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Fill factor related issues in hydrogenated amorphous Si solar cells

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ABSTRACT

It is a fact that the fill factor (*FF*) decreases with decreasing $\mu\tau$ product, increasing illumination intensity, increasing absorber thickness, and long wavelength illumination in well-engineered hydrogenated amorphous silicon (a-Si:H) solar cells. The *FF* issues in the a-Si:H solar cell are not just a contact issue as in crystalline Si solar cell, but are more interesting and complicated issues that relate to the quality of materials and solar cell operating conditions. In past, a simple parameter of “collection length” or drift length, which is defined as $\mu\tau E$, was quite successful to explain the fact. In this article, we extensively study the collection length in terms of the internal electric field, which changes with the quality of material and operating condition. The Analysis of Microelectronic and Photonic Structures (AMPS) simulation shows that the decrease in fill factor is caused by photogenerated space charge trapped in the band-tail states rather than in defects when the defects are relatively small. This charge screens the applied field, reducing the internal field and the collection length, which reduce the *FF*. A voltage V_s from the photogenerated space charge was introduced to describe the behavior. This voltage varies with light intensity for large valance band-tail width and low hole mobility a-Si:H absorbers. The simulation also found that the space charge in mid-gap states is small compared with that in the tails and can be ignored under normal solar-cell operating conditions. Experimentally, the photocapacitance measurement was used as a means to probe the space charge. The decrease of *FF* with the increasing light intensity can be qualitatively explained by the light intensity dependence of photocapacitance, the declining electric field, and the decreasing collection length.

1. Introduction

The key feature of hydrogenated amorphous Si (a-Si:H) *p*–*i*–*n* or *n*–*i*–*p* solar cells is that photogeneration occurs in the region with a high electric field (i.e., the intrinsic (*i*) layer). We define carrier collection length, or drift length, as $\mu\tau E$, where μ and τ are the carrier mobility and the lifetime, respectively, and E is the electric field. The carrier collection length is a unique parameter in the operation of hydrogenated amorphous Si solar cells that distinguishes them from the other types of solar cells. To achieve a high-efficiency solar cell, it is highly desirable that the collection length should be greater than the *i*-layer thickness such that photogenerated carriers can be collected effectively. As a consequence, the fill factor (*FF*) in a-Si:H solar cells is not simple as in the crystalline Si solar cell which only relates to the contact: the *FF* relates to the collection length as well. As an example, Fig. 1 shows four subfigures often observed in a well-engineered and optimized a-Si:H solar cell that *FF* is affected by $\mu\tau$ product [1], *i*-layer thickness, light intensity, and illuminating wavelength. It is well-known that the *FF* also is affected greatly by interfaces, especially *p*/*i* interface. Many research groups have done excellent work of optimizing the *p*/*i* interface to achieve very high *FF*. The optimized high *FF* solar cells are the fundamentals for this study. In past, the effect of $\mu\tau$ product on the *FF* has been well studied because it relates to the Staebler–Wronski Effect (SWE) [2]. Namely, the electron $\mu\tau$ product decreases with prolong light exposure. The increase of defects caused by the light exposure decreases the $\mu\tau$ product, so does the *FF* [3]. Because the electron $\mu\tau$ product is greater than the hole $\mu\tau$ product in a-Si:H material, and assuming that electric field across the *i*-layer is uniform, it is common to conclude that the major effect on the *FF* is caused by the electron, not the hole. However, the argument of the electron cannot explain the other facts in the *FF* such as its dependence on the *i*-layer thickness and light intensity. It is important to realize that the collection length depends on the electric field as well. Therefore, understanding and probing of the electric field in the *i*-layer are crucial for operating high efficiency a-Si:H solar cells.

Illumination generates electrons and holes. The recombination of electrons and holes leads to a loss of carriers. The drift of carriers and the nature of blocking contacts lead to photogenerated space charge. The space charges are mainly due to the free carriers and the trapped

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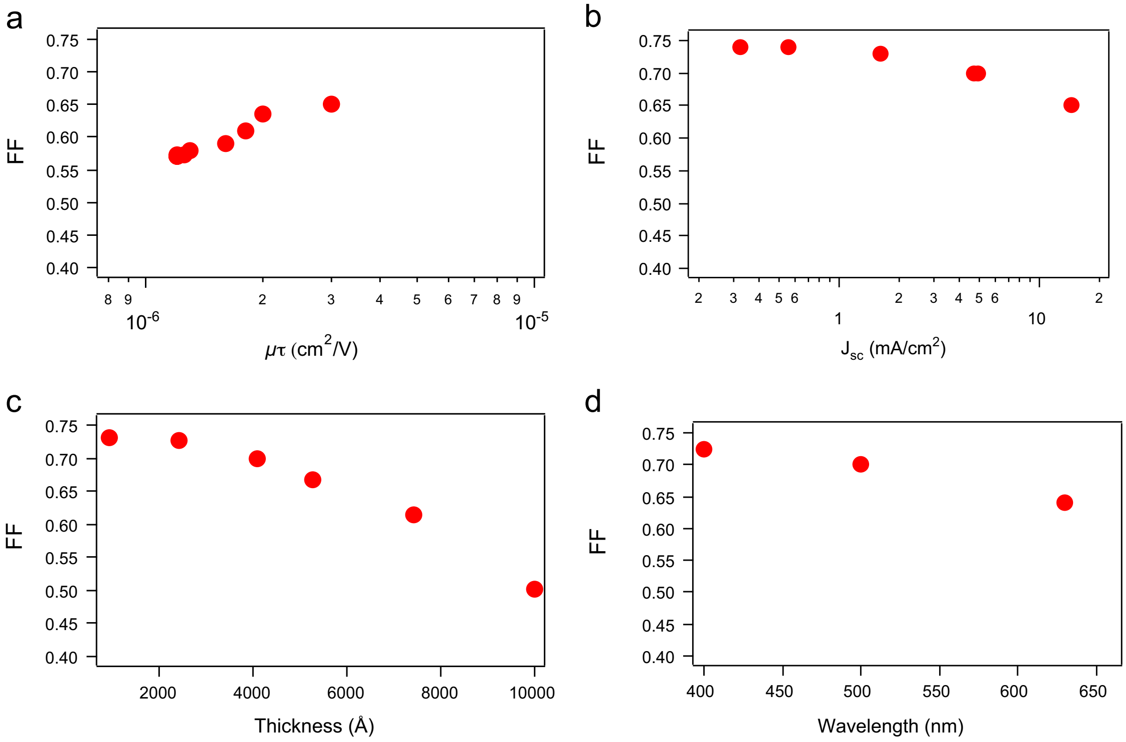

Fig. 1. (a–d) The four typical results of *FF* in a-Si:H solar cell; (a) a function of $\mu\tau$ product [1], (b) a function of light intensity or J_{sc}, (c) a function of *i*-layer thickness, and (d) a function of incident photon energy or wavelength.

charges in both mid-gap states and band-tail states. These space charges screen the applied field and reduce the internal field, thus reducing the collection length and the *FF*. A complete approach to this problem entails solving the transport equations of electrons and holes in the device: namely, electron and hole continuity equations, electron and hole current equations, and Poisson's equation. A simple closed form solution for the five equations mentioned above is not available. Therefore, the Analysis of Microelectronic and Photonic Structures (AMPS) simulation program [4] was used for modeling the behavior of solar cells, especially the change of electric field for different absorbers under various operating conditions. From the past simulations, it is concluded that the decrease in fill factor is caused by photogenerated space charge trapped in the band-tail states rather than in defects [5]. Recent simulations show that space charge trapped in the band-tail states is mainly caused by the wider valance band-tail width.

To simplify the effect of space charge, the voltage V_s from photogenerated space charge is introduced. This concept is similar to the built-in-potential (V_{bi}) and the applied voltage (V_a). However, the V_s is a parameter that varies with the quality of the absorber materials and operating condition such as light intensity. For example, as the light intensity increases, more electrons and holes are produced, and more photogenerated space charges are trapped in the band-tail states, resulting in a decrease in the electric field in the *i*-layer. The decrease of the electric field can be described in a term of V_s/d, where d is the thickness of the *i*-layer. Experimentally, a photocapacitance experiment was carried out to verify the photogenerated space charge in the a-Si:H solar cells.

2. Experimental

2.1. AMPS simulation

In general, a complete approach to *FF* issues entails solving the transport equations of electrons and holes in an a-Si:H solar-cell device. Although a simple closed-form solution is not available, one can solve the transport equations numerically [6,7]. The AMPS (1D) simulation program was used for modeling the behavior of a-Si:H *p*–*i*–*n* solar cells. The details of the use of AMPS have been published elsewhere [8]. To test the hypothesis, the space charge and electric field distribution were studied with the *p*–*i*–*n* solar cells, with varying light intensity, mid-gap defects, conduction band-tail width, valance band-tail width, and electron and hole mobility.

The modeled baseline solar cell has a homojunction *p*–*i*–*n* structure with the bandgap of 1.72 eV. The thickness of the *p*-layer is 100 Å, the thickness of the *i*-layer is 5000 Å, and the thickness of the *n*-layer is 250 Å. The thicknesses of doped layers are close to the experimental solar cells fabricated at the National Renewable Energy Laboratory (NREL). The modeling uses a Gaussian distribution of mid-gap states and an exponential distribution of the band-tail states of the conduction band and the valance band in the *i*-layer. The experiment simulates the modeled cell with increasing light intensity from 0.01 sun to 10 sun, then repeats the simulation with changing *i*-layer properties of the band-tail width of the conduction band (E_a) and the valance band (E_d), and the defect density of the mid-gap state (N_d). The changes with carrier mobility of electron (μ_e) and hole (μ_h) were also simulated.

2.2. Photocapacitance

Experimentally, one cannot easily measure the electric field in the *i*-layer, but one can measure the effect of space charge using the well-established capacitance technique. The photocapacitance (C_{ph}) [9] is a sensitive probe of the *i*-layer field distortion. It measures the response of space charge to the applied voltage. The photocapacitance is defined by subtracting the capacitance in dark from its value in light. Crandall did theoretical studies of photocapacitance earlier [9,10]. The Regional Approximation was applied to solve the transport equations and analytical solutions were obtained only for the two extreme cases. The beauty of