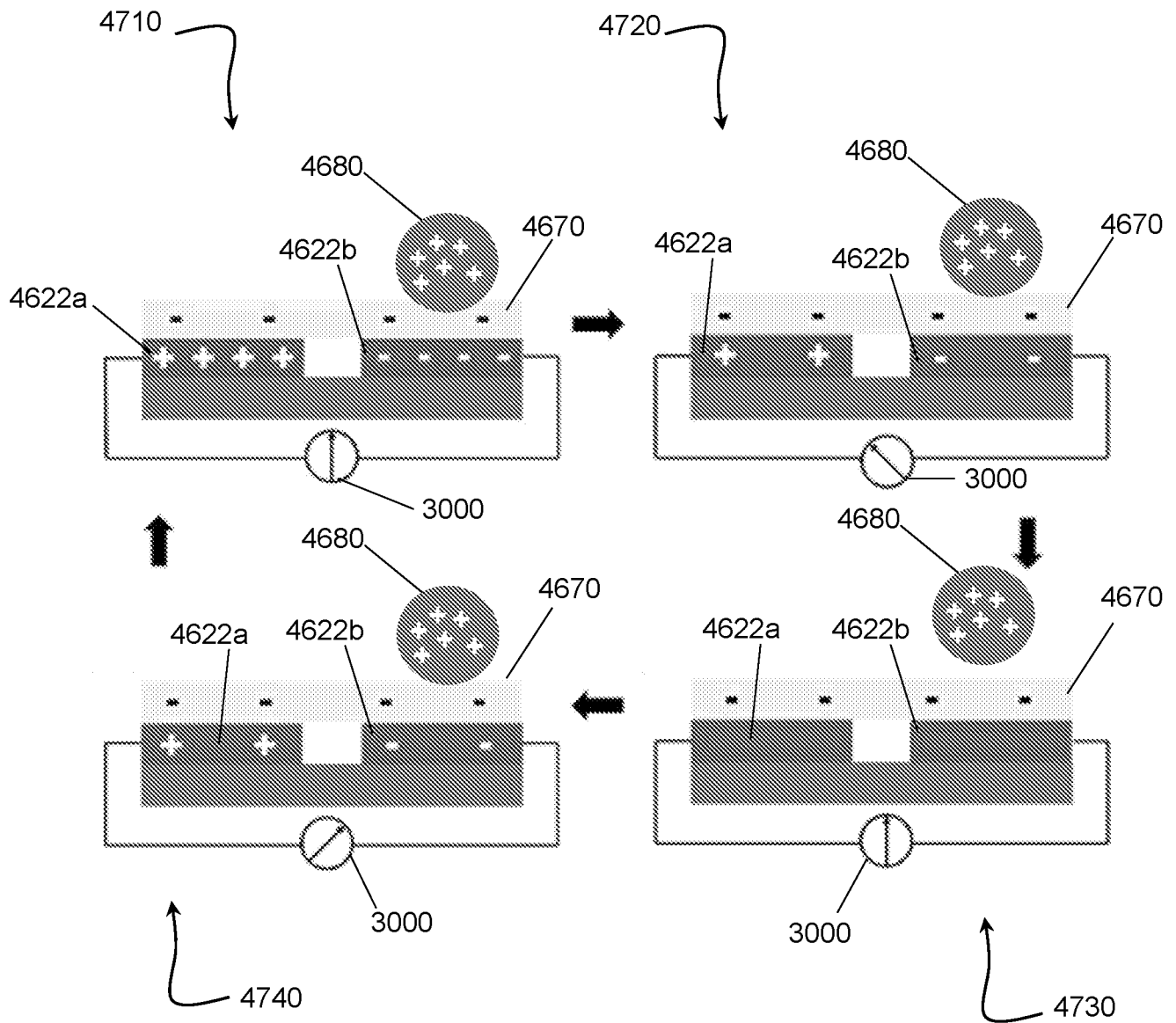


Figure 47A

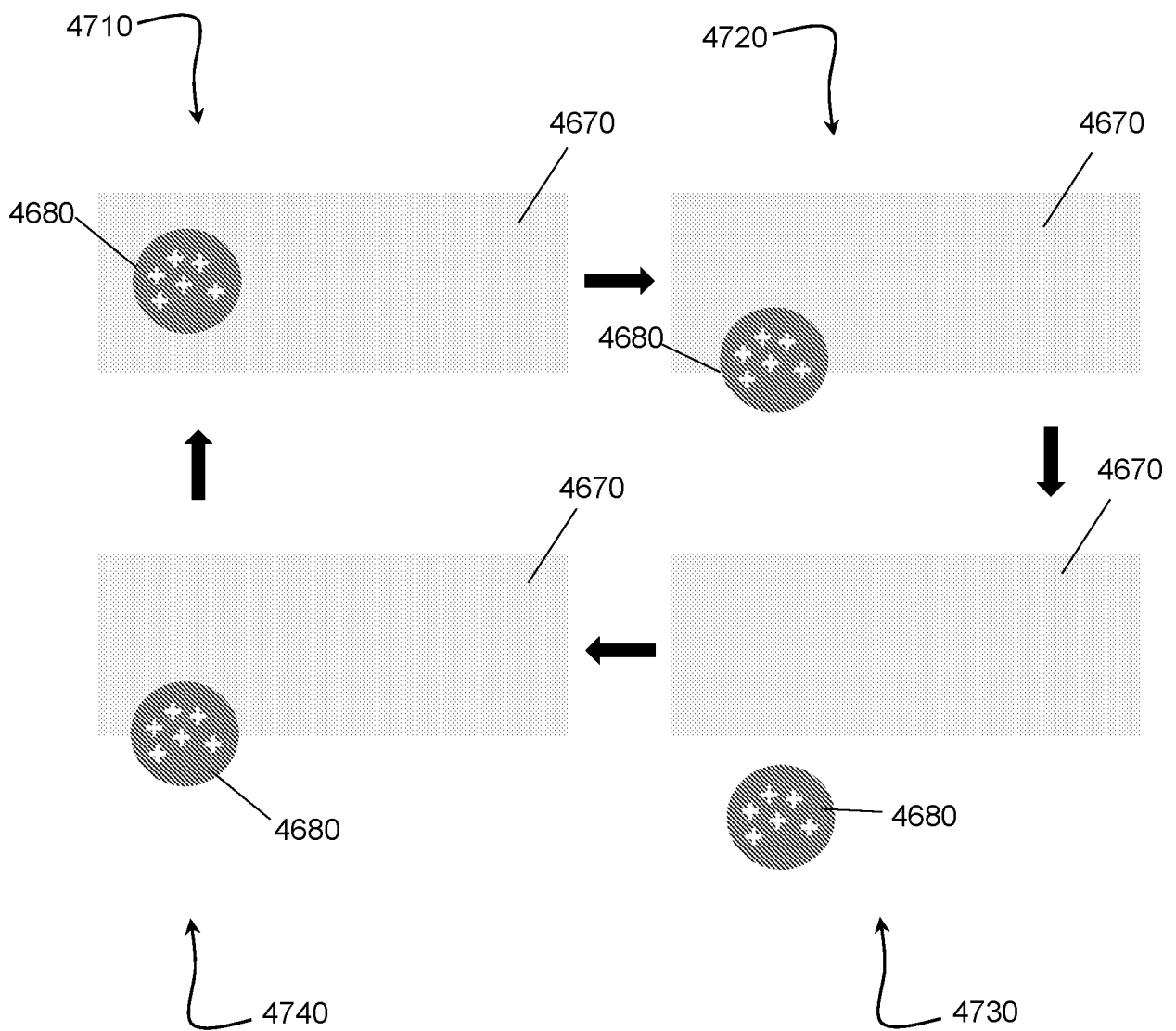


Figure 48

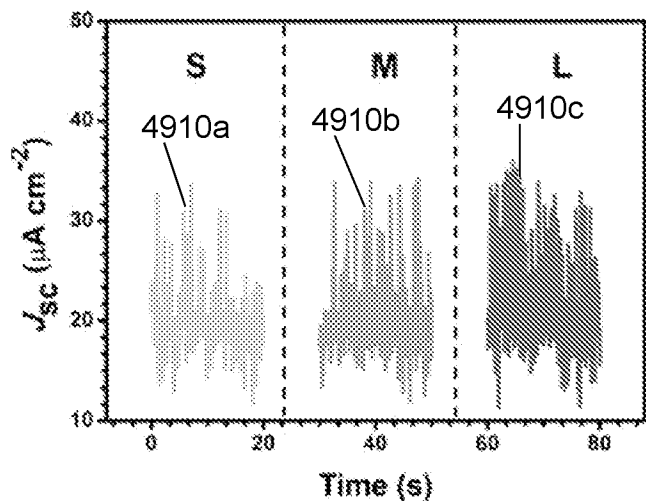


Figure 49A

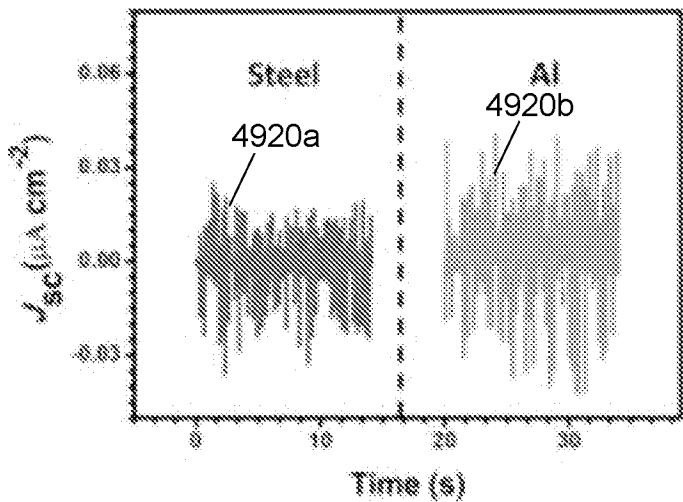


Figure 49B

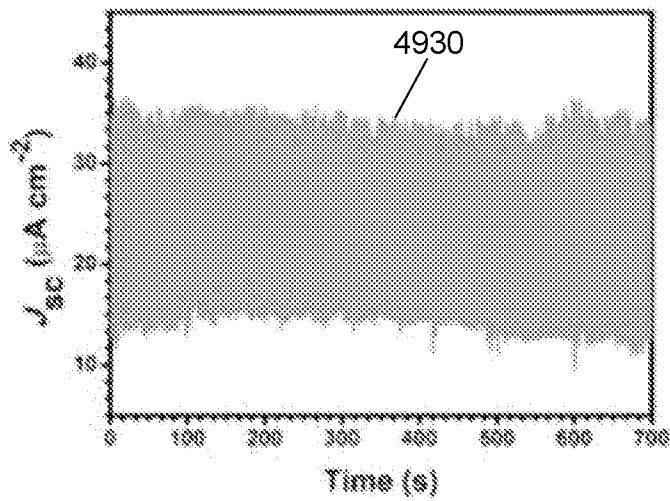


Figure 49C

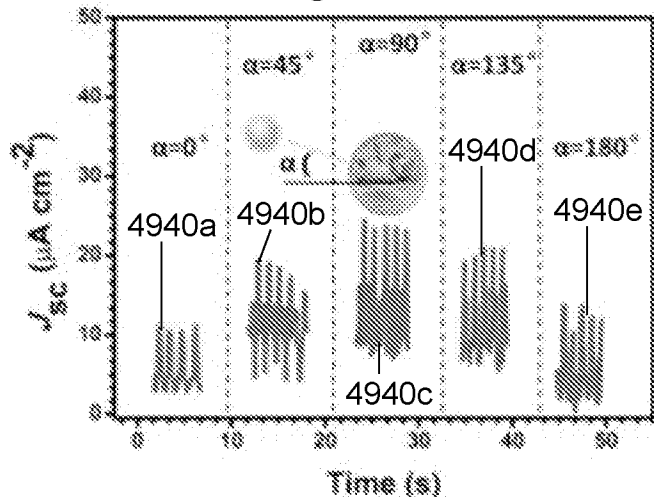


Figure 49D

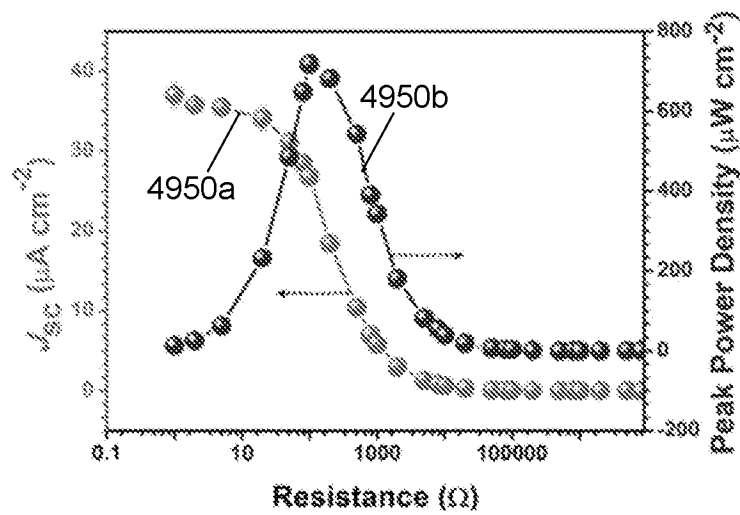


Figure 49E

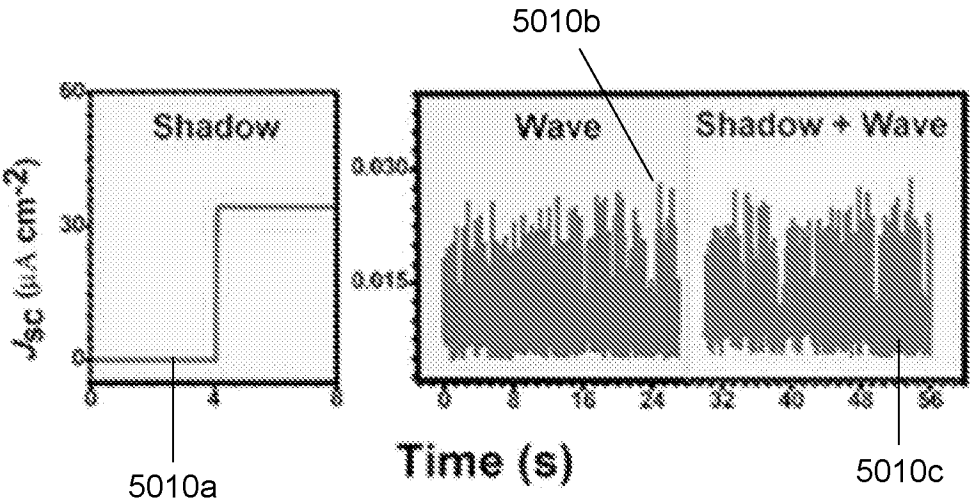


Figure 50A

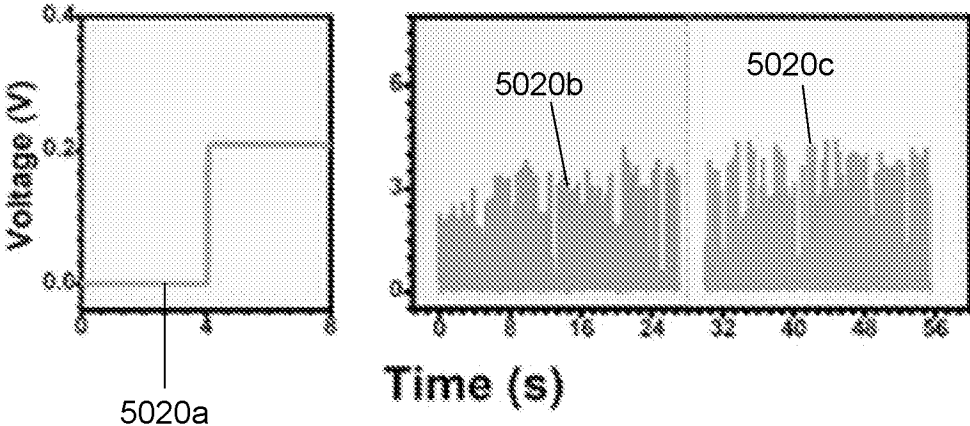


Figure 50B

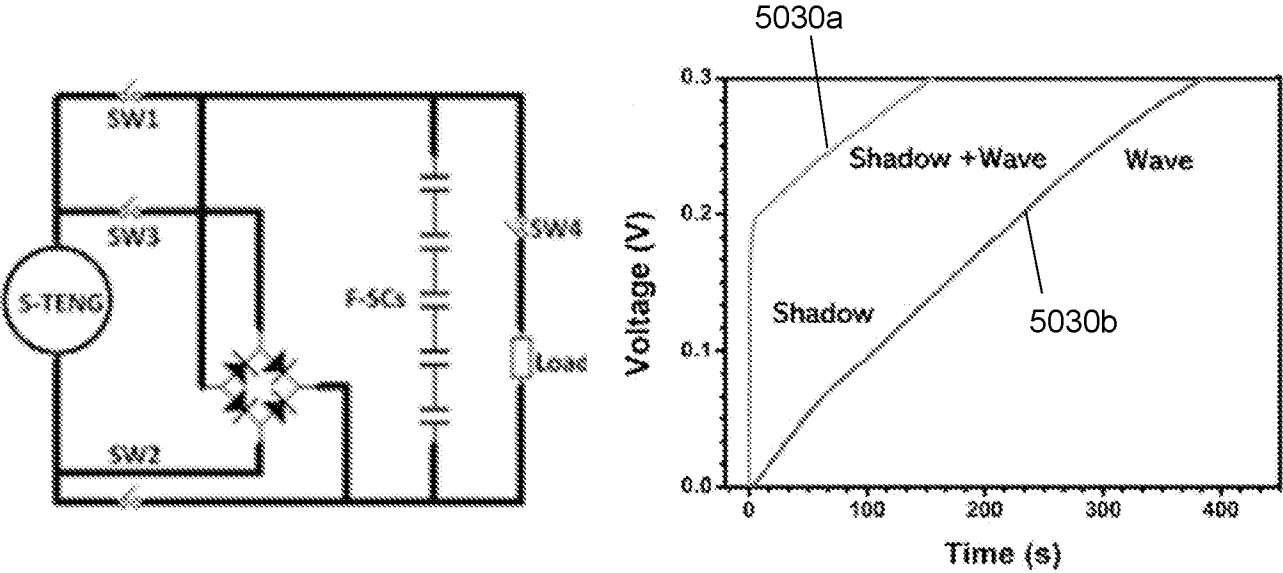


Figure 50C

Figure 50D

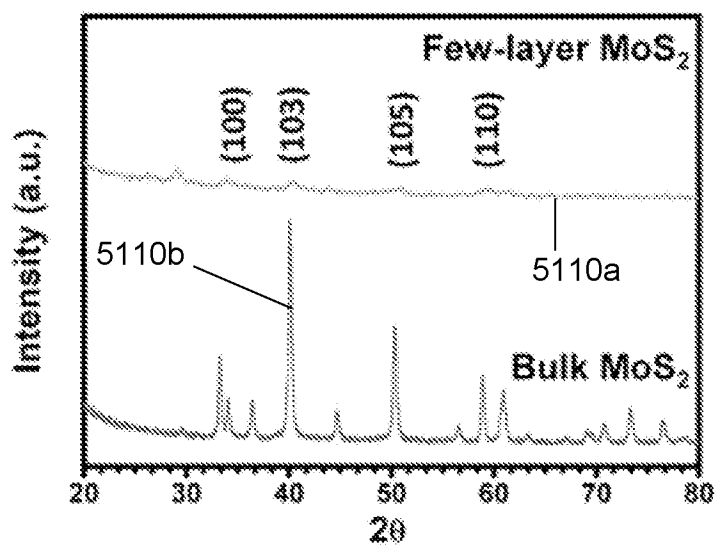


Figure 51A

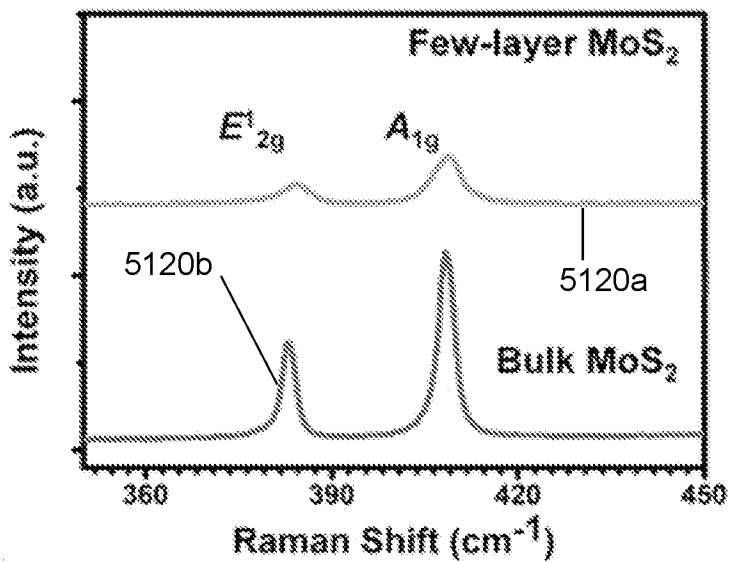


Figure 51B

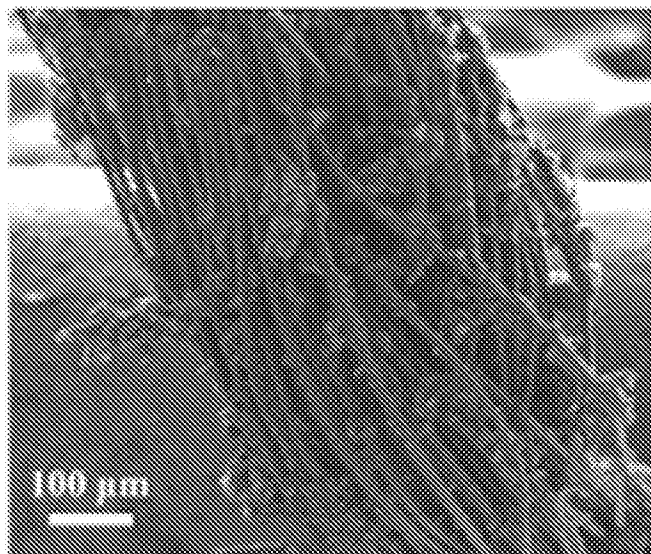


Figure 51C

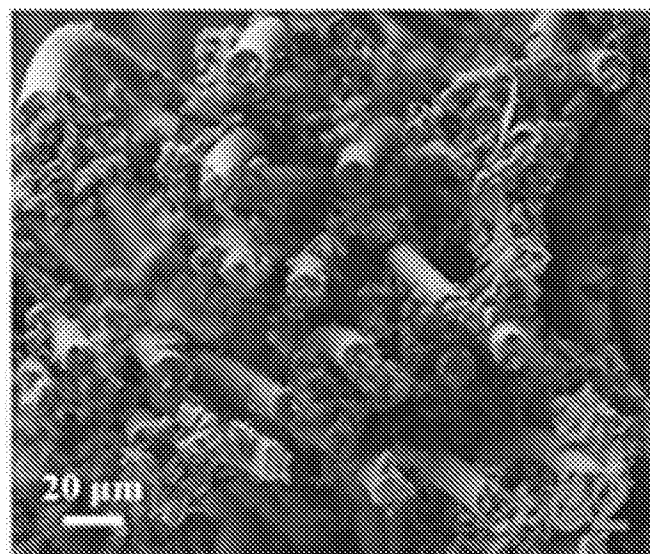


Figure 51D

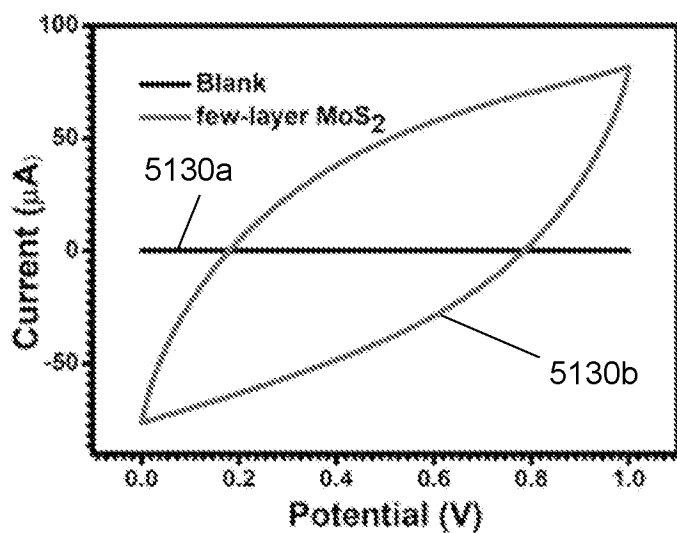


Figure 51E

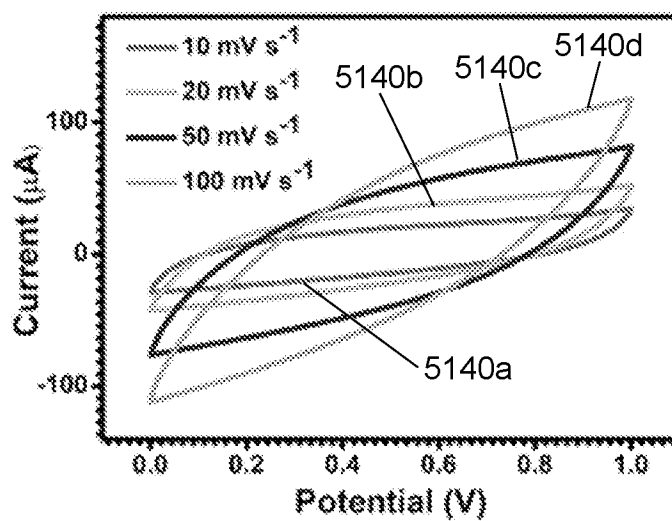


Figure 51F

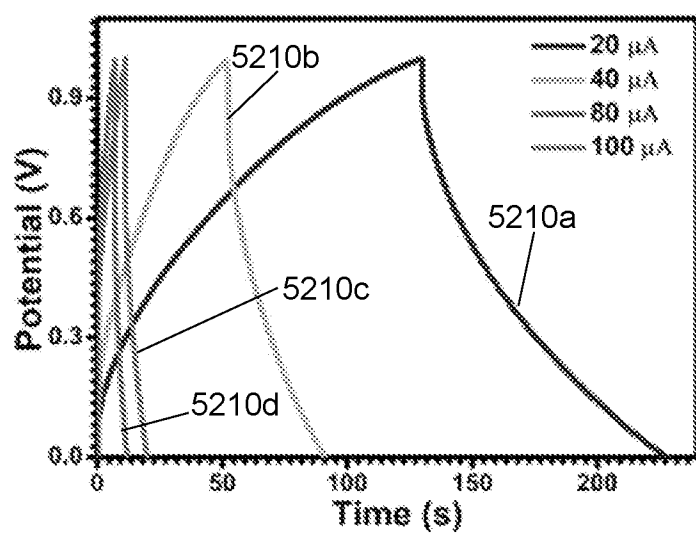


Figure 52A

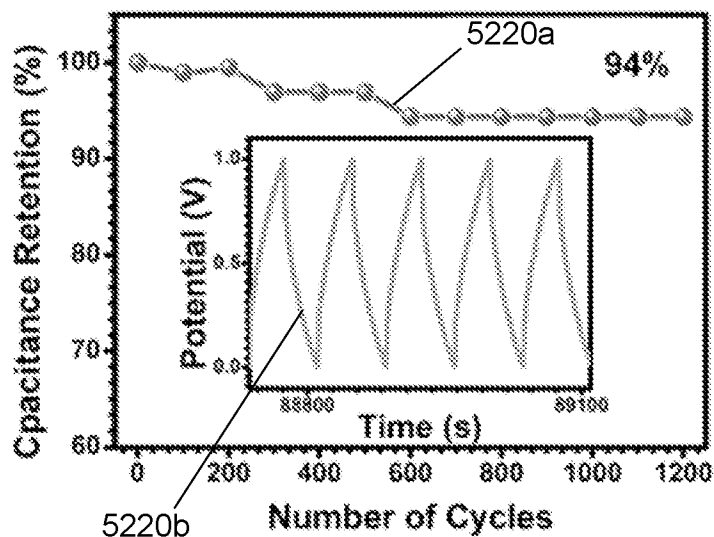


Figure 52B

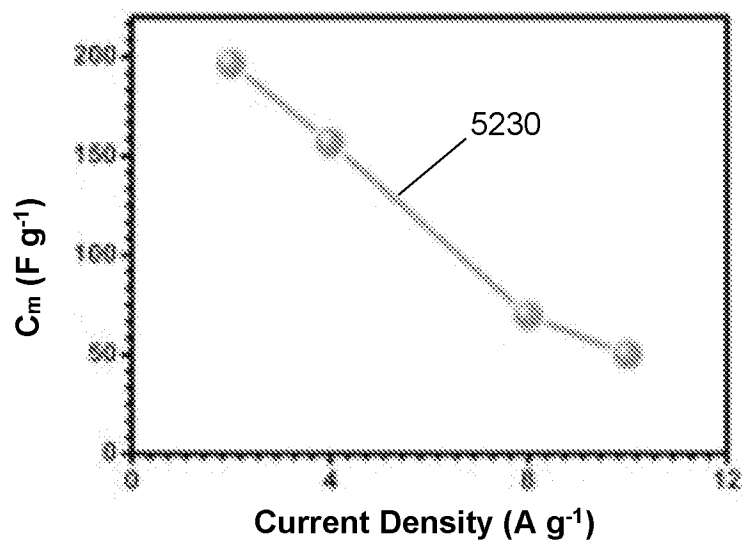


Figure 52C

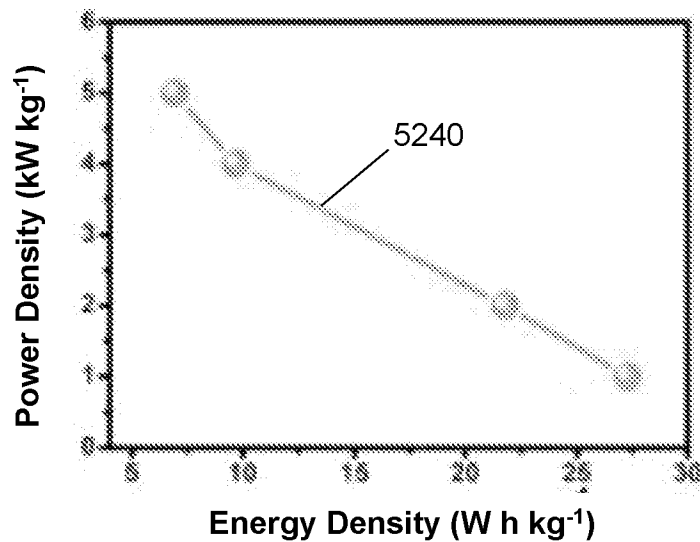


Figure 52D

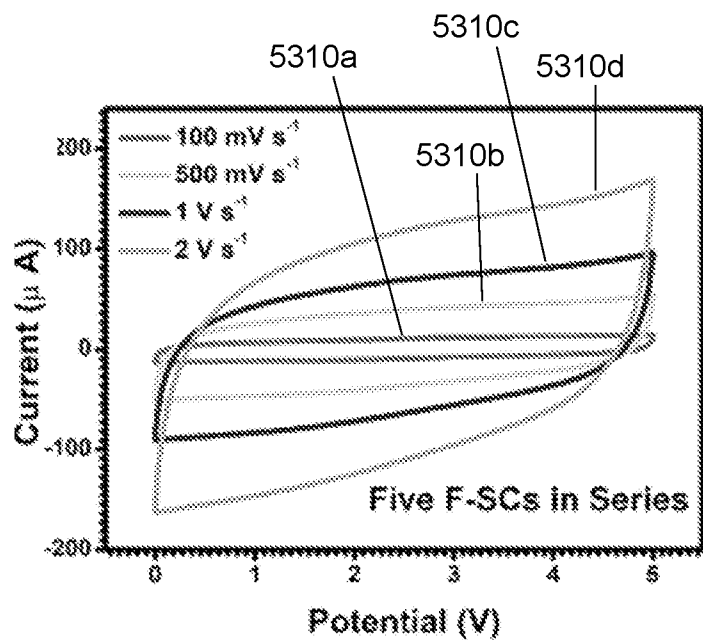


Figure 53A

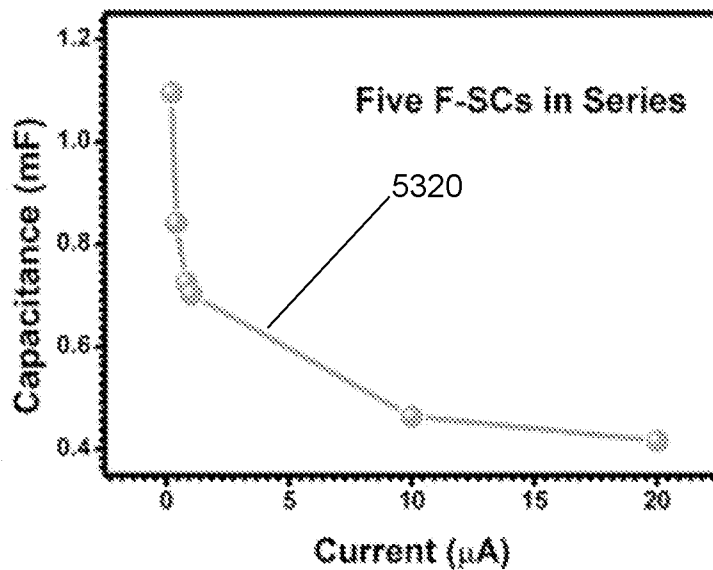


Figure 53B

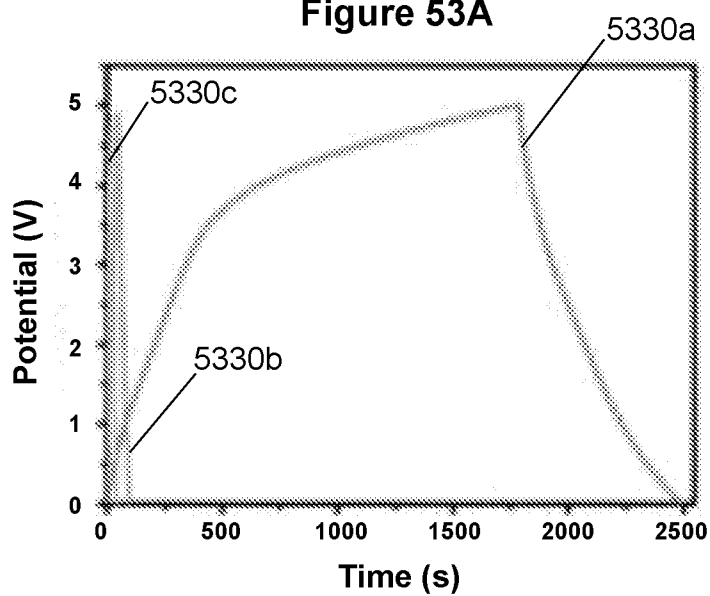


Figure 53C

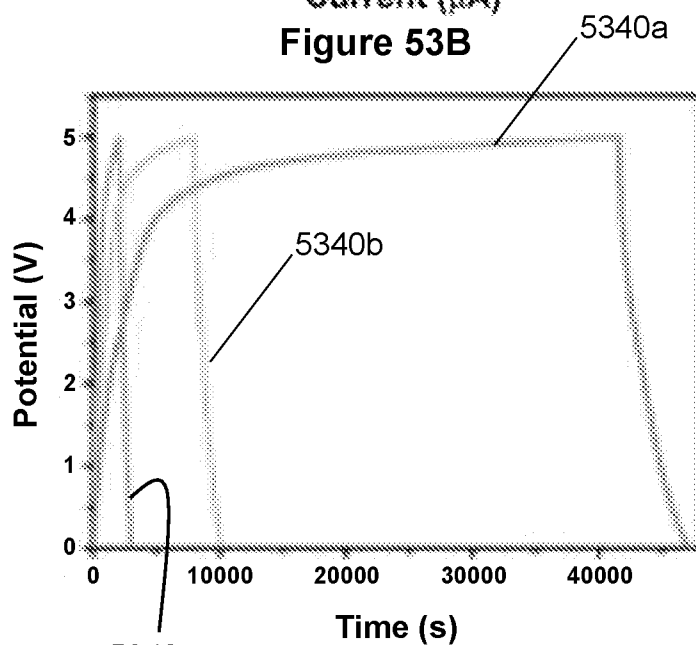


Figure 53D

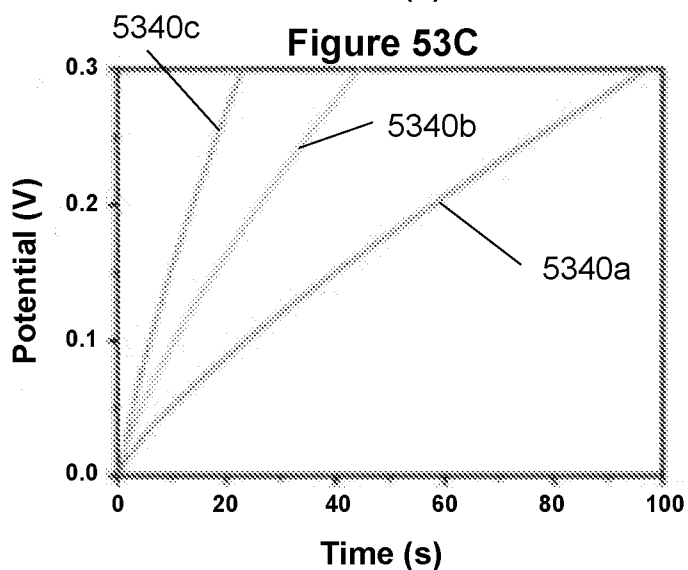


Figure 53E

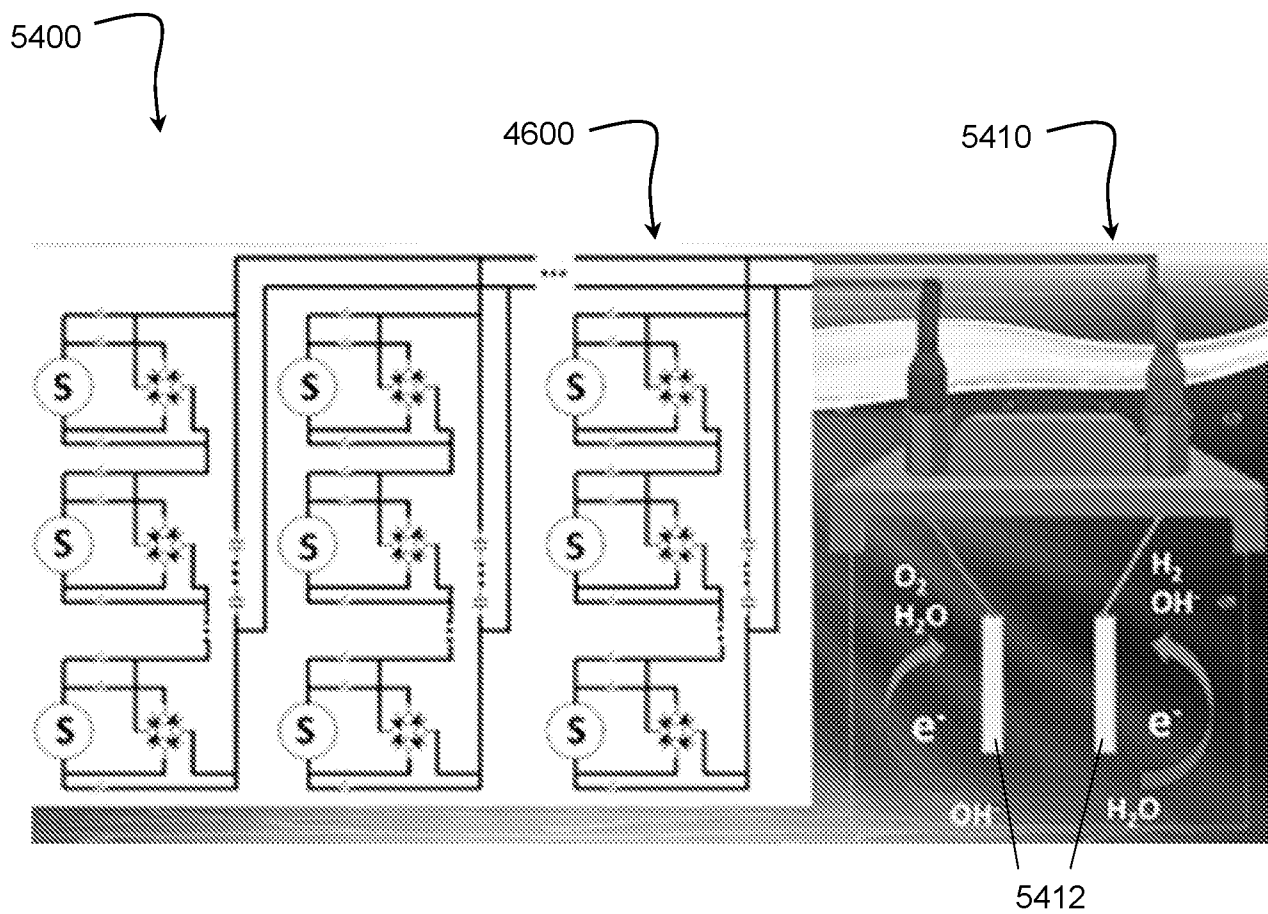


Figure 54A

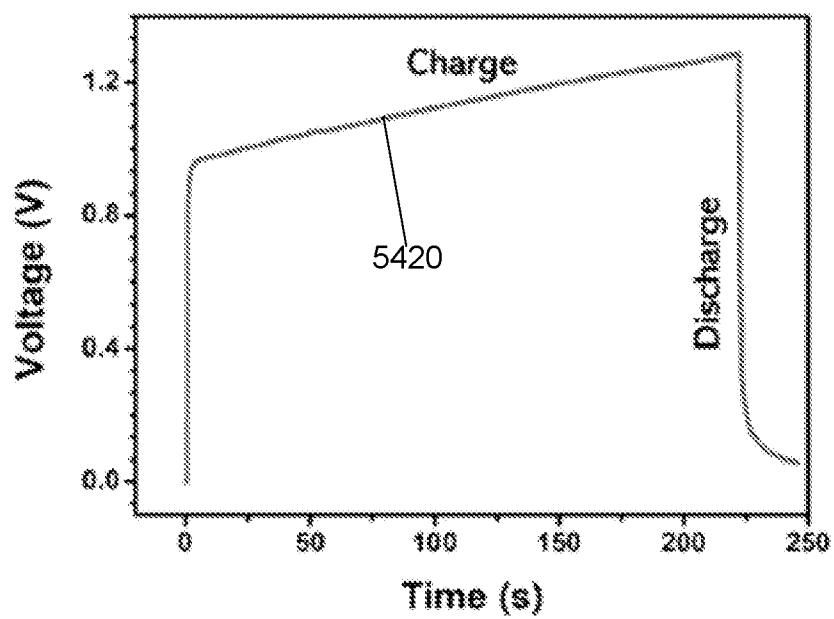


Figure 54B

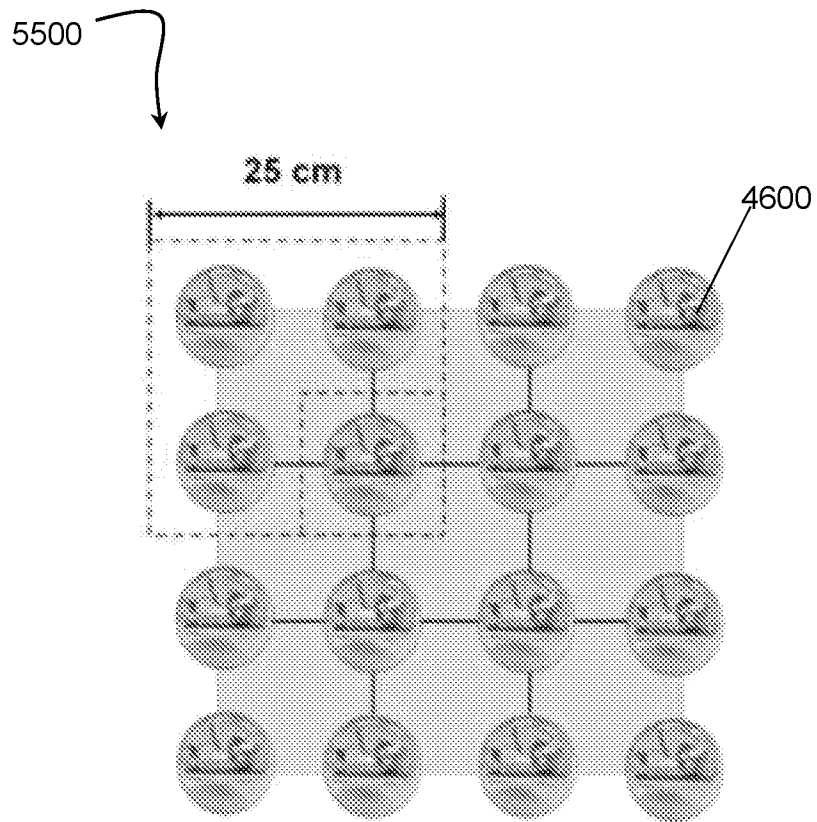


Figure 55

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2021/050206

A. CLASSIFICATION OF SUBJECT MATTER**H01L 31/00 (2006.01) H02N 1/04 (2006.01)**

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01L, H02N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

FAMPAT/IEEE Xplore/CNKI: hybrid, composite, 混合, 复合, generator, 发电机, harvesting, scavenging, 能量收集, 能量挖掘, 能量采集, triboelectric, tribovoltaic, TENG, friction, contact, 摩擦电, 摩电, 摩擦带电, 摩擦起电, 摩擦发电, 接触起电, 接触发电, light, illumination, irradiation, sunshine, solar, 光, 日光, 日照, 太阳光, 照明, 照射, permeable, transparent, translucent, 透光, 透明, 半透明, shadow, 阴影, 暗影, contrast, 对比, Schottky, 肖特基, 萧特基, 肖脱基, barrier, 势垒, 位障, 能障, work function, 逸出功, and other relevant terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	ZHANG Q. ET AL., Shadow enhanced self-charging power system for wave and solar energy harvesting from the ocean. <i>Nature Communications</i> , 27 January 2021, Vol. 12, pages 616 [Retrieved on 2021-06-21] <DOI: 10.1038/S41467-021-20919-9> Whole document	1-30
X	ZHANG Q. ET AL., Energy harvesting from shadow-effect.. <i>Energy & Environmental Science</i> , 15 April 2020, Vol. 13, No. 8, pages 2404-2413 [Retrieved on 2021-06-21] <DOI: 10.1039/D0EE00825G> Whole document	31-38

☒ Further documents are listed in the continuation of Box C.☒ See patent family annex.

*Special categories of cited documents:

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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Date of the actual completion of the international search

21/06/2021

(day/month/year)

Date of mailing of the international search report

23/06/2021

(day/month/year)

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2021/050206

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	RAVI S. K. ET AL., Optical manipulation of work function contrasts on metal thin films. <i>Science Advances</i> , 2 March 2018, Vol. 4, No. 3, pages eaao6050 [Retrieved on 2021-06-21] <DOI: 10.1126/SCIADV.AAO6050> Whole document	
A	JEON S.-B. ET AL., Self-cleaning hybrid energy harvester to generate power from raindrop and sunlight. <i>Rapid Communication</i> , 7 February 2015, Vol. 12, pages 636-645 [Retrieved on 2021-06-21] <DOI: 10.1016/J.NANOEN.2015.01.039> Whole document	
A	CN 109698636 A (HENAN UNIVERSITY) 30 April 2019 Whole document of the original non-English language document (a machine translation is enclosed only for your reference)	
A	SARI F. N. I. ET AL., Direct Growth of MoS ₂ Nanowalls on Carbon Nanofibers for Use in Supercapacitor. <i>Scientific Reports</i> , 20 July 2017, Vol. 7, pages 5999 [Retrieved on 2021-06-21] <DOI: 10.1038/S41598-017-05805-Z> Whole document	

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2021/050206

Note: This Annex lists known patent family members relating to the patent documents cited in this International Search Report. This Authority is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
CN 109698636 A	30/04/2019	NONE	