論文 / 著書情報
Article / Book Information

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Title(English)	Study of efficiency limiting factors of thin-film solar cells using transient response analysis
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種別(和文)	論文要旨
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（博士課程）
Doctoral Program

論 文 要 旨

THESIS SUMMARY

系・コース： Department of, Graduate major in	電気電子 エネルギー	系 コース	申請学位（専攻分野）： Academic Degree Requested	博士 Doctor of	（ 工学 ）
学生氏名： Student's Name	福田遼太郎		審査員主査： Chief Examiner	山田明	

要旨（英文800語程度）
Thesis Summary（approx.800 English Words ）

Energy demand has been increasing year by year alongside population growth. The global population is expected to exceed 10 billion, and energy consumption is projected to triple by 2100. However, fossil fuels—the primary energy source to date—pose challenges such as limited reserves and their contribution to global warming, prompting countries worldwide to shift toward clean energy. In Japan, thin-film solar cells are gaining attention as a key clean energy technology due to their versatility in applications such as building-integrated and vehicle-mounted systems, particularly given the country's limited flat land area.

However, the structural complexity of thin-film solar cells has led to various enigmatic characteristics, making it difficult to establish precise guidelines for improving conversion efficiency and long-term stability. Unlike conventional silicon solar cells, which consist of single-crystal and single-element structures, major thin-film solar cell materials are polycrystalline and multi-element. As a result, fluctuations in composition at different locations, as well as unique defects and ion behavior, contribute to their unusual properties. This study aims to identify the factors behind these complex responses and develop strategies for enhancing efficiency and stability.

To address this issue, we focused on two promising thin-film solar cell materials: $Cu(In,Ga)Se_2$ (CIGS) and perovskite solar cells. Among the puzzling responses observed in these materials, we examined the following three phenomena: (1) In CIGS solar cells, electron beam-induced current (EBIC) measurements reveal a carrier collection efficiency distribution that cannot be explained by theoretical models. (2) Long-term photo-thermal excitation, commonly known as heat-and-light soaking (HLS) treatment, increases carrier concentration in CIGS solar cells, leading to improved efficiency. (3) In perovskite solar cells, JV curve hysteresis occurs, where the efficiency measured through JV characterization changes depending on the direction of applied voltage.

For (1), it has been discussed that composition fluctuations at grain boundaries alter the band structure, leading to changes in carrier behavior during EBIC measurements. For (2), the phenomenon is attributed to a gradual charge transition associated with a unique defect in CIGS known as the V_{Se}-V_{Cu} (VV) complex defect, which undergoes structural changes. For (3), particularly in $MAPbI_3$ (MAPI) perovskite solar cells, it is argued that charged iodine and MA vacancies move significantly within the MAPI layer over a relatively short time, contributing to the observed hysteresis.

To analytically verify these hypotheses and further deepen the discussion, we developed a dynamic model. Traditional simulation models used for silicon solar cells assume that carrier concentration and band structure remain nearly constant during operation. However, such simplistic models fail to reproduce the complex behaviors observed in thin-film solar cells. To overcome this limitation, we constructed a dynamic model that accurately calculates the relationship between defect charge transitions, transient ion conduction, and grain boundary structures in CIGS, as well as variations in carrier behavior during measurement.

Through this research, three major findings were obtained. First, by analyzing the unique EBIC response in CIGS solar cells, we identified the critical role of conduction band offsets (ΔE_V) at grain boundaries (GBs). Our simulations demonstrated that when ΔE_V exceeds 0.3 eV, carrier accumulation in grain interiors (GIs) significantly alters the band structure, leading to characteristic EBIC peaks at GBs. This result highlights the importance of multi-excitonic behavior andΔE_V -induced electric fields in determining carrier transport properties. Second, by modeling the charge transition mechanisms of VV defects, we successfully determined key defect parameters through Bayesian optimization and reproduced experimentally observed variations in various processes and measurements. By constructing a model that reproduces not only the magnitude of acceptor concentration changes but also the rate of acceptor concentration change in HLS process and the time variation observed in the EBIC response, we provided valuable insights into the long-term stability of CIGS solar cells. Third, in perovskite solar cells, we developed a computational model that quantitatively describes ion migration dynamics, revealing the distinct roles of positive and negative ions in device performance. Positive ion movement was identified as the primary factor behind JV hysteresis, while negative ion redistribution contributed to gradual efficiency degradation. These findings provide a comprehensive understanding of ionic conduction and its impact on perovskite solar cell stability, advancing strategies for performance optimization.

Furthermore, actual solar cells do not operate in a steady state but rather in a quasi-steady state under bias and light exposure. By comparing characteristics using the developed dynamic model, significant differences in the characteristics were

observed between steady-state and quasi-steady-state conditions. This finding indicates that achieving further efficiency improvements and enhanced stability in thin-film solar cells requires shifting the discussion from conventional steady-state analysis to a focus on quasi-steady-state conditions.
These insights contribute to the broader understanding of thin-film solar cell physics, bridging the gap between experimental observations and theoretical modeling. By elucidating the fundamental mechanisms behind carrier transport, defect dynamics, and ionic conduction, this study lays the groundwork for future advancements in efficiency and stability.