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Low light illumination study on commercially available homojunction photovoltaic cells

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HIGHLIGHTS

- COTS PV cells are tested under indoor and narrow light spectra.
- InGaP is the most efficient under low light conditions (0.5–100 $\mu W_{opt}/cm^2$).
- InGaP is selected for isotope battery.
- Optimal incident wavelength (614 nm) for InGaP is identified in model.

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ABSTRACT

Low illumination (10^{-4} suns) and indoor light energy harvesting is needed to meet the demands of zero net energy (ZNE) building, Internet of Things (IoT), and beta-photovoltaic energy harvesting systems to power remote sensors. Photovoltaic (PV) solar cells under low intensity and narrow (±40 nm) light spectrum conditions are not well characterized nor developed, especially for commercially available devices and scalable systems. PV operating characteristics under 1 sun illumination decrease at lower light intensity and narrow spectrum conditions (efficiency drops from ~25% at 100 mW_{opt}/cm^2 to 2% at 1 $\mu W_{opt}/cm^2$). By choosing a PV with a bandgap that matches the light source operating wavelength, the total system efficiency can be improved. By quantifying losses on homojunction photovoltaics (thermalization and leakage current), we have determined the theoretical optimized efficiency for a set of PV material and a selected set of light sources. We measure single-junction solar cells' parameters under three different light sources (indoor light and narrow spectrum LED sources) with light intensities ranging from 0.5 to 100 $\mu W_{opt}/cm^2$. Measurements show that indium gallium phosphide (InGaP) PV has the highest surface power density and conversion efficiency (29% under ≈1 $\mu W_{opt}/cm^2$ from a 523 nm central peak LED). A beta-photovoltaic experimental study identifies InGaP to be optimized for use with the ZnS:Cu, Al and tritium at STP. The results have guided the selection of PV material for scalable isotope batteries and other low-light energy harvesting systems.

1. Introduction

Autonomous systems and sensors have been rapidly increasing in use and importance for commercial environmental monitoring, as well as residential applications, and commercial applications over the past decade [1,2]. This growth in popularity of independent, wireless systems and sensors has led to rise of the Internet of Things (IoT) [3]. They are embedded in home appliances, outdoor weather stations, and remote monitoring system of physical characteristics and events. Presently, to increase sensor lifetime and independence from the primary grid most sensors have standby/sleep modes at low power consumption ranging from 1 nW_e to 1 μW_e (Fig. 1), and shift into dynamic/wakeup mode from an external environmental stimulus or remote user command [4–7]. Yet, this does not solve the limiting factor for energy storage for a lengthy operation of 10 years or longer. Most wireless sensor networks (WSNs) for outdoor and indoor applications use chemical batteries, especially since indoor conditions limit energy harvesting opportunities. Commercial chemical batteries have storage lifetimes of less than a decade when stored under standard conditions even when unused. In order for the IoT to be more successful and grow, thousands of unattended, embedded systems and sensors

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Nomenclature

a-Si	amorphous silicon
ARL	US Army Research Laboratory
β-PV	beta-photovoltaic
CL	cathodoluminescence
DSC	dye-sensitized solar cells
E_g	bandgap of semiconductor device
E_{ph}	incident photon energy
E	total power density of visible EM radiation
EQE	external quantum efficiency
EM	electromagnetic
FF	fill factor
FWHM	full width at half maximum
GaAs	gallium arsenide
IDEC	indirect energy conversion
iBAT	isotope battery or radioisotope battery
I_0, I_d	dark current
I_{sc}, I_g	short circuit current
InGaP	indium gallium phosphide
IR	infrared
IoT	internet of things
I-V	current-voltage
J_{sc}	short circuit current density
LIL	low illumination light
LPV	laser power converter or photovoltaic
mc-Si	monocrystalline silicon
MJ	multi-junction
MPP	maximum power point
NPRL	NanoPower Research Labs
OPV	organic photovoltaic
P_{in}	input power of light source
PV	photovoltaic
QE	quantum efficiency
R_s	series resistance
R_{sh}	shunt resistance
RF	radio frequency
RL	radioluminescence
RIT	Rochester Institute of Technology
RPD	radiant power density
S_e	specific power density
STC	standard test conditions
STP	standard temperature and pressure
TL	thermalization loss
V_{oc}	open circuit voltage
V_m	voltage of the maximal power point
WSN	wireless sensor network
ZNE	zero net energy

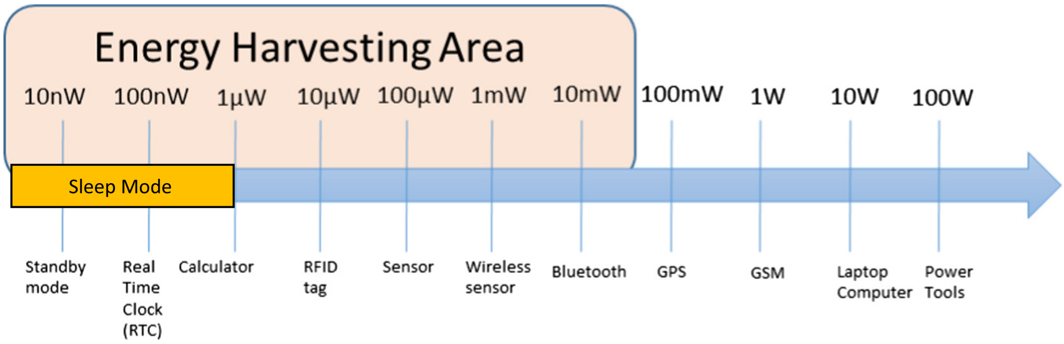

Fig. 1. Power levels for portable electronic devices and correlated energy harvesting capabilities [54].

would need to be spread everywhere: indoor and outdoor environments, remote and urban, terrestrial and aquatic. They may be located in harsh and remote locations, where replacing many batteries can be inefficient, and otherwise difficult without established logistic lines. The need for a blanket of sensors and systems and their replacements generate complex logistic chains and large labor costs. The ultimate goal is to establish an energy harvester system that can provide power to an autonomous system or sensor without use of energy storage. If autonomous sensors can be developed to harvest ambient energy, the WSN operation lifetime could last beyond the infrastructure lifespan or be limited to only the ambient energy source lifetime, such as with a radioisotope battery system. Indoor and other low-light energy harvesting photovoltaic cells (PVs) can power autonomous sensors similar to outdoor systems. Artificial lighting is constantly radiating during daily facility operation at a constant peak intensity unlike outdoor solar lighting. Indoor light energy harvesting could meet and satisfy demands of Net Zero Building Systems (ZNE) [8]. This would be beneficial for power recycling programs since indoor lighting is 25% of facility power consumption [9].

Indoor photovoltaic (IPV) systems' need to operate in conditions that are not standard, but diverse due to different light spectra and intensities (W_{opt}/cm^2). Muller [10], Randall [11], and Roundy [12] have presented indoor lighting models using office space lighting values where the light spectrum was fixed following artificial lighting and the light intensity was varied. The light intensity in the model changes with respect to time of day, month in the year, and room location, e.g. middle of room or near office window. These models only include silicon PV types and mixed lighting conditions based on CFL, incandescent, and solar light spectrum excluding UV light. Previous work on silicon (Si) PVs, dye-sensitized solar cells (DSC), and organic photovoltaics (OPVs) using the indoor light model conditions have been characterized for indoor light harvesting by Steim [13], Sacco [14], De Rossi [15], and Corazza et al. [16] Sacco et al. [14] measured OPV, DSC, and Si PVs under artificial illumination conditions, using incandescent, halogen, and fluorescent bulbs. DSC and silicon spherical and crystalline micro-cells (Si-μsph) showed the highest power conversion efficiency of 4.41% and 5.89% at 5000 lx. De Rossi et al. [15] showed that an optimized DSC outperforms silicon PV devices under CFL and warm white LED. The power conversion efficiency of DSC is approximately 13% at 200 lx [15]. PCDTBT was found to be the most promising OPV with an efficiency of 16.6% at 300 lx from a fluorescent lamp [17]. In general, these papers suggest that DSC