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Low-temperature plasma processing for Si photovoltaics

S.Q. Xiao [a,b,*], S. Xu [a], K. Ostrikov [c,d]

[a] Plasma Sources and Applications Centre (PSAC), NIE, and Institute of Advanced Studies, Nanyang Technological University, 1 Nanyang Walk, Singapore 637616, Singapore
[b] Key Laboratory of Advanced Process Control for Light Industry (Ministry of Education), Department of Electronic Engineering, Jiangnan University, Wuxi 214122, China
[c] Plasma Nanoscience Centre Australia (PNCA), CSIRO Materials Science and Engineering, P.O. Box 218, Lindfield, New South Wales 2070, Australia
[d] Plasma Nanoscience, School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia

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ABSTRACT

There has been a recent rapid expansion of the range of applications of low-temperature plasma processing in Si-based photovoltaic (PV) technologies. The desire to produce Si-based PV materials at an acceptable cost with consistent performance and reproducibility has stimulated a large number of major research and research infrastructure programs, and a rapidly increasing number of publications in the field of low-temperature plasma processing for Si photovoltaics. In this article, we introduce the low-temperature plasma sources for Si photovoltaic applications and discuss the effects of low-temperature plasma dissociation and deposition on the synthesis of Si-based thin films. We also examine the relevant growth mechanisms and plasma diagnostics, Si thin-film solar cells, Si heterojunction solar cells and silicon nitride materials for antireflection and surface passivation. Special attention is paid to the low-temperature plasma interactions with Si materials including hydrogen interaction, wafer cleaning, masked or mask-free surface texturization, the direct formation of p–n junction, and removal of phosphorus silicate glass or parasitic emitters. The chemical and physical interactions in such plasmas with Si surfaces are analyzed. Several examples of the plasma processes and techniques are selected to represent a variety of applications aimed at the improvement of Si-based solar cell performance.

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* Corresponding author at: Key Laboratory of Advanced Process Control for Light Industry (Ministry of Education), Department of Electronic Engineering, Jiangnan University, Wuxi 214122, China.
E-mail addresses: larring0078@hotmail.com (S.Q. Xiao), shuyan.xu@nie.edu.sg (S. Xu), kostya.ostrikov@csiro.au (K. Ostrikov).

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1. Introduction

1.1. General overview of Si photovoltaics

Existing power systems can be considered as a prime cause for current greenhouse or global warming effects as more than 75% of the energy is produced from fossil fuel [1]. The utilization of fossil fuels, especially coal causes a major environmental impact due to the emissions of greenhouse gases such as CO_2, SO_x and NO_x that pollute the atmosphere. Therefore, there is an urgent need for a robust and sustainable power production and distribution approach which is reliable, environment friendly and economic. In contrast to fossil fuels, photovoltaic (PV) solar energy is considered as a possible solution of the climate change or global warming problems since PV solar cells can provide electricity without producing carbon dioxide and other greenhouse gas emissions. Among feasible renewable energy sources, PV solar energy is among the most promising technologies for a sustainable future because sunlight is abundant and distributed all over the Earth. The amount of solar energy reaching the Earth within 1 h equals to the total annual energy need of all of mankind [2]. Moreover, the available energy resources are nearing exhaustion and solar energy may have to serve as the main energy source in the future.

Among the PV materials, silicon, the second most abundant element on Earth has attracted a tremendous interest in solar cell applications. This is why Si-based solar cells have been extensively studied by a large number of research groups all over the world [3–12]. In general, Si-based solar cells can be divided into two categories: the bulk silicon technology and thin-film silicon technology. At present, the bulk silicon technology dominates the PV market with a proportion of more than 85% including monocrystalline silicon (c-Si) and polycrystalline silicon (poly-Si), which reach industrial photo-conversion efficiencies of around 18.5% and 17.0%, respectively [13].

The cost of bulk silicon technology has reduced significantly as the conversion efficiency has increased drastically with the introduction and application of more sophisticated technologies. In comparison, silicon thin-film technology is always considered as the "younger cousin" of the bulk silicon technology which may potentially become the leading technology of solar energy production, although this expectation has not materialized yet. The arguments favoring the Si thin-film technology have been based on a substantial potential for cost reduction due to thinner layer usage, cheap deposition processes, compatibility with large-area and mass production, as well as a large choice of rigid or flexible substrates (glass, metal, plastic, etc.). That is to say, thin-film silicon technology constitutes one of the most promising ways for low-cost PV solar cells and modules even though the industrial cells currently show the record conversion efficiencies of only around 13% [14,15].

1.2. Plasma technologies in Si photovoltaics

In the past twenty years, a number of low-temperature plasma sources and plasma facilities, such as capacitively coupled radio-frequency (rf) plasma-enhanced chemical vapor deposition (PECVD) [11,12,16–18], very high frequency (VHF) PECVD [7,9,10,19–21], microwave plasma (MP) CVD [22–26] and inductively coupled plasma (ICP) CVD [27–29] have been successfully applied for the fabrication of PV devices including bulk Si solar cells and thin-film Si solar cells. With the growing consensus that the climate change is inevitable, low-temperature plasmas are set to play a key role in the development of a cleaner and more environmentally conscious world, especially in the development of PV power as a clean, sustainable energy source [30].

For bulk Si solar cells, the plasma sources find numerous applications, e.g., the surface passivation by means of silicon nitride (SiN_x:H) films [29,31–34] and the plasma etching processes for removal of phosphorus silicate glass (PSG) or parasitic emitters [27,35], for wafer cleaning [36–39] as well as masked and mask-free surface texturization [40–42]. For thin-film Si solar cells and HIT (heterojunction with intrinsic thin-layer) solar cells, however, almost all the fabrication processes including the formation of p–n junction, the interface passivation and the surface texturing for light trapping are accomplished by utilizing plasma facilities [6–12,14,16,17,19–21].

As a consequence, plasma-assisted fabrication of Si-based PV materials and complex assemblies is a topic that is continuously increasing in importance, both for fundamental research and for existing and potential industrial applications. The desire to produce Si-based PV materials with consistent performance and reproducibility and at an acceptable cost stimulates a growing number of major research and research infrastructure programs, and a rapidly increasing number of publications in the field of low-temperature plasma for Si PV devices. Therefore, large-scale