INTRODUCTION

In recent years, our understanding of the electrical performance of various PV technologies under artificial or natural low light conditions has grown significantly. The main motivating factor for such measurements has been the desire to add to the growing knowledge on how to efficiently harvest ambient light energy in office spaces and homes for powering a variety of electronic devices, particularly Internet-of-Things smart sensors.

PV cells composed of various cell technologies (a-Si, c-Si, III-V semiconductors, dye-sensitized, and perovskite) have been compared under low light conditions for indoor energy harvesting purposes. Various types of artificial lighting have been investigated to determine the highest energy density cells for each source. Specific spectra in low
light have also been tested for energy harvesting charging circuits from 100 lux to 1000 lux. After determining the optimal bandgap of PV materials for the various artificial lighting conditions, battery and supercapacitor charging circuits have been designed to optimize the performance of the entire system under these conditions.\textsuperscript{11-13} Many other PV module charging circuits have been designed based on analytical models or previous characterization work.\textsuperscript{14-18} Circuit designs vary, but the predominant designs utilize, maximum power point tracking (MPPT), DC-DC conversion, for supercapacitor or rechargeable battery (NiMH, NiCd, or Li-ion) loads.\textsuperscript{14-18} In these prior studies, performance changes over the charging process, from low to full charge, were not addressed. Outside of low light energy harvesting, PV battery charging variations, however, have been reported for car battery applications, from no charge to a full charge of 20 Ah.\textsuperscript{19}

We report on tests where a small, low-capacity battery is charged as part of a novel, high-efficiency charging circuit. Three different PV mini-modules were tested, all while exposed to the same, well-defined artificial light source. These mini-modules were custom built for low light energy harvesting. The performance of the entire circuit was evaluated with and without a device load attached, and the former coming in the form of a wireless smart sensor in full operation. Each version of the overall system is ultimately evaluated based on its performance in providing charge to low-capacity batteries so as to maintain continuous operation of wireless sensor motes. The following data characterize charging performance for different PV modules technologies (Si, GaAs, and GaInP). Finally, the feasibility of operating a wireless sensor mote indefinitely under indoor lighting conditions is addressed as part of a summary discussion.

2 | EXPERIMENTAL DETAILS

2.1 | Test setup and electrical measurements

Three different photovoltaic mini-module technologies were prepared: passivated emitter and rear contact (PERC) Si cells, GaAs cells, and GaInP cells. All module and cell sizes were kept constant for a more direct inter-comparison. The PV mini-modules that were designed for these experiments were composed of twelve individual 2 cm × 2 cm solar cells as shown in Figure 1. For all three cell technologies, three cells were wired in series and four columns of such cells were connected in parallel to provide the voltage required to satisfy the charging circuit’s minimum voltage requirement. The substrate that holds the cells is a printed circuit board (PCB) with a pair of gold-coated copper contacts for each cell: one for connecting the backside of the cell to the PCB using low temperature reflow solder paste and another for wire bonding from the contact to a busbar electrode on top of the cell. One benefit of this application and design is that if one or multiple cells are damaged or disconnected, the mini-module will still provide electrical power through the remaining branches.

Each PV mini-module was placed on a stage inside a dark box having only an opening on its top. Through this opening, a warm white light emitting diode (LED) was projected onto the mini-module (Figure 2). This light source is similar in emission spectrum to typical indoor residential or commercial LED lighting sources.\textsuperscript{7} The mini-modules were fully illuminated by the light source (ie, an overfill condition). The LED is fan cooled and was operated in dc mode with its current controlled in 1 mA increments, and the light irradiance was constant throughout the course of the measurements.

The effective irradiance ratio, $F$, on the test mini-modules was determined using a calibrated reference cell and a procedure that has been previously described.\textsuperscript{20} In this procedure, the light intensity is adjusted so that the mini-module is exposed to an illuminance of exactly 1000 lx as achieved using a previously established reference light source with a correlated color temperature (CCT) of 3000 K and a total irradiance of 2.93 W/m\textsuperscript{2}. Its emission spectrum is shown in Figure 3. This condition is achieved by calculating a spectral mismatch parameter between the cells on the mini-module and the reference solar cell. The LED source current was adjusted to make the effective irradiance ratio, $F = 1$ within 0.5%. The process was repeated for each mini-module to make sure they were all exposed to exactly the same illumination condition for

\begin{figure}[h]
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\includegraphics[width=\textwidth]{figure1.png}
\caption{Images of (A) Si mini-module and (B) GaAs mini-module used in these experiments}
\end{figure}
consistency between results. This lighting condition is much less intense compared with the standard outdoor spectrum at air mass 1.5 G, which has a total irradiance of 1000 W/m² and an illuminance of ≈100 000 lx. Figure 3 also shows the AM 1.5 G standard sun spectrum (ie, the standard sun) for a visual comparison to our LED source.

Prior to the extensive battery charging experiments, current vs voltage (I-V) measurements were performed on all three mini-modules under the lighting condition described above to determine the modules’ characteristic parameters: short circuit current, $I_{sc}$; open-circuit voltage, $V_{oc}$; maximum power point, $P_{m}$; and the associated maximum voltage, $V_{m}$, and maximum current $I_{m}$; fill factor (FF); and the estimated power conversion efficiency of each module under the given LED lighting condition, $\eta$.

Measurements of the instantaneous electrical power supplied by the PV mini-module and from the battery charging circuit were conducted with a sample rate of 50 kHz using a multi-channel data acquisition (DAQ) system. To measure the PV current, charging circuit output current, and battery charge current, voltage was measured across 1 Ω sense resistors. The tolerance of these resistors is 5%. This results in uncertainties of 5.04% for current measurements and 5.04% for power measurements. The voltage measurements have an uncertainty of less than 0.005%.

The rechargeable Li-ion batteries used in these experiments were LIR2032 coin batteries with a nominal 40 mAh charge capacity. The batteries are designed for 3.6 V operation, but have a maximum charge voltage of 4.2 V and are overcharge protected.

The custom-designed battery charging circuit board utilizing an LTC3105 chip functions with a DC/DC converter and maximum power point control (MPPC). Five convenient bayonet nut coupling (BNC) terminals were built into the PCB for real-time monitoring of the PV voltage and current, circuit output and battery charging currents, and the battery
voltage. The MPPC voltage is modulated by a trimmer potentiometer (trim pot). The circuit’s output voltage is 4.18 V to match the batteries.

The circuit is designed with a capacitor to supply the burst current at the output pin to charge the battery. As seen in Figure 4, the amplitude of the burst current increased with the output power of each module while maintaining about the same pulse frequency under the same light source of 1000 lx and CCT of 3000 K. It was observed that the pulse frequency increases if the light intensity increases while the current amplitude remained constant for each module. A sampling rate of 50 kHz is required to measure each peak of the burst current with enough temporal precision, so the charge into the battery can be calculated (ie, the charge equals the integral of the measured current over time).

3 | MEASUREMENT RESULTS AND DISCUSSION

3.1 | I-V curve performances

As noted previously, I-V curve measurements were taken for each mini-module while illuminated by the LED light source described above (CCT of 3000 K and illuminance of 1000 lx\textsuperscript{20}). Figure 5 shows the I-V curve, and Table 1 summarizes the performance parameters of each mini-module under this lighting condition. The GaInP module harvests the most energy, as it is the most efficient, with an estimated module power conversion efficiency (PCE) of 23.1%, and has the largest open-circuit voltage and fill factor as compared to the other two mini-modules. The GaAs module is 14.1% efficient and the Si module’s PCE is 9.3%. Note that these module PCE values are significantly lower than values reported in reference\textsuperscript{20} for individual solar cells of the same type (GaAs: 22.8%, GaInP: 26.8%, and Si: 12.5%). In particular, the fill factors in mini-module form are lower as compared to individual cells.

One reason for the lower performance of the mini-modules is the extra series resistance that is introduced when solar cells are wired in series. Also, it has previously been reported that diced solar cells can suffer from defects and imperfections that can produce edge recombination effects resulting in lower electrical performance.\textsuperscript{21} The degraded performance is particularly amplified under low light conditions. Due to the limited number of individual cells in our stock, we could not effectively match all higher quality cells into one mini-module; mismatch between the cells can affect the overall (mini-)module performance. Still, the single-cell trends that were reported previously hold in this mini-module form as well, with the GaInP cells clearly presenting the best option for low light energy harvesting under visible-spectrum light sources. In Table 1, note that the V_\text{oc} is the sum of three individual cell voltages in series and the I_\text{sc} is roughly the sum of four individual cell currents.

3.2 | Full charge study

The coin battery was inserted into the circuit to be charged when it was at about half charge (20 mAh) with no other load attached. The battery was then charged to 4.18 V, at which point the circuit stopped supplying power to the battery. Total charge in mAh supplied to the battery as a function of time (in hours) is shown in Figure 6(A). Figure 6(B,C), respectively, plot the corresponding time series data for the battery voltage and the charging power supplied to the battery (ie, product of input battery current and battery voltage). The GaInP module supplied the most power to the circuit charging, 3.05 mW. The measured powers did deviate from the I-V characteristics because the mini-modules were connected to a charging circuit with MPPC control. Parasitic losses and MPPC tuning resulted in slightly lower power from the mini-modules. The average charging power from the circuit was 2.60 mW when powered by the GaInP mini-module, resulting in a circuit efficiency of 85.2%. Of the three mini-modules, the battery charged to full capacity in the least amount of time with the GaInP module. Due to its lower power density (1.96 mW from the mini-module), the GaAs module charged the battery in 52 hours with an average charging power of about 1.34 mW and a circuit efficiency of 68.4%. The Si mini-module took about 90 hours to fully charge the battery. That combination yielded an average charging power of 0.79 mW and a PV power of 1.36 mW, thus yielding a circuit efficiency of 58.0%. The circuit efficiency degrades as the supplied power decreases, supporting the requirement to maintain 1.4 V at the VAUX pin and a fixed load on the circuit.
A wireless sensor mote, Figure 7(A), was connected to the battery charging circuit in parallel, as shown in Figure 7(B), to test its power demands on the charging circuit. The mote operates in a wireless mesh network where the motes are operated in responder mode with a controller manager with a serial connection into a computer. The manager is used as

**TABLE 1**  
$I$-$V$ curve measurement parameters for three solar cells under the same 1000 lux 3262K test spectra

| Device | $V_{oc}$ (V) | $I_{sc}$ (mA) | FF | $V_m$ (V) | $I_m$ (mA) | $P_m$ (mW) |
|--------|-------------|-------------|----|---------|--------|--------|
| Si     | 1.175       | 2.003       | 0.590 | 0.850   | 1.633  | 1.388  |
| GaAs   | 2.310       | 1.957       | 0.441 | 1.530   | 1.303  | 1.993  |
| GaInP  | 3.309       | 1.453       | 0.677 | 2.550   | 1.275  | 3.252  |

**FIGURE 6**  
Charging of a 40 mAh lithium-ion battery from half charge to full charge using Si, GaAs, and GaInP mini-modules. From top to bottom, total charge (mAh), battery voltage (V), and charging power (mW) plotted against time (h)

**FIGURE 7**  
Linear Technology wireless sensor mote (A). Configuration of charging circuit and mote during testing (B). Mote was connected in parallel to the charging circuit and battery ("Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by NIST, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose." (NIST Disclaimer).)
the interface to communicate and control the motes. The motes only perform tasks and operations as directed by the manager. The Si module was selected to charge the battery, while the mote was connected. This selection was made to investigate whether the lowest power mini-module tested was satisfactory to charge the battery with an additional load. The same illumination conditions (i.e., warm white LED with CCT of 3000 K and illuminance of 1000 lx, room temperature of about 22°C) were followed for these measurements. The mote was turned on with the battery near full charge. The mote was then sent a ping request by the manager every 8 seconds. Eight seconds was the shortest interval between pings to ensure a successful ping response. The mote would then respond with data including the ping time response, temperature in Celsius, and battery voltage in millivolts. During charging, the mote’s power requirements were met by receiving output power from the circuit while the battery was charged with the remaining power. If the LED source was turned off and the PV module produced no power, then the battery and mote would be in series allowing for the battery to discharge and supply power to the mote.

The battery charging with the Si mini-module was compared with and without the mote attached. The rate of charge to the battery was lower with the mote attached as seen in Figure 8(A), confirming that the mote was consuming power and reducing the charging rate. Figure 8(B) shows the mote’s sensed voltage across its battery terminals. The sensor’s sensitivity is 7 mV as demonstrated by the step shape in the plot. The battery reached full charge in about an hour and continued operating at full charge for about 2 hours. When the LED was turned off, the mote gradually discharged the battery to the initial voltage from before charging over the course of 2 hours.

Figure 9(A) shows that with the mote attached, the charging power is generally less than the charging power without the mote. However, there are points when the mote is not communicating with the mote manager, and therefore, the charging power is about the same as when no mote is attached. The mote’s intermittent power draw is better exemplified in Figure 9(B), where the charge power is plotted as a function of time over a very short interval. Every few seconds, the mote is active and draws power to communicate, reducing the charging power directed to the battery by 0.4 mW. When it is not communicating with the mote manager, the charging power is very nearly the same as when the mote is not attached. The mote draws 0.22 mW on average with a peak draw of about 0.40 mW.

3.4 | Discussion

The results of these measurements reveal that if the PV mini-modules are sized appropriately, even silicon solar cells with a PCE of less than 10% under visible-spectrum LED lighting can supply enough power to keep low-capacity batteries (i.e., <100 mAh) from discharging completely. Our findings show that for a relatively sophisticated wireless mesh sensor with many electronic components, one needs to supply an on-demand power of at least 0.4 mW. But, since the charging electronics themselves require some power to operate, the PV mini-module should be sized to supply at least 0.8 mW to keep the battery trickle-charged all the time while the mote continues to report data around the clock. If a sensor’s power demands or frequency of communication is lower, then a smaller PV mini-module can be designed and utilized.

![Figure 8](image_url)

**Figure 8** Plot (A) shows the charge supplied to the battery with and without the mote connected using the Si mini-module. Plot (B) shows the mote’s battery voltage measurement while the mini-module is illuminated and then under dark conditions.
One important caveat regarding these measurements is that the light source was left on continuously at the same steady illumination level during charging. Obviously, real-life sensors are subjected to more intermittent lighting. In residential buildings and some commercial buildings, daylight in addition to artificial lighting can have a substantial effect on the charging capabilities of such circuits while night times most certainly result in a battery discharge. This study provides a baseline set of data for operation of such circuits and more measurements, particularly in real-life settings, are needed to understand the effect of intermittent lighting or even room temperature fluctuations on the operation of a PV-connected sensor. However, interior well-lit environments of large commercial buildings where ceiling lights are left on continuously or for very long periods should result in outcomes similar to the findings reported here. We have also shown that by increasing the power conversion efficiency of the PV cells by a factor of $\approx 2.5$ (ie, GaInP as compared to the Si mini-module) can generate sufficient power to reduce the footprint of the mini-module by a similar factor.

4 | CONCLUSIONS

Characteristics of a low light energy harvesting battery charger were presented for three different photovoltaic mini-modules. Each photovoltaic mini-module was able to charge a 40 mAh lithium-ion battery under an illuminance of 1000 lx. The time required to charge the battery from a state low charge to full charge was determined by the module’s power output. The GaInP mini-module charged the battery in the shortest time, followed by the GaAs mini-module, and with the Si mini-module taking the longest.

The Si mini-module, which has the lowest PCE under a visible-spectrum LED light, was also used to charge a 40 mAh battery while a wireless sensor mote was attached. This test was conducted to assess the charger’s ability to supply sufficient power for a device to continually operate. Using this comparatively inefficient mini-module, the battery was still being charged while the mote was active for times when the light source was also on.

Our findings show the operation of wireless sensor motes with PV mini-modules because many commercial buildings offer more-than-sufficient indoor lighting conditions. Future research will focus on mote operation using PV energy harvesting under intermittent, variable-spectra artificial light, and daylight to further investigate the feasibility of this energy harvesting technology for wireless sensor applications.

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