Solar Energy Materials & Solar Cells 119 (2013) 1–11

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

High efficiency multi-junction thin film silicon cells incorporating nanocrystalline silicon

Subhendu Guha*, Jeffrey Yang, Baojie Yan

United Solar Ovonic, 1100 W. Maple Road, Troy, MI 48084, United States

ARTICLE INFO

Available online 9 May 2013

Keywords:
Photovoltaic
Thin film silicon
Solar cell
Nanocrystalline

ABSTRACT

Significant advances have been made in the recent years to improve the efficiency of single- and multi-junction solar cells incorporating nanocrystalline silicon (nc-Si:H). The improvements have resulted from the development of high quality intrinsic material, novel doped layers, superior back reflector and appropriate device design. Stable active-area efficiency of 13.6% for small-area cells and aperture-area efficiency of 11.85% for large-area devices have been achieved. In this paper, we discuss the key activities that led to these high efficiencies with emphasis on substrate-type solar cells. Manufacturing issues and future research directions to improve efficiency further are also discussed.

1. Introduction

Hydrogenated amorphous silicon (a-Si:H) has received a great deal of attention as a low cost material for production of solar cells [1]. The disorder inherent in the material allows the use of only a thin film to absorb sunlight. The deposition process is compatible with large scale manufacturing, and several manufacturers have introduced photovoltaic products based on a-Si:H in the market. The major challenge in this technology is the improvement of efficiency. The disorder in the material results in defects that act as recombination centers impeding the transport of photo-absorbed carriers. The phenomenon of light-induced generation of metastable defects also limits cell efficiency. Multi-junction structures with component cells using intrinsic materials of different bandgaps have been used to capture a wider spectrum and reduce light-induced degradation. Triple-junction cells, where the middle cell uses hydrogenated amorphous silicon germanium (a-SiGe:H) of about 1.6 eV bandgap and the bottom cell uses a-SiGe:H of about 1.4 eV bandgap, have resulted in active-area initial and stable cell efficiencies of 14.6% and 13.0%, respectively [2]. The efficiency is still lower than that of other thin film based solar cells; for example a cell efficiency of greater than 20% has been reported for $CuInGaSe_2$ thin film technology [3].

An important milestone in the progress of thin film silicon technology is the development of high quality nanocrystalline silicon (nc-Si:H), also referred to in the literature as microcrystalline silicon [4]. The material can be deposited using plasma-enhanced chemical vapor deposition (PECVD) similar to that used to deposit a-Si:H. It has much better response than a-Si:H at wavelengths greater than 800 nm and does not suffer from light-induced degradation, when incorporated in the middle or the bottom cells that are not exposed to the high energy photons.

Since the report of the first device grade nc-Si:H [5], significant progress has been made in our understanding of nc-Si:H that has resulted in further improvement of material quality. The incorporation of this material in multi-junction structure has resulted in achieving initial active-area cell efficiency of 16.3% [6]. Several companies have also started manufacturing of double-junction products incorporating this material. In this paper, we shall discuss the key requirements that are needed to obtain high solar cell efficiencies using nc-Si:H. Manufacturability of such devices and future directions to improve efficiency will also be discussed.

2. Key requirements for high efficiency

Multi-junction cells incorporating thin film silicon absorber materials of different bandgaps can capture a wide spectrum of sunlight resulting in high efficiency. Cells have been made with both transparent superstrate (light entering from glass) and opaque substrate structures (light entering from the top transparent conducting oxide); the discussions in this paper will focus more on substrate structures. Various structures of multi-junction cells on stainless steel substrate incorporating nc-Si:H are shown in Fig. 1. Both double- and triple-junction structures have been used. In order to obtain high efficiency, the total current should be at least 30 mA/cm^2. For a double-junction structure, the top cell has to produce more than 15 mA/cm^2 needing thick cells that are susceptible to large light-induced degradation. For the triple-junction cells incorporating a-Si:H or

---

* Corresponding author. Tel.: +1 248 332 8457.
E-mail address: subhenduguha01@gmail.com (S. Guha).

0927-0248/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.solmat.2013.03.036

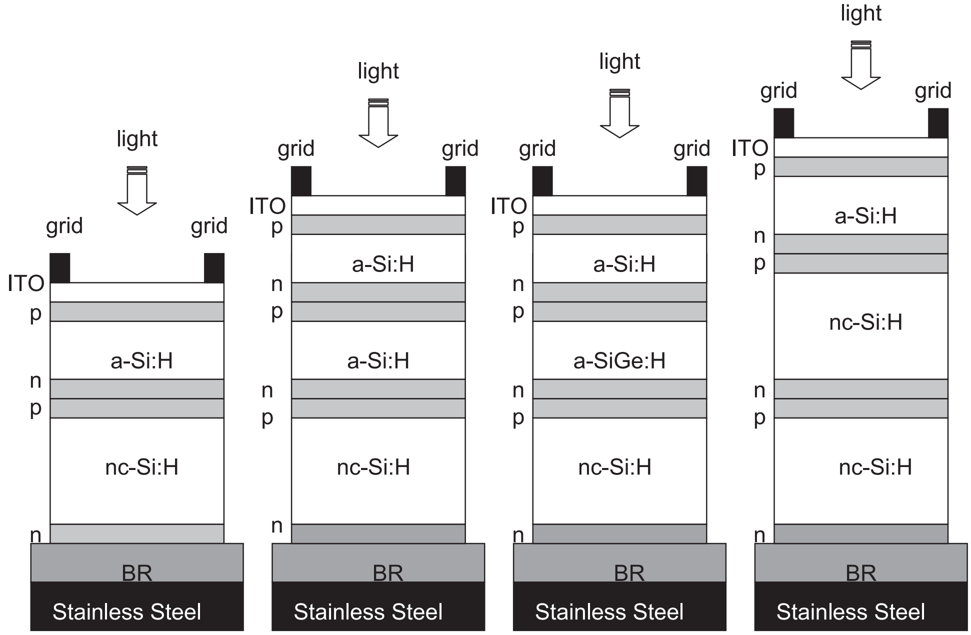

Fig. 1. Schematic diagram of different cell structures incorporating nc-Si:H on stainless steel substrates.

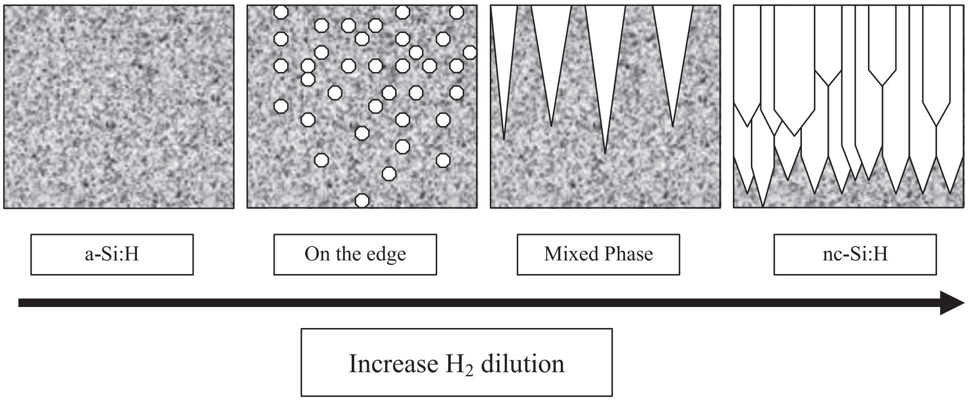

Fig. 2. Schematic diagram showing the evolution of nanocrystallites with increasing hydrogen dilution.

a-SiGe:H in the middle cell, the same problems remain to a lesser extent. The best cell structure to obtain high stable efficiency is the triple-junction structure incorporating nc-Si:H in both the middle and the bottom cells.

Key requirements for obtaining high efficiency are high quality intrinsic material, transparent doped material with high conductivity, superior back reflector (BR), and appropriate device design. We shall discuss each of the issues in the following sub-sections.

2.1. *Intrinsic material*

2.1.1. *a-Si:H and a-SiGe:H*

These materials have been investigated extensively in the last three decades. Conventional PECVD using both radio frequency (*rf*) and very high frequency (*vhf*) has been used to deposit high quality material. Hydrogen dilution of the active gas has played the most important role in defining the material quality [7]. Fig. 2 shows a schematic of the structure evolution as the hydrogen dilution increases [1]. Materials made with no or very low hydrogen dilution show an amorphous structure. With increasing hydrogen dilution, isolated nanometer-sized crystallites or linear structures of intermediate range order are incorporated in the amorphous matrix. The tiny crystallites grow with increasing hydrogen dilution forming cone-shaped structure as the hydrogen dilution further increases. For very dilute mixture, columnar growth starts taking place and cracks begin to develop in the films with adverse effect on material properties. The best a-Si:H or a-SiGe:H material is grown at a hydrogen dilution just below the amorphous to nanocrystalline transition. Interestingly, the best quality nc-Si:H is grown just above the edge.

Hydrogen dilution has been used successfully to grow both a-Si:H and a-SiGe:H materials. The best material with optimum hydrogen dilution shows lower defect density, narrower bandtail and lower light-induced degradation than materials with no or low hydrogen dilution [1,8]. While the incorporation of Ge in Si reduces the bandgap to capture red light, it also increases the defect density and enhances light-induced degradation. Innovative bandgap profiling, where the Ge-content in the alloy is continuously changed during growth [9], has been used successfully to improve carrier transport in actual cell configuration. The inherent limitation of the a-SiGe:H alloy has led to increasing focus on nc-Si:H.

2.1.2. *nc-Si:H*

One of the advantages of using nc-Si:H in a multi-junction structure shown in Fig. 1 is the compatibility of its deposition with