

論文 / 著書情報
Article / Book Information

題目(和文)	フレキシブル基板上 Cu(In,Ga)Se ₂ 太陽電池の研究
Title(English)	Study of Cu(In,Ga)Se ₂ Solar Cells on Flexible Substrate
著者(和文)	Adiyudha Sadono
Author(English)	Adiyudha Sadono
出典(和文)	学位:博士(工学), 学位授与機関:東京工業大学, 報告番号:甲第10802号, 授与年月日:2018年3月26日, 学位の種別:課程博士, 審査員:山田 明,中川 茂樹,間中 孝彰,宮島 晋介,PHAM NAM HAI,和田 隆博
Citation(English)	Degree:Doctor (Engineering), Conferring organization: Tokyo Institute of Technology, Report number:甲第10802号, Conferred date:2018/3/26, Degree Type:Course doctor, Examiner:,,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	要約
Type(English)	Outline

Study of Cu(In,Ga)Se₂ Solar Cells on Flexible Substrate

Author : Adiyudha Sadono

Supervisor : Akira Yamada

Thesis Outline/Summary

In Chapter 1 [Introduction], background and motivation of this research was discussed. Harvesting sun energy via photovoltaics module is one of the solution to solve energy and environmental problem. To increase the usage of photovoltaics flexible solar cell is attracting owing to its less weight and wide field of application. Thin film solar cell with Cu(In,Ga)Se₂ (CIGS) absorber layer has potential to be used as flexible solar cells absorber layer shown by its high efficiency on rigid glass. As flexible substrate, polyimide (PI) film is one of the best candidate due to its stability and insulator characteristics which doesn't need additional barrier layer. Our group has proposed fabrication of CIGS solar cells on PI-coated soda-lime glass (SLG) which is easier to used and could be made thinner than conventional PI film [1]. In this study, increasing the efficiency of flexible CIGS solar cells fabricated on PI-coated SLG was attempted by several experiments focusing on improving CIGS bulk and interface.

In Chapter 2 [Fundamental Physical Properties of Cu(In,Ga)Se₂ (CIGS) Material and Solar Cells], the feature and characteristics of CIGS thin-films along with its fabrication process were explained.

In Chapter 3 [Flexible CIGS Solar Cells Problems and Challenges], the problem and challenges that appeared during fabrication of flexible CIGS on PI-coated SLG was discussed. The problems on fabricating high efficiency flexible solar cells are mainly come from low deposition temperature approximately 450 °C which is maximum temperature that PI film can tolerate. Three main problems were discussed, which are (1) deep notch in band profile, (2) alkali diffusion, and (3) interface recombination. The deep notch in band

profile was caused by slow Ga diffusion at low temperature, in which reduce the V_{OC} and FF. While, alkali diffusion is a well-known problem in flexible CIGS because not using SLG that normally become the Na diffusion source. Moreover, low temperature deposition also contributes to different Na diffusion and other material which could reduce the carrier concentration. Therefore, investigation of alkali diffusion is necessary especially for CIGS on PI-coated SLG. Finally, the interface recombination is a common problem to CIGS solar cell that need to be solved both at high temperature or low temperature.

In Chapter 4 [New Band Profile Design for $Cu(In,Ga)Se_2$ Deposited at Low Temperature], single-graded band structure with Cu-deficient layer was proposed as a new band profile design to suppress the effect of deep notch that reduce the performance of CIGS deposited at low temperature [2]. First, fabrication at high temperature was investigated to compare it with conventional three-stage method. Then, application on low temperature deposited CIGS was investigated, which achieved higher efficiency than conventional double-graded CIGS. The deposition of Cu-deficient layer proven to effective to reduce the interface recombination owing to hole repelling effect that increase the efficiency of single-graded CIGS from 12% to 14.5%.

In Chapter 5 [Effects of Alkali Metal on $Cu(In,Ga)Se_2$ Solar Cells], Comprehensive investigation of alkali diffusion effect on CIGS both from substrate and external incorporation was conducted. NaF post-deposition treatment (PDT) was proposed to increase the carrier concentration, while KF-PDT was proposed to reduce the interface recombination by passivation effect [3,4]. NaF-PDT increased the performance of CIGS deposited on alkali-free glass and achieving same efficiency with the one deposited on SLG. NaF-PDT also increase the efficiency of CIGS that already has Na diffusion from 13% to 15%. By conducting of KF-PDT, 17% of efficiency was achieved by passivation effect showed by hole formation in the surface. In the end, KF-PDT was conducted to newly proposed single-graded CIGS, however, it was shown ineffective. Measurement by Auger Electron Spectroscopy (AES)

shown that the Ga contribute to the hole formation. This experiment indicated that Ga in the surface is necessary to form passivation layer with point contact that give beneficial effect to suppress the recombination at the interface.

In Chapter 6 [Improvement of Surface Passivation by Cu-deficient Layer Deposition on Alkali Treated Cu(In,Ga)Se₂ Solar Cells], combination of alkali treatment and deposition of Cu-deficient layer was proposed to maximize the passivation effect on CIGS surface as method to increase the efficiency further [5]. The deposition of Cu-deficient layer contributes to hole formation in the surface of alkali treated CIGS regardless of single-graded or double-graded. However, due to ineffectiveness of KF-PDT on single-graded CIGS, no significant improvement can be achieved. On the other hand, deposition of Cu-deficient layer on alkali treated double-graded CIGS proven to be effective to increase the FF further by passivate the point contact area by hole repelling effect that suppress the interface recombination and contribute to smoother CIGS/CdS interface by controlling the hole formation. Final efficiency exceeding 18% was achieved by combination of KF-PDT and Cu-deficient layer deposition which is higher than best efficiency of CIGS deposited on high temperature using the same equipment.

Future prospects

The proposed band profile, single-graded CIGS with Cu-deficient layer, shows promising characteristics with efficiency higher than conventional double-graded CIGS. However, the efficiency stuck at around 15% due to ineffectiveness of KF-PDT. Therefore, another approach is necessary to improve the performance of single-graded CIGS whether by changing KF deposition condition or finding a totally new method/material to improve the surface passivation. Simultaneous evaporation of KF and In under Se atmosphere proposed by Lepetit, et. al, could be one of alternative to get passivation layer by KF due no reaction with CIGS needed [6]. PDT using heavy alkali metal that demonstrate world record efficiency could also work owing to its position in Ellingham diagram [7]. Regardless of the methods, understanding the chemical reaction that form passivation layer and its

characteristics are necessary for further improvement.

In case of improvement for double-graded CIGS, KF-PDT with Cu-deficient layer deposition already shows high efficiency. However, this improvement was achieved without optimizing another component of CIGS solar cell, e.g. CdS buffer layer or i-ZnO layer. It has been reported that thinner CdS could be applied owing to passivation layer by KF-PDT [8], consequently thinning i-ZnO layer also can be think of to increase the efficiency further. Through controlling KF-PDT and CIGS surface condition, different hole number, size, and density that correlate to passivation effect is possible [9]. Therefore, optimization of this hole ‘patterning’ and Cu-deficient layer deposition condition could open new possibilities to higher efficiencies.

Finally, as the final aim is to fabricate high efficiency photovoltaics on flexible substrate, investigation of proposed fabrication method on module/mini module size will be the next topics. The realization of high efficiency flexible solar cells could open new world with solar cells attached in any kind of surface to produce electricity, especially in things that require weightless module such us satellite, or airplane.

Reference

- [1] A. Sadono, M. Hino, M. Ichikawa, K. Yamamoto, Y. Kurokawa, M. Konagai, and A. Yamada, *Jpn. J. Appl. Phys.* **54**, 08KC16 (2015).
- [2] T. Ogihara, A. Sadono, T. Nishimura, K. Nakada, and A. Yamada, *Jpn. J. Appl. Phys.* **56**, 62301 (2017).
- [3] A. Sadono, T. Ogihara, M. Hino, K. Yamamoto, and A. Yamada, *Electron. Mater. Lett.* **12**, 494 (2016).
- [4] A. Sadono, T. Ogihara, M. Hino, K. Yamamoto, K. Nakada, and A. Yamada, *Jpn. J. Appl. Phys.* **56**, 08MC15 (2017).
- [5] A. Sadono, T. Ogihara, K. Nakada, and A. Yamada, 33rd European Photovoltaic Solar energy Conference and Exhibition, 2017, .
- [6] T. Lepetit, S. Harel, L. Arzel, G. Ouyard, and N. Barreau, *IEEE J. Photovoltaics.* **6**, 1316 (2016).
- [7] P. Jackson, R. Wuerz, D. Hariskos, E. Lotter, W. Witte, and M. Powalla,

Phys. Status Solidi - Rapid Res. Lett. **10**, 583 (2016).

- [8] A. Chirila, P. Reinhard, F. Pianezzi, P. Bloesch, A. R. Uhl, C. Fella, L. Kranz, D. Keller, C. Gretener, H. Hagendorfer, D. Jaeger, R. Erni, S. Nishiwaki, S. Buecheler, and A. N. Tiwari, Nat. Mater. **12**, 1107 (2013).
- [9] P. Reinhard, B. Bissig, F. Pianezzi, H. Hagendorfer, G. Sozzi, R. Menozzi, C. Gretener, S. Nishiwaki, S. Buecheler, and A. N. Tiwari, Nano Lett. **15**, 3334 (2015).