Shunt Resistance Optimized Indoor Photovoltaic System for Powering Internet of Things

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Abstract

This article proposes a photovoltaic system of ultrathin silicon solar cell by using indoor lighting through enhanced shunt resistance, nanostructure of light-trapping, and tubular daylight system for powering the internet of things (IoT) devices. Simulation results show that, by increasing the shunt resistance from 100 $\Omega\cdot$cm$^2$ to 104 $\Omega\cdot$cm$^2$, the efficiency of indoor solar cell can be improved from less than 0.5% to be over 14%. Moreover, with the help of ultrathin wafer and nanostructure of light-trapping to improve the near-infrared light absorption and open circuit voltage, the efficiency of the indoor amorphous silicon (a-Si) heterojunction solar cell can be further improved to be 17.09%. The tubular daylight system is an excellent supplement to the light indoor intensity and thus can increase the power production.

I. Introduction

Our world is fast evolving where two factors are the keys to the rapid development of our society: information and energy. In terms of information, receiving, transmitting, storing and processing of information are fundamental, and the ultimate goal is to connect all things around us together. This is known as internet of things (IoT).

In order to realize IoT, the devices are supposed to be installable anywhere and also to be internet accessible at any time. These requirements almost make it impossible for interconnection with wires, not only for information but also for powering. A real IoT world calls for both of wireless internet access and powering.[1]

Unlike traditional electronic devices, such as washing machine or computers that require comparably high power, IoT devices consist of several wireless devices consuming low power, such as sensors, data transmitter and receivers. These devices work in two modes: active and sleep. In active mode, their power demand ranges from a few dozen microwatts to a few hundred microwatts. Even less power consumption when they work in sleep mode. However, these devices generally work in a comparatively isolated area. This makes it hard and unworthy to connect them into the power grid. Despite that a small battery can easily power these devices for a few weeks or even months, this method is still discouraged by comparatively short maintenance circle and high labor cost. Fortunately, such lower power consumption can be potentially fulfilled with small size photovoltaic (PV) systems.

As the light intensity of indoor is typically less than 1% of that outside, the efficiency of indoor solar cells is much lower due to lower open circuit voltage ($V_{OC}$). Previous studies have been mainly focused on characterization methods, different solar cell structure such as perovskite and dye sensitized cell working at very lower light intensity, but with either analysis of the indoor light spectrum or enhanced light-trapping missing.

In this work, a detailed study of ultrathin solar cell combined with enhanced shunt resistance, light-trapping nanostructure and tubular daylight system under indoor lighting condition is presented. Thus,
the solar cell demonstrates efficiency of over 15%, which could easily meet the power demand of IoT devices.

II. BACKGROUND

Despite the progress in III-V and other new semiconductors for solar cell application, silicon-based solar cell still occupies 90% of the market [1]. In the past years, silicon solar cells were disregarded due to the low performance under low illumination and the relatively high cost. On the other hand, the record efficiency of silicon solar cell is 26.7% up to now [2] for a thickness of 165 μm against the Shockley–Queisser (SQ) limit of 29.4% [3]. And the cost of silicon solar cell has fallen over 70% over the last decade [4], [5], which makes it now a promising candidate for indoor application.

The condition and behavior of solar cell under indoor lighting are very different from the standard AM 1.5 condition of full sunlight. At AM 1.5, the spectral range is broad, and the power density is 1000 W/m$^2$. The standard of lighting design for buildings are listed in Table 1. The intensities span 100 - 1000 lux (1-10 W/m$^2$), which is 100-1000 times lower than that of AM 1.5.

Due to the much lower light intensity, the indoor solar cell not only has a much lower power production but also delivers a lower power conversion efficiency because of the depressed light-generated voltage.

However, indoor light has unique advantages over outdoor light. For instance, the bandgap of silicon is 1.12 eV corresponding to the photon wavelength of 1107 nm. Assuming that all photons that has energy higher than 1.12 eV can be absorbed, and only 1.12 eV of every photon absorbed is transferred into electrical power. Thus, photons that have wavelength shorter and closer to 1107 nm will deliver higher conversion efficiency. The majority wavelength of solar photon lies around 500 nm. While the most commonly indoor light source available on the market has been the LED or incandescent lamp, whose peak wavelength lies around 600~700 nm, closer to 1107 nm than the solar spectrum. As a result, the indoor light spectrum has higher conversion efficiency than the solar spectrum for silicon solar cells.

Many researches have been dedicated to the performance improvement of indoor solar cell. One of those methods applied special materials or structures such as halide perovskites photovoltaic [7] or organic solar cell [8], which are quite expensive and present immature technologies. Other works concentrated on low light conditions but not specifically at indoor light spectrum [9].

Table 1 Standard of lighting design for buildings [6]
Illuminance (lx)

<table>
<thead>
<tr>
<th>Room</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedroom</td>
<td>75~150</td>
</tr>
<tr>
<td>Living room</td>
<td>100~300</td>
</tr>
<tr>
<td>Dining room</td>
<td>150</td>
</tr>
<tr>
<td>Kitchen</td>
<td>100~150</td>
</tr>
<tr>
<td>Public library</td>
<td>300</td>
</tr>
<tr>
<td>Office/Meeting room</td>
<td>300~750</td>
</tr>
<tr>
<td>Classroom</td>
<td>300~500</td>
</tr>
<tr>
<td>Supermarkets/Stores</td>
<td>300~500</td>
</tr>
<tr>
<td>Hospital</td>
<td>300~750</td>
</tr>
<tr>
<td>Demonstration</td>
<td>200~300</td>
</tr>
<tr>
<td>Gym</td>
<td>300~1000</td>
</tr>
</tbody>
</table>

To optimize the indoor solar cell, we propose three approaches in this article: increase of the shunt resistivity, incorporation of ultrathin wafer with light-trapping structure, and introduction of tubular daylight system.

With regard to the increase of the shunt resistivity, it arose from a finding that the poor performance of solar cells under indoor lightening was mainly limited by the shunt resistance. In principle, the shunt resistivity ($R_{sh}$, unit of kΩ.cm$^2$) has negligible effect on the solar cell performance in the outdoor light, but it becomes catastrophic in low light. For $R_s$ dropping from tens of kΩ.cm$^2$ to a few kΩ.cm$^2$, the efficiency of a solar cell under indoor lighting can drop from over 20% to less than 5% [10], [11]. Even for the commercial cells with $R_{sh}$ of 10 kΩ.cm$^2$, the efficiency still decreases to be lower than 15% under low-intensity lighting.

In addition, the narrow, short wavelength range means that indoor silicon cells no longer need thick substrate for light trapping so that 10~20 µm-thick material can be enough. Thinner substrate leads to greater mechanical flexibility. Note that a-Si heterojunction solar cell provides an opportunity to integrate logic circuits on the same substrate. Our results indicate that silicon heterojunction solar cells have great potential to be used for powering the indoor devices.

Incorporating tubular daylight devices (TDD) into the building structure or optimizing the solar cell structure were proven to be very effective, especially for low-light condition. The TDD system consists of (at least) three different components: a hemisphere light collector lying outside the building, a sun pipe to transfer the collected light, and a diffuser to diffuse the collected light into the room. Other supplemental
parts would include ultraviolet and infrared reflector, dimming devices and even inside system solar cells. Introduction of TDD is a worthy supplement to the indoor lighting, since TDD provides benefits in many ways: energy saving and thus economical, improving physical and mental health, and environmentally friendly.

Table 2 Parameters of baseline solar cell.

| Parameter  | Value  
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>200 $\mu$m</td>
</tr>
<tr>
<td>Emitter doping/$\text{cm}^3$</td>
<td>$10^{18}$</td>
</tr>
<tr>
<td>$J_{\text{inc}}$ ($\text{mA/cm}^2$)</td>
<td>46.29</td>
</tr>
<tr>
<td>Base doping/$\text{cm}^3$</td>
<td>$10^{14}$</td>
</tr>
<tr>
<td>$J_{\text{ref}}$ ($\text{mA/cm}^2$)</td>
<td>5.95</td>
</tr>
<tr>
<td>BSF doping/$\text{cm}^3$</td>
<td>$10^{18}$</td>
</tr>
<tr>
<td>$J_{\text{tra}}$ ($\text{mA/cm}^2$)</td>
<td>4.49</td>
</tr>
</tbody>
</table>

III. SIMULATION PROCESS

Simulations of the solar cell under low light condition and the effect of the shunt resistance were performed by using Synopsys Sentaurus TCAD and Matlab. Sentaurus is an advanced device simulator capable of simulating electrical, thermal, and optical characteristics of a wide variety of semiconductor devices [12], which has also been an industrial standard tool in semiconductor processing and manufacturing. Particularly, Sentaurus is compatible with external packages such as illumination, which makes it easy to plug in at any spectrum.

The simulation of Sentaurus does not take the shunt resistance into consideration unless using mixed mode simulation to create an external circuit with a shunt resistor. However, that is time consuming and thus unnecessary. So, the I-V data were exported from Sentaurus and plugged into Matlab for the calculation combined with the shunt resistance. The equivalent circuit is shown in Figure 1 and the relevant equation (1) is below.

The load current can be calculated as [13]:

$$I = I_L - I_0 \exp \left( \frac{qV}{n k T} \right) - \frac{V}{R_{SH}}$$

$\text{(1)}$

$I_L$ is the light generated current,
Table 3 Efficiency of baseline silicon solar cell under AM 1.5 and 1% of AM 1.5 with different shunt resistances.

<table>
<thead>
<tr>
<th>$R_{SH}$ (Ω.cm$^2$)</th>
<th>infinite</th>
<th>$10^6$</th>
<th>$10^4$</th>
<th>$10^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eff (%) 1 sun</td>
<td>25.23</td>
<td>25.23</td>
<td>25.19</td>
<td>21.34</td>
</tr>
<tr>
<td>Eff (%) 1% sun</td>
<td>14.23</td>
<td>14.22</td>
<td>12.5</td>
<td>0.33</td>
</tr>
</tbody>
</table>

$I_0$ is the reverse saturation current of the cell,

$k$ is the Boltzmann constant,

$T$ is the room temperature (300K),

$V$ is the output voltage of solar cell,

$n$ is the diode's ideality factor,

$R_{SH}$ is the shunt resistance,

$q$ is the electron charge.

The simulated output current includes $I_L$ and $I_0$ so the effect of the shunt resistance can be calculated separately. The light-generated current $I_L$ decreases linearly with the light intensity while the decrease of voltage is slow. As the light intensity decreases, the shunt current takes bigger percentage of the light-generated current.

Because the simulated I-V curve does not take account of the shunt current, it is later calculated by using Matlab.

The baseline a-Si heterojunction solar cell was made with p-type emitter, n-type base and a back surface field (BSF). The front surface was textured with random upright pyramids and anti-reflection coating (ARC). The parameters for the baseline solar cell are listed in Table 2, where $J_{inc}$, $J_{ref}$ and $J_{tra}$ denote the equivalent current densities of incident light, reflected light, and transmitted light, respectively.

Figure 2 shows the output curve of the baseline solar cell under 1 sun condition with different shunt resistances. It can be seen that, when the shunt resistivity is larger than $10^4$ Ω.cm$^2$, their I-V curves almost overlap. Compared with the performance of the same a-Si heterojunction solar cell with light intensity of 1% of AM 1.5 (Figure 3), the performance of solar cell is obviously more sensitive to $R_{sh}$ changes at low light intensity. The detailed data comparison is listed in Table 3.
The results shown in Table 3 indicate that solar cell at very low light intensity is more sensitive to the shunt resistance. As the shunt resistance declines from $10^4 \, \Omega \cdot \text{cm}^2$ to $10^2 \, \Omega \cdot \text{cm}^2$, the efficiency only decreases from 14.23% to 12.5%. This shrinkage of efficiency is largely due to the decrease of the output voltage, $V_{OC}$. The $V_{OC}$ of solar cell under different light intensity condition is defined below [14].

$$V'_{OC} = V_{OC} - \frac{n k T}{q} \ln X \quad (2)$$

$V'_{OC}$ is the open circuit voltage under current illumination.

$V_{OC}$ is the open circuit voltage under one sun.

$X$ is the concentration of sunlight.

At 1% of sunlight, $V_{OC}$ declines to be 0.12 V, which is very close to the proportion of efficiency decrease.

As shown in Table 3, if the shunt resistance reduces to 100 $\Omega \cdot \text{cm}^2$, the decrease of efficiency due to the lowered light intensity would drop dramatically. The efficiency of baseline silicon solar cell with different shunt resistances at different light intensities are shown in Figure 4. As the light intensity drops to 1%, the shunt current also declines with the voltage, which is comparably small while the light-generated current decreases to be only 1%. So, the proportion of the shunt current to the light-generated current rises dozens of times. When the shunt resistance is very high, the increase of the shunt current proportion exhibits little difference. However, if the shunt resistance is very low, the output current would decrease a lot and therefore the efficiency drops.

IV. ULTRATHIN SOLAR CELL

The lowered $V_{OC}$ is an important reason for poor efficiency under low light condition. To mitigate this issue, ultrathin cell with advanced light-trapping structures is proposed.

There have been consistent attempts to reduce the silicon thickness for many reasons. Firstly, in the manufacturing of silicon solar cell, the material contributes up to 14% of the total cost. As a result, reducing the silicon wafer thickness can deliver a great economic benefit, plus the reduced processing time in multiple steps. Secondly, due to the indirect bandgap of c-Si, the efficiency is limited by the Auger recombination. Thinner wafers help to reduce the total power loss and thus, significantly increasing $V_{OC}$ of the solar cell. The theoretical efficiency limit for solar cell with a thickness of 10 $\mu$m is 28.5%. Yet, in order to achieve that goal, the light-trapping methods have to be changed accordingly. Thirdly, the mechanical property of ultrathin solar cell can change from fragile to flexible, which will broaden the relevant applications.

As mentioned in the previous section, $V_{OC}$ decreases with the light intensity, which is another important reason for the efficiency decrease of indoor solar cell. In fact, this problem could be mitigated by using
ultrathin solar cells. Yet, due to the decrease of base thickness, the light path in ultrathin solar cell is also decreased. To achieve better light absorption, it is important to apply proper light-trapping method.

As discussed before, the peak intensity of the spectrum of LED or incandescence light has longer wavelength. Since this solar cell is specially for indoor application, the light absorption in longer wavelength needs extra attention.

Three different light-trapping methods, namely back reflection, scattering, and internal reflection, are shown in Figure 5(a) and their light absorption properties comparison are shown in Figure 5(b). Single-pass absorption indicates that only perfect ARC is applied on the front surface. The double-pass absorption means that a perfect back-side reflection is added to the structure, which prolong the light path significantly while the third method includes ARC, back-side reflection and Lambertian scatters.

Table 4 Performance of a-Si heterojunction solar cell with enhanced light-trapping under incandescence light.

<table>
<thead>
<tr>
<th>Thickness (μm)</th>
<th>$V_{OC}$ (V)</th>
<th>$J_{SC}$ (mA/cm²)</th>
<th>FF (%)</th>
<th>Eff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.543</td>
<td>0.41</td>
<td>73.2</td>
<td>16.28</td>
</tr>
<tr>
<td>100</td>
<td>0.57</td>
<td>0.398</td>
<td>73.5</td>
<td>16.67</td>
</tr>
<tr>
<td>50</td>
<td>0.592</td>
<td>0.389</td>
<td>75.2</td>
<td>17.29</td>
</tr>
<tr>
<td>15</td>
<td>0.607</td>
<td>0.356</td>
<td>79.2</td>
<td>17.09</td>
</tr>
</tbody>
</table>

The results show that these methods could greatly improve the light absorption coefficient of silicon solar cells for longer wavelength photons, and thus are beneficial for indoor solar cells. In the literature, some studies have been aimed at improving the solar cell optical absorption in longer wavelength. Many of those studies focused on the front/back side nanostructures, demonstrating potential of light absorption in the near-infrared wavelength [16].

Recent studies showed that, when grated with optimized circular pillars (Figure 6), the optical absorption in the near-infrared wavelength could increase by 75% [17]. As the spectrum of LED or incandescence light varies between different products, the overall optical generation enhancement may vary by 5~10%.

Simulations were carried out on a-Si heterojunction solar cell with different thicknesses. Apart from thickness, the other parameters are kept the same as the baseline solar cell. These solar cells all have front surface random upright pyramids and anti-reflection coating. The principal parameters are listed in Table 4.
As can be seen, although $J_{SC}$ still decreases when the wafer is thinned, $V_{OC}$ and fill factor (FF) continue increasing and the overall performance is upgraded. So, ultrathin a-Si heterojunction solar cell with proper light-trapping structure could potentially be one of the great choices for indoor solar cells.

V. INCORPORATING TUBULAR DAYLIGHTING DEVICES

In theory, the maximum luminous efficacy is 680 lm/W if the entire radiation focuses on the wavelength of 555 nm. While the minimum luminous efficacy would be 26 lm/W when all the radiation is at the wavelength of 450 nm [18]. However, in practice, the light source varies a lot. Compared to the luminous efficacy of solar irradiation of 110~120 lm/W, the luminous efficacy of artificial light source is much lower, ranging from 15 to 120 lm/W. For incandescent light, the efficacy often doesn't exceed 18 lm/W. The upper limit of incandescent light is around 55 lm/W when the tungsten filament works at the melting point.

To improve the overall luminous efficacy of indoor light, tubular daylight system is proposed. With the help of solar tracker and concentrator system, it is possible to direct 30,000 lm of sunlight into the building through a light pipe with a diameter of only 0.1 meter [19]. Dimming devices could be introduced to prevent intensive sunlight and to direct extra light to the solar cell.

Based on the recent researches [20], indoor solar cell incorporating daylight system, solar concentrators and beam splitter could significantly improve performance. Depending on the system design, cost, and size, the final efficiency of indoor solar cell can be increased by ~ 10% to exceeding 60%, which is sufficient for powering IoT devices. Therefore, in addition to the improvement of mental and visual comfortability, indoor solar cell with tubular daylight devices not only improves the power production but also the living environment, so is promising for a number of applications in future.

VI. CONCLUSION

This work reports on indoor a-Si heterojunction solar cell with ultrathin base and near-infrared enhanced light-trapping. By applying the heterojunction structure, the shunt resistance is declined and thus largely reduced the power loss, boosting the efficiency from less than 5% to be 14.23%. The ultrathin base and near-infrared enhanced-light-trapping structure reduced the recombination and ameliorated the optical absorption in the solar cell, and thus improving the efficiency of indoor solar cell from 14.23% to 17.09%. Along with the daylight tubular system, the performance of indoor solar cell could be further improved.

Declarations

All authors disclosed no relevant relationships

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The authors have no relevant financial or non-financial interests to disclose.

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Shujian Xue, Guangan Yang, Xing Zhao, Jianfei Wu, Run Li, Binhong Li and Yong Xu. The first draft of the manuscript was written by Shujian Xue and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

All the data should be available in this paper, if further data is needed, please contact the first author.

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Figures

Figure 1

Equivalent circuit for calculating the shunt resistance [13]
Figure 2

I-V curve of the baseline silicon solar cell under AM1.5 with different shunt resistances
Figure 3

I-V curve of baseline silicon solar cell under 1% of AM1.5 with different shunt resistances.

Figure 4

The efficiency of baseline silicon solar cell with different shunt resistance under different light intensity.
Figure 5

Ultrathin silicon solar cell (a) with different state-of-the-art light-trapping methods, (b) and their optical absorption properties [15].
Figure 6

Solar cell with periodic nano-pilar structure.