

SELF-POWERED SENSOR AND METHOD OF FORMING THE SAME

Technical Field

[0001] Embodiments relate generally to a self-powered sensor and a method of forming a self-powered sensor.

Background

[0002] Self-powered sensors can be widely used in many applications where wiring and batteries are inappropriate. Researches have been carried out for years in efforts to provide convenient power to the remotely mounted sensors by harvesting solar energy and other forms of energies. Powered by solar cells or ambient light generators, the sensors can acquire and distribute telemetry data in buildings or agriculture. Even in industrial facilities and many places with limited accessibility, the maintenance-free sensors are able to monitor processes over long periods. In order to operate the sensors under limited availability of energy sources, elaborate power-management, low power consumption and internal energy storage are required.

[0003] Current self-powered sensor systems include an energy harvesting attachment to power the sensor. The additionally attached energy harvester for the sensor, however, occupies additional space and adds bulk to the sensor system.

Summary

[0004] Various embodiments provide a self-powered sensor. The self-powered sensor includes a solar cell having a transparent or semi-transparent electrode, wherein the solar cell is configured to at least substantially absorb light of a first wavelength range for

generating electrical energy and configured to at least substantially transmit light of a second wavelength range. The self-powered sensor further includes an energy storage configured to store the electrical energy generated by the solar cell; and a detector electrically connected to the energy storage to receive the electrical energy and configured to detect the transmitted light of the second wavelength range. The electrode of the solar cell is configured to have at least one of a selected thickness or a selected material dependent on a desired absorptance of the solar cell for light of the first wavelength range and a desired transmittance of the solar cell for light of the second wavelength range.

[0005] Various embodiments further provide a method of forming a self-powered sensor. The method may include selecting at least one of a thickness or a material for a transparent or semi-transparent electrode of a solar cell dependent on a desired absorptance of the solar cell for light of a first wavelength range and a desired transmittance of the solar cell for light of a second wavelength range; providing the solar cell having the electrode with the selected at least one of the thickness or the material, the solar cell being configured to at least substantially absorb light of the first wavelength range for generating electrical energy and configured to at least substantially transmit light of the second wavelength range; coupling an energy storage to the solar cell for storing the electrical energy generated by the solar cell; and electrically connecting a detector to the energy storage to receive the electrical energy and to detect the transmitted light of the second wavelength range.

Brief Description of the Drawings

[0006] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following

description, various embodiments are described with reference to the following drawings, in which:

Figs. 1A and 1B show schematic diagrams of a self-powered sensor according to various embodiments.

Fig. 2 shows a schematic diagram of a self-powered sensor system according to various embodiments.

Fig. 3 shows a schematic diagram illustrating an arrangement of a self-powered sensor according to various embodiments.

Fig. 4 shows a schematic diagram illustrating an operation of a self-powered sensor according to various embodiments.

Fig. 5 shows a schematic diagram illustrating a structure of a self-powered sensor according to various embodiments.

Fig. 6 shows a plot illustrating integrated absorptance and overall transmittance of IR light by a solar cell as a function of the thickness of a semi-transparent electrode according to various embodiments.

Fig. 7 shows a plot illustrating light transmittance of a solar cell with a semi-transparent Ag/ITO electrode having a 120nm ITO layer and a 60nm ITO layer, respectively, according to various embodiments.

Fig. 8 shows a plot illustrating current density-voltage characteristics of a perovskite solar cell with a semi-transparent Ag(20nm)/ITO(60nm) electrode according to various embodiments and a perovskite solar cell with opaque Ag electrode measured under simulated AM 1.5G illumination of 100 mW/cm^2 .

Fig. 9 shows a plot illustrating current density-voltage characteristics measured for an IR detector in the dark and radiated by an IR LED, with and without an IR translucent perovskite solar cell of various embodiments.

Fig. 10 shows a flowchart illustrating a method of forming a self-powered sensor according to various embodiments.

Description

[0007] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized, and structural and logical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0008] For self-powered applications, one of the key technologies lies in the integration of an IR (Infrared) translucent light harvesting device with an IR detector. Solar cells are specifically engineered to perform the dual functions of selective visible light harvesting for energy generation and infrared light transmission at the same time. The main challenge of this technology is the concurrent realization of high energy conversion efficiency and high transmittance of the desired wavelength in a single device. Various embodiments in this description provide a self-powered sensor which realizes high energy conversion efficiency as well as selective noise filtering, and at the same time achieves high transmittance of desired wavelength.

[0009] Figs. 1A and 1B shows a schematic diagram of a self-powered sensor according to various embodiments.

[0010] As shown in Figs. 1A and 1B, a self-powered sensor 100, 150 includes a solar cell 102, an energy storage 104 and a detector 106. The solar cell 102 is configured to at least substantially absorb light of a first wavelength range for generating electrical energy and configured to at least substantially transmit light of a second wavelength range. The

solar cell 102 may also be referred to as a photovoltaic cell or a photovoltaic device, which converts the energy of light into electricity by the photovoltaic effect. The energy storage 104 is coupled to the solar cell 102 for storing the electrical energy generated by the solar cell 102. Example of the energy storage 104 may be a capacitor, or a battery, e.g. a rechargeable battery. The detector 106 is electrically connected to the energy storage 104 to receive the electrical energy, and is configured to detect the transmitted light of the second wavelength range. The detector 106 may also be referred to as a photodetector or a light sensor.

[0011] The solar cell 102 includes a transparent or semi-transparent electrode configured to have at least one of a selected thickness or a selected material dependent on a desired absorptance of the solar cell for light of the first wavelength range and a desired transmittance of the solar cell for light of the second wavelength range. The transparent or semi-transparent electrode may be either a cathode or an anode, or both. The desired absorptance may be a value representing the percentage of the light of the first wavelength range that is absorbed by the solar cell 102, for example, a value between 10-90% or between 20-100%, such as a value of 95%, 80%, 70% or 60%. The desired transmittance may be a value representing the percentage of the light in the second wavelength range which can be transmitted through the solar cell 102, for example, a value between 10-90% or between 20-95%, such as a value of 95%, 80%, 70% or 60%.

[0012] In various embodiments, the transparent or semi-transparent electrode of the solar cell 102 may be configured to have at least one of the selected thickness or the selected material to optimize at least one of the absorptance of the solar cell for light of the first wavelength range or the transmittance of the solar cell for light of the second wavelength range. In various embodiments, the transparent or semi-transparent electrode of the solar cell 102 may be configured to have either one or both of the selected thickness and

the selected material to either optimize the absorptance for light of the first wavelength range (e.g., maximize the absorptance, or to configure the absorptance to be close to or reach the desired absorptance), or optimize the transmittance for light of the second wavelength range (e.g. maximize the transmittance, or to configure the transmittance to be close to or reach the desired transmittance), or optimize both the absorptance for light of the first wavelength range and the transmittance for light of the second wavelength range (e.g. balance said absorptance and transmittance to achieve an optimized performance of the solar cell).

[0013] In various embodiments, the first wavelength range may include a wavelength range of visible light, or a wavelength range covering most of the wavelength length range of visible light, e.g. the first wavelength range may include a wavelength range of 360nm - 760nm. The first wavelength range may further include a wavelength range of ultraviolet light, e.g. 200 nm – 360nm. In various embodiments, the first wavelength range may at least partially cover the wavelength range of visible light and ultraviolet light, e.g. including a wavelength range of 200nm – 760nm, or including a sub-range of 200nm -760nm, such as 250-760nm, 300-760nm, or 300-700nm. In various embodiments, the second wavelength range may include a wavelength range of infrared light, e.g., a wavelength range of 760nm - 940nm substantially covering near-infrared light. The second wavelength range may further include a wavelength range covering one or more of short-wavelength infrared light, mid-wavelength infrared light, long-wavelength infrared light or far-infrared light. For example, the second wavelength range may include a wavelength range of 760nm – 1mm, or a sub-range of 760nm – 1mm. The solar cell 102 configured for substantial transmission of infrared light may be referred to as an IR translucent solar cell. The detector 106 for detecting the infrared light may be referred to as an IR detector. In various embodiments below, exemplary embodiments may be described with the light of the first wavelength

range being visible light and the light of the second wavelength range being infrared light. However, it is understood that in various embodiments, the first wavelength range and the second wavelength range may be various other wavelength ranges to enable absorption and transmission of different wavelengths. For example, light of the first wavelength range to be substantially absorbed by the solar cell may include visible light and one or more of a portion of infrared light or ultraviolet light; and light of the second wavelength range to be substantially transmitted by the solar cell may include infrared light and a portion of visible light. By selecting either one or both of the thickness and the material of the electrode of the solar cell 102, and/or selecting active material (e.g. light absorbing material) of the solar cell 102, the first wavelength range and the second wavelength range may be configured or modified accordingly, and furthermore, the absorptance of the solar cell for light of the first wavelength range and the transmittance of the solar cell for light of the second wavelength range may be configured or modified accordingly towards or to reach the desired absorptance and/or the desired transmittance.

[0014] In various embodiments, the second wavelength range is different from the first wavelength range, such that light of the first wavelength range is substantially absorbed and filtered by the solar cell 102 and light of the second wavelength range is substantially transmitted through the solar cell 102.

[0015] According to various embodiments, the self-powered sensor 100, 150 may include more than one solar cell 102, which may be combined to form a solar panel or a photovoltaic module, for example.

[0016] In various embodiments, the selected thickness of the transparent electrode is selected from a range of 60nm to 120nm. In various embodiments, the selected thickness of the semi-transparent electrode may be selected from a range of 60nm to 170nm.

[0017] According to various embodiments, the selected material of the transparent electrode may include an indium tin oxide (ITO) layer. In other words, the transparent electrode may be an ITO electrode. In various embodiments, the thickness of the ITO layer may be selected from a range of 60nm to 120nm.

[0018] According to various embodiments, the selected material of the semi-transparent electrode may include an indium tin oxide (ITO) layer and at least one of a metal layer or a conductive polymer layer. The metal layer may include Au, Ag, Al, or other suitable metal. The conductive polymer may include polyaniline, or PEDOT:PSS (poly(3,4-ethylenedioxythiophene) polystyrene sulfonate). The semi-transparent electrode may improve the light absorption in first wavelength range and light transmission in the second wavelength range. In an exemplary embodiment, the semi-transparent electrode may be an Ag/ITO electrode including an ITO layer and an Ag layer, or an Al/ITO electrode, for example. In an exemplary embodiment, the ITO layer may have a thickness of about 60nm and the metal (e.g. Ag) layer may have a thickness of about 20nm. In various embodiments, the ITO layer may have a thickness selected from a range of 60nm to 120nm, and the metal (e.g., Ag) layer may have a thickness selected from a range of 0nm to 50nm. In various embodiments, the entire thickness of the semi-transparent electrode may be selected from a range of 60nm to 170nm.

[0019] According to various embodiments, the selected material of the semi-transparent electrode may include an indium tin oxide (ITO) layer, a metal layer, and a layer of inorganic or organic material. In an exemplary embodiment, the semi-transparent electrode may include an Al/ITO electrode, or an Al/LiF/ITO electrode. The thickness of the respective layers of the semi-transparent electrode may be selected or optimized based on the optical characteristics of the solar cell 102.

[0020] The detector 106 may include an IR transparent electrode (e.g. cathode and/or anode) same as the transparent or semi-transparent electrode of the solar cell described in various embodiments above. In various embodiments, the detector 106 may be an organic photodetector, a polymer semiconductor photodetector, a semiconductor p-n junction photodetector, a quantum well infrared photodetector, or a quantum-dot infrared photodetector. The detector 106 may include other infrared detector materials, such as mercury cadmium telluride, indium antimonide, indium arsenide, or lead selenide.

[0021] According to various embodiments above, the transparent or semi-transparent electrode may have the thickness and/or the material selected or determined based on the optical and electronic characteristics of an active layer of the solar cell 102 (e.g. a perovskite layer) to balance the photovoltaic performance with IR transmission.

[0022] According to various embodiments, the solar cell 102 may include a transparent substrate, an electron transporting layer arranged on the transparent substrate, an active layer arranged on the electron transporting layer, a hole transporting layer arranged on the active layer, and the transparent or semi-transparent electrode arranged on the hole transporting layer.

[0023] According to various embodiments, the transparent substrate may include one of an Indium tin oxide (ITO) coated glass or a Fluorine-doped tin oxide (FTO) coated glass. The electron transporting layer may include titanium dioxide (TiO_2), for example.

[0024] In various embodiments, the active layer may include a perovskite structured material, such as methylammonium lead triiodide ($\text{CH}_3\text{NH}_3\text{PbI}_3$), $\text{LaVO}_3/\text{SrTiO}_3$, or $\text{H}_2\text{NCHNH}_2\text{PbX}_3$ ($\text{X} = \text{I}, \text{Cl}, \text{Br}$). In various embodiments, the active layer may include an organic/polymer material, such as P3HT (Poly(3-hexylthiophene)), PTB7 (Poly[[4,8-bis[(2-ethylhexyl)oxy]benzo[1,2-b:4,5-b']dithiophene-2,6-diyl][3-fluoro-2-[(2-ethylhexyl)carbonyl] thieno[3,4-b]thiophenediyl]]), or PCBM ([6,6]-Phenyl-C61-butyric

acid methyl ester), for bulk heterojunction solar cells. In various embodiments, the active layer may include other thin film photovoltaic materials such as ruthenium-polypyridine dyes (DSSC) or CIGS (copper indium gallium selenide). The active material in the active layer may be selected based on its light harvesting effectiveness and energy conversion efficiency in solar cells, and its optical characteristics (e.g., light absorption wavelength range and light transmission wavelength range).

[0025] The hole transporting layer may include spiro-OMeTAD (2,2',7,7'-Tetrakis[N,N-di(4-methoxyphenyl)amino]-9,9'-spirobifluorene). In other embodiments, the hole transporting layer may include polymer (e.g. P3HT, PTAA, etc.) and/or p-type nano material (e.g. Molybdenum disulfide (MoS₂), graphene oxide, etc.). In an exemplary embodiment, the semi-transparent electrode may include a metal layer, e.g. a silver (Ag) layer, arranged on the hole transporting layer and an indium tin oxide (ITO) layer arranged on the silver layer. In an exemplary embodiment, the transparent electrode may include an ITO layer arranged on the hole transporting layer. The ITO layer may be a low temperature ITO (LT.ITO) layer deposited at a low processing temperature of less than 60°C. In an exemplary embodiment, the solar cell may have a layer sequence of FTO glass/TiO₂/CH₃NH₃PbI₃ /spiro-OMeTAD/Ag/LT.ITO.

[0026] According to the self-powered sensor 100 shown in the embodiments of Fig. 1A, the solar cell 102 is arranged between the detector 106 and a light source 108. In this arrangement, incident light from the light source 108 is first received at one side of the solar cell 102, which substantially absorbs light of the first wavelength range, e.g. visible light, and generates electrical energy for storing in the energy storage 104. The solar cell 102 further substantially transmits light of the second wavelength range, e.g. infrared light, which is then detected by the detector 106 at the other side of the solar cell 102. The absorption of visible light by the solar cell 102 means that the visible light, representing the

noise for the infrared light to be transmitted, is substantially filtered out of the incident light. Accordingly, the sensor according to the various embodiments achieves improved IR sensing sensitivity due to noise reduction achieved through filtering of the visible light from the ambient light source by the solar cell 102 before transmission to the IR detector 106.

[0027] According to the self-powered sensor 150 shown in the embodiments of Fig. 1B, the solar cell 102, the detector 106 may be arranged at the same side as the light source 108 against an objective 110. The light source 108 may emit a range of wavelengths, e.g. white light, which is received by the solar cell 102. The solar cell 102 may absorb visible light and UV light in the received white light for energy generation. The solar cell 102 may also transmit infrared light in the received white light which is then reflected by the objective 110 and transmitted back through the solar cell 102 for reception and detection by the detector 106. In an exemplary embodiment, the light source 108 may be powered by the energy storage 104, for example.

[0028] According to various embodiments, the detector 106 may be sequentially aligned or overlaid with the solar cell 102 along a direction of light transmission path to receive the light transmitted through the solar cell 102, e.g. as shown in Figs. 3 – 5 below. According to various embodiments, the detector 106 may be integrated with the solar cell 102 to form a single and integrated sensor. According to various embodiments, the detector 106 is arranged to contact or face a surface of the solar cell 102 from which the light of the second wavelength range is transmitted.

[0029] The self-powered sensor 100, 150 may be included in an integrated sensor system 200 as shown in Fig. 2.

[0030] According to various embodiments, the self-powered sensor system 200 may include the solar cell 102, the rechargeable battery 104 and the detector 106 described above. Various embodiments described in Figs. 1A and 1B above are analogously valid for the

embodiments of Fig. 2, and vice versa. The solar cell 102 may be an IR translucent photovoltaic (PV) device configured to at least substantially transmit IR light, and the detector 106 may be an IR detector configured to detect IR light. The light source 108 may be an IR light source or a white light source, and the IR light from the light source 108 may be detected by the detector 106. The sensor system 200 may further include a control unit 210, which may be powered by the rechargeable battery 104, and may receive the output of the detector 106 for further controlling.

[0031] According to the embodiments of Fig. 2, high performance IR translucent solar cell can be integrated with the IR detector 106 in a single structure in order to overcome the space limitations for IR sensors. The integrated, energy-harvesting IR translucent sensor system 200 will enable new applications that require very small and thin sensor systems, such as health monitoring, and sensing in pipelines or moving parts of engines.

[0032] Fig. 3 shows a schematic diagram illustrating an arrangement 300 of a self-powered sensor according to various embodiments. Various embodiments described in Figs. 1A and 1B above are analogously valid for the embodiments of Fig. 3, and vice versa.

[0033] As shown in Fig. 3, the detector 106 may be overlaid with the solar cell 102 to receive the light transmitted through the solar cell 102. As shown in Fig. 3, the detector 106 may be arranged to contact a surface of the solar cell 102 from which the light of the second wavelength range is transmitted out of the solar cell 102, e.g. the transparent or semi-transparent electrode or the transparent substrate of solar cell 102. In other embodiments, the detector 106 may be arranged to be spaced apart from and face the surface of the solar cell 102 from which the light of the second wavelength range is transmitted, for example, as shown in Fig. 1A and 1B. Incident light, e.g. solar light and indoor light, from the light source 108 is received at the opposite surface of the solar cell 102 for energy harvesting and

IR light transmission. The light source 108 may be an artificial light source, such as a light bulb, or may be natural light source, e.g. the sun.

[0034] According to various embodiments, the detector 106 may be integrated with the solar cell 102 to form a single and integrated sensor, as shown in Fig. 3.

[0035] In various embodiments, the solar cell 102 and the detector 106 may be sequentially integrated or aligned along a direction of light transmission path. Accordingly, photo energy harvesting and IR sensing functions are combined in a single compact and lightweight structure. In this context, the sequentially integrated/aligned structure of the solar cell 102 and the detector 106 may refer to a structure in which the detector 106 is stacked after the solar cell 102 along the path of light transmission. For example, the detector 106 is stacked vertically on the solar cell 102 along the light transmission path as shown in Fig. 5 below, or the solar cell 102 and the detector 106 are aligned horizontally along the light transmission path as shown in Fig. 4. In other words, the solar cell 102 and the detector 106 are aligned in sequence along the light transmission path such that light is first transmitted through the solar cell 102 and is subsequently transmitted to the detector 106. The light transmission path may be an incident light transmission path, such as the light transmission path from the light source 108 to the detector 106 in Fig. 1A, or may be a reflected light transmission path, such as the reflected light transmission path from the objective 110 to the detector 106 in Fig. 1B. This arrangement allows the solar cell 102 to perform the dual functions of energy harvesting and optical filtering, and further achieves a compact form factor for the sensor system (i.e., solar cell integrated with detector).

[0036] Fig. 4 shows a schematic diagram 400 illustrating an operation of a self-powered sensor according to various embodiments. The self-powered sensor includes the solar cell 102 and the detector 106 described above. Various embodiments described in Figs. 1A, 1B, 2 and 3 above are analogously valid for the embodiments of Fig. 4, and vice versa.

[0037] As shown in Fig. 4, ambient light 410 is received from one surface of the solar cell 102. Visible light 412 in the ambient light 410 is absorbed by the solar cell 102, and IR light 414 in the ambient light 410 is transmitted out of the solar cell 102 and is received by the detector 106. According to various embodiments, the IR translucent solar cell 102 acts as a noise filter by absorbing the visible light (i.e. noise), thus increasing the sensitivity and accuracy of the IR detector 106.

[0038] Fig. 5 shows a schematic diagram 500 illustrating a structure of a self-powered sensor according to various embodiments.

[0039] As shown in Fig. 5, the self-powered sensor includes the detector 106 and the solar cell 102 described in various embodiments above.

[0040] According to an exemplary embodiment wherein the solar cell 102 is configured to absorb visible light and to transmit infrared light, the IR translucent solar cell 102 needs to be configured to absorb the maximum amount of visible light to maximize power efficiency and prevent the transmission of light with other wavelengths except for those in the IR region in order to provide an efficient self-powered sensor. The IR translucent solar cell 102 may be based on transparent or semi-transparent thin film organic or perovskite solar cells.

[0041] Fig. 5 shows an exemplary embodiment of a semi-transparent perovskite or thin film solar cell 102 to realize power generation, and provide power and noise filtering for the IR detector 106. The solar cell 102 may include a transparent substrate 522, an electron transporting layer 528 arranged on the transparent substrate 522, an active layer 530 arranged on the electron transporting layer 528, a hole transporting layer 532 arranged on the active layer 530, and the electrode 534 arranged on the hole transporting layer 532.

[0042] According to various embodiments, the transparent substrate 522 may include one of an Indium tin oxide (ITO) coated glass or a Fluorine-doped tin oxide (FTO) coated

glass, wherein the layer 524 is the glass layer and the layer 526 may be the coated ITO or FTO layer. The electron transporting layer 528 may include titanium dioxide (TiO_2), for example. The active layer 530 may include perovskite, such as methylammonium lead triiodide ($\text{CH}_3\text{NH}_3\text{PbI}_3$), $\text{LaVO}_3/\text{SrTiO}_3$, or $\text{H}_2\text{NCHNH}_2\text{PbX}_3$ ($\text{X} = \text{I}, \text{Cl}, \text{Br}$); or may include an organic/polymer material, such as P3HT, PTB7 or PCBM; or may include other thin film photovoltaic materials such as ruthenium-polypyridine dyes (DSSC) or CIGS. The hole transporting layer 532 may include spiro-OMeTAD. In other embodiments, the hole transporting layer 532 may include polymer (e.g. P3HT, PTAA) and/or p-type nano material (e.g. MoS_2 , graphene oxide). In an exemplary embodiment, the electrode 534 may be a semi-transparent electrode, which may include a silver (Ag) layer arranged on the hole transporting layer 532 and an indium tin oxide (ITO) layer arranged on the silver layer, and may be denoted as an Ag/ITO electrode 534. In an exemplary embodiment, the electrode 534 may be a transparent electrode, which may only include an ITO layer arranged on the hole transporting layer 532, and may be denoted as an ITO electrode 534. The ITO layer of the electrode 534 may be a low temperature ITO (LT.ITO) layer deposited at a low processing temperature of less than 60°C . The ITO layer of the electrode 534 may act as refractive index matching layer to enhance the transmittance of infrared light, and also improves the lateral conductivity of the electrode 534 which may act as a top cathode.

[0043] In an exemplary embodiment, the solar cell may have a layer sequence of FTO glass/ TiO_2 / $\text{CH}_3\text{NH}_3\text{PbI}_3$ /spiro-OMeTAD/Ag/LT.ITO. In an exemplary embodiment, the solar cell may have a layer sequence of ITO glass/ TiO_2 / $\text{CH}_3\text{NH}_3\text{PbI}_3$ /spiro-OMeTAD/Ag/LT.ITO.

[0044] The top electrode 534 is optimized according to various embodiments above, e.g. by selecting at least one of the thickness or material for the top electrode 534, to enhance light harvesting in the active layer 530 of the solar cell 102 as well as the transmission of IR

light through the solar cell 102. As shown in Fig. 5, ambient light 510 is transmitted into the solar cell 102, which absorbs visible light of the ambient light 510 and transmits infrared light 514 of the ambient light 510 to the detector 106.

[0045] Fig. 6 shows a plot 600 illustrating integrated absorptance of the perovskite layer ($\text{CH}_3\text{NH}_3\text{PbI}_3$ layer) of the perovskite solar cell 102 and overall transmittance of IR light by the perovskite solar cell 102 as a function of the ITO layer thickness in the semi-transparent Ag/ITO electrode (e.g. the top Ag/ITO electrode 534) according to various embodiments. The integrated absorptance of the solar cell is reflected by the current density (J_{SC}) 610 of the solar cell. In the simulation of Fig. 6, simulation results of photocurrent generated under 100 mW/cm^2 AM 1.5G illumination shown by 610 and transmittance of 800nm IR light shown by 620 with varying ITO layer thicknesses are shown, wherein the thickness of the Ag layer in the Ag/ITO electrode is fixed at 20nm.

[0046] The region 630 in Fig. 6 indicates a thickness range of 60nm-120nm, where perovskite solar cell with reasonable visible light absorptance 610 and high IR transmittance 620 can be achieved if the thickness of the top ITO layer of the semi-transparent electrode is chosen within this range. The results in Fig. 6 indicate that the perovskite solar cell 102 with high IR transmission can be achieved at an ITO layer thickness of 90 nm, wherein the photocurrent 610 achieved for the solar cell with the semi-transparent Ag(20 nm)/ITO(90 nm) electrode is greater than 95% of that achieved with an opaque Ag electrode. The results in Fig. 6 also show that relative maximum light absorption in active layer occurs at an ITO layer thickness of 140 nm for the Ag/ITO electrode, wherein more than 47% of the incident IR light is transmitted.

[0047] Fig. 7 shows a plot 700 illustrating light transmittance performance of IR translucent solar cell 102 with a semi-transparent Ag/ITO electrode having a 120nm ITO layer and a 60nm ITO layer, respectively, according to various embodiments. In the

simulation of Fig. 7, the Ag layer of the semi-transparent Ag/ITO electrode is fixed at 20nm.

[0048] As shown in Fig. 7, the transmittance 710 of IR light for the semi-transparent Ag/ITO electrode of 60nm ITO thickness and the transmittance 720 of IR light for the semi-transparent Ag/ITO electrode of 120nm ITO thickness both increase substantially for IR light with wavelengths higher than 760nm. The transmittance 710 of IR light for the semi-transparent Ag/ITO electrode of 60nm ITO thickness is higher than the transmittance 720 of IR light for the semi-transparent Ag/ITO electrode of 120nm ITO thickness for IR light with wavelengths higher than about 800nm.

[0049] Fig. 8 shows a plot 800 illustrating J-V (current density-voltage) characteristics of a perovskite solar cell 102 with a semi-transparent Ag(20nm)/ITO(60nm) electrode according to various embodiments and a perovskite solar cell with opaque Ag electrode measured under simulated AM 1.5G illumination of 100 mW/cm².

[0050] The J-V characteristics measured under simulated AM 1.5G illumination of 100mW/cm² for the IR translucent perovskite solar cell 102 of FTO glass/TiO₂/CH₃NH₃PbI₃ /spiro-OMeTAD/Ag/LT.ITO structure is plotted as 820 and the J-V characteristics measured for the opaque control solar cell of 100nm Ag cathode is plotted as 810 in Fig. 8. The opaque control cell has a power conversion efficiency (PCE) of 12.6 ± 0.2%, while the IR translucent solar cell 102 of the embodiments above has a PCE of 12.0± 0.2%. It is envisaged that the quality of the semi-transparent cathode of Ag(20 nm)/ITO(60 nm) is suitable for application in IR translucent perovskite solar cell 102 of various embodiments above, as there was no observable deterioration in PCE for the IR translucent solar cell 102 relative to the control cell.

[0051] In order to achieve high transparency, a combination of Ag(20 nm)/ ITO(60 nm) cathode was selected for application in the IR translucent solar cells, resulting in an IR

transmittance (800 nm) over 40% and an integrated Jsc over 95% of that achieved by the opaque control device, as shown in the results of Fig. 7 and Fig. 8.

[0052] Fig. 9 shows a plot 900 illustrating J-V characteristics measured for an IR detector in the dark and radiated by an IR LED, with and without an IR translucent perovskite solar cell 102 of various embodiments.

[0053] In Fig. 9, the photoresponse 910 of the IR detector in the dark shows a photocurrent of 0 mA. According to the photoresponse 920 of the IR detector 106 when integrated with the IR translucent perovskite solar cell 102 of various embodiments above, there is about 50% reduction in photocurrent measured for the integrated IR detector as compared to the photoresponse 930 without the IR translucent solar cell 102. Such a reduction in current is anticipated and is attributable to the transparency or semi-transparency of the top electrode used in the solar cell 102, as more than 40% of the IR light is transmitted through and out of the perovskite solar cell 102. The on/off current ratios for the IR detector with and without the integrated solar cell 102 are both over 1000. Compared with the power consumption of 20 mW for the IR detector, the 80-100mW power generated by a 4cm² (2 cm x 2 cm) IR translucent perovskite solar cell is sufficient for a self-powered IR sensor of various embodiments.

[0054] The power dissipation of IR sensor can range from 50 mW to 300 mW, with the most common values being 75 mW, 100 mW, 215 mW and 250 mW. According to the self-powered sensor of various embodiments, the solar cell with a power conversion efficiency of 12% is enough to drive the sensor system with a small area of about 10-20cm².

[0055] According to various embodiments above, the solar cell 102 is translucent to light of the second wavelength range, e.g. the IR light, which is the activation source for the detector 106. The working principle of the self-powered sensor is that the solar cell 102 substantially absorbs light of the first wavelength range, e.g. visible light, for energy

harvesting and substantially transmits the IR light to the IR detector 106. The solar cell acts as a noise filter by absorbing the visible light (i.e. noise), thus increasing the sensitivity and accuracy of the IR detector 106. Through proper selection of the active materials in the active layer of the solar cell 102, and optimal design of the device structure of the solar cell 106 (i.e. the material and thickness of the electrode of the solar cell), the IR transparent solar cell 102 in the integrated sensor 100, 150, 300, 400, 500 may achieve 100% visible light absorption and 50% IR light transparency. From the simulation results above, it is shown that the integrated sensor possesses a high power conversion efficiency of 12% measured under air mass 1.5 global irradiation and is able to provide sufficient power, from a small device area, to drive the entire sensor system. The performance of the integrated sensor holds great potential for applications in the military, scientific analysis, homeland security, medical diagnosis, industrial and automotive areas. Besides applications such as heat and motion detection, the IR sensor can be used to achieve optical matching between the spectral responsivity of the IR translucent solar cell and the IR detection wavelengths.

[0056] According to various embodiments above, a self-powered sensor 100, 150, 300, 400, 500 is provided which integrates an IR detector with an IR translucent solar energy harvesting device (i.e. the solar cell) and an energy storage unit. The self-powered sensor 100, 150, 300, 400, 500 is configured into a self-powered, flexible, and lightweight assembly. The sensor platform, based on an integration of IR translucent photovoltaic device, such as an organic solar cell or perovskite solar cell, IR lighting and detector with power storage, provides significant cost benefits as well as functional superiority for applications in different low cost sensor devices, signal monitoring, and compact information systems. The solar cells 102 in various embodiments have visible light harvesting, energy generation, optical filtering (sensor noise reduction) and IR translucency functions combined in a single structure.

[0057] The self-powered sensor of various embodiments can be widely used in many applications where conventional power sources (wall socket or single charge batteries) are unavailable or inappropriate. These maintenance-free sensors are able to monitor processes over long periods even in industrial facilities and places with limited accessibility. The green sensor is self-powered, which requires minimal maintenance and does not draw power from the grid.

[0058] Fig. 10 shows a flowchart 1000 illustrating a method of forming a self-powered sensor 100, 150, 300, 400, 500 according to various embodiments. Various embodiments described above are analogously valid for the method described hereinafter, and vice versa.

[0059] At 1002, at least one of a thickness or a material for a transparent or semi-transparent electrode of a solar cell is selected dependent on a desired absorptance of the solar cell for light of a first wavelength range and a desired transmittance of the solar cell for light of a second wavelength range.

[0060] At 1004, the solar cell having the transparent or semi-transparent electrode with the selected at least one of the thickness or the material is provided. The solar cell is configured to at least substantially absorb light of the first wavelength range for generating electrical energy and configured to at least substantially transmit light of the second wavelength range.

[0061] At 1006, an energy storage is coupled to the solar cell for storing the electrical energy generated by the solar cell.

[0062] At 1008, a detector is electrically connected to the energy storage to receive the electrical energy, and to detect the transmitted light of the second wavelength range.

[0063] According to various embodiments, the first wavelength range may include a wavelength range of visible light, and the second wavelength range may include a wavelength range of infrared light.

[0064] According to various embodiments, the method may further include selecting at least one of the thickness or the material of the transparent or semi-transparent electrode to optimize at least one of the absorptance for light of the first wavelength range or the transmittance for light of the second wavelength range.

[0065] According to various embodiments, the thickness of the transparent electrode may be selected from a range of 60nm to 120nm. According to various embodiments, the thickness of the semi-transparent electrode may be selected from a range of 60nm to 170nm.

[0066] According to various embodiments, the material of the transparent electrode may be selected to include an indium tin oxide layer.

[0067] According to various embodiments, the material of the semi-transparent electrode may be selected to include an indium tin oxide layer and a silver layer.

[0068] According to various embodiments, the thickness and the material of the semi-transparent electrode may be selected to include the indium tin oxide layer with a thickness of about 60nm and the silver layer with a thickness of about 20nm.

[0069] According to various embodiments, providing the solar cell may include the following steps. A transparent substrate may be provided, wherein the transparent substrate may include one of an Indium tin oxide coated glass or a Fluorine-doped tin oxide coated glass. An electron transporting layer may be formed on the transparent substrate, wherein the electron transporting layer may include titanium dioxide, for example. An active layer may be formed on the electron transporting layer, wherein the active layer may include perovskite, e.g., methylammonium lead triiodide, $\text{LaVO}_3/\text{SrTiO}_3$, or $\text{H}_2\text{NCHNH}_2\text{PbX}_3$ ($\text{X} = \text{I, Cl, Br}$); or may include an organic/polymer material, e.g. P3HT, PTB7 or PCBM; or may include other thin film photovoltaic materials, e.g. ruthenium-polypyridine dyes (DSSC) or CIGS. A hole transporting layer may be formed on the active layer, wherein the hole

transporting layer may include spiro-OMeTAD. In other embodiments, the hole transporting layer may include polymer (e.g. P3HT, PTAA) and/or p-type nano material (e.g. MoS₂, graphene oxide). In an embodiment, the semi-transparent electrode may be formed on the hole transporting layer, which may include forming a silver layer on the hole transporting layer and forming an indium tin oxide layer on the silver layer. In another embodiment, the transparent electrode may be formed on the hole transporting layer, which may include forming an indium tin oxide layer on the hole transporting layer.

[0070] According to various embodiments, the detector may be sequentially aligned or overlaid with the solar cell along a direction of light transmission path to receive the light transmitted through the solar cell.

[0071] According to various embodiments, the detector may be integrated with the solar cell. According to various embodiments, the detector 106 is arranged to contact or face a surface of the solar cell 102 from which the light of the second wavelength range is transmitted.

[0072] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

Claims

What is claimed is:

1. A self-powered sensor, comprising:
 - a solar cell configured to at least substantially absorb light of a first wavelength range for generating electrical energy and configured to at least substantially transmit light of a second wavelength range;
 - an energy storage coupled to the solar cell for storing the electrical energy generated by the solar cell; and
 - a detector electrically connected to the energy storage to receive the electrical energy, and configured to detect the transmitted light of the second wavelength range;wherein the solar cell includes an electrode configured to have at least one of a selected thickness or a selected material dependent on a desired absorptance of the solar cell for light of the first wavelength range and a desired transmittance of the solar cell for light of the second wavelength range, wherein the electrode is transparent or semi-transparent;
- wherein the first wavelength range comprises a wavelength range of visible light, and the second wavelength range comprises a wavelength range of infrared light;
- wherein the detector is an infrared detector configured to detect the transmitted light of the second wavelength range comprising the wavelength range of infrared light;
- and
- wherein the solar cell is configured to act as a noise filter by at least substantially absorbing light of the first wavelength range comprising the wavelength range of visible light.

2. The self-powered sensor of claim 1,
wherein the electrode is configured to have at least one of the selected thickness or the selected material to optimize at least one of an absorptance of the solar cell for light of the first wavelength range or a transmittance of the solar cell for light of the second wavelength range.
3. The self-powered sensor of claim 1 or claim 2,
wherein the selected thickness of the transparent electrode is selected from a range of 60nm to 120nm; or
wherein the selected thickness of the semi-transparent electrode is selected from a range of 60nm to 170nm.
4. The self-powered sensor of any one of claims 1 to 3,
wherein the selected material of the transparent electrode comprises an indium tin oxide layer.
5. The self-powered sensor of any one of claims 1 to 3,
wherein the selected material of the semi-transparent electrode comprises an indium tin oxide layer and a silver layer.
6. The self-powered sensor of claim 5,
wherein the semi-transparent electrode comprises the indium tin oxide layer with a thickness of about 60nm and the silver layer with a thickness of about 20nm.

7. The self-powered sensor of any one of claims 1 to 6, wherein the solar cell comprises:
 - a transparent substrate;
 - an electron transporting layer arranged on the transparent substrate;
 - an active layer arranged on the electron transporting layer ;
 - a hole transporting layer arranged on the active layer; and
 - the transparent or semi-transparent electrode arranged on the hole transporting layer.
8. The self-powered sensor of any one of claims 1 to 7,
 - wherein the detector is sequentially aligned with the solar cell along a direction of light transmission path to receive the light transmitted through the solar cell.
9. The self-powered sensor of any one of claims 1 to 8,
 - wherein the detector is arranged to contact or face a surface of the solar cell from which the light of the second wavelength range is transmitted.
10. A method of forming a self-powered sensor, the method comprising:
 - selecting at least one of a thickness or a material for an electrode of a solar cell, dependent on a desired absorptance of the solar cell for light of a first wavelength range and a desired transmittance of the solar cell for light of a second wavelength range, wherein the electrode is transparent or semi-transparent;
 - providing the solar cell having the electrode with the selected at least one of the thickness or the material, the solar cell being configured to at least substantially absorb light of the first wavelength range for generating electrical energy and configured to at least substantially transmit light of the second wavelength range;

coupling an energy storage to the solar cell for storing the electrical energy generated by the solar cell; and

electrically connecting a detector to the energy storage to receive the electrical energy, and to detect the transmitted light of the second wavelength range;

wherein the first wavelength range comprises a wavelength range of visible light, and the second wavelength range comprises a wavelength range of infrared light;

wherein the detector is an infrared detector configured to detect the transmitted light of the second wavelength range comprising the wavelength range of infrared light;

and

wherein the solar cell is configured to act as a noise filter by at least substantially absorbing light of the first wavelength range comprising the wavelength range of visible light.

11. The method of claim 10, further comprising:
selecting at least one of the thickness or the material of the electrode to optimize at least one of an absorptance of the solar cell for light of the first wavelength range or a transmittance of the solar cell for light of the second wavelength range.
12. The method of claim 10 or 11, further comprising:
selecting the thickness of the transparent electrode from a range of 60nm to 120nm;
or
selecting the thickness of the semi-transparent electrode from a range of 60nm to 170nm.
13. The method of any one of claims 10 to 12, further comprising:

selecting the material of the transparent electrode to include an indium tin oxide layer.

14. The method of any one of claims 10 to 12, further comprising:
selecting the material of the semi-transparent electrode to include an indium tin oxide layer and a silver layer.
15. The method of claim 14, further comprising:
selecting the thickness and the material of the semi-transparent electrode to include the indium tin oxide layer with a thickness of about 60nm and the silver layer with a thickness of about 20nm.
16. The method of any one of claims 10 to 15, wherein providing the solar cell further comprises:
providing a transparent substrate;
forming an electron transporting layer on the transparent substrate;
forming an active layer on the electron transporting layer;
forming a hole transporting layer on the active layer; and
forming the electrode on the hole transporting layer.
17. The method of any one of claims 10 to 16, further comprising:
sequentially aligning the detector with the solar cell along a direction of light transmission path to receive the light transmitted through the solar cell.
18. The method of any one of claims 10 to 17, further comprising:

arranging the detector to contact or face a surface of the solar cell from which the light of the second wavelength range is transmitted.

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