論文 / 著書情報
Article / Book Information

題目(和文)	Cu(In,Ga)Se2太陽電池の高効率化に向けたヘテロ接合界面に関する研究
Title(English)	Study of Heterojunction Interface for High-efficient Cu(In,Ga)Se2 solar cells
著者(和文)	西村 昂人
Author(English)	Takahito Nishimura
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10800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10800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 Heterojunction Interface for High-efficient $Cu(In,Ga)Se_2$ solar cells

Presented by Takahito Nishimura and Directed by Professor Akira Yamada
Department of Physical Electronics, Graduate School of Science and Engineering,
Tokyo Institute of Technology

Photovoltaic power generation is expected as one of clean renewable energy sources to solve environmental and energy issues. $Cu(In,Ga)Se_2$ (CIGS) is promising materials for absorber of solar cells because of its unique characteristics. CIGS which has high absorption coefficient enable to be applied for absorber of flexible lightweight thin-film solar cells, and therefore it is possible to realize reduction of mass production cost by roll-to-roll deposition in continuous high-speed manufacturing process. The highest conversion efficiency of 22.9% has been achieved in CIGS solar cells. In this thesis, to further enhance conversion efficiency in CIGS solar cells, required condition for suppression of recombination at CdS/CIGS hetero junction interface in CIGS solar cells was theoretically analyzed, and the effectiveness of Cu-deficient layer (CDL) on CIGS was experimentally suggested, finally establishing the unique control methods of CDL.

A guideline for improvement of CdS/CIGS hetero interface in CIGS solar cells was suggested using one-dimensional device simulation. Carrier concentration and energy bandgap in surface layer (SL) at the hetero interface were changed to reproduce effects of donor doping and valence band offset (ΔE_V), respectively, on CIGS surface region. High conversion efficiency of 22.1% and 21.6% was obtained by suppressing interfacial recombination when SL had high donor concentration (N_D) of 1.0 x 10^{18} cm^{-3} and high ΔE_V of 0.2 eV, respectively, although the efficiency was 19.6% in SL with low N_D of 1.0 x 10^{15} cm^{-3} and with ΔE_V of 0 eV. It was revealed that the required condition for SL to boost conversion efficiency is $N_D > |N_{A,\,CIGS}|$ ($|N_{A,\,CIGS}|$: absolute acceptor concentration in CIGS) or $\Delta E_V \geq 0.15$ eV.

CIGS and $Cu(In,Ga)_3Se_5$ (Cu-deficient material with Cu/(Ga+In) of 0.33) films were compared to discuss the effects of CDL formed on CIGS surface. The higher Cd content at the surface region in $Cu(In,Ga)_3Se_5$ than CIGS was observed when CdS layer was deposited on the top of the films. The bandgap of 1.51 eV in $Cu(In,Ga)_3Se_5$ was wider than that of 1.22 eV in CIGS. These results suggest a promotion of Cd-diffusion and a formation of $\Delta E_V \sim 0.29$ eV between CIGS and $Cu(In,Ga)_3Se_5$ owing to Cu vacancies in $Cu(In,Ga)_3Se_5$. The same cross-section of a CIGS solar cell with an efficiency of 18.5% fabricated by three-stage process was compositionally, electrically, and structurally evaluated. CDL (Cu/(Ga+In) of 0.31) with high Cd contents of 3.4at% unintentionally formed on the CIGS surface had lower carrier concentration of 4.8 x 10^{10} cm^{-3} than that of 10^{14}–10^{16} cm^{-3} in CIGS grain interior. This implies difficulty of Cd-doping into the CIGS surface to satisfy the condition of $N_D > |N_{A,\,CIGS}|$ owing to insufficient activation of Cd atoms. In contrast, the formation of ΔE_V is effective to satisfy the condition of $\Delta E_V \geq 0.15$ eV owing to low Cu/(Ga+In) ratio of 0.31.

Suppression effect of recombination at CdS/CIGS interface by introducing $Cu(In,Ga)_3Se_5$ was investigated in CIGS solar cells with energy bandgap of 1.2 and 1.4 eV. Open-circuit voltage (V_{OC}) in both solar cells was clearly improved from 0.62 to 0.64 V and from 0.66 to 0.75 V, respectively, with increasing $Cu(In,Ga)_3Se_5$ thicknesses from 0 to 5 nm. This result suggests the effectiveness of ΔE_V at the CdS/CIGS interface by CDL formation to suppress interfacial recombination.

Growth mechanism of CDL during CIGS deposition by three-stage process was revealed, and Se irradiation process was proposed for control of CDL. Se irradiation process leads to follow effects; (i) thin and homogeneous Cu_2Se layer was formed in the second stage; (ii) Cu_2Se changes to coexistence condition of Cu-deficient $Cu_{2-x}Se$ solid and Cu–Se liquid. A uniform CDL with a thickness of 150–200 nm was formed via control of $Cu_{2-x}Se$ on CIGS with irradiation time of 5 min, whereas the CDL formed at an irradiation time of 10 min was rough and non-uniform.

The effect of CDL formation on performance in CIGS solar cells was investigated. V_{OC} and fill factor (*FF*) were successfully increased up to 0.672 V and 76.2% in a CIGS solar cell with an irradiation time of 5 min, and a maximum efficiency of 19.8% was achieved. These results suggest that the uniform CDL on CIGS leads to efficiency enhancement in CIGS solar cells. At an irradiation time of 10 min, V_{OC} and *FF* decreased to 0.633 V and 72.9% owing to rough and non-uniform CDL. Finally, the Se irradiation step is a simple, unique process that can boost the performance of CIGS solar cells.