Investigation of the incident light intensity effect on the internal electric fields of GaAs single junction solar cell using bright electroreflectance spectroscopy

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**ABSTRACT**

The incident light intensity (Iex) effect on a GaAs single junction solar cell (SC) was investigated using bright electroreflectance spectroscopy (BER) and current-voltage (J-V) measurements at room temperature. The p-n junction electric field (Fpn) of the SC was evaluated by analyzing the Franz Keylde oscillation (FKO) in the BER spectra.

The Iex effect on Fpn was investigated at various incident light intensities from 0.03 to 25 suns. The Fpn decreased gradually with increasing Iex due to the photovoltaic effect. For the forward bias voltage, some part of the electrons and holes drifted to the p and n sides, respectively, and produced the induced electric field in the same direction of the Fpn. Therefore, the Fpn increased up to 2.5 suns. At more than 2.5 suns, most of the electrons and holes moved to the n and p sides and decreased the Fpn due to the photovoltaic effect.

In addition, the Fpn was examined under light illumination as a function of different DC bias voltages (−0.2–0.4 V). The Fpn decreased with increasing bias voltage due to the decrease in potential barrier. The Fpn increased with increasing bias voltage due to the decrease in the photogenerated carrier-induced electric field for high Iex.

1. Introduction

A concentration-type solar cell is the most promising strategy for reducing the cost of materials and improving the efficiency of solar cells. GaAs was proposed for use in high-efficiency solar cells because it has a band gap of approximately 1.4eV, which is the theoretical high efficiency [1–3]. The GaAs-based compound semiconductor has been adopted for concentrated photovoltaic (CPV) solar cells (SCs) [4,5]. Recently, GaAs concentration single-junction solar cells have achieved up to 29.1% efficiency at 117 suns [6,7].

In the early stages of development for CPVs, the solar cell characteristics, such as short circuit current density (Jsc), open circuit voltage (Voc), and fill factor (FF), were studied to understand the efficiency limit related to the light intensity [6–9]. Recently, these characteristics were reported to be influenced by the shunt and series resistance of the SC structure [2].

Moreover, the junction electric field (F) of a SC is an essential parameter under equilibrium illumination conditions because it can separate the electron-hole pairs to generate a photocurrent [10–13]. Generally, F can be tuned by controlling the doping concentrations of a p-n junction. Therefore, F can affect the solar cell efficiency [8]. When SC devices are exposed to sunlight, F can decrease with increasing incident light intensity because of the photovoltaic effect [14,15].

Therefore, understanding the change in F on the concentration SC with light intensity could explain the efficiency limit of CPV over a critical light intensity. Bright Electro-reflectance (BER) spectroscopy can be adopted to examine the optical properties of solar cell structures at the device level. The shapes of the BER spectrum depend on the strength of the applied bias voltage and additional pump or probe beam intensity [16,17]. The line shape of the BER spectrum has been demonstrated to be the third derivative of the unperturbed dielectric function [14]. When an internal electric field exists in a semiconductor, Franz-Keldysh oscillations (FKOs) can appear in a BER spectrum. The strength of the internal electric fields can be determined by FKO.
The conventional BER setup is maintained as low as possible to minimize light. Internal electric series source meter, these parameters are determined by measuring the circuit voltage, short circuit current, \( V_{oc} \), and detected using a p-i-n silicon photodiode and fed into the lock-in field as an excitation source. The white light beam from a tungsten-halogen lamp was used to illuminate the SC to obtain the BER spectra. The recombination of the probe beams on the samples and obtain the inherent characteristics can be modeled based on the one diode model using the Shockley equation [18]:

\[
J = J_0 - J_s \left( \exp \left( \frac{q(V + JR_s)}{nkT} \right) - 1 \right) - \frac{V + JR_s}{R_{SH}}
\]

(1)

where \( J_0 \) is the dark saturation current density; \( J_s \) is the photo-generated current density; \( V \) is the voltage; \( T \) is the Kelvin temperature; \( k \) is the Boltzmann constant and \( n \) is the diode ideality factor. Here, \( R_s \) and \( R_{SH} \) are the series and shunt resistances, respectively. The equation for the series and shunt resistances was used to analyze the solar cell [19].

The dependence of the estimated parameters on the light concentration was studied based on the proposed curve fitting procedure. Fig. 3 shows the dependence of the open circuit voltage (\( V_{oc} \)), short circuit current density (\( J_{sc} \)), fill factor (FF), and conversion efficiency (\( \eta \)) on the light concentration.

As shown in Fig. 3(a), \( J_{sc} \) can be described with a linear function of the concentration as follows [16]:

\[
J_{sc} = X \cdot J_{sc,1sun}
\]

(2)

where \( X \) is the concentration factor and \( J_{sc,1sun} \) is the short circuit current density at one sun (1000 W/m²). \( J_{sc} \) increased linearly with increasing intensity of the incident light because the number of photogenerated carriers is proportional to the intensity of incident light.

Fig. 3(b) shows the \( V_{oc} \) behavior by changing the concentration. This can be explained by Eq. (3) as follows [17]:

\[
V_{ocX} = V_{oc} + \frac{kT}{q} \ln X
\]

(3)

where \( V_{ocX} \) is the open circuit voltage at \( X \) suns concentration. The open circuit voltage increases logarithmically as a function of the short circuit current density. Therefore, the \( V_{oc} \) is increased by increasing the \( J_{sc} \). Generally, the built-in voltage is affected by the bandgap of the SC. In addition, the bandgap is a function of temperature [20]. Because a continuous light source was used, the change in temperature of the solar cell with the light intensity was confirmed. The temperature effect on the SC was measured by electroluminescence (EL) spectroscopy. The inset in Fig. 3(b) shows the peaks of the EL spectra with the intensity of the incident light. The change in the bandgap in the entire measurement region was approximately 10 meV. Here, the change caused by the temperature in the bandgap energy can be neglected because it is significantly smaller than the variation range of the open voltage (i.e., 130 meV). The logarithmic fits to these data can be used to extract the effective mean ideality factor for the GaAs SC. The calculated ideality factor was 1.98. The ideality factor of the GaAs single-junction solar cell was approximately 1.83 [10].

Fig. 3(c)-(d) show the FF and \( \eta \) in the solar cell according to the concentration of illuminated light. As shown in Fig. 3(c), the FF decreased at higher irradiation intensities. Generally, the FF decreases when \( R_s \) increases or \( R_{SH} \) decreases. The causes of the FF variation by \( R_s \) and \( R_{SH} \) with increasing \( L_0 \) will be discussed below. Fig. 3(d) also shows that the efficiency depends on \( L_0 \). The FF decreased from 1 sun to 3.45 suns, but the increase in open-circuit voltage was greater, so the \( \eta \) is increased. By increasing the \( L_0 \) above the 3.45 suns, the \( \eta \) continuously decreases because the slope of decrement of the FF is faster than that of the FF from 1 to 3.45 suns. The \( J_{sc} \), \( V_{oc} \), FF, and \( \eta \) are summarized in Table 1.

As observed in the \( \eta \) and FF, the \( R_s \) and \( R_{SH} \) significantly affect the structure under different illuminated light intensities. The illuminated light intensity (0.03–25 suns) was changed by the ND filters and the reflected light was detected by the Si photodiode detector.

3. Result and discussion

To match the operating environment of the solar cell as much as possible, current-voltage curves were measured using a continuous white light (tungsten-halogen lamp). The mathematical relation of the I-V characteristics can be modeled based on the Shockley equation [18]:

\[
J = J_0 - J_s \left( \exp \left( \frac{q(V + JR_s)}{nkT} \right) - 1 \right) - \frac{V + JR_s}{R_{SH}}
\]

(1)

where \( J_0 \) is the dark saturation current density; \( J_s \) is the photo-generated current density; \( V \) is the voltage; \( T \) is the Kelvin temperature; \( k \) is the Boltzmann constant and \( n \) is the diode ideality factor. Here, \( R_s \) and \( R_{SH} \) are the series and shunt resistances, respectively. The equation for the series and shunt resistances was used to analyze the solar cell [19].

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As observed in the \( \eta \) and FF, the \( R_s \) and \( R_{SH} \) significantly affect the structure under different illuminated light intensities. The illuminated light intensity (0.03–25 suns) was changed by the ND filters and the reflected light was detected by the Si photodiode detector.
shape of the I-V curves \[21\]. To explain the variation in the FF with the light intensity, the RS and RSH were analyzed by fitting the I-V curves using equation (1); the results are presented in Fig. 4. Fitting was performed using Labview and Matlab programs. RS decreased with increasing light intensity because of the increase in the active layer conductivity. The active layer of the solar cell is a photoconductor, and the number of absorbed photons by the active layer increases with increasing light intensity, which causes an increase in the number of charge carriers and conductivity of the active layer. As a result, the resistance of the sample decreased with increasing conductivity \[22\]. Moreover, RSH decreases with increasing light intensity. This variation can be explained by a combination of tunneling and trapping of the carriers through the defect states in the space charge region. The defects act as recombination centers or traps depending on the relative capture cross-sections of the electrons and holes for the defects. A low RS value is preferred to avoid power loss via a decrease in Jsc, maximum power point, and \(\eta\) of the solar cell \[6,10\]. In contrast to RS, RSH must be higher to avoid the leakage current in the Space Charge Region (SCR) \[11\] and losses in the Voc.

The SC efficiency may improve by understanding the electric field around the p-n junction, which may be a function of the photon energy intensity. The electric field can vary because of the photovoltaic effect caused by excess photo-generated carrier screening of the \(F_{pc}\). The photo-generated electron-hole pairs can be separated efficiently by the

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Table 1

<table>
<thead>
<tr>
<th>Solar concentration (sun)</th>
<th>Jsc (mA/cm²)</th>
<th>Voc (V)</th>
<th>FF (%)</th>
<th>(\eta) (%)</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>25.69</td>
<td>0.93</td>
<td>55.73</td>
<td>13.34</td>
</tr>
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<td>2.8</td>
<td>73.60</td>
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<td>14.19</td>
</tr>
<tr>
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<td>90.07</td>
<td>0.99</td>
<td>55.33</td>
<td>14.37</td>
</tr>
<tr>
<td>4.4</td>
<td>116.9</td>
<td>1.00</td>
<td>53.80</td>
<td>14.28</td>
</tr>
<tr>
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<td>1.02</td>
<td>52.70</td>
<td>14.19</td>
</tr>
<tr>
<td>7.36</td>
<td>193.0</td>
<td>1.02</td>
<td>52.20</td>
<td>14.04</td>
</tr>
<tr>
<td>11.43</td>
<td>298.2</td>
<td>1.05</td>
<td>48.67</td>
<td>13.42</td>
</tr>
</tbody>
</table>
electric field around the junction, which means that the internal electric field of the SC is very important.

Therefore, the photovoltaic effect is an essential factor to examine the SC efficiency. The BER spectrum consists of the band to band transition and Franz Keydsh oscillations (FKOs) which appeared above the bandgap and the FKO are sensitive to the electric field. The FKO period is related directly to the surface and interface electric field strength in the SC. The fast Fourier transform (FFT) for the FKO was used to determine the period of the FKO in the frequency domain. The frequency of the oscillation is inversely proportional to the electric field. Fig. 5(a) and (b) shows the BER spectra and the FFT results for the FKO under −200 mV and +200 mV of reversed and forward bias and the one sun condition at room temperature. As we can see in Fig. 5(b), by increasing the DC bias voltage, the frequency of oscillation is increased, so the total electric field is decreased.

To examine the photovoltaic effect caused by the light intensity, sun intensity-dependent BER measurements were performed at room temperature using a 190 W tungsten halogen lamp. In addition, a DC bias voltage was applied. The electric field in the FFT method was considered to be the p-n junction electric field because the surface electric field could not be observed due to ohmic contacts. The periods of the FKO of BER spectra change with the light intensity and DC bias voltage. The shapes of the FKO change because of the changing electric field and overlapping FKO signals [8].

The electric field (Fp,i) strength of the single junction solar cell was measured using the BER setup, as shown in Fig. 2. Fig. 6 shows the internal electric fields versus the reversed zero and forward DC bias voltages for several solar concentrations. When the Iex increases, carriers are generated by the light concentration ratio, and the electrons and holes in the p-i-n junction drift to the n-type and p-type side, respectively. The photo-generated carriers produce an electric field in the opposite direction of the built-in electric field and decrease the internal electric field. Therefore, for a zero bias voltage, the electric field decreased with increasing Iex. Moreover, for the reversed DC bias voltage, the total potential barrier increases in the built-in direction and the photo-generated-induced electric field increases in the opposite direction, which causes a decrease in the total electric field [9].

As shown in Fig. 6, the Fp,i variation for a reversed bias is more than a zero bias voltage. The electric field by the reversed bias voltage moves a large number of carriers to the p-side and n-side compared to the zero bias voltage and increases the accumulated carriers. The photo-generated induced electric field increases with increasing carrier density. Therefore, the electric field is decreased more than that under a zero bias voltage.

The forward electrical dc bias voltage was considered. For the applied forward DC bias voltage, the potential barrier decreases. As a
result, the electron and holes can drift easily to the p and n sides at low light intensity. The number of photo-generated carriers decreased and $F_{pn}$ increased until the carriers in the p and n side become balanced. The photo-generated carriers and carrier accumulation increased with increasing solar concentration. In addition, the induced electric field increased and the total electric field decreased.

The internal electric field dependence at DC bias voltage ($-0.2$–$0.4$ V) was examined, as shown in Fig. 7. At a low light intensity, for the forward bias, the $F_{pn}$ decreased with increasing electrical bias voltage because of the decrease in potential barrier [9]. For the reversed bias voltage, $F_{pn}$ increased with increasing electrical bias voltage because of the increase in potential barrier. By increasing the $I_{sc}$, the photogenerated carrier accumulation was increased in the n and p sides. For a forward bias voltage, the accumulated carriers in the n-type side and p-type side decreased due to the increasing forward bias voltage. Furthermore, the induced electric field of the accumulated carrier decreased in the opposite direction of the $F_{pn}$, which caused an increase in $F_{pn}$. On the other hand, the reversed bias voltage increases the photogenerated carrier accumulation in the n-type side and p-type side. The accumulated carrier-induced electric field was increased. Therefore, the $F_{pn}$ decreased with increasing reversed bias voltage.

As shown in Figs. 6 and 7, the electric field of the p-n junction was saturated due to the increasing the light intensity. At a high sun intensity, the number of accumulated carriers reached equilibrium, and the electric field then saturated. In the experiments, the electrical bias modulation and light intensity dependence were investigated [11].

4. Conclusion

This study proposed a simple way to concentrate light using lenses to focus light onto a small area. The solar characteristics of the single junction GaAs SC, such as $J_{sc}$, $V_{oc}$, fill factor, and efficiency, were obtained from the $J-V$ measurements. The cell efficiency of the GaAs concentrator was 14.37% for 3.45 suns. The resistance impact on the solar conversion efficiency was considerable.

To examine the $I_{sc}$ effects on the internal electric field ($F_{pn}$) of GaAs SC, $I_{sc}$-dependent bright electroreflectance (BER) spectroscopy was performed with various $I_{sc}$ (0.03–25 suns). FKO s due to the internal electric fields were observed. The FFT results of the FKOs show the electric field as a function of the incident light intensity and DC bias voltage. For a reversed and zero DC bias voltage, $F_{pn}$ decreased gradually with increasing $I_{sc}$ due to the photovoltaic effect. For a forward DC bias (+200 mV), $F_{pn}$ increased until 2.5 suns due to the decreased potential barrier, and increasing the carrier accumulation resulted in a gradual decrease in $F_{pn}$ with increasing $I_{sc}$.

In addition, the electric field was changed by increasing the forward and reverse bias voltages at constant light illumination. For $I_{sc}$ below one sun, the $F_{pn}$ decreased and increased with increasing forward and reverse bias voltage, respectively, due to the photovoltaic effect. By increasing $I_{sc}$, the induced photogenerated carrier electric field increased, which altered the electric field variation behavior. In high $I_{sc}$, the electric field increased with increasing forward bias and decreased for a reversed bias voltage.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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Fig. 7. Electric field ($F_{pn}$) versus electrical DC bias voltage from 0.05 to 25 sunlight concentration.