Journal of Manufacturing Processes 20 (2015) 397–405

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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

Technical Paper

Surface wrinkling for increasing the short circuit current density of thin film solar cells deposited on chemically oxidized silicone surface

Himanshu Ingale, Murali M. Sundaram*

Department of Mechanical and Materials Engineering, University of Cincinnati, Cincinnati, OH, USA

ARTICLE INFO

Article history:
Received 16 June 2014
Received in revised form 24 August 2014
Accepted 24 August 2014
Available online 16 September 2014

Keywords:
Solar cell texturing
Surface wrinkling
Light trapping

ABSTRACT

Solar cell technology is one of the most promising sources of clean energy. However, some limitations include low efficiency, high manufacturing cost, and large consumption of material. A novel method of depositing a thin film direct bandgap semiconductor material on lightweight substrate, which would result in higher specific power (kW/kg), is explored in this work. The efficiency of such solar cells can be further increased by providing a textured surface, resulting in reduced optical losses therefore increasing light trapping. This paper reports a novel method which makes use of a mechanical instability in a soft material (polydimethylsiloxane) to make wrinkles on its surface by chemically oxidizing the surface using Piranha solution. Further, these wrinkles were arranged in order by applying external force to the soft material before chemical oxidation. Theoretical studies have been carried out and found more than 10% increase in transmittance and short circuit current if a cadmium telluride (CdTe) solar cell is to be deposited on such substrate.

1. Introduction

Thin film solar cell technology is rapidly gaining attention due to its advantages such as cheap production cost, versatility, flexibility and ease of handling. Conventionally, thin film solar cells are grown on 1–4 mm thick glass substrates, wherein only a few microns thick layers are needed for the actual solar cell stack. Solar cells with high specific power can be manufactured if glass is substituted with a lightweight substrate, as glass substrate accounts for nearly 90% of the total weight of the cell. Also, solar cells deposited on flexible and lightweight substrates are advantageous over solar cells deposited on glass for both terrestrial and space applications where high specific power and flexibility are required for curved shaping or rolling. Flexible solar cells give more possibilities for integration into buildings, solar cars and boats, consumer electronics and portable electronics [1]. Cadmium telluride (CdTe) is one of the preferred materials for thin film solar cells, due to its optimum bandgap for the efficient photo-conversion and robustness for industrial production [2]. However, most of the thin film solar cells must compromise between achieving complete optical absorption using films that are thicker than the optical absorption length and achieving efficient conversion of the absorbed photons into photocurrent [3]. This results in increased thickness of the active layer of thin film, thus increasing the overall cost of the production. Hence, light trapping is essential to achieve high efficiencies in thin cells [4].

The present research aims to accomplish the aforementioned objective of manufacturing a lightweight flexible polymer substrate with a texturing pattern on it. Buckling instability is taken advantage of in soft material polydimethylsiloxane (PDMS), which consists of repeated units of $-O-Si-(CH_3)_2-$. PDMS is treated with a piranha solution, a strong acid which is a mixture of sulfuric acid and hydrogen peroxide. This substance causes the formation of an oxidized surface on PDMS that is harder than the regular PDMS substrate [5,6]. This leads to the introduction of a bi-layer system, in which the difference in elastic modulus generates compressive stresses and forms surface wrinkles. Furthermore, these wrinkles can be arranged in an orderly fashion under the guidance of external forces before oxidization.

2. Literature review

When a thin elastic film is coated on top of a pre-strained soft substrate, followed by release of the pre-strain, a mismatch in equilibrium states arises between the two layers, causing a buckling instability in the bilayer system. This leads to formation of various wrinkling patterns that bring the system to a new equilibrium state. When a soft substrate is expanded, some of the external energy is converted into the potential energy within the substrate. When a

* Corresponding author. Tel.: +1 513 556 2791; fax: +1 513 556 3390.
E-mail address: murali.sundaram@uc.edu (M.M. Sundaram).

http://dx.doi.org/10.1016/j.jmapro.2014.08.008
1526-6125/

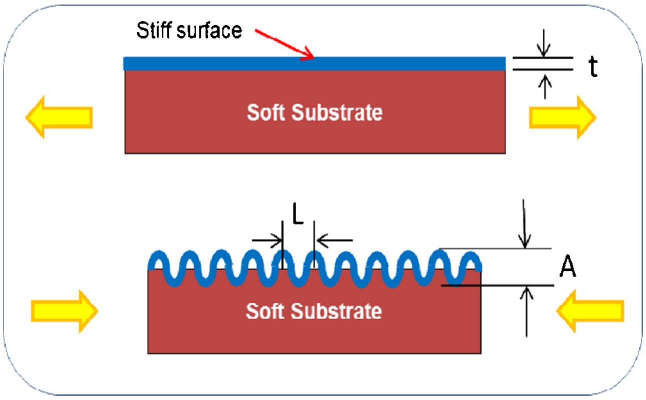

Fig. 1. Schematics of wrinkle formation through buckling instability in a bilayer system (t = thickness of hard film, L = wavelength, A = amplitude of the wrinkle).

thin film is coated on the top of the pre-strained substrate, followed by release of the strain, a new equilibrium state must be reached due to mismatch of the two equilibrium states between soft substrate and hard thin film. This results in the formation of wrinkles shown schematically in Fig. 1, which is the result of minimization of the total elastic energy in the thin layer and the soft substrate.

Spontaneous formation of such structures on a solid surface of micrometer to sub-micrometer scale is a potentially more efficient alternative to conventional micromachining techniques. Mechanical buckling instability is one such phenomenon, which has received increased attention for its potential to create ordered wrinkling structures on a micrometer to sub-micrometer scale. Recently, these instabilities have been exploited for assembling colloidal particles [7], stretchable silicon substrates for electronics [8], measuring mechanical properties of thin films [9], protein pre-concentration [10], tunable wetting and tunable open channel microfluidics [11]. Several methods to harness ordered surface wrinkles on soft substrate have been reported so far. These methods include: treating PDMS surface with oxygen plasma [12], UV zone treatment [13] and ion implantation [14].

However, these methods not only require sophisticated equipment, but are also incapable of creating a surface pattern on large region. If spontaneous surface wrinkling can be applied to a large region for creating microstructures, it can be more cost effective than conventional techniques of micro-fabrication. One such method was first proposed that involves treating PDMS surface with the mixture of sulfuric acid and nitric acid [5]. Later, this technique to harness ordered surface wrinkles on PDMS was used for large region surface wrinkling [15].

One example of a simple approach to harness ordered surface wrinkles is to deposit a thin, hard layer on top of a soft, expanded substrate, and then release the strain within the substrate. In this example, wrinkles were fabricated by depositing a thin Au layer on a thermally expanded PDMS film, followed by cooling the substrate to the room temperature [16]. However, since the thin film is not covalently bonded to the soft substrate, it tends to delaminate from the substrate under a large strain. To address this issue, a thin, hard layer can be formed directly on the PDMS surface by oxidizing the top layer. In this study, a chemical method is used to achieve the aforementioned wrinkling on a PDMS surface.

3. Experimentation

This study involves the use of Piranha solution, which oxidizes the surface of PDMS by forming silanol groups. Piranha solution is a strong acid mixture normally consisting of concentrated sulfuric acid and hydrogen peroxide, commonly used as a cleaning agent for wafers in the soft-lithography process. The chemical reaction

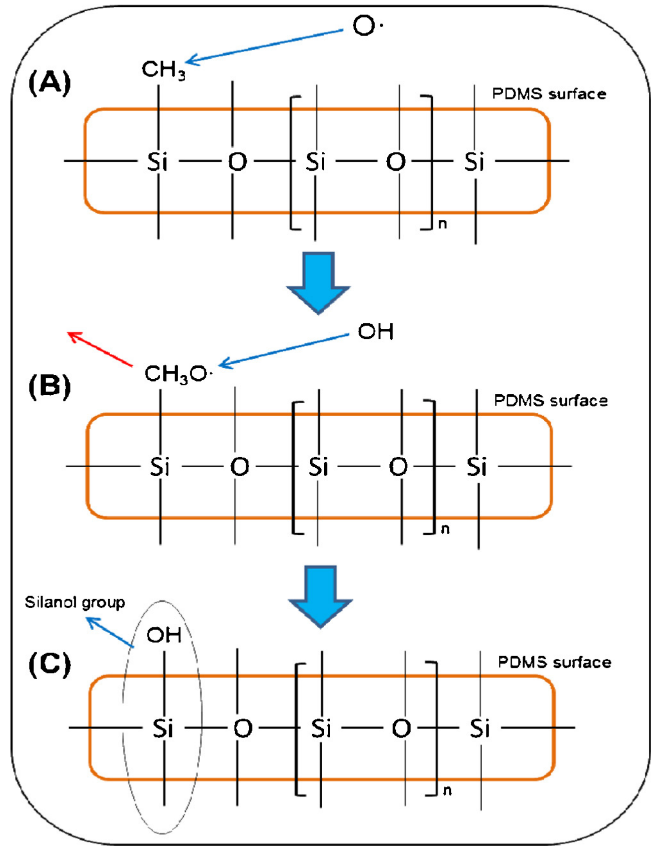

Fig. 2. Methyl group in PDMS gets replaced by silanol group. (A) Methyl group being attacked by reactive oxygen species from Piranha solution forming unstable CH_3O^-. (B) Unstable CH_3O^- is detached from —Si—O branch. (C) Left vacancy is taken by OH^- to form silanol group.

between concentrated sulfuric acid with hydrogen peroxide generates hydronium ions, bi-sulphate ions and a reactive atomic oxygen species as shown in Eq. (1).

$$H_2SO_4 + H_2O_2 = H_3O^+ + HSO_4^- + O\cdot \quad (1)$$

The reactive atomic oxygen species is the primary agent for the formation of an oxidized PDMS surface, breaking the Si—CH_3 bonds in the substrate to form a silanol group (Si—OH). The process begins with the destruction of the bonds within a methyl group by the reactive oxygen, forming unstable CH_3O^-. This ion is detached from —Si—O— branch and the vacancy in the structure is filled by OH^- to form silanol group [6]. The chemistry of the process is shown in Fig. 2. A schematic of the entire process and experimental setup is shown in Fig. 3. Experimental materials and methods are described below.

3.1. Materials

PDMS pre-polymer consisting of siloxane base and curing agent (Sylgard 184 Dow Corning), concentrated sulfuric acid (>96%) and hydrogen peroxide (30%).

3.2. Preparation of PDMS substrate

Two different samples of PDMS were prepared by mixing pre-polymer siloxane base and curing agent in the ratio 10:1 and 10:0.4. The mixture was then poured into a petri dish at a room temperature and allowed to settle for 15 min. The PDMS with 10:0.4 siloxane base to curing agent ratio was then divided into two different samples, one of which was cured at 60 °C for 1 h and