Recent Progress in Solar Cell Technology for Low-Light Indoor Applications

Soyeon Kim1, Muhammad Jahandar1, Jae Hoon Jeong1 and Dong Chan Lim1,*

1Surface Technology Division, Materials Center for Energy Convergence, Korea Institute of Materials Science (KIMS), Changwon 51508, Republic of Korea

Abstract: Photovoltaic cells have recently attracted considerable attention for indoor energy harvesting for low-power-consumption electronic products due to the rapid growth of the Internet of Things (IoT). The IoT platform is being developed with a vision of connecting a variety of wireless electronic devices, such as sensors, household products, and personal data storage devices, which will be able to sense and communicate with their internal states or the external environment. A self-sustainable power source is required to power such devices under low light indoor environments. Inorganic photovoltaic cells show excellent device performance under 1 Sun illumination and dominate the market for outdoor applications. However, their performance is limited for indoor applications with low incident light intensities as they exhibit low photo-voltage. Among the emerging photovoltaic technologies, organic photovoltaics have unique advantages, including solution processibility, flexibility, and lightweight tailorable design; hence, they are considered the best solution for indoor light harvesting applications due to their high photo-voltage, strong absorption of UV-visible wavelengths, and a spectral response similar to that emitted by modern indoor lighting systems. In this review article, we discuss the factors affecting device performance of different photovoltaic technologies under low incident light intensities or indoor conditions and provide a comprehensive analysis of future opportunities for enhancing indoor performance of the photovoltaic devices. Furthermore, we discuss some of the results of semi-transparent organic solar cell which is operated under complex environmental conditions like low illumination, incident light angle etc. Based on the results, one can suggest that semi-transparent organic solar cell is more suitable for progressive indoor solar cell. After highlighting the factors that limit indoor device performance of photovoltaic cells, we discuss potential applications of IoT devices powered by organic photovoltaic cells in indoor lighting environments.

Keywords: Indoor lights, indoor photovoltaics, IoT, low-light intensity, photovoltaics, transparent OPV.

1. INTRODUCTION

As society moves towards renewable energy sources in order to decarbonize electric power generation, Photovoltaic (PV) technologies are expected to play an important role. The continuous research and development of high-efficiency, low-cost, and solution-processible PV technologies can provide an infinite source of energy and novel opportunities to exploit PV in energy harvesting applications from low-light intensity/indoor environments [1-13]. In such applications, solar cell devices need to operate under very different conditions than those experienced outdoors, e.g., light illumination intensities that are typically 10-1000 times lower than direct sunlight, different orientations, and different light source spectra [2, 5, 7, 10]. The development of a light-harvesting technology that provides significant output power under low-light intensity and indoor environments has great prospects for applications in the field of domestic and building management systems. Energy harvesting under low-light intensity or indoor conditions has attracted considerable attention due to the unique requirements of the Internet of Things (IoT). The IoT concept promises a future where a wide variety of devices, such as consumer electronics, sensors, household products, and personal data storage devices will be connected through the internet and will be able to sense and communicate with their internal states or the external environment. Such devices will be integrated with wireless communication systems and are expected to be independent of the electric grid, so self-powered systems are essential [14-18].
Over the last decade, a tremendous increase in device performance of various PV materials, such as crystalline silicon (c-Si), amorphous silicon (a-Si), Copper Indium Gallium Selenide (CIGS), Organic Photovoltaics (OPV), Perovskite Solar Cells (PSC), and Dye-Sensitized Solar Cells (DSSC), has been reported under outdoor and simulated AM 1.5G spectral conditions. Although c-Si, a-Si, and CIGS PVs have shown excellent device performance under 1 Sun conditions and dominated the market for outdoor applications, they exhibited low photo-voltages and a significant drop in performance when used under low-light intensities or indoor conditions [19-27]. Furthermore, as the PV industry has been developed with the aim of mass producing Si-based devices for outdoor applications, the options for customizing the device architectures, designs, geometries, and fabrication processes to suit new applications are limited. Among the emerging PV technologies, OPV, PSC, and DSSC technologies have the unique advantages of solution processibility, flexibility, lightweight components, and the ability to customize the design and geometry. Hence, they are currently considered the best candidates for indoor light harvesting applications due to their high photo-voltages and spectral response in the visible region [28-32].

2. DESIGN CONSIDERATIONS FOR OPTIMIZING INDOOR PV PERFORMANCE

The existing body of literature is limited regarding the photovoltaic performance of PV devices under low-light or indoor environments. In particular, in the case of emerging solution-processed PV technologies, there are very few reports of PV performance under such conditions and no standard testing conditions or models have been developed [33-38]. Several researchers have studied the device performance of various PV technologies under low-light conditions, indoor artificial light sources, and various light intensities of different spectra. Some studies provided a basic understanding of the development of simulation tools and PV performance models for indoor conditions [39-41].

It is a well-established fact that the output power of a PV device depends on the spectra and intensity of the incident light source, size of the PV module/device, and the distance between the device and the light source. A schematic illustration describing these factors is shown in Fig. (1). The most important factor, which can significantly affect the PV device performance under indoor light conditions, is the spectral response of the device. Fig. (2) shows the spectra of various light sources used to evaluate PV device performance under standard measurement conditions and low-light or indoor conditions.

In general, PV device performance is characterized by measuring I-V curves under standard testing conditions (AM 1.5G, 100 mW/cm², 25°C). The fundamental difference between indoor and outdoor applications is the spectrum and intensity of the light source. The standard solar spectrum (AM 1.5G) is shown in Fig. (2h), overlaid with the spectral response of various PV technologies. The majority of light
Recent Progress in Solar Cell Technology for Low-Light Indoor Applications

Current Alternative Energy, 2019, Vol. 3, No. 1

Fig. (2). Spectra of the different indoor light sources. (a) Xenon lamp, (b) incandescent lamp, (c) fluorescent lamp, (d) halogen lamp, (e) cool white LED, (f) warm white LED, (g) human eye sensitivity spectrum, and (h) AM 1.5G spectrum overlaid with spectral response of various photovoltaic devices. (A higher resolution / colour version of this figure is available in the electronic copy of the article).

Sources currently used for indoor lighting are fluorescent lamps, incandescent lamps, and Light-Emitting Diode (LED) lamps. Both fluorescent and white LED lamps are used for indoor applications and they emit light in wavelength ranges from 350 nm to 750 nm. While the size of the device, distance from the light source, and light source intensity have significant effects on the output power in indoor environments, the spectral response of the PV device under indoor light conditions is the most crucial factor determining the output power. As indoor light sources emit radiation in the UV-vis spectral range, PV devices with good spectral response in the visible region are suitable candidates for indoor applications.

Besides, these considerations for efficient indoor PV device operation, the angle of incident light to the PV device or the orientation of the PV device and transparency of the PV device could also affect the device performance and need to be considered as an important factor.

3. CHOICE OF PHOTOVOLTAIC MATERIALS FOR INDOOR OPERATION

The major energy source available in buildings is light, which can be easily collected using PV devices. The available indoor light source can be either natural or artificial light and there is a range of available PV technologies to suit different type of light sources and intensities. As the artificial light sources (with different spectral properties) are changing over time, from incandescent and fluorescent light to LED lights, which are currently attracting significant interest due to the significant energy savings they provide, it is important to select a suitable PV material to match the indoor light source spectrum and intensity in order to optimize the output power.

To date, silicon-based solar cells dominate the market share for outdoor PV applications due to their spectral response designed to match natural sunlight. The spectral sensitivity mismatch of commonly used indoor lighting e.g., fluorescent and LED lamps limits the performance of silicon solar cells for indoor applications. Li et al. studied polycrystalline silicon and a-Si solar cells under different light sources (incandescent, fluorescent, and LED lamps) with 500 lx light intensity to investigate the influence of the spectral response and suitability of the different solar cells for given combinations of light source and intensity. Fig. (3) shows photographs of the different types of Si-based PV devices used in the study and their output power under different light sources with a light intensity of 500 lx [42]. In general, the polycrystalline (MC-SP0.8) and amorphous (AM-5608 and AM-1815) silicon solar cells showed maximum output power under an incandescent lamp illumination, followed by compact fluorescent and white LED lamps. Among these three types of silicon solar cells, the polycrystalline cell showed a much higher output power under the incandescent illumination compared to the compact fluorescent or LED lamps, which could limit the scope of such cells to only incandescent light sources. The major factor restricting the use of polycrystalline silicon solar cells in indoor environments is its poor spectral response under the UV-vis spectrum.
Over the past few years, solution-processed OPV technology has attracted considerable attention due to the simple processing method and the large-scale roll-to-roll manufacturing process that allows upscaling of the technology. The development of new donor materials increased the Power Conversion Efficiency (PCE) from less than 4% to over 11% (under 1 Sun) in a short period of time [43-45]. With an increasing interest in the development of PV technologies for indoor applications, OPVs are becoming the most promising contender as it is easy to tune their bandgap and they have a well-matched spectral response to the UV-vis spectrum emitted by common indoor fluorescent and LED lights. The dynamic change in research trends from poly(3-hexylthiophene-2,5-diyl) (P3HT) donor material to new poly[N-9′-heptadecanyl-2,7-carbazole-alt-5,5-(4′,7′-di-2-thienyl-2′,1′,3′-benzothiadiazole)] (PCDTBT), poly[[4,8-bis[(2-ethylhexyl)oxy] benzo[1,2-b:4,5-b′]di(thiophene-2,6-diyl)][3-fluoro-2-[(2-ethylhexyl)carbonyl]thieno[3,4-b]thiophenediy]] (PTB7), and several other novel donor materials, has extended the horizon of highly efficient organic PVs and taken a step forward towards commercialization of low-cost PVs. To date, the device performance of most Bulk-Heterojunction (BHJ) systems has been evaluated under 1 Sun conditions. Recently, some few studies of organic PV systems have been performed, including polymer and organic small-molecule based devices for indoor applications [46-48].

Harrison et al. studied three representative donor polymer materials (P3HT, PCDTBT, and PTB7) in blends with fullerene derivatives to investigate their response to low-light conditions using fluorescent lamps [49]. Among these three systems, PCDTBT-based BHJ devices performed best, producing 13.9 µW/cm² output power, corresponding to a PCE of 16.6% at 300 lx (Fig. 4b). On the other hand, PTB7-based devices showed the highest efficiency under 1 Sun conditions (Fig. 4a), but the low open circuit voltage under low-light limited the overall device performance compared to PCDTBT. The high performance of these OPV blend systems under low-light intensity demonstrated the reasonable potential to the other PV technologies regardless of much lower device performance under 1 Sun condition. They also studied other device performance parameters in order to better understand the device behavior under low-light intensities and fabricated a 14 cm × 14 cm OPV module with a large active area of 100 cm², which showed a PCE of 11.2% under a low-light intensity of 300 lx, as shown in Fig. (4c-e).

Recently, Aoki reported exciting device performance results for OPVs for indoor energy harvesting under fluorescent and LED light sources [50]. Fig. (5) shows a schematic of the developed OPV module and typical J-V curves of both OPV and a-Si solar cells under illumination of 50-1000 lx. Due to the well-matched absorbance spectrum of the OPV device with the emission spectrum of room light, the current density of the device was much higher than that of a comparable a-Si module. Furthermore, the device performance under LED light was analyzed as it is currently the preferred indoor lighting source. Daylight LED (color temperature 5000 K) and warm-color LED (color temperature 2700 K) light sources were used, while full white fluorescent light (color temperature 5000 K) was used as a reference. OPV absorbers have narrow and broad External Quantum Efficiency (EQE) curves over the range of 370 to 720 nm, depending on the material, and cover the full emission spectrum of LEDs, whereas a-Si has a peak in the EQE curve at 600 nm and lower EQE values for wavelengths <400 nm and >650 nm compared to OPV materials. Hence, the OPV showed higher device performance under all tested indoor lights (light intensity of 1000 lx) compared to the a-Si device.

Most recently, Harrison et al. reported solution-processible small-molecule PV cells as a potential candidate for indoor energy harvesting [51]. They obtained a PCE over 10% under standard measurement conditions (1 Sun, AM 1.5G), and a PCE of over 28% under a fluorescent lamp with
a light intensity of 1000 lx, by optimizing the photoactive layer using the solvent vapor annealing technique. These results are not only higher than Si-based PVs, but are also comparable to the performance of gallium arsenide PV cells (Fig. 6a, b). In addition, the ratios of the voltage at the Maximum Power Point (MPP) to the Open Circuit Voltage (OCV) were similar for indoor and 1 Sun conditions, which is unique and allows a less-power-consuming method to track the MPP for a broad range of light intensities (Fig. 6c). Furthermore, they estimated the charging time for rechargeable batteries of different capacity under 1000 lx, as shown in Fig. (6d). Although the charging time was long, it could be sufficient for electronics that consume less power than the average output power of the indoor PV cells.

In addition, a solution-processible PV technology that has recently attracted a great deal of attention for indoor energy harvesting is Perovskite Solar Cells (PSC), due to their bandgap tunability and spectral response suitable for indoor lighting spectra. In a short period of development, PSCs have achieved PCE values over 21%; however, their anomalous hysteresis is a complex issue that makes reliable assessment of the device performance difficult [52, 53]. In order to address these challenges, Ludmila et al. proposed two assessment methods for measuring the PCE of PSC. The first method is the measurement of device performance using a solar simulator based on an LED light source with a wide range of light intensities (0.001 to 100 mW/cm²) (Fig. 7a-d) [54]. As the overestimate error, the PCE of Dye-sensitized Solar Cell (DSC) and PSC devices increase dramatically at low-light intensities due to the internal capacitance at the interfaces of hybrid solar cells, the measurement of current below 0.01 mW/cm² shows constant value given high PCE, which is related to the capacitive current and origin of the
hysteresis (Fig. 7e). The author suggested using a combination of the LED solar simulator and $P_{\text{max}}$ tracking as a standard to evaluate the PCE of these types of solar cell technologies. The current from the c-Si solar cell could not be measured at 0.001 mW/cm$^2$ due to a lack of any photo response, while the DSC and PSC devices showed constant measurable current values, even below 0.001 mW/cm$^2$.

Although the device performance of OPV cells is significantly lower than c-Si and PSC devices under standard simulated AM 1.5G illumination, it is superior under LED light, which is increasingly used as an indoor light source. Christie et al. compared the device performance of silicon PV cells under various illumination sources other than AM 1.5G and observed that changing the light source from AM 1.5G to...
indoor lights changed both the intensity and spectrum of the incident light [55]. The device performance of the c-Si PV cells was strongly dependent on the light source intensity, with a weak dependence on spectrum. They showed that a PCE of over 20% can be achieved using OPVs with a white LED light source, which was similar to the value obtained for polycrystalline silicon PVs, but higher than a-Si and CIGS solar cells (Fig. 8). OPV devices have shown high PCE values under various indoor light sources and measurement conditions while having the unique advantages of being flexible, lightweight, ultrathin, and semitransparent. These promising properties demonstrate the high potential of OPV devices for indoor energy harvesting applications.

Finally, Minnaert et al. proposed a technique for studying the PV device performance for indoor applications by characterizing the devices under artificial light sources [56]. Their study compared different types of PV technologies under various indoor environments by simulating the efficiencies based on the quantum efficiencies of the different PV cells and the spectra of artificial light sources. The light sources used in their study were a white Fluorescent Lamp (F2), broadband Fluorescent Lamp (F7), narrow tri-band Fluorescent Lamp (F11), standard high-pressure sodium lamp (HP1), standard metal halide lamp (HP5), cool LED, and warm LED. The spectrum of each light source and EQE spectra of the various PV technologies are shown in Fig. (9). The indoor light sources were categorized into three different classes according to the indoor PV device performance. Hence, it is not necessary to test the devices under all artificial light sources to demonstrate their potential for indoor lighting environments. Therefore, the PV cells can be measured under one light source, depending on their spectral response, in order to characterize their suitability for indoor applications.

4. PERSPECTIVES TO IMPROVE PERFORMANCE OF INDOOR PV DEVICES

The design of PV devices for indoor applications is undoubtedly a challenging task due to the range of different light conditions related to the various light sources used inside buildings and their variations in intensity and spectral characteristics. Indoor PVs must be optimized for specific illuminance conditions. Therefore, regardless of the device type, general light management approaches for indoor PV, such as light trapping, use of the surface plasmonic effect, and spectrum matching with the light source, are also being intensively investigated. In this section, we discuss various approaches for improving the performance of indoor PV devices.

4.1. Light Trapping by Anti-Reflection Coatings and Surface Texturing

Conventional light trapping methods used for silicon solar cells (application of Anti-Reflection Coatings (ARC) and surface texturing), have already resulted in effective light trapping performance. An ARC is an optical coating applied to the surface of a film to reduce reflection. ARCs consist of a thin layer of dielectric material, with a specific thickness able to introduce interference effects in the coating; the wave reflected from the top surface of the ARC is out of phase with the wave reflected from the semiconductor surfaces. These out-of-phase reflected waves destructively interfere with one another, resulting in reduced reflectance [57-61]. The principle of light trapping was shown in Fig. (10).

Surface texturing involves roughening the surface of a substrate or various layers in the PV structure to form an uneven or pyramid-like pattern on the surface. The pyramid pattern increases the light absorption due to scattering and multiple reflections from the sloping pyramid walls, where some of the reflected light can impact other walls and be absorbed, rather than lost. This increased light absorption results in higher cell efficiency. A recent study demonstrated optical amplification using polystyrene particles on silicon surfaces [62].

Therefore, ARC and surface texturing methods can achieve light trapping and reduce light reflectance. In addition, internal reflection from the back of the PV can increase the length of the absorption path in the solar cell and the total light absorption. Hence, these methods allow operation of the solar cell with weak light intensity.
Fig. (9). (a-c) Spectral irradiance of different light sources (d) EQE of different photovoltaic technologies. (e) Calculated relative output power of various photovoltaic cells under different light conditions compared to AM 1.5G spectrum as a reference. *(A higher resolution / colour version of this figure is available in the electronic copy of the article).*

Fig. (10). Light trapping by (a) surface texturing and (b) Anti-Reflection Coating (ARC). *(A higher resolution / colour version of this figure is available in the electronic copy of the article)*.
4.2. Surface Plasmonic Effect

Plasmons are the oscillations of coherent delocalized free electrons in metals. In metal nanoparticles, the plasmons are surface plasmons that exist locally on the particle surface. Surface Plasmon Resonance (SPR) refers to the resonant oscillation of conduction electrons at the interface between materials with a negative dielectric constant (e.g., metal) and positive dielectric constant when stimulated by incident light. SPR is an interaction between electromagnetic waves and plasmons, which is usually observed in the visible to near-infrared wavelength range. The produced plasmon-polariton has the increased size than incident light and properties and shape of an exponentially decreasing extinction wave (evanescent wave) with distance at the vertical direction from the interface [63]. The SPR phenomenon results in light energy being converted to surface plasmons and accumulated on the surface of metal nanoparticles. Hence, light can be manipulated over dimensions smaller than the diffraction limit of light.

There are two types of SPR phenomena: Propagating Surface Plasmon Resonance, (PSPR) observed smooth plate-shaped metal (10-200 nm thick) and dielectric interface, and a Localized Surface Plasmon Resonance (LSPR) observed in metal nanoparticles. This photo-controlled SPR phenomenon can be useful for trapping light in solar cells. The SPR phenomenon can be applied in solar cell in three different ways, as shown in Fig. (11). The first method involves depositing metal nanoparticles on the light incidence surface to promote scattering and increase the length of the path of the light in the device to enhance absorption.

Second, the LSPR effect serves as a subwavelength antenna, which increases the electric field of light in the wavelength range where LSPR occurs. This allows more electrical energy to be generated at a specific wavelength. Finally, the third method involves the use of wave-shaped metal films that trap light by surface plasmon-polariton excitation at the metal-semiconductor interfaces, increasing light absorption.

Therefore, the SPR effect can also be effectively applied in solar cell research focusing on indoor environments [64-66].

4.3. Spectrum Matching

As shown in Fig. (2), the spectrum of indoor light (including incandescent lamps, LEDs, and halogen lamps) is mainly located in the visible region, so the energy band gap of indoor PV devices needs to be optimized for this spectrum, rather than that of the sun. In the case of commercial c-Si solar cells with an efficiency of 18% in Standard Test Condition (STC) (generally, AM 1.5G spectrum (100 mW/cm² (1 Sun)), the efficiency drops significantly to below 5% under indoor lighting; it is necessary to distinguish between the spectrum and the intensity of light when analyzing factors affecting efficiency. The loss according to the spectrum is generated by thermal motion (thermalization) and spatial relaxation of charge carriers, and non-absorption of light. The theoretically optimized Eg for the spectrum of AM 1.5G is approximately 1.3 to 1.4 eV, while that for general interior lighting of the reference Fig. (12) has a wider Eg of about 1.9 eV (650 nm), corresponding to a theoretical efficiency of up to 60% under LED light. In the case of sodium discharge lamp, an optimum Eg of 2.1 eV (590 nm) gives a 70% efficiency, while for a monochromatic light sourced an optimum Eg of 3.5eV (350 nm) gives an 80% efficiency [67]. Comparing the various materials available for indoor applications, wide-Eg materials such as Si, CdTe, perovskites, dye, a-Si, GaInP, and OPV are potential candidates. Hence, it is expected that improved performance of indoor PV devices will be achieved via further materials research to match the Eg of PV materials to the spectra of indoor light sources. Recent studies have demonstrated spectral matching for various materials [68-70].

5. LOW-LIGHT INTENSITY OPERATION OF SEMI-TRANSPARENT ORGANIC PHOTOVOLTAICS

Due to design flexibility and transparency with high open-circuit voltages, organic photovoltaics obtained prominent attention for low-light intensity or indoor applications. Besides, the incident light spectra and distance of the photovoltaic device from the light source, the indoor light intensity and orientation of the photovoltaic device to the incident light are the major factors that could translate the photovoltaic device output power. To show the potential of organic photovoltaics for indoor energy harvesting under 2000 lx with respect to the incident light angle, we designed the semi-transparent organic solar cells modules having MoO3/Ag/MoO3 (OMO) semi-transparent electrode.

Fig. (13a) shows the non-transparent and semi-transparent 10 x 10 cm² organic solar cell modules with an active area of 40 cm². Under standard measurement condition (1 Sun, 100 mW/cm²), the non-transparent and semi-transparent solar cell modules showed maximum output power of 321 mW and 214 mW respectively. Whereas, under room light with intensities of 2000 lx and 750 lx, the semi-transparent...
OPV module shows relatively higher output power (Fig. 13b). The difference is clear, as under low light intensity, all the light is absorbed by the active layer and there is a negligible light reflection from the non-transparent silver electrode and re-absorption in the active layer. On the other hand, in the case of semi-transparent OPV module, there is a direct light absorbance from the ITO/glass substrate side as well as indirect/reflective light absorbance from semi-transparent OMO electrode side that improves the overall output power of semi-transparent OPV module under low-light illumination as compare to non-transparent OPV module. The phenomena of light absorbance in non-transparent and semi-transparent OPV modules is illustrated schematically in Fig. (14a) and the contribution of the output power under 2000 lx light intensity with respect to the OPV module illumination side are illustrated in Fig. (14b). In the case of light illumination from substrate side (bottom), the output power of non-transparent OPV module is higher than semi-transparent OPV module. Whereas, in case of light illumination from the electrode side (top), the output power of semi-transparent OPV module is higher. We compared output power of both type of OPV modules after the sum of top and bottom sides and found that the power of semi-transparent OPV module is higher than non-transparent OPV module under low illumination.

To further investigate the potential of non-transparent and semi-transparent OPV modules for indoor light applications, we measured the output power of both types of modules with respect to the incident light angle under a light
Recent Progress in Solar Cell Technology for Low-Light Indoor Applications

6. APPLICATIONS

To date, most research groups have studied solar cells for outdoor applications, such as streetlights and Building Integrated PVs (BIPVs). As these solar cells are powered by the sun, they obviously only generate power during the day (intensive energy collection over a short period), while indoor PV can generate power continuously. Due to their current low efficiency under indoor light illumination and little active research in this field, indoor PV products have not been widely commercialized. However, continuous power generation using Product-Integrated PVs (PIPVs) driven by indoor light is becoming increasingly attractive for powering small appliances that do not have large power requirements. In this section, we review the power requirements of applications in indoor environments. To compare the power consumption, we used commercially available PIPVs for which we compared the maximum power under artificial irradiance with a Compact Fluorescent Lamp (CFL), as shown in Fig. (16a). In general, commercially available PIPVs have a power range intensity of 2000 lx (Fig. 15). On direct light illumination ($\theta = 90^\circ$), the non-transparent OPV module shows higher output power than semi-transparent OPV module whereas, this difference reduces significantly at an angle of $45^\circ$ and semi-transparent OPV module outperforms at an angle of $0^\circ$ where no direct light is illuminated to the OPV module. Our experimental results suggest that the semi-transparent photovoltaics could perform better compare to non-transparent photovoltaics under indoor environment, especially when the photovoltaic devices are not directly illuminated by the indoor lightening system.

Fig. (14). (a) Schematic illustration of the non-transparent and semi-transparent OPV device structure and bifacial absorption of light, (b) Bifacial power of non-transparent and semi-transparent OPV module under low-light illumination (2000 lx). (A higher resolution / colour version of this figure is available in the electronic copy of the article).

Fig. (15). (a) Scheme of the angle dependence measurements. (b) Power change of non-transparent and semi-transparent OPV module with various incident light angle (angle dependence) under low-light illumination (2000 lx). (A higher resolution / colour version of this figure is available in the electronic copy of the article).
Fig. (16). (a) Power requirements of various applications with a built-in solar cells and (b) product-integrated PVs (PIPVs). (A higher resolution / colour version of this figure is available in the electronic copy of the article).

Fig. (17). Photographs of various potential indoor OPV applications. Lamp-integrated OPVs: (a) flexible type (b) rigid type (c) Various kinds of Arduino UNO sensors (d) Handrail UV cleaner (by CLEARWIN) linked to flexible OPVs (by KIMS & KOLON) which was exhibited at the KIMS Tech Fair 2018 in CECO. (A higher resolution / colour version of this figure is available in the electronic copy of the article).
of 1 µW to 100 mW. These products are based on the physical measurement of artificial and natural light illumination in an indoor environment. A PV mouse (Bondidea) with a built-in a-Si solar cell had a power consumption of 0.41 mW under CFL light illumination. An a-Si solar cell remote control (Philips) had a power consumption of 0.77 mW, while a kitchen scale with a built-in multi-crystalline silicon (mc-Si) solar cell had a power consumption of 0.96 mW. Schematic diagrams of various potential indoor PIPV applications are shown in Fig. (16b), which all have a low power consumption (<1 mW) [71].

Due to the outstanding performance of OPVs compared to Si solar cells under indoor light illumination, they can generate power more than Si solar cells. For example, a 10% PCE OPV (10 cm × 10 cm) generated 5-10 mW under 0.5-1 mW/cm² illumination (~500-1000 lx), whereas an a-Si cell of a similar size generated only 1.2 mW. By taking advantage of OPV materials, our research group has produced products that can be used in daily life. Such products include an OPV with an output power of 500 mW that directly absorbs light from indoor lamps and can operate an Arduino UNO microcontroller or mini air conditioner. Moreover, due to the flexibility of the OPV, it can be used on flexible curved surfaces like curtains, blinds, and lampshades, which is not possible with rigid Si solar cells. Photographs of lamp-integrated OPVs are shown in Figs. (17a-17c) shows various sensors with functions closely related to our daily activities that could be powered by an Arduino UNO, including a (i) kit body, (ii) ultrasonic distance sensor, (iii) light flux sensor, (iv) soil moisture sensor, (v) fine dust sensor, (vi) digital humidity sensor, (vii) Bluetooth sensor, (viii) near-infrared motion sensor, (ix) analogue temperature sensor, (x) analogue humidity sensor, (xi) digital temperature sensor, (xii) knock sensor, (xiii) vibration sensor, and (xiv) heart beat sensor. The kit body (Fig. 17c (i)) requires a power consumption of ~300 mW, while the others (Fig. 17c (ii)-(xiv)) require a power consumption of <100 mW. Moreover, a UV handrail cleaner (CLEARWIN) based on an OPV device (by KIMS & KOLON) is shown in Fig. (17d); this product was exhibited at the KIMS Tech Fair 2018 in Changwon Exhibition Convention Center (CECO) and received much attention. In summary, both OPVs and existing PIPVs (silicon solar cells) can be integrated into various applications, such as mouse, remote control, laser pointer, smart card, kitchen weight scale, wristwatch, e-price label, wireless sensor, and charger devices, as well as office and house appliances. These applications can be powered by PVs equipped with batteries.

CONCLUSION

In summary, we have reviewed the various photovoltaic technologies and discuss the potential of these photovoltaic technologies for indoor energy harvesting and highlight the key factors to be considered during the evaluation of the photovoltaic devices for indoor applications. Silicon photovoltaics may dominate the market for large power outdoor applications due to their spectral response designed to match natural sunlight but, may not be ideal for low power indoor applications due to spectral mismatch of commonly used indoor lighting systems. Among the emerging PV technologies, organic photovoltaics have the unique advantages of solution processibility, flexibility, lightweight, and the ability to customize the design and geometry and have great potential for indoor light harvesting applications due to their high photo-voltages and well-matched spectral response in the visible region. The better device performance of organic photovoltaics under dim/low-light intensity compared to other photovoltaic technologies opens a new untapped avenue for indoor energy harvesting applications.

CONSENT FOR PUBLICATION

Not applicable.

FUNDING

This work was supported by Korea Institute of Materials Science (KIMS) and by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (MOTIE) (2018201010636A, Development of energy harvesting materials and modules for independent power source for smart sensors and 20173030014180, Development of transparent flexible metal grid electrode films for solar cell application).

CONFLICT OF INTEREST

None of the authors of this review paper has a competing interests and financial relationship, direct or indirect, with other people that could inappropriately influence or bias the content of the paper.

ACKNOWLEDGEMENTS

S. Kim and M. Jahandar contributed equally to this work. Moreover, the authors would like to thank all members of Materials Center for Energy Convergence under Korea Institute of Materials Science (KIMS).

REFERENCES


Recent Progress in Solar Cell Technology for Low-Light Indoor Applications


