ELECTROPHYSICAL PROPERTIES OF GaAs P–I–N STRUCTURES FOR CONCENTRATOR SOLAR CELL APPLICATIONS

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This paper is dedicated to electro-physical characterisation of a GaAs p-i-n structure grown for solar cell applications, which was carried out by light and dark current-voltage (IV) and Deep Level Transient Fourier Spectroscopy (DLTFS) methods. The conversion efficiency and open-circuit voltage were determined from \( I-V \) measurement at 1 and 20× sun light concentrations. Three electron like defects TA\(_{n1}\), TA\(_{n2}\), TD\(_n\) and one hole like defect TB\(_p\) obtained by DLTFS measurements were confirmed. The origin of these defect states was stated as native GaAs impurities.

**Key words:** solar cell, GaAs concentrator solar cell, \( I-V \) measurement, DLTFS, defects

1 INTRODUCTION

Solar energy is one of the many energy forms harnessed by humanity in order to produce electricity in an environmental friendly and efficient way. Among the various solar cell technologies [1–3], GaAs concentrator solar cells have the potential to achieve higher conversion efficiencies and are promising for space and terrestrial applications [4, 5]. These solar cell structures are optimized for specific applications — such as satellites, photovoltaic concentrator systems and laser power beaming. The record efficiency 28.8\%, GaAs solar cell had achieved in 2011 [5]. Due to their good properties such as high quantum efficiency and good irradiation tolerance, they are the ideal choices for space applications [7, 8]. In comparison with Si space solar cells, the radiation reliability of GaAs solar cells is over 20% higher and the efficiency of energy conversion is 20–25% and above. The lifetime in orbits of GaAs solar cells is 40–60% over the one of Si solar cells [9, 10].

Key factor of development is to understand recombination dynamics in GaAs solar cell structures. Valuable feedback for the technology process is provided by the Deep Level Transient Fourier Spectroscopy (DLTFS) method, which represents a unique technique of electrically active defect and recombination centre investigation.

The aim of this paper is to introduce and discuss results of DLTFS defect investigations of the GaAs concentrator solar cell grown by Atmospheric Pressure Metal Organic Vapour Phase Epitaxy (AP-MOVPE).

In addition, temperature dependent dark and light current voltage characteristics at two light concentrations were carried out to gain further insight on the structure operation and performance.

2 EXPERIMENTAL

2.1 Device processing

The investigated p GaAs:Zn/i GaAs/n GaAs: Si solar cell was grown by AP-MOVPE on a n-type GaAs (Si doped) substrate at the Wroclaw University of Science and Technology. The GaAs p-i-n junction was sandwiched between a Si doped GaAs substrate with \( n = 1 \div 2 \times 10^{18} \text{cm}^{-3} \) and a 50 nm thick Zn doped \( p^+ = 1 \div 3 \times 10^{19} \text{cm}^{-3} \) cap layer. GaAs p-i-n with thicknesses of 200/800/200 nm was connected with the substrate by a n type GaAs 200 nm thick buffer layer with \( n = 2 \div 3 \times 10^{18} \text{cm}^{-3} \).

Doping concentrations of the p-i-n region was as follows: \( p \) layer \( p = 2 \div 3 \times 10^{18} \text{cm}^{-3} \) and \( n \) layer as a gradient \( n = 2 \div 3 \times 10^{18} \text{cm}^{-3} \) to \( n = 1 \div 2 \times 10^{17} \text{cm}^{-3} \), Fig. 1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Thickness</th>
<th>( n, p ) (cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>p GaAs cap:Zn</td>
<td>- 50 nm</td>
<td>1×10(^18)</td>
</tr>
<tr>
<td>p GaAs:Zn</td>
<td>- 200 nm</td>
<td>2×10(^18)</td>
</tr>
<tr>
<td>i GaAs</td>
<td>- 200 nm</td>
<td></td>
</tr>
<tr>
<td>n GaAs:Si</td>
<td>- 800 nm</td>
<td>gradient 1×10(^17) to 2×10(^18)</td>
</tr>
<tr>
<td>n(^+) GaAs:Si buffer</td>
<td>- 200 nm</td>
<td>2×10(^18)</td>
</tr>
<tr>
<td>n GaAs:Si substrate</td>
<td>- 350 nm</td>
<td>2×10(^18)</td>
</tr>
</tbody>
</table>

Fig. 1. Material compositions and layer properties of the investigated p-i-n sample

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Light $I$–$V$ measurements allowed us to determine basic output photovoltaic parameters: open circuit voltage $V_{OC}$, short circuit current density $J_{SC}$, fill factor $FF$, and conversion efficiency $\eta_f$, which are summarized for $T = 300$ K in Tab. 1. Temperature dependent output parameters for $1 \times$ sun and $20 \times$ sun light concentration are shown in Figs. 4(a)–(d).

Table 1. Solar cell output parameters extracted from light $I$–$V$ characteristics of the GaAs p-i-n structure at $T = 300$ K

<table>
<thead>
<tr>
<th>$V_{OC}$ (V)</th>
<th>$J_{SC}$ (A/cm$^2$)</th>
<th>$V_{max}$ (V)</th>
<th>$J_{max}$ (A/cm$^2$)</th>
<th>$FF$ (%)</th>
<th>$\eta_f$ (%)</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.74</td>
<td>0.02</td>
<td>0.62</td>
<td>0.015</td>
<td>74.7</td>
<td>9.09</td>
<td>1 $\times$ sun</td>
</tr>
<tr>
<td>0.87</td>
<td>0.35</td>
<td>0.73</td>
<td>0.323</td>
<td>76.6</td>
<td>11.70</td>
<td>20 $\times$ sun</td>
</tr>
</tbody>
</table>

Figure 4(a) shows a negligible change of $J_{SC}$ with $T$ for both $1 \times$ sun and $20 \times$ sun light concentrations. More significant temperature dependencies are observed for $V_{OC}$, $FF$ which are consequently reflected also in $\eta_f$, Fig. 4(b)–(d). The decrease of the $V_{OC}$ upon the temperature has a physical origin and it can be explained by considering the following equation

$$V_{OC} = \frac{AKT}{q} \ln \frac{J_{SC}}{J_{Sat}}$$

where $A$ is the ideality factor, $J_{Sat}$ is the saturation current density and $J_{SC}$ is the short-circuit current density. $J_{Sat}$ is strongly related with intrinsic carrier concentration of the GaAs, which increases upon the increase of temperature resulting into the increase of $J_{Sat}$. While the $V_{OC}$ is reciprocally proportional to the saturation current, the $V_{OC}$ increases with the decrease of $T$, Fig. 4(b).

Both $V_{OC}$ and $FF$ have downward trends with the $T$ and determine the temperature behaviour of $\eta_f$. The temperature dependent $\eta_f$ allowed us to determine temperature coefficients of efficiency $\eta_{TKR}$ (in the linear temperature region 200–400 K) with values of $-0.37$ and $-0.31 \% / ^\circ C$ for light concentrations 1 $\times$ sun and 20 $\times$ sun, respectively. Such a coefficient describes the relative decrease of the efficiency with the increase of $T$.

Considering (1) it is obvious that high $J_{Sat}$ has a detrimental effect on the $V_{OC}$ and thus on the output photovoltaic performance. High quality materials with low concentration of defects are required to keep the $J_{Sat}$ low. The investigation of electrically active recombination centres is therefore crucial for optimization of solar cells. Using the DLTFS method, four deep energy levels were detected (Figs. 5, 6) in the investigated structure. Three of them, labelled by us as TA$_{n1,2}$ and TD$_{n}$, are linked to majority traps and one labelled as TB$_{p}$ to a minority trap. We have produced several DLTFS spectra sets by experiments with different initial measurement conditions filling ($U_{F}$) and reverse ($U_{R}$) voltages, capacitance transient period width - time period ($T_w$) and filling pulse length ($T_F$). Typical DLTFS spectra measured on the GaAs p-i-n solar structure are displayed in Fig. 5.
Temperature dependent current-voltage characteristics of the GaAs p-i-n structure measured in the dark (a) — and under solar simulator with (b) — 1× sun, and (c) — 20× sun concentrated light.

Table 2. Calculated and compared deep energy level parameters of TA_{n1}, TA_{n2} and TB_p before and after data selection with various evaluation procedures

<table>
<thead>
<tr>
<th>Trap</th>
<th>( \Delta E_T ) (eV)</th>
<th>( \sigma_T ) (cm²)</th>
<th>( \Delta E_{T_{\text{ref}}} ) (eV)</th>
<th>( \sigma_{T_{\text{ref}}} ) (cm²)</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA_{n1}</td>
<td>0.486</td>
<td>5.11 × 10^{-16}</td>
<td>0.48 eV</td>
<td>3.8 × 10^{-16}</td>
<td>EC2 [12]</td>
</tr>
<tr>
<td>TA_{n2}</td>
<td>0.400</td>
<td>1.57 × 10^{-17}</td>
<td>0.37 eV</td>
<td>4.0 × 10^{-18}</td>
<td>[13]</td>
</tr>
<tr>
<td>TB_p</td>
<td>0.691</td>
<td>2.34 × 10^{-16}</td>
<td>0.63 eV</td>
<td>4.0 × 10^{-17}</td>
<td>Zn/Ni [12]</td>
</tr>
<tr>
<td>TD_n</td>
<td>0.747</td>
<td>2.95 × 10^{-15}</td>
<td>0.73 eV</td>
<td>1.3 × 10^{-14}</td>
<td>As_{Ga} [15]</td>
</tr>
</tbody>
</table>

The reverse and filling voltage variation allowed us to estimate the type and layer origin of these specific responses. Since in the case of a p-i-n structure the depletion region is located at the i-layer, the active layer of the solar cell, the presence of these defect states can greatly affect the efficiency.

Figure 4(b) shows higher \( V_{OC} \) for 20× sun compared to 1× sun light concentration. This phenomenon could be explained by considering (1). While the \( J_{Sat} \) is not dependent on light, the \( V_{OC} \) increases with the increase of \( J_{SC} \) at the higher light concentration.

The FF exhibits initial increase upon the decrease of \( T \), which is followed by saturation in the temperature region of 200-100 K. The FF is a very complex parameter, which describes the current transport, recombination of carriers and contact properties in the structure.

At slightly forward biased conditions hole injection to the i-layer is ensured thereby the DLFTS curve should include also results from minority carrier traps. Higher filling voltages should increase the injection thereby amplifying initial or reveal additional minority traps. This procedure is visible in Fig. 5(a), where in the first case at higher \( U_P \) value (0.3 V) the minority trap TB_p indicated increasing tendencies, while in the second at a very low value of reverse voltage \( U_R = -2 V \) the minority response disappeared revealing an additional majority trap TD_n, Fig. 5(b). Figure 6 shows the obtained Arrhenius curves where TA_{n1,2} and TB_p were calculated at \( U_R = -0.1 V \) \( U_P = 0.3 V \) \( T_W = 0.5, 1, 3 \) ms and \( t_P = 0.3 \) ms, while TD_n was identified at \( U_R = -2 V \), \( U_P = 0.05 V \), \( T_W = 2.5 \) s and \( t_P = 0.8 \) ms. At \( U_R = -0.1 V \), \( U_P = 0.3 V \) not only the peak amplitude of TB_p but also TA_{n1,2} was increased. This fact indicated that one of the TA_{n1,2} complex (EC2 or EL16) has a more significant concentration at the i/n interface. Also higher hole injection (\( U_P = 0.3 V \), increased peak of TB_p) made possible to more precisely detect the TB_p level. TD_n was identified as EL2 (EX2) a frequently described and discussed arsenic antisite defect of GaAs, by lowering the reverse voltage to -2 V.

At these measurement parameters of the TA_{n1,2} level was also evident present, but unfortunately it was no separable by the deconvolution method, Fig. 5(b). Only the presence of TA_{n1} was confirmed more strongly suggesting that TA_{n2} is located near the i/n interface.

Table 2 lists the evaluated deep energy levels with their parameters (activation energy \( \Delta E_T \), capture cross-section \( \sigma_T \)) and the probable origin of the deep energy level. All energy levels that were evaluated were identified as well-known material defects of GaAs. Electron energy level TA_{n1} was identified as EC2 (0.48 eV, 3.8 × 10^{-16} cm²) and was originated from a Ni_{Ga} complex [13]. It is highly probable that this defect state was introduced by the growth process. The second electron energy level TA_{n2} was identified as EL16 (0.375 eV, 4.0 × 10^{-18} cm²) [14]. Not many reports were published about this defect state, therefore the possible origin of a complex defect state between EC2 and EL16 is thereby not clearly understood. In our interpretation the TA_{n2} level (EL16) could be introduced by the GaAs-i interface of the GaAs p-i-n sample, which together with the
Our investigation showed, that the deep energy level $T_{Bp}$ highly corresponds with a single p type deep energy level $HC1 (0.63 \text{ eV}, 4.0 \times 10^{-17} \text{cm}^2)$. According to the literature $HC1$ was observed in VPE samples diffused with Zn (Ni, Zn), which were used to study hole traps [13]. Zn creates a shallow p type donor level at 0.024 eV so it was ruled out.

Definite origin of $HC1$ was not stated however a minority character trap caused by majority carrier capture (electron) was described. A further example of this energy state showed a hole trap population including the energy 0.63 eV where oxygen was also discussed possibly accommodating certain charge states [15]. Presence of oxygen in MOVPE grown samples are frequently observed, therefore we can not entirely rule out this consideration. The electron trap $TDn$ probably corresponds with defects $EX2$ or $EL2$. $EL2$ is a mid-gap defect level of GaAs, more precisely an arsenic antisite defect. $EX2$ is a formation of $EL2$ identified in annealed GaAs samples by rapid thermal annealing process [16].

It was suggested that $EX2$ is a complex of two vacancies and an antisite without interstitial arsenic atoms ($V_{As}, V_{Ga}, As_{Ga}$). To ensure a more pure growth process further investigations are needed in connection with all possible relations of the observed defects and the growth technology.

Fig. 4. Extracted (a) — $J_{SC}$, (b) — $V_{OC}$, (c) — $FF$, and (d) — $\eta_f$ as a function of temperature at 1× sun and 20× sun light concentration.

Fig. 5. DLTFS measurements of the GaAs p-i-n sample at different reverse ($U_R$) and filling voltage ($U_F$) conditions.
Arrhenius curves of the GaAs p-i-n sample after DLTFS parameter variations. Arrhenius curves (a) – of the complex defect state TA_{n1,2} with defined reference data (EC2+EL16), (b) – of the defect state TB_p with reference data HC1, (c) – of the defect state TD_n with reference data EL2 and EX2.

4 CONCLUSION

This paper summarises the results of temperature dependent light and dark I–V measurements and DLTFS study of a GaAs p-i-n solar cell structure. Comparing output performance at different light conditions, the higher conversion efficiency as well as better temperature coefficient of efficiency measured at 20x sun light intensity indicated a good applicability of developed structures for concentrator applications. Four electrically active defects were confirmed by means of DLTFS. These were identified with high probability in connection with the growth process as well-known material defects of GaAs originated from a Ni_{Ga} complex, Oxygen and the arsenic antisite defect EL2. To achieve an increased efficiency, improved GaAs quality and the optimization of the solar cell design decreased concentration of recombination centres are needed.

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