Emerging Photovoltaics for Self-Sustaining Devices

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Abstract
We present a short overview of emerging photovoltaic (PV) technologies in the context of their application has optical energy harvesters in self-sustaining devices. Thin-film photovoltaic technologies enable the fabrication of low-cost, large-area PV harvesting systems. Under the lighting conditions of our typical living environments, the ability to tune their absorption spectra through bandgap engineering in emerging PV cells, offers the possibility to reach superior performance when compared with commercial Si PV technologies. To date, these emerging technologies show a power conversion efficiency with values in the range from 25 to 35%. This makes it possible for a single squared centimeter of these emerging PVs, to produce from tens and up to a few hundreds of microwatt of electrical power under artificial lighting. This enormous potential to harvest energy from ambient light should enable a wide range of self-sustaining devices.

Author Keywords
Photovoltaic cells; Energy harvesting.

CSS Concepts
• **Hardware~Power and Energy~Energy generation and storage~Renewable energy**; *Photovoltaic devices*;

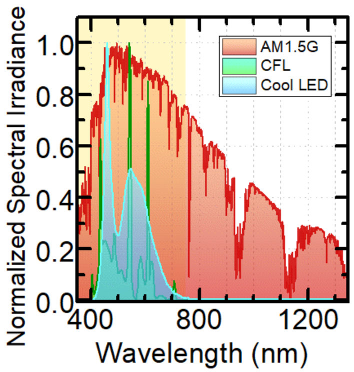

Figure 1: Normalized spectral irradiance of sunlight, CFL and LED light sources.

Introduction

Our living environments are flooded with light. The resources of optical energy from natural and artificial sources are enormous but largely untapped to produce the electrical power needed to enable the sensing, computing, communication and actuation of self-sustainable interactive devices [1-3].

The photovoltaic effect is one of the most efficient ways to convert optical into electrical power. The photovoltaic effect occurs in photodiodes; two-terminal devices with a build-in asymmetry designed to allow unidirectional current flow across a light-sensitive semiconducting layer. When light is absorbed in the semiconducting layer, this asymmetry enables the generation of a photovoltage and a photogenerated electric current across the two terminals of the device and results in the generation of electrical power. The efficiency of this conversion, known as the power conversion efficiency (PCE), is ultimately limited by the probability associated with light being absorbed in the semiconducting layer and with the conditions of thermodynamic equilibrium between the device and its environment. Photodiodes operated in the so-called photovoltaic mode (*i.e.* in forward bias), are colloquially known as solar cells but we will refer to them as photovoltaic (PV) cells.

Here we will highlight recent developments on emerging PV technologies, particularly organic [4, 5] and metal-halide perovskite [6, 7] PVs. We will discuss potential and challenges faced by these PV technologies for the development of self-sustainable interactive devices.

Light sources

Sunlight is the most abundant source of optical energy at our disposal. Fig. 1 shows the spectral distribution of sunlight on earth's surface; closely resembling the emission spectrum of a blackbody at ca. 5800 K with a peak wavelength near 500 nm. Light sources are characterized by their spectral irradiance per unit wavelength. The global standard spectrum, called air mass 1.5 global (AM1.5G), has a peak irradiance ca. 155 $\mu Wcm^{-2}nm^{-1}$ and a total irradiance of 100 $mWcm^{-2}$.

In contrast, indoor light sources typically operate at irradiance levels that are between 10 and 0.1 $mWcm^{-2}$. Artificial light sources used for indoor illumination have very narrow spectral bandwidths when compared to sunlight. Figure 1 also shows the spectral irradiance of a white light-emitting diode (LED) and a compact fluorescent lamp (CFL). This is a critical difference, because as we will discuss, this implies that theoretical maximum values for the PCE of PVs designed for artificial light can be higher than those for sunlight.

In a living environment, many sources of light may contribute to the total illuminance or spectral irradiance. The overall light collected by a PV cell is then the linear combination of the contributions of individual light sources. To optimize energy generation, PV cells need to be designed for specific lighting conditions where they will operate. For instance, in a particular study conducted in Germany over the winter [8], it was estimated that during a 30 day period the irradiance over a wall opposite of a window in a west-facing room typically varied from 0 to ca. 700 μWcm^{-2}. Surprisingly, they also found that artificial light sources (CFL in this particular case) contributed only ca. 35% of the total irradiance at that particular location. In some particular days, the irradiance increased up to 5 $mWcm^{-2}$ during sunset. This highlights the need for designing PV harvesting systems for their specific operational environment. Also, they

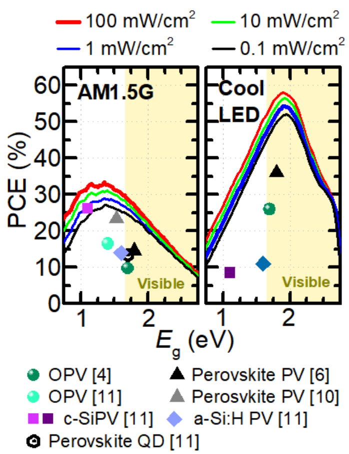

Figure 2: Theoretical limit of the PCE as a function of the PV's bandgap for sunlight with a standard AM1.5G spectra and a cool LED spectra with various irradiance values. Symbols are the experimental PCE values reported in the literature and certified by NREL for some emerging PV technologies and for c-Si and a-Si:H PV.

estimated that the room received an average irradiance of 80 μWcm^{-2} in that particular month.

Theoretical limits

To estimate how much optical power can be converted into electricity by a PV cell, we use the principle of detailed balance to provide a theoretical estimation of this limit [8, 9]. This approach only takes into account losses due to radiative recombination, and neglects other loss mechanisms such as optical, thermal and resistive losses. The particular device design and semiconductor material in the PV cell influences these losses.

Following [8], we used the spectral irradiance in Figure 1 and the software EtaOpt to calculate the theoretical limits under AM1.5G sunlight, hereon referred to as sunlight, and Cool-LED illumination for the PCE of PV cell having a semiconductor layer with a bandgap energy (E_g). The spectral irradiance of these sources varied from 100 mWcm^{-2} to 0.01 mWcm^{-2}, to capture the typical range of irradiance values found outdoors and indoors. Here, E_g represents the minimum energy that a photon needs to have for it to be absorbed by the semiconductor and produce free charge carriers in a PV cell. The E_g in these simulations was varied from 0.75 eV (corresponding to a wavelength of 1653 nm) to 2.75 eV (or 451 nm).

Lines in Figure 2 show the irradiance dependent theoretical PCE maximum values as a function of E_g. The PCE increases as a function of irradiance and reaches a maximum value of 33 % for E_g =1.15 eV under 100 mWcm^{-2} (red line) of sunlight. At 1 mWcm^{-2} of sunlight, a typical level of irradiance in an office environment, a maximum PCE of 28.9% is reached for an E_g=1.35 eV. In contrast, under 1 mWcm^{-2} of a cool-LED illumination the maximum PCE of 54.3% is reached for a PV with a E_g=1.92 eV. For this type of illumination E_g does not change significantly with irradiance. As shown in [8], the same trends shown in Fig. 2 for LED illumination are observed for CFL.

Emerging Photovoltaic Technologies

Emerging PV are attractive because they are based on semiconductors generally processed from solution at lower temperatures than those typically used for processing Si PVs. This makes emerging PVs generally compatible with flexible substrates and low-cost additive manufacturing fabrication methods. Dye-sensitized, perovskite, organic and quantum-dot cells belong to this class of PV technologies [10]. In recent years, perovskite PVs with an E_g ca. 1.5 eV have reached laboratory-scale PCE values under sunlight up to ca. 25.2%, which are comparable to the 26.1% achieved in champion crystalline Si PV (c-Si PV) cells under similar conditions (squares in Figure 2) [11]. Organic PV (OPV) with an E_g ca. 1.4 eV and quantum-dot (QDPV) cells with an E_g ca. 1.7 eV, have also seen a dramatic growth in efficiency with record PCE values now reaching 17.4% in OPV and 16.6% in QDPV under sunlight [11]. In Figure 2, for completeness we have added record PCE values for amorphous Si PV (a-Si:H PV) as diamonds.

The performance of emerging PV technologies for indoor illumination has also seen a rapid increase in recent years [1, 2, 12]. In particular, perovskite PV with an E_g=1.8 eV (black triangles in Fig. 2) have reached maximum PCE values of ca. 36% under 1000 lux of a CFL light source and 14.6% under 100 mWcm^{-2} of sunlight [6]. For this particular CFL source, an illuminance of 1000 lux represented an incoming

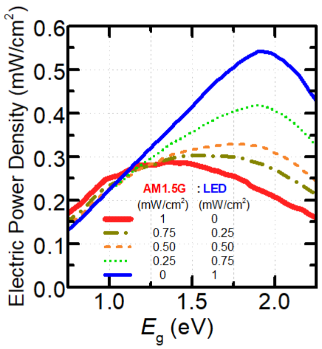

Figure 3: Estimated electrical power density generated at a constant optical power input of 1 mW/cm^2 for different ratios of AM1.5G sunlight and LED illumination.

irradiance of 760 μWcm^{-2} and 275 μWcm^{-2} of electrical power density generated by the PV cell.

On the other hand, OPVs with an E_g=1.7 eV (green circles in Fig. 2) have reached maximum PCE values of ca. 26% under 1000 lux of a LED light source, and 9.8% under 100 mWcm^{-2} of sunlight. Under this LED illumination, 1000 lux corresponded to 302 μWcm^{-2} leading to the generation of 79 μWcm^{-2} by the OPV [4]. This output electrical power density is similar to another report of OPVs with a PCE of 28% that under 1000 lux (278 μWcm^{-2}) of a CFL light source yielded 78 μWcm^{-2} [13].

A word of caution is to note that an illuminance value (e.g. 1000 lux), the photometric quantity representing power per unit area weighted by the spectral response of the human eye, can represent very different irradiance values, even if the same kind of light source is used (*i.e.* CFL or LED). Consequently, to assess the potential for generating electrical power, it is important to specify the optical input and electrical output power density as well as the spectral characteristics of the light source.

Assessment of potential

Based on theoretical estimates of the maximum PCE, Figure 3 shows a numerical exercise where it is assumed that a room is illuminated at a constant optical power of 1 mWcm^{-2} throughout day and night. The different lines represent the results of different ratios of AM1.5G sunlight and LED illumination. This exercise illustrates some of the design considerations that would need to be accounted for when designing PV systems. For instance a single PV with a E_g=1.1 eV could generate ca. 0.25 mWcm^{-2} even if the ratio of illumination sources changes throughout the day. If the illumination ranges from 0.75 mWcm^{-2} sunlight and 0.25 mWcm^{-2} LED to 1 mWcm^{-2} LED lighting, then a PV system with an E_g=1.9 eV will produce significantly more electrical power than the one with a bandgap of 1.1 eV; as the spectral composition changes.

Regardless of these considerations, given recent progress, it is not unreasonable to think that emerging PVs with E_g ca. 1.9 eV and PCE values approaching 40-45% will be available. Hence, emerging PVs could reliably produce 100's of μWcm^{-2} under indoor illumination conditions. These levels of energy harvesting will enable self-sustainable devices that require only a few cm^2 to generate sufficient power for wireless communication and computing operations.

Energy Storage

Although it is clear that light resources are very abundant, daily and environmental variations will continue to present challenges for the continuous supply of electrical power. Hence, any discussion regarding the development of self-sustainable devices will need to consider the option at hand for integration of energy-storage solutions, such as flexible batteries or supercapacitors. Progress in this area is also exciting but outside of the scope of this overview but excellent overviews exist in the literature [1, 14].

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