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Photon-induced defects and dynamics of photogenerated carriers in Cu(In, Ga)Se_2 thin film solar cells

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ABSTRACT

A detailed understanding of charge-carrier behavior could provide new avenues to improve the performance of the solar cell by enhancing the active materials and electronic properties. In the present work, the transport mechanism of photogenerated carriers in Cu(In,Ga)Se_2 or CIGS)-based solar cells is investigated by analysis of the temperature-dependent current density-voltage (*J-V)* curves obtained under various illumination (i.e., dark, AM 1.5G, 650 nm, and 405 nm). The results demonstrate that *J-V* curve distortion, termed the "roll-over" effect, is significantly correlated with the illumination wavelength and, more importantly, is strongly associated with the persistent characteristics of the CIGS solar cell. In addition, the nature of the photo-induced defects and their influence on the transport mechanism of the photogenerated carriers were investigated via deep level capacitance profiling (DLCP) and admittance spectroscopy (AS) under various illumination conditions. The photo-capacitance results indicate distinct spatial distributions and persistent behaviors depending upon the illumination wavelength. Based on the findings in this work, the origin of the non-ideal *J-V* behavior in the CIGS solar cell is explained, and the spatial defect distribution and illumination wavelength sensitivity are discussed.

1. Introduction

Recently, Cu(In,Ga)Se_2 or CIGS-based thin film solar cells have achieved efficiencies in excess of 23%. Thus, in-depth physical analyses of the material and the devices constructed therefrom are becoming increasingly important for continued progress [1,2]. To enhance the performance of solar cells, various properties based on the electronic band structure have been investigated. These include the current density-voltage (*J-V)* characteristics based on the circuit and device, the diode qualities [3], and the series and shunt resistances [4,5]. Additionally, capacitance analysis for the p-n junction has been performed, including examination of the charge density and frequency-dependent spatial distribution and dynamics of charge carriers in relation to the defect states [6–8]. Further, as a function of temperature and illumination, the transport process [3,9], persistent behavior [10–16], and intrinsic material properties such as the band structure [4,17] have been examined for CIGS solar cells. While individual analyses of these solar cells have been thoroughly performed, continued progress in this field requires a comprehensive understanding of the device characteristics obtained via direct observation.

Compared with the intrinsic charge-carrier transport properties in the dark, illumination generates excess carriers that experience distinct transport mechanisms. This can be verified by the lack of overlap between the dark and photo current density-voltage curves. The voltage-dependence of the light current density, J_{light}, of CIGS solar cells rarely follows the relationship with the short circuit current density, J_{SC}, given by Eq. (1) [18]:

$$J_{light}(V) = J_{dark}(V) + J_{SC}, \tag{1}$$

Rather, the voltage-dependence of J_{light} is related to the photo current density, J_{ph}, in accordance with Eq. (2):

$$J_{light}(V) = J_{dark}(V) + J_{ph}(V) \tag{2}$$

The voltage dependence can be seen as a distortion of the *J-V* curves,

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