Anti Reflection (AR) Coating for Indium Gallium Nitride (InGaN) Solar Cells


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Anti Reflection (AR) Coating for Indium Gallium Nitride (InGaN) Solar Cells

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**Title:** Anti Reflection (AR) Coating for Indium Gallium Nitride InGaN Solar Cells


**Abstract:**
This report describes enhanced solar energy harvesting using an optimized anti reflection (AR) coating consisting of a double layer stack of silicon dioxide (SiO$_2$) and silicon nitride (Si$_3$N$_4$) films. First, we made theoretical calculations for the minima of reflection curves and then performed experiments with different thicknesses of SiO$_2$ and Si$_3$N$_4$ layers. The low temperature SiO$_2$ and Si$_3$N$_4$ films were produced by low pressure chemical vapor deposition (LPCVD). Our experimental results agree qualitatively with the theoretical findings. The optimized SiO$_2$ and Si$_3$N$_4$ layers were 500 and 750 Å, respectively. We also observed an increase of transmission in ultraviolet (UV) region from 75% for an indium gallium nitride (InGaN) substrate without AR coating to greater than 90% for the same layer with AR coating. By using an optimized AR coating we observed a 20% increase in InGaN solar cell efficiency.
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1. Introduction

Silicon (Si) solar cells have seen much improvement in performance in terms of power conversion efficiency and the cost per watt in production, and as such, are the leading photovoltaic device, enjoying 80% of current solar cells market share (1, 2). Recently many attempts have been made (3–5) to improve the solar cell performance by using plasmonic materials, nanostructures, and various anti-reflection (AR) coatings. However, silicon solar cell response in ultraviolet (UV) part of solar spectrum is limited. Indium gallium nitride (InGaN) quantum well (QW) structure is of special interest for solar cells because of its enhanced responsivity in UV region of the solar spectrum. Using a hybrid solar cell structure made with an InGaN QW structure on top and a Si solar cell in bottom is expected to enhance the solar energy conversion efficiency (6). Since the open circuit voltage (V_{oc}) for InGaN solar cell is about 2.0 V and about 0.5 V for an Si solar cell, combining four Si solar cells in series can enable voltage matching with an InGaN solar cell, creating a useful high voltage hybrid solar cell. In addition, the InGaN epitaxial layer is very resistant to environmental corrosion and hence can protect the Si solar cell when used as the top layer.

The key to making such hybrid structures is to design and fabricate a top InGaN solar cell with the AR coating optimized for the entire solar spectral region. In this report, we present the experimental results of the design and development of various types of AR coatings on an InGaN solar cell structure. Both theoretical models and experimental results are presented. We discovered that a double-layer AR coating with silicon nitride (Si₃N₄) on bottom and silicon dioxide (SiO₂) on top provides a minimum reflection.

2. Experimental

InGaN/gallium nitride (GaN) multiple quantum well (MQW) and p-i-n solar cell structures were grown on double-side-polished 50-mm-diameter (0001) sapphire substrates by metal-organic chemical-vapor deposition (MOCVD). The InGaN solar cell structures consist of the following:

- a 1-µm unintentionally doped GaN template layer,
- a 2-µm Si-doped n-GaN layer ([Si]=6x10^{18} cm^{-3}),
- a 10-nm highly Si-doped n⁺-GaN layer ([Si]=2x10^{19} cm^{-3}),
- a 30-period undoped MQW active region with 2.6-nm In₀.₂Ga₀.₈N QWs and 6.7-nm GaN barriers,
• a 40-nm highly Mg-doped smooth p⁺-GaN layer ([Mg]=5x10¹⁹ cm⁻³),
• a 30-nm Mg-doped smooth p-GaN layer ([Mg]=2x10¹⁹ cm⁻³), and
• a 15-nm highly Mg-doped p⁺-GaN contact layer.

The device characteristics were measured by wafer-level probing at room temperature. Dark and illuminated current versus voltage (I-V) measurements were taken using an Agilent HP 4156 C parametric analyzer. An unfiltered Newport solar simulator provided broadband illumination with an equivalent AM1.5G illumination intensity of approximately 1.0 sun (100 mW/cm²).

3. Results and Discussions

AR coatings on solar cells consist of a thin layer of dielectric material of a specially chosen thickness so that interference effects in the coating cause the wave reflected from the AR coating’s top surface to be out of phase with the wave reflected from the semiconductor surfaces. These out-of-phase reflected waves destructively interfere with one another, resulting in zero net reflected energy. The thickness of the AR coating is chosen such that the wavelength in the dielectric material is one quarter the wavelength of the incoming wave. For a quarter wavelength AR coating of a transparent material with a refractive index \( n \) and light incident on the coating with a free-space wavelength \( \lambda_0 \), the thickness \( d \), which causes minimum reflection, is calculated by

\[
 d = \frac{\lambda_0}{4n}
\]

(1)

Reflection is further minimized if the refractive index of the AR coating is the geometric mean of that of the materials on either side; that is, glass or air and the semiconductor. This is expressed by

\[
 n_1 = \sqrt{n_0n_2}
\]

(2)

The reflectance of the incident light is a function of thicknesses of the AR coating layer, the incidence angles, and the refractive index of the medium. We used the simulation model developed by Paul Shen to calculate the reflectance of AR coating layer with different materials and thicknesses. Figure 1 shows the simulated reflection coefficients for different Si₃N₄ and SiO₂ film thicknesses. We observed minimum reflection for the AR coating layer consisting of 500 Å of Si₃N₄ and 750 Å of SiO₂. Reflectance increases as the SiO₂ layer either increases or decreases
for the same Si₃N₄ layer thickness of 500 Å. The reflectance for this optimized double-layer coating is also decreased in UV region.

Figure 1. Reflectance simulation curve for different combination of Si₃N₄ and SiO₂ films less than 5% in the entire spectral region between 3000 to 10000 Å. The reflectance also decreases in the UV region of 3500 to 4000 Å, which is the operating region for InGaN solar cells.

The experimental reflectance results of different AR coating layer are shown in figure 2. We used Perkin Elmer UV-visible-IR spectrometer to record the reflectance and transmission data. The AR coating layer consisting of only an Si₃N₄ film with a 400-Å thickness has the highest reflectance whereas the double-layer AR coating with 400 Å of Si₃N₄ and 550 Å SiO₂ has the least reflectance. Though not shown here, we also observed lower reflectance for the double-layer AR coating with 400 Å of Si₃N₄ and 750 Å of SiO₂. By comparing figures 2 and 3, it is observed that the theoretical reflectance curve has a lower value compared to the experimental curves. This may be due to the fixed refractive index value used in calculating the theoretical curves; in practice, it may be worth varying the value using different In composition in InGaN epitaxial layer.
In figure 3, we show the experimental transmission data for different AR films. We observed highest transmission characteristics for double-layer AR film with 400 Å of $\text{Si}_3\text{N}_4$ and 750 Å of $\text{SiO}_2$ films. Transmission for this optimized thickness is higher for entire spectral range of 4000–10000 Å. As seen in figure 3, the transmission of visible light in the spectral region of 4500 to 10000 Å increases from 75% to more than 90% when the optimized double-layer AR coating is used. Also the transmission through AR1 film ($\text{Si}_3\text{N}_4$ 400 Å and $\text{SiO}_2$ 750 Å) is higher than AR2 ($\text{Si}_3\text{N}_4$ 400 Å and $\text{SiO}_2$ 900 Å).
The I-V characteristics of InGaN solar cells under illumination, with and without AR coating, are shown in figure 4. We used an unfiltered Newport solar simulator with broadband illumination with an equivalent AM1.5G illumination intensity of approximately 1.0 sun (100 mW/cm²). We used 1-mm² InGaN solar cell grid-structured top p-metal. While both the devices exhibit an $V_{oc}$ of 2.0 V independent of the AR coating, the short circuit current ($I_{sc}$) is about 20% higher for the device with the AR coating compared to the device without the AR coating due to the increase in absorption in the structure. The observed photovoltaic response for these devices is comparable to the results from similar devices reported by Farrell et al. (7).
Figure 4. I-V curves for InGaN solar cell with and without AR coating.

4. Conclusions

We simulated the double-layer AR coating characteristics with minima in the UV region for enhanced InGaN solar cell performance. Experimentally, we found that the double-layer AR coating consist of 400 Å of Si$_3$N$_4$ and 750 Å of SiO$_2$ is suitable for AR coating for a broad range of solar energy absorption. We observed about a 20% increase in the short circuit voltage when using the optimized device structure.
5. References


### List of Symbols, Abbreviations, and Acronyms

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>AR</td>
<td>anti-reflection</td>
</tr>
<tr>
<td>GaN</td>
<td>gallium nitride</td>
</tr>
<tr>
<td>InGaN</td>
<td>indium gallium nitride</td>
</tr>
<tr>
<td>$I_{sc}$</td>
<td>short circuit current</td>
</tr>
<tr>
<td>I-V</td>
<td>illuminated current versus voltage</td>
</tr>
<tr>
<td>MOCVD</td>
<td>metal-organic chemical-vapor deposition</td>
</tr>
<tr>
<td>MQW</td>
<td>multiple quantum well</td>
</tr>
<tr>
<td>QW</td>
<td>quantum well</td>
</tr>
<tr>
<td>Si</td>
<td>silicon</td>
</tr>
<tr>
<td>Si$_3$N$_4$</td>
<td>silicon nitride</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>silicon dioxide</td>
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<tr>
<td>UV</td>
<td>ultraviolet</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>circuit voltage</td>
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