

Progress and limitations of thin-film silicon solar cells

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ABSTRACT

The major issues of thin-film silicon solar cells have been the light-induced metastability of hydrogenated amorphous silicon (a-Si:H) and the weak infrared light absorption of hydrogenated microcrystalline silicon ($\mu\text{-Si:H}$). In order to overcome these challenges, we have developed a novel deposition process for a-Si:H and an improved light trapping scheme for $\mu\text{-Si:H}$ light absorbers, leading to four record independently-confirmed conversion efficiencies with single-junction and multijunction device structures. In this article, we review some technological progresses that led to the notable improvement in thin-film silicon solar cells, and address some limitations imposed by the absorber layer quality as well as the cell design.

1. Introduction

Over the past four decades, thin-film silicon solar cells have been recognized as one of the cost-effective alternative candidates to crystalline silicon solar cells because of several advantages such as lower consumption of raw material, scalability for mass-production, and application to light-weight flexible modules. Research and development have started since the first deposition of hydrogenated amorphous silicon (a-Si:H) was reported in 1975 (Spear and LeComber, 1975) followed by the demonstration of a working p-i-n solar cell by Carlson and Wronski (1976). In 1990s, hydrogenated microcrystalline silicon ($\mu\text{-Si:H}$) – sometimes called hydrogenated nanocrystalline silicon (nc-Si:H) – has emerged as an alternative light-absorbing material (Wang and Lucovsky, 1990; Meier et al., 1994) that exhibits light sensitivity extending to longer wavelengths compared to a-Si:H. Thanks to the different bandgap energies of a-Si:H (~ 1.7 eV) and $\mu\text{-Si:H}$ (1.1 eV), these materials have been integrated into double- (Fischer et al., 1996; Yamamoto et al., 2004), triple- (Saito et al., 2005; Kim et al., 2013) and quadruple-junction (Si et al., 2014; Schüttauf et al., 2015; Kirner et al., 2015) solar cells. However, their solar cell efficiency is still low compared to the other technologies based on inorganic absorber materials including crystalline silicon, III-V, Cu(In, Ga)Se₂ and CdTe (Green et al., 2017). The inferior device performance of thin-film silicon is mainly ascribed to two issues: the light-induced metastability in a-Si:H known as the Staebler-Wronski effect (Staebler and Wronski, 1977), and the weak infrared absorption of $\mu\text{-Si:H}$ because of its indirect bandgap nature. To tackle these challenges, we have proposed a novel deposition process for a-Si:H and a light trapping scheme for $\mu\text{-Si:H}$ absorbers. As a result, we have achieved record-breaking efficiencies in several

single-junction and multijunction devices (Green et al., 2017).

Deposition of device-grade a-Si:H and $\mu\text{-Si:H}$ is generally performed by plasma-enhanced chemical vapor deposition (PECVD) with a standard parallel-plate electrode geometry (diode configuration, see Fig. 1(a)). SiH₄ is used as a source gas and the material phase from a-Si:H to $\mu\text{-Si:H}$ is controlled by varying the H₂ dilution ratio. For a-Si:H, it is widely known that reducing the deposition rate mitigates the light-induced degradation. On the contrary, increasing the deposition rate results in a-Si:H exhibiting a greater density of nano-sized voids and dihydride bonds (or hydrides at the surface of pores), as revealed by infrared spectroscopy (Bhattacharya and Mahan, 1988; Nishimoto et al., 2002; Smets et al., 2003) and positron annihilation spectroscopy (Melskens et al., 2014). A recent electron-paramagnetic resonance study suggests that metastable dangling bonds on the internal surface of nano-voids are the origin of the light-induced degradation of a-Si:H (Fehr et al., 2014). One of the triggers of creating a porous microstructure in a-Si:H is the incorporation of higher-order silane radicals and/or polyhydride nano-clusters generated in the SiH₄ glow-discharge process. The contribution of these species with respect to the main deposition precursor (known as SiH₃) was reported as a factor that affects the metastability of a-Si:H (Takagi et al., 1999; Koga et al., 2004). To reduce the incorporation of such unwanted species during a-Si:H deposition, a remote plasma process using a triode electrode configuration (see Fig. 1(b)) has been proposed as a radical separation technique (Matsuda et al., 1983), which provides denser a-Si:H films containing a lower dihydride bond density. Although the deposition rate is an order of magnitude lower in the triode PECVD ($< 10^{-1}$ nm/s) compared to the conventional diode PECVD ($> 10^{-1}$ nm/s), the light-induced degradation of the single-junction a-Si:H solar cells can be

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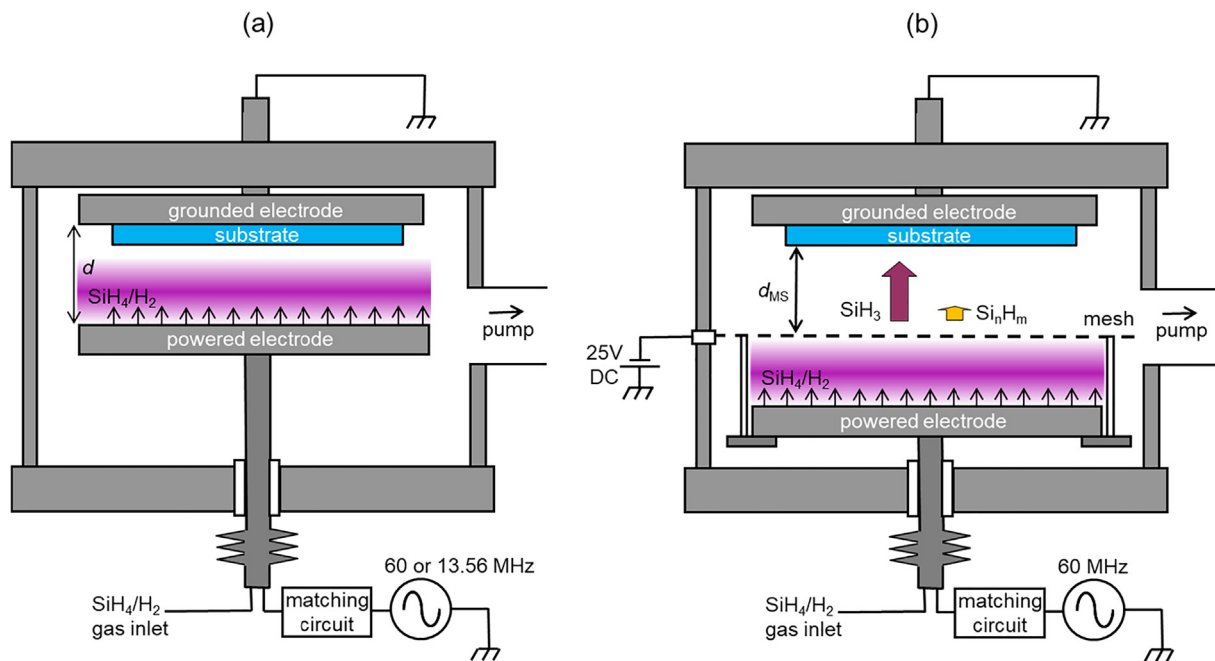


Fig. 1. Schematic illustrations of the (a) diode and (b) triode PECVD chambers used in this work.

reduced while keeping the initial performance high (Shimizu et al., 2005; Sonobe et al., 2006; Matsui et al., 2013). However, our previous study showed that a further reduction of deposition rate does not lead to any improvement in light-soaking metastability (Matsui et al., 2015a). The results seem to indicate that it is impossible to make perfectly stable a-Si:H, and some light-induced degradation is unavoidable.

To develop high-efficiency $\mu\text{-Si:H}$ solar cells, light trapping plays a key role in boosting the weakly-absorbed infrared light in the thin $\mu\text{-Si:H}$ layer. Conventionally, naturally grown (or chemically/physically etched) pyramids or craters of transparent conductive oxide (TCO) layers and metals have been used as substrates for solar cells to scatter the incident light into various angles. However, the material quality of $\mu\text{-Si:H}$ deteriorates when deposited on textured surfaces. It was reported that excessively steep textures often induce “cracks” in $\mu\text{-Si:H}$ films, resulting in a conversion efficiency decrease (Python et al., 2008, 2009; Li et al., 2009). Modification of the texture shape from V-shape to U-shape is known to mitigate the crack formation (Python et al., 2008). However, even with U-shaped textures, the formation of cracks is still observed with an increase in absorber thickness.

A novel light trapping technique using honeycomb-shaped periodic patterns has been developed and applied to $\mu\text{-Si:H}$ n-i-p solar cells (Sai et al., 2012). The surface morphology of the textured substrate was systematically designed to provide effective light trapping of infrared light while preserving the high-quality $\mu\text{-Si:H}$ growth without giving rise to texture-induced cracks. Through optimization not only of the

texture design but also of the absorber deposition, front TCO and p-i interface layers, we have demonstrated an abrupt improvement of solar cell performance compared to the best devices made on random texture based on naturally grown or chemically-etched substrate.

In this paper, we review some advances in material and device processing developed in our lab for fabricating high-efficiency thin-film silicon solar cells. In the first section, we present the current state and understanding of the metastability issue of a-Si:H solar cells. The second section describes the material and device properties of $\mu\text{-Si:H}$ deposited on our novel light trapping substrate. In these sections, some key issues that determine the device-grade quality of a-Si:H and $\mu\text{-Si:H}$ are discussed based on the characterization of sub-bandgap defect absorption spectroscopy. In the third section, we give a summary of the multijunction devices developed based on our state-of-the-art solar cell materials and devices. We discuss the limitations of solar cell performance imposed by the absorber quality and cell design.

2. Experimental details

2.1. a-Si:H solar cells

Fig. 1 shows schematic illustrations of the (a) diode and (b) triode PECVD chambers used for the deposition of a-Si:H absorber layers. Table 1 details the parameters used for the two types of depositions. For diode PECVD (Fig. 1(a)), two deposition chambers were used: in the

Table 1

Deposition parameters used for the diode and triode PECVD. The parameters that were changed to control the deposition rate of a-Si:H are highlighted.

Deposition system	Diode	Diode	Triode	Triode
Chamber	PC5	PC4	PC5	PC2
Excitation frequency	60 MHz	13.56 MHz	60 MHz	60 MHz
Glow-discharge power density (P_{GD})	10–57 mW/cm²	10–50 mW/cm²	30 mW/cm ²	30 mW/cm ²
SiH ₄ /H ₂ flow rate	20/20 sccm	20/100 sccm	20/20 sccm	20/20 sccm
Gas pressure	20 Pa	133 Pa	20 Pa	6.7 Pa
Substrate temperature (T_s)	210 °C	180 °C	210 °C	210 °C
Interelectrode distance (d)	20 mm	15 mm	N/A	N/A
Mesh-substrate distance (d_{MS})	N/A	N/A	10.5 mm	9–17 mm
Mesh aperture ratio (A_{mesh})	N/A	N/A	Single mesh: 5, 10, 30, 60%	Single mesh: 10, 60%
Mesh DC bias	N/A	N/A	Staggered double mesh: 10%	–25 V
			–25 V	

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