Internal Electric Fields of Flexible GaAs Solar Cells Fabricated Using Epitaxial Lift-off

Received November 20, 2019; revised December 6, 2019; accepted December 9, 2019

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ABSTRACT

We have investigated the optical and electrical properties of flexible GaAs solar cells (SCs) fabricated by the epitaxial lift-off process using photoreflectance (PR) spectroscopy. The as-grown GaAs solar cells were transferred on Au/polyimide (ELA) and polydimethylsiloxane (PDMS; ELP) flexible substrates. In the PR spectra, low energy interference oscillations by internal multi-reflection were observed below the GaAs transition signals. The internal electric fields (F_int) were calculated to be 98.7 and 81.8 kV/cm for the ELA and ELP SCs, respectively. SCs produced by the ELA process exhibited fewer defects and higher F_int than the ELP SC.

Keywords: GaAs, Solar cell, Epitaxial lift-off, Defects

1. Introduction

GaAs is a direct transition semiconductor with high light absorption characteristics and theoretically has a band gap energy (1.42 eV) near 1.40 eV that can maximize the efficiency of solar cells (SCs). The efficiencies of GaAs SCs have been reported to be up to 29.1% in single junction structures [1]. In order to increase the efficiency of SCs by increasing the short-circuit current (J_sc), methods of extending the absorption wavelength range or increasing the number of photogenerating carriers have been used. For this purpose, approaches such as preparing surface anti-reflective coatings using nanostructures, controlling the thickness of the absorption layer using light-trapping, and introducing quantum dots into the active layer have been used [2-5]. In addition, multi-junction SCs have been introduced to extend the absorption wavelength range or increasing the number of photons in the photogenerating carriers have been used. This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licenses/by-nc/3.0) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

In this study, the optical properties of a sample transferred to a polydimethylsiloxane (PDMS) substrate using ELO-processing (ELO-layer/PDMS; ELA) and a sample bonded to an Au/polyimide layer (ELO-layer/Au/polyimide; ELP) were investigated using excitation intensity (Iexc) and temperature-dependent photoreflectance (PR). The defects generated during the ELO process were studied by comparing the photoluminescence (PL) measurement results for ELP and ELA.

2. Experimental methods

The n+-n-p+ GaAs SCs were grown on a GaAs substrate using molecular beam epitaxy for the ELO process. In order to proceed with the ELO process, the GaAs substrate was bonded to an AlAs sacrificial layer using ELO-processing (ELO-layer/AlAs/GaAs; ELP). In addition, the Au/polyimide layer was used as an etch stop layer through a chemical mechanical polishing (CMP) process. Figures 1(a) and 1(b) show the ELA and ELP SC structures after the ELO process. After the ELO process, the ELA and ELP SC structures exhibited p'-n-n' structures. The reference GaAs (Ref) SC was grown on a GaAs substrate; the resultant SC exhibited a p'-n-n' structure. In the ELA sample, Au was deposited on the polyimide thin film and sample on which growth was completed, and then Au-to-Au bonding was performed. The AlAs sacrificial layer was...
etched by dipping the sample into HF solution and the epilayer and substrate were separated. ELA was fabricated by etching the GaAs and InGaP layers through CMP. In the ELO process of the ELP SC, the AlAs sacrificial layer was etched by immersing the grown sample in HF solution to separate the epilayer and substrate, and the separated epilayer was transferred onto a PDMS/glass substrate. After that, GaAs and InGaP layers were etched as the last step of the ELA process. The detailed procedure is described in the previous study [13]. A SC device was fabricated to study the effects of defects generated during the ELO process on solar cell efficiency. In order to investigate the defects in ELP and ELA SCs, PL experiments were performed at 300 K. A He-Ne (633 nm) laser was used as the excitation light source in PL and PR measurements.

3. Results and discussion

In a previous study, we reported the excitation- and temperature-dependent PL results of the Ref, ELA, and ELP SCs [13]. In the PL spectra at 300 K, strong emission signals due to the band-to-band transition in GaAs were observed around 1.425 eV. The signals with multiple peaks which were not observed in the Ref SC were observed at an energy lower than the GaAs signal in the ELA and ELP SCs. Therefore, these signals are assigned to the defect states generated during the ELO process [13]. Additional peaks were produced by the interference effect of internal multi-reflection (IMR) [8]. Defect states can affect the internal electric field ($F_{int}$) in the space-charge region. Since the photo-generated carriers are separated by the $F_{int}$ and move electrodes, the change of the $F_{int}$ in the SC is very important. The presence of the effects of IMR in the PL spectra indicates that interference phenomena will also be observed in the PR spectrum.

Figure 2 shows the PR spectra of Ref, ELA, and ELP SCs at 300 K and the excitation intensity was 156 mW/cm². In the PR spectra of the Ref, ELA, and ELP SCs, GaAs transition signals were observed around 1.425 eV and the Franz-Keldysh oscillations (FKOs) due to the $F_{int}$ were also observed above the GaAs bandgap energy. Vibrating signals below the GaAs bandgap energy in the ELA and ELP SCs are low energy interference oscillations (LEIOs) [14,15]. In the Ref SC, the amplitude of the LEIO signal was weak and the period was shorter than those of the ELA and ELP SCs. The amplitude and period of the LEIO can be influenced by the structure, shape of the reflection, and defect state density of the thin films. The period of FKO signals was longest for the Ref SC and shortest for the ELP SC. As the FKO period is inversely proportional to the strength of the electric field [16], the $F_{int}$ strength is inferred to be the greatest in the Ref SC and weakest in the ELP SC. Fast Fourier transform (FFT) analysis was used to calculate the $F_{int}$ strength more accurately [17]. The calculated $F_{int}$ of the Ref, ELA, and ELP SCs were 122, 98.7, and 81.8 kV/cm, respectively. The defect states decrease the carrier’s doping concentration and thus reduce the strength of the $F_{int}$ at the p-n junction. The $F_{int}$ was strongest in the Ref SC, which had the lowest density of defect states.

Figure 3 shows the PR spectra of the Ref, ELA, and ELP SCs as a function of excitation intensity at 300 K. With increasing excitation intensity, all SCs exhibited an increasing amplitude and decreasing period. The increase in amplitude was due to the increase in modulation effects as more photo-generated carriers were generated by higher excitation laser intensity. A decrease in the FKO period indicated that the strength of $F_{int}$ was reduced. This is due to the increased photovoltage effect by the photo-generated carriers. When light is incident...
onto the SC from the outside, the photo-generated carriers in the space charge region are moved by the $F_{\text{int}}$ and accumulate on each side of the p-n junction, where they form another electric field in a direction opposite to that of $F_{\text{int}}$. Therefore, total $F_{\text{int}}$ gradually decreases as excitation intensity increases.

Figure 4 shows the $F_{\text{int}}$ (calculated with FFT) of the Ref, ELA, and ELP SCs as a function of excitation intensity at 300 K. As the excitation intensity increases to 156 mW/cm$^2$, the $F_{\text{int}}$ of the Ref, ELA, and ELP SCs are 122, 98.7, and 81.8 kV/cm, respectively. Lower $F_{\text{int}}$ values are due to the relatively high defect densities of ELA and ELP SCs that are caused by stresses during the separation process. The Au-to-Au bonding process of the ELA SC suppressed much of the defect generation that occurs in ELP SC during the ELO process. To increase the efficiency of ELO SCs, more research on a technique for reducing the number of defects during ELO process will be needed.

4. Conclusions

In this study, the defect effects generated in the GaAs SCs through the ELO process were investigated by PR spectroscopy. In the process of separating the epilayer and GaAs substrate in the ELO process, defects occurred due to the stresses that deform thin film SCs. At 156 mW/cm$^2$, the $F_{\text{int}}$ of the Ref, ELA, and ELP SCs are 122, 98.7, and 81.8 kV/cm, respectively. Lower $F_{\text{int}}$ values are due to the relatively high defect densities of ELA and ELP SCs that are caused by stresses during the separation process. The Au-to-Au bonding process of the ELA SC suppressed much of the defect generation that occurs in ELP SC during the ELO process. To increase the efficiency of ELO SCs, more research on a technique for reducing the number of defects during ELO process will be needed.

Acknowledgements

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education under grant numbers NRF-2017 R1A6A3A11028070 and NRF-2018R1D1A1B07050824. This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20163030013380). This study was partially supported by the Priority Research Centers Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2014R1A6A1031189).

References

[1] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, Prog. Photovoltaics Res. Appl. 21, 1 (2013).
[2] P. Yu, C. H. Chang, C. H. Chiu, C. S. Yang, J. C. Yu, H. C. Kuo, S. H. Hsu, and Y. C. Chang, Adv. Mater. 21, 1618 (2009).
[3] J. Oh, H. C. Yuan, and H. M. Branz, Nat. Nanotechnol. 7, 743 (2012).
[4] V. Aroutiounian, S. Petrosyan, and A. Khachatryan, J. Appl. Phys. 89, 2268 (2001).
[5] Y. Cheng, M. Fukuda, V. R. Whiteside, M. C. Debnath, P. J.
Vallely, T. D. Mishima, M. B. Santos, K. Hossain, S. Hatch, H. Y. Liu, and I. R. Sellers, Sol. Energy Mater. Sol. Cells 147, 94 (2016).

[6] Y. Yazawa, K. Tamura, S. Watahiki, T. Kitatani, J. Minemura, and T. Warabisako, Sol. Energy Mater. Sol. Cells 50, 229 (1998).

[7] Y. Kim, K. Y. Ban, C. Zhang, J. O. Kim, S. J. Lee, and C. B. Honsberg, Appl. Phys. Lett. 108, 103104 (2016).

[8] J. Maeda, Y. Sasaki, N. Dietz, K. Shibahara, S. Yokoyama, S. Miyazaki, and M. Hirose, Jpn. J. Appl. Phys. 36, 1554 (1997).

[9] Y. Sasaki, T. Katayama, T. Koishi, K. Shibahara, S. Yokoyama, S. Miyazaki, and M. Hirose, J. Electrochem. Soc. 146, 710 (1999).

[10] J. J. Schermer, G. J. Bauhuis, P. Mulder, E. J. Haverkamp, J. van Deelen, A. T. J. van Niftrik, and P. K. Larsen, Thin Solid Films 511, 645 (2006).

[11] E. Yablonovitch, D. M. Hwang, T. J. Gmitter, L. T. Florez, and J. P. Harbison, Appl. Phys. Lett. 56, 2419 (1990).

[12] E. Yablonovitch, T. Gmitter, J. P. Harbison, and R. Bhat, Appl. Phys. Lett. 51, 2222 (1987).

[13] M. G. So, S. J. Lee, H. J. Jo, J. S. Kim, T. T. Nguyen, Y. Kim, and S. J. Lee, New Phys.: Saegulli. 69, 806 (2019).

[14] S. J. Lee, S. SaeidNahaiea, J. O. Kim, S. J. Lee, and J. S. Kim, Appl. Sci. Converg. Technol. 28, 46 (2019).

[15] S. Hildebrandt, M. Murtagh, R. Kuzmenko, W. Kircher, and J. Schreiber, Phys. Status Solidi A 152, 147 (1995).

[16] H. J. Jo, Y. H. Mun, J. S. Kim, and S. J. Lee, J. Korean Phys. Soc. 69, 80 (2016).

[17] M. Nowaczyk, G. Sek, J. Misiewicz, B. Sciana, D. Radziewicz, and M. Tlaczala, Thin Solid Films 380, 243 (2000).