Solar Energy Materials & Solar Cells 130 (2014) 490–494

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Efficient flexible thin film silicon module on plastics for indoor energy harvesting

M. Foti [a], C. Tringali [a], A. Battaglia [b], N. Sparta [a,b,c], S. Lombardo [c], C. Gerardi [a,*]

[a] IPD R&D—STMicroelectronics, 95121 Catania, Italy
[b] 3SUN , 95121 Catania, Italy
[c] CNR IMM, 95121, Catania, Italy

ARTICLE INFO

Article history:
Received 28 January 2014
Received in revised form
30 July 2014
Accepted 31 July 2014

Keywords:
Flexible PV
a-Si:H
Energy harvesting

ABSTRACT

We report on flexible photovoltaic cell fabricated on polymeric substrate optimized for indoor energy harvesting. We have fabricated small area modules (up to 30 cm^2) obtained by monolithic integration of a-Si:H p-i-n solar cells deposited by PECVD at low temperature with excellent mechanical strength, high ability of folding and very good stability. The photovoltaic thin film module is optimized for indoor light generated by indoor lamps and has efficiency as high as 9.1% on aperture area even at less than 100 lx of light intensity (under F12 fluorescent lamp spectrum). The optimized system can be used to energize thin film batteries and can be assembled in a flexible system associated with a wireless sensor network or other electronic devices.

1. Introduction

Wireless communication networks (router nodes, sensor networks, camera network, etc.) use batteries as source of energy. These batteries have limited lifetimes and this factor plays a major role in determining the life of a wireless node in the network. Moreover, the battery replacing means additional cost and battery waste.

In order to obtain an extended lifetime of the system, it should be able to harvest energy from renewable resources in the device environment. A good solution in case of wireless networks is represented by photovoltaic (PV) cells. Commercial PV cells used in energy harvesting applications typically exhibit low power conversion efficiencies at low light intensities. This is because the cells are not optimized with respect to the required operating range that is typically between 100 and 500 lx. Thin-film solar cells based on hydrogenated amorphous silicon (a-Si:H) are attractive for their cost effective and wide range applications. In fact, a-Si:H cells can be deposited on low cost substrates, including glass, ceramic, flexible plastic or metal foils [1]. The most widely deposition techniques for hydrogenated amorphous silicon are the plasma enhanced chemical vapor deposition (PECVD) [2] and the hot wire chemical vapor deposition (HWCVD) [3,4] techniques. The HWCVD method is a very effective technique since it has advantages of a simple fabrication process and a high deposition rate along with highly reliable thin film quality for several phases of thin films by switching the change of flow rates [5]. On the other hand, the PECVD technique is more widely diffused in existing large area silicon thin film manufacturing plants. In this work we have used standard PECVD technique, which is typically used for deposition on glass and metal substrates, also for the low-cost realization of a-Si:H solar cells on plastics.

The high absorption coefficient in the visible wavelength range makes a-Si:H suitable for indoor where the light is provided by conventional lamps. Fig. 1 shows the comparison between solar spectrum AM1.5G and typical indoor spectrum of a F12 fluorescent lamp. Due to the different spectral densities, 1 W/m^2 corresponds to 106.3 lx for AM1.5G spectrum, whereas it corresponds to 296 lx for F12 spectrum.

In this work we have developed an a-Si:H based process for the fabrication of flexible and photovoltaic modules on a polyimide substrate for indoor energy harvesting devices.

The a-Si:H absorber layer properties have been optimized by using low temperature and cost-effective plasma-enhanced CVD deposition (PECVD) with RF frequency of 13.56 MHz. Typically, the deposition rates are in the range of 0.1–0.5 nm/s. A material with good electronic quality requires a dense and a homogeneous network of amorphous Si with minimum void density. Such conditions dictate low deposition rates. Hydrogen dilution has a strong influence on the properties of a-Si. However, a high hydrogen dilution rate is associated with a reduction in the deposition rate. In fact, by increasing the hydrogen dilution, R, defined as hydrogen to silane flux ratio, hydrogen effusion from

* Corresponding author.
E-mail address: cosimo.gerardi@st.com (C. Gerardi).

http://dx.doi.org/10.1016/j.solmat.2014.07.048
0927-0248/

the film during the growth takes place [6] and the total hydrogen concentration incorporated in the material decreases [7]. Hydrogen also reacts with the strained Si–Si bonds of the amorphous structure contributing to the Si–Si bond breaking and atomic rearrangement towards the crystalline configuration [8]. Further increase of hydrogen dilution raises the microcrystalline volume fraction, however, the layer photosensitivity decreases by three orders of magnitude [9]. High-performance a-Si:H solar cells were prepared at a hydrogen-to-silane dilution ratio just below the onset of microcrystalline phase.

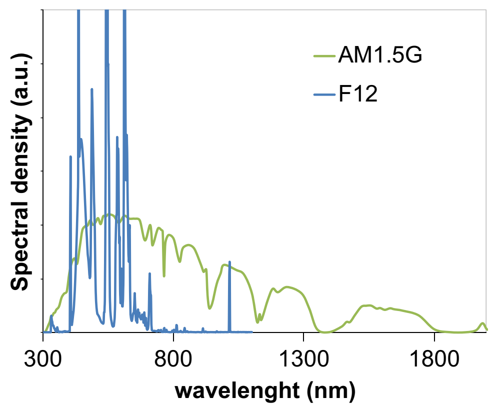

Fig. 1. Comparison between AM1.5G solar and F12 lamp spectrum. The lamp spectrum is mainly concentrated in a spectral range that is very suitable for a-Si:H.

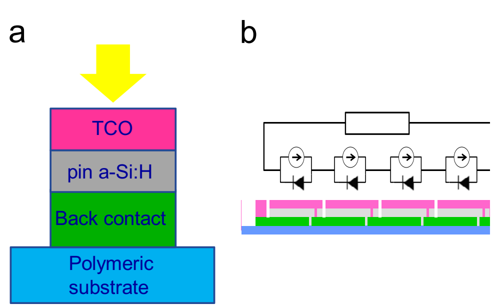

Fig. 2. (a) Design and (b) fabrication structure of the flexible silicon module on polyimide foil.

In addition to the absorber material optimization, the electrical properties of the interface between contact layers and a-Si:H for different types of materials (metallic and transparent conducting oxide contacts) have been studied with the purpose of improving the contact structure, by increasing Voc and reducing plasma induced damaging.

Then we have fabricated flexible thin film PV modules consisting of several cells monolithically connected with a Mo/p-i-n a-Si:H/ZnO:Al structure deposited on top of a polyimide layer.

The PV modules, with area up to 30 cm^2 size, show power conversion efficiency on aperture area of 9.1% at 300 lx under F12 spectrum and excellent mechanical robustness which enables the module to be folded many times without significantly affecting PV performances.

2. Material and methods

Hydrogenated amorphous silicon (a-Si:H) has been deposited by plasma enhanced chemical vapor deposition (PECVD) either on SnO_2:F or on Mo layers by using an UNAXIS KAI 1 M system. Deposition temperature was kept at 190 °C, SiH_4 flows varied from 100 to 20 sccm and H_2 flows from 40 to 800 sccm. The hydrogen dilution ratio, defined as $R=H_2/SiH_4$, was varied between 2 and 40.

In situ p and n doping of the p-i-n cell structure was obtained by using tri methyl borane (TMB) and PH_3. The choice of materials used as front and back contacts, typically transparent conductive oxide layers (TCO) or metal for the back, plays a fundamental role on cell performances [10–14]. We studied different regimes of H_2/SiH_4 ratios at 190 °C, in particular we describe two cases with $R=2$ and $R=5$, respectively.

As on thin film silicon stress is directly correlated with SiH_2/SiH_3 bonding configuration, we have performed stress measurements for the different deposition conditions used for cell

Table1
Film stress measurement of a-Si-H film deposited at 190 °C temperature and different R values.

Temperature (°C)	$R=H_2/SiH_4$	Stress (GPa)
190	2	+1.8 (tensile)
190	5	−4.33 (compressive)

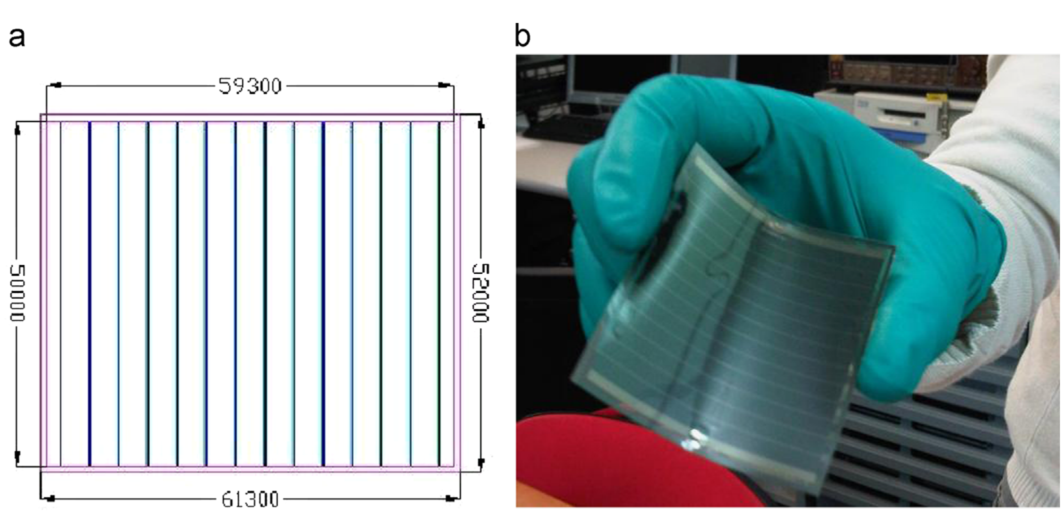

Fig. 3. (a) Layout and (b) picture of the flexible silicon module on polyimide.