Evaluating Photovoltaic Performance Indoors

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ABSTRACT

A new approach to evaluating photovoltaic performance under artificial illumination is demonstrated. Several photovoltaic technologies are characterized under a standardized set of conditions in which radiant intensity and spectral composition of a light source are systematically varied. The results underscore the importance of establishing clear standards for photovoltaic characterization in emerging fields like energy harvesting.

INTRODUCTION

Shrinking energy requirements of modern microelectronics could enable energy scavenged from ambient environments to supplement or replace traditional power storage mechanisms [1], [2]. Harvesting energy from waste light and vibration is of particular relevance to low-power portable devices and distributed networks, which operate in areas with variable energy resources [1].

While solar energy is abundant outdoors, on average Americans spend 90% of their time indoors, in artificial light [3]. Photovoltaic devices are classically optimized for the solar spectrum. But while sunlight intensity outdoors is typically 100mW/cm^2, indoor light levels are orders of magnitude dimmer, typically <100μW/cm^2 at table-height [2]. Furthermore, because energy-efficient fluorescent and LED lighting have largely replaced incandescent bulbs, the spectral profile of artificial light has changed from broad, low-temperature blackbodies to sharp peaks. Photovoltaic efficiency under these nonstandard conditions varies drastically from efficiencies derived at AM 1.5 irradiance. In this paper, we quantify these differences.

The irradiance and spectral composition of light indoors depend on the light source itself. Calculations in this paper based on spectral distributions, material band gaps, and literature results suggest that for fluorescent spectra at typical indoor intensities, semiconductors with band gaps wider than crystalline silicon attain higher theoretical efficiencies [4].

In this paper we develop a compact, easily reproducible setup for testing photovoltaics under low-intensity (10-100 μW/cm^2) fluorescent light spectra consistent with exhaustive measurements of indoor artificial lighting conditions. We then test several photovoltaic technologies to determine relationships between spectral content, intensity, electronic band gap, and power conversion efficiency. We conclude that wider-band gap semiconductors possess distinct advantages for energy harvesting indoors, and establish an effective method for testing photovoltaics in the indoor environment.

BACKGROUND

Estimation of Ultimate Efficiency

Wider-band gap semiconductors can provide high solar cell efficiencies in indoor applications because artificial spectra are contained within the visible range. The spectral profile of fluorescent lamps is very different from the blackbody profile of a thermal light source (see Fig. 1).

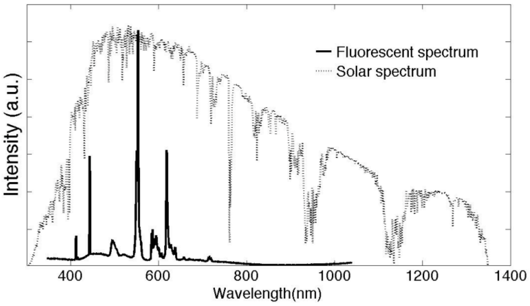

Figure 1 Typical AM 1.5 and cold-cathode fluorescent spectra.

To demonstrate how substantially different spectral inputs can impact photovoltaic efficiency, we estimate ultimate efficiency limits for several materials and light spectra. Shockley defines ultimate efficiency simply as

$$\eta \equiv \frac{NE_g}{E_{incident}} \tag{1}$$

where N is the number of photons at or in excess of the band gap energy E_g, and $E_{incident}$ defines the total energy contained in the spectrum [5]. This simple formulation assumes that each photon incident on a semiconductor in excess of its band gap has the exact same effect, and each photon below the gap has no effect. While nonidealites in absorption, radiative recombination, and so forth are ignored, this expression nonetheless provides a valuable first-order limit to photovoltaic efficiency.

Shockley also neglects the energy loss associated with separating exciton pairs. This is a good approximation for crystalline silicon and many other inorganic semiconductors with binding energies below thermal energy at room temperature (< 26 meV), where excitons dissociate freely under normal conditions. For excitonic systems like organic bulk heterojunctions (BHJs), binding energies are orders of magnitude larger, and result in substantial energy losses [6]. To evaluate BHJs while accounting for these losses, 0.3 eV was subtracted from the optical band gap energy in ultimate efficiency calculations. Scharber et al. found 0.3 eV to be the energy reduction due to the gap in donor and acceptor LUMO levels required to adequately separate charge carriers in 26 types of conjugated polymer BHJs [4], [7].

	Solar	CFL	CCFL	LED
x-si	49%	50%	52%	54%
a-si	37%	74%	70%	80%
OPV	28%	63%	59%	63%

Table 1 Maximal efficiency values for crystalline silicon, amorphous silicon, and organic solar cells under different spectral illumination.

The results of this calculation are displayed in Table 1 for cold-cathode (CCFL) and compact fluorescent lamps (CFL) at similar color temperatures, sunlight, and LED light, assuming band gaps of 1.1 eV, 1.7 eV, and 1.8 eV for single crystal silicon, amorphous silicon, and P3HT/PCBM bulk heterojunctions, respectively [8]. We note an important trend reflected in this estimate: we expect amorphous silicon and organic BHJs to outperform crystalline silicon under fluorescent and LED spectra.

In Fig. 2 we see that for non-excitonic systems, there exists a peak in ultimate efficiency at a unique electronic band gap value that depends strongly on the spectral characteristics of the source.

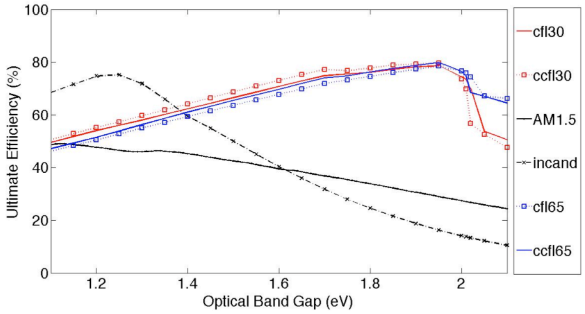

Figure 2 Dependence of ultimate efficiency on electronic band gap and spectral composition in non-excitonic systems. Each curve corresponds to a different light source: cfl and ccfl refer to compact and cold cathode fluorescent, 30 and 65 refer to 3000 K and 6500 K color temperatures, incand refers to incandescent, and AM 1.5 refers to the NREL AM 1.5 solar spectrum.

Characterization of Indoor Energy Resources

Irradiance levels indoors are also very variable over time and must be rigorously characterized to quantify total available energy. This was accomplished in a previous study in which light sensors in buildings, subways, and outdoor urban environments at night were monitored over multiple years [2].

These experiments establish a typical irradiance range of 0-100μW/cm^2 that we implement in IPV testing. While previous experiments have sought to characterize photovoltaic behavior under fluorescent spectra and a range of intensities, none to our knowledge have probed the low intensities that we assert to be most relevant to indoor photovoltaic applications [9].

MEASUREMENT

Design, Fabrication, and Calibration

An indoor photovoltaic testing setup was designed according to irradiance results of [2]. To replicate indoor lighting environments the light seen by the energy harvester should be Lambertian. A simplified integrating sphere was constructed to compress the uniformly diffuse indoor lighting environment into a low-cost, compact testing system, pictured in Fig. 3.

Figure 3 Indoor lighting simulator cross-section (left) and photo (right). PV cell is placed at the top center. Note the visible attenuation and uniformity at the top surface.

A 9" X 9" cube with opaque white acrylic walls induces multiple reflections of the light source, while multiple sheets of rough, frosted clear acrylic disrupt the directionality of the light and promote attenuation while maintaining the spectral profile of the source. Multiple black acrylic sheets with periodic square holes further attenuate the maximum intensity to 100 μW/cm^2. Extremely uniform (less than 1% intensity variation) diffuse light is output to the sample at the top of the box, 8.5” from the light source.

Light Source

To evaluate photovoltaic performance over a continuous range of fluorescent intensities, dimmable cold-cathode fluorescent lamps of different color temperatures were used as sources. The CCFLs were 8 mm tri-phosphor tubes (Tecnolux, Brooklyn) dimmed between 10-100μW/cm^2 using a digitally-controlled Lutron Radio RA-2 dimmer and repeater. The system was programmed to perform full I-V sweeps at specified intensity levels for each lamp and each photovoltaic device.

To ensure that CCFLs were a good substitute for CFLs (which cannot be electronically dimmed over the same range), their spectral and temporal characteristics were compared. Spectral match between lamps of similar color temperature was good (evidenced also by similar behavior in Fig. 2), but differences in temporal behavior were measured. The frequency of the CCFLs (25 kHz) was twice that of the CFLs (12.5 kHz), and the amplitude of CCFL intensity oscillations was also greater. Due to the larger variation in CCFL intensity, energy harvested from the two sources will differ, but with appropriate calibration this difference could be overcome. For the purposes of this demonstration no such compensation was required.

Photovoltaic Integration

Several photovoltaic technologies were tested in the IPV setup, and power conversion efficiencies were determined as a function of intensity (see Fig. 4). Purchased monocrystalline silicon (x-si) and amorphous silicon (a-si), and home-built Plexcore PV2000 organic cells from Plextronics Corporation (PV2000) were chosen. These materials have optical band gaps of 1.1, 1.7, and 1.8 eV respectively. Based on Table 1, we expect the longer-band gap semiconductors with low exciton binding energies to be optimal materials for fluorescent lamps. We would also expect amorphous silicon and organic semiconductors to perform well under low intensities relative to crystalline silicon because of their strong absorptivity and good carrier separation.

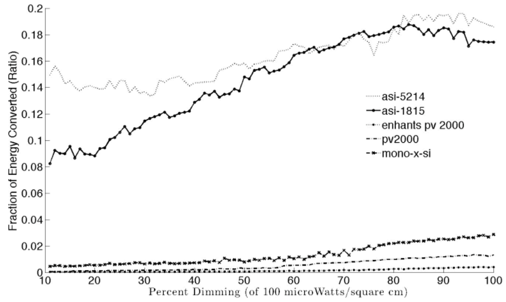

Figure 4 Power conversion efficiency of a single crystal (x-si) PV cell, two amorphous (a-si) cells, and two organic cells (PV2000) under dimmable CCFLs at 6500 K.

In Fig. 4 we see that under 100µW/cm^2 amorphous silicon power conversion efficiency is an order of magnitude greater than that of crystalline silicon. For low-intensity fluorescent spectra, the IPV testing setup unambiguously demonstrates that amorphous silicon is a superior material to monocrystalline silicon, and provides a quantitative measure of comparison for IPV performance.

CONCLUSION

Reliable and standardized assessment of indoor photovoltaic performance is essential to the field of energy harvesting. While solar resources are well characterized for outdoor PV, indoor lighting features a range of intensities and spectra that may benefit from nonstandard semiconductor technologies. We have created a compact, reproducible IPV characterization setup in accordance with a wealth of indoor irradiance measurements that can evaluate photovoltaics under a range of spectra and irradiance levels. With this setup, we verify that amorphous silicon, with its relatively wide band gap and low exciton binding energy, is a superior choice for energy harvesting from indoor lighting spectra. We hope to accelerate energy harvesting through the introduction of a standard for indoor photovoltaic evaluation.

ACKNOWLEDGMENTS

The authors gratefully acknowledge contributions from Dr. Nadia Pervez, Dr. Yu-Jen Hsu, Hassan Edrees, Douglass Crauder, and David Ablon, and funding from the NSF Graduate Research Fellowship Program.

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