Solar Energy Materials & Solar Cells 130 (2014) 303–308

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Enabling thin silicon technologies for next generation c-Si solar PV renewable energy systems using synchrotron X-ray microdiffraction as stress and crack mechanism probe

A.S. Budiman [a,*,1], G. Illya [b], V. Handara [b], W.A. Caldwell [c], C. Bonelli [d], M. Kunz [e], N. Tamura [e], D. Verstraeten [d]

[a] Singapore University of Technology & Design (SUTD), Engineering Products Design (EPD) Pillar, 20 Dover Drive, Singapore 138682, Singapore
[b] Center for Solar Photovoltaics Materials & Technology (CPV), Surya University, Boulevard Gading Serpong O/1, Summarecon Serpong, Tangerang 15810, Indonesia
[c] SunPower Corporation, R&D, San Jose, CA 95134, USA
[d] TOTAL Gas & Power, R&D Division, 92400 Courbevoie, France
[e] Advanced Light Source (ALS), Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA 94720, USA

ARTICLE INFO

Article history:
Received 5 March 2014
Received in revised form
26 June 2014
Accepted 16 July 2014

Keywords:
Thin silicon
Solar cell
Synchrotron X-ray microdiffraction
Stress
Fracture

ABSTRACT

Recently, there has been a strong commercial push toward thinner silicon in the solar photovoltaic (PV) technologies due to the significant cost reduction associated with it. Tensile stress (normal, in-plane) and fracture of the silicon cells are increasingly observed and reported for products of crystalline solar cell technologies. In an effort to shed light on these topics, stress measurements and mapping of the solar cells in the vicinity of the most typically observed crack initiation locations using synchrotron X-ray microdiffraction technique was conducted and are reported in this paper. The technique is unique as it has the capabilities to quantitatively determine stresses in silicon and to map these stresses with a micron resolution, all while the silicon cells are already encapsulated.

With this technique, we aim to gain fundamental understanding of the stress magnitudes as well as characteristics that could lead to crack initiation and propagation. We have thus far found evidences of both extrinsic (device related) as well as intrinsic (crystallographic) nature of silicon cracking, which further confirm that the control of mechanical stress is the key to enable thin silicon solar cell technologies in the coming years. This study represents an ongoing high impact technology research that addresses real and important fundamental materials issue facing the crystalline silicon solar PV industry and contributes directly to the industry drive to reduce cost of PV systems to grid parity.

1. Introduction

Silicon solar cell technology remains the most efficient and powerful way to commercially harness the sun's power for conversion to electricity. In order to keep improving the market adoption rate and thus providing solar energy that is cost-competitive with existing energy sources, the global silicon solar PV industry is aggressively reducing the cost of solar PV systems through innovations in materials and processes used in the manufacturing. One potential area of significant cost reduction is through the use of thinner silicon cells ($<150\,\mu m$). However, coupled with other recent trends in the solar PV module technologies (thinner glass, lighter or no metal frames as well as increased use of some types of polymers for encapsulation of the cells), high stress and fracture of the silicon cells are increasingly observed and reported for products using thin silicon solar cell technologies. Cell cracks immediately lower module efficiency and can lead to premature aging of the entire package/module.

Studying the fracture mechanisms in thin silicon solar cells has thus increasingly become both an interesting topic scientifically as well as an important subject technologically during recent years especially with the oncoming development of the new generations of solar PV renewable energy systems. More specifically, fractures in the thin silicon solar cells have been proposed to result from the high stress concentration area near the solder joints and busbars that provide interconnection between the cells [1–5]. Studying how stresses especially in these areas evolve during introduction

* Corresponding author. Tel.: +65 6499 4503.
E-mail address: suriadi@alumni.stanford.edu (A.S. Budiman).
[1] Formerly of SunPower Corporation, R&D, San Jose, CA 95134, USA.

http://dx.doi.org/10.1016/j.solmat.2014.07.029
0927-0248/

of the solder joints in the solar cell assembly lines as well as later on during service and operational conditions/loading of the devices will be crucial in highlighting the propensity to fracture as well as its actual initiation and propagation mechanisms in the thin silicon solar cells. Crack propensity here is defined as the susceptibility of the material to initiate cracks and/or for the cracks to grow further. A material can be more susceptible to fracture when the stress level of the overall system is elevated due to the operational conditions or mechanical loading of the device/system. Therefore, the stress level in the material is approaching its fracture toughness which depends not only the strength of the materials but also the ubiquitous presence of crack-like defects and their size. Quantitatively, this happens when the stress intensity, $\boldsymbol{K}$, has approached the materials' critical stress intensity, $\boldsymbol{K_c}$, or more generally, when the value of the strain energy release rate, $\boldsymbol{G}$, has approached the critical value of the strain energy release rate of the material, $\boldsymbol{G_c}$. $\boldsymbol{K_c}$ or $\boldsymbol{G_c}$ here is a measure of fracture toughness which depends on both the strength of the material and its inherent flaw sizes [1].

However previous studies in the literature up to date on silicon cell fracture in c-Si solar PV technologies have been largely focused on the crack detection and imaging techniques [2,3,6–9]. Lacking the capacity to quantitatively characterize mechanical stress, which is the ultimate driving force of any crack initiation and propagation, these studies did not reveal much fundamental understanding of what affects the propensity to crack, the various failure modes, and, most importantly, the processes and loading conditions that lead to different states of mechanical stresses that ultimately cause different modes of the cracks. Synchrotron X-ray microdiffraction (μSXRD) has thus proved to be a suitable technique to elucidate stress and crack propensity in stringed silicon solar cell assemblies. This technique provides quantitative determination of stresses (normal, hydrostatic and shear) in silicon as well as in solder joint material with a micrometer resolution [10–11]. It is non-destructive and the X-ray beam has reasonable penetration depth which enables one to do *in situ* study of stresses in the silicon during cell operations or loading. This approach can thus provide us with the quantitative examination of stress and its evolution during the processes and operations of the devices in the realistic setting.

Stringed cell assemblies have always used solders and interconnects and they have always been the high stress concentration areas in the assemblies (Fig. 1(a)). As the silicon cells get thinner ($<150\ \mu m$), they acquire much higher sensitivities toward these high stresses and thus an increased propensity to cracks. Solders and metal interconnects induce high stresses in the silicon cells due to their typically very different coefficient of thermal expansion (CTE) values compared to that of silicon. Upon cooling from their typically high temperature introduction (solder reflow process), the CTE mismatch leads to high tensile in-plane stress in the silicon cell and this is what leads to crack initiation and propagation [3–5,12]. Most cell cracking observed in PV products from various companies as well as those reported in the literature [2–5,12] are indeed initiated from the solder joint areas and typically propagate following the metallization lines. It is thus our main focus in this study to measure stress in the silicon cell around solder joint area after lamination and cooling processes, as well as to investigate further the source of these stresses, i.e. the solder joint itself.

The rest of the article is divided into three sections. Brief descriptions of the μSXRD technique used in the present work and sample preparation needed are in Section 2. In Section 3, we present and discuss the stress measurement in the silicon solar cell around a solder joint as well as the microstructure evolution of the solder joint materials comparing between as-reflowed solder joint materials and after thermal cycles and provide analysis how it could further aggravate the stress in the silicon near the solder joint area. The last section summarizes the significance of the findings and concludes the present study.

2. Experimental

A solar PV module typically is a sandwich of a glass, a front encapsulant layer, a stringed cell assembly, a back encapsulant layer and finally a backsheet. However, in this study, we built only a mini module, which satisfied our purpose to study the stress in the silicon after lamination process. Our mini module consists of one $125\ mm \times 125\ mm$ monocrystalline solar cell covered by encapsulant layers on both sides, a transparent backsheet layer at the back side, and a glass at the front side, laminated at high temperature using industry-typical processes and recipes (all materials are those typically used in the global PV industry) as shown in Fig. 1(b) (schematically, also showing how the *in situ* X-ray microdiffraction experiment was set up). Fig. 1(c) shows the actual mini module sitting on the sample stage in the X-ray microdiffraction experiment.

Stress measurements in the silicon around the solder joint were performed by synchrotron X-ray micro-diffraction at beamline 12.3.2 at the Advanced Light Source (ALS) of the Lawrence Berkeley National Laboratory [10]. The stress measurement in the silicon solar cell here is unique and novel as it is done while the solar cell is already laminated (encapsulated by transparent polymers and glass) thus representing the actual solar PV system in operations in the field. This approach thus allows *in situ* stress measurement of the silicon solar cell while the mini module is, for

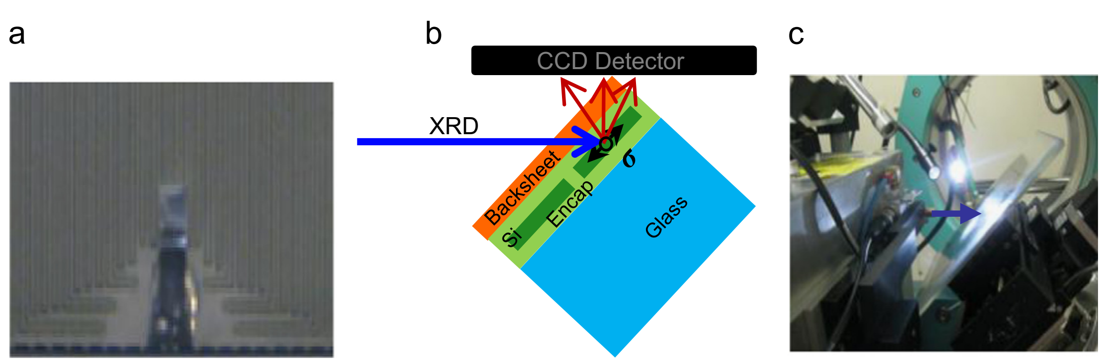

Fig. 1. (a) Optical image of silicon cell around solder joint. (b) The incoming synchrotron focused X-ray beam (the blue arrow) penetrates through the transparent backsheet layer (orange colored) and the back-side encapsulant layer (light green colored) and is diffracted by the silicon crystal (red arrows) allowing its crystallographic information to be captured by the Charge-Coupled Device (CCD) detector (black colored), which can then be translated into stress and, thus, crack propensity information. (c) The *in situ* experimental using synchrotron X-ray micro-diffraction, where the encapsulated mini module sits on a XY piezoelectric sample stage tilted at 45°. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)