Plasma enhanced chemical vapor deposition process optimization for thin film silicon tandem junction solar cells

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ABSTRACT

Industry has previously established a 10% stable total module efficiency 1.1×1.3 m^2 thin film silicon tandem junction (TJ) module manufacturing baseline. A similar silicon TJ cell manufacturing process has been established, using a plasma enhanced chemical vapor deposition (PECVD) tool with an excitation frequency of 13.56 MHz, which was modified to handle 30×30 cm^2 substrates. Extensive PECVD process window characterization was undertaken for the silicon layers that have the biggest impact on device performance. Single layer silicon on glass data and 1×1 cm^2 single junction and TJ solar cell data for amorphous intrinsic silicon and microcrystalline intrinsic silicon layers have been collected. Single layer characterization data for p-doped microcrystalline silicon oxide layer (μc-SiO$_x$:H-p) for aluminum doped zinc oxide substrates is being presented, as well as solar cell data. The manufacturability of the μc-SiO$_x$:H-p process is being considered. Finally, we present the best solar cell results obtained with the optimized PECVD process, as well as baseline performance data.

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1. Introduction

Thin film silicon photovoltaics is an attractive technology. It uses widely abundant and non-toxic materials. The low temperature manufacturing process is very energy efficient and is scalable to produce several terawatts of solar modules per year. Great accomplishments have been made in the last years. The 10% stable total area module efficiency milestone has been reached by Applied Materials and a number of other industrial players [1–6]. Production costs are now generally considered to be below 1 $/W, a milestone that had been perceived as extremely challenging only a few years ago. The thin film silicon market size has reached GW level in 2010 [7], opening the door to a future rapid price reduction through progression along an industrial learning curve [8].

The silicon plasma-enhanced chemical vapor deposition (PECVD) process performed in a capacitively coupled reactor has a long history, and has been run on a large number of different Applied Materials' platforms. From 10×10 cm^2 and 30×30 cm^2 reactors used in academic research [9], the process has been transferred to ARISTO™ 1 m^2 and later 1.4 m^2 industrial vertical inline prototypes [10]. The process has then been scaled up and introduced to mass production on 1.78 m^2 substrates [11]. The AKT™ is a horizontal deposition platform and has initially been developed as a PECVD cluster tool for liquid crystal display manufacturing. The solar silicon deposition process was also run on

different substrate sizes: on the 30×30 cm^2 Gen2 (this paper), as well as on 62×75 cm^2 Gen4 [12], 1.1×1.3 m^2 Gen5 [1,2,13] and 2.2×2.6 m^2 Gen8.5 in the lab and in mass production [3,14–16].

The goal of PVcomB is to bring fundamental science and thin film photovoltaics manufacturing industry together. Research results from academic partners can be tested on-campus in a manufacturing-like module line. A direct transfer from Gen2 to Gen8.5 manufacturing lines was proven to be straightforward [3]. During PECVD process ramp-up at PVcomB, extensive process window characterization has been performed for amorphous intrinsic silicon (a-Si:H-i) top cell layer, microcrystalline intrinsic silicon (μc-Si:H-i) bottom cell layer and p-doped microcrystalline silicon oxide (μc-SiO$_x$:H-p) top cell layer for aluminum doped zinc oxide (AZO) substrates. The fundamental understanding of the deposition processes generated in this way helped us to improve solar cell performance.

2. Materials and methods

All single layers and all solar cells in this work have been prepared and characterized at PVcomB. The AKT™1600 at PVcomB uses an excitation frequency of 13.56 MHz, and has been modified, since the original Gen2 display manufacturing format of 37×47 cm^2 is slightly larger than that of the 30×30 cm^2 substrate size used at PVcomB. Glass handling, as well as process kits and substrate holder inside the process chambers were adjusted to accommodate the smaller format. Since the chamber and gas panel configuration are unique, the sequencing as well

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as the cleaning and conditioning concept needed to be adjusted from the best known method: e.g. the bottom cell n- and i-layer had to be separated in order to prevent phosphorous contamination of the p/i junction. For silicon single layers, reflection and transmission spectra are measured either on a Perkin Elmer Lambda 1050 spectrometer or on a self-built mapping table with Avantes AvaSpec-2048-USB2 spectrometer. The measured spectra are fitted with a Tauc–Lorentz oscillator model, and thickness and refractive index are extracted from the fit. Absorption is calculated from the measured reflection and transmission spectra, and E04 optical band gap is defined as the photon energy for which the absorption coefficient of the material is equal to 10^4 cm^{-1}. Raman spectra are collected on silicon single layers and doped silicon oxide layers on glass with a custom made setup that uses a green laser of 532 nm wavelength and a SP-2500i Monovista spectrometer. The single layers used are approximately 300 nm thick. A six peak fitting method is used to calculate the Raman crystalline fraction f_c [17–19]. The lateral conductivity of doped layers is measured with a self-built multi-pin measurement head.

A stack of 80 nm sputtered AZO and 200 nm Ag is used as a back contact for solar cells. Solar cells are defined by laser scribing after silicon deposition and back contact deposition. Top cell thickness is below 300 nm and bottom cell thickness is below 2000 nm for the baseline samples. 1×1 cm^2 solar cell current–voltage (I–V) parameters are measured with a dual-source class AAA solar simulator (Wacom WXS-155S-L2). Conversion efficiency (η), fill factor (FF), open circuit voltage (V_{oc}) and current density (J_{sc}) are automatically extracted from the measured I–V curves. Light soaking is usually limited to 168 h, since after this time most of the light induced degradation has already taken place. Details about cell preparation and characterization can be found elsewhere [3].

The AZO front contact layers have been sputter deposited on a Gen8.5 ATON™ at Applied Materials [13]. From the Gen8.5 substrates, "quarter-sized" Gen5 substrates were cut and sent to PVcomB. They were stored on L-racks and cut into 30×30 cm^2 samples, washed and etched with diluted hydrochloric acid. In many cases the AZO substrates were stored for more than two years before high efficiency solar cells were made on them, demonstrating the excellent long-term stability of these substrates. Recently, PVcomB has introduced the use of the AZO annealing process developed at Helmholtz-Zentrum Berlin [20, 21]. The annealing process improves the transmission of the AZO and leads to a reduction in parasitic light absorption that enhances J_{sc} [22, 23]. A stabilized efficiency improvement of approximately 0.4% absolute on Applied Materials AZO has been demonstrated [23].

Energy dispersive X-ray (EDX) spectroscopy was performed on particles collected in the AKT™15 k at Applied Materials with an EDX-Microprobe Oxford INCA 350 system.
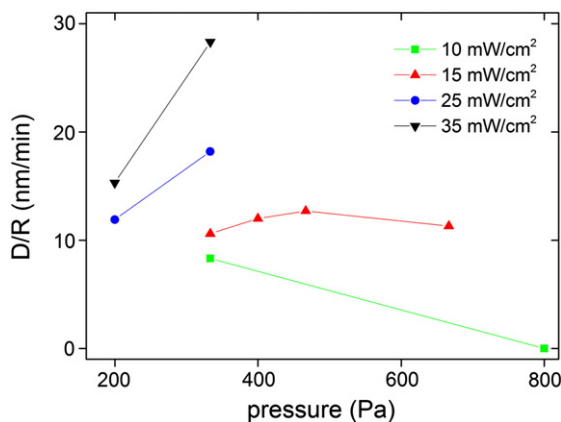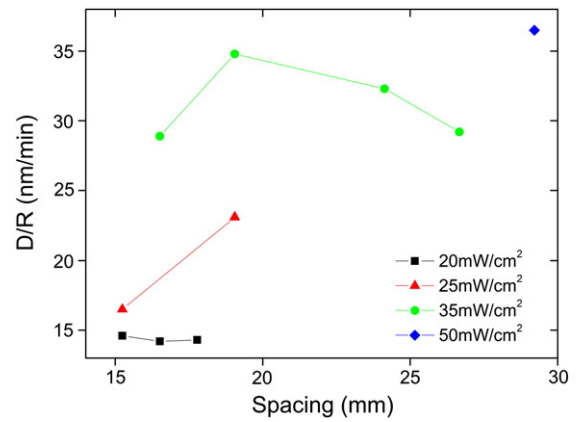

Fig. 2. Deposition rate D/R for different power densities as a function of electrode gap spacing.

Nonlinear extended electron dynamics (NEED) has specifically been developed for PECVD processes with pressures of several hundred Pascal [24]. At PVcomB, a Hercules N250 NEED sensor, by Plasmetrex GmbH, is attached to a custom made insertion in the PECVD chamber window port. It is used together with a plasma resonance circuit model based on an electrodynamics- and model-based approach, where the electron mass is treated as inductance and collisions with neutrals are treated as resistance. The model predicts two interesting parameters. Firstly, the dimensionless normalized plasma resistivity, that is proportional to collision rate over the square of electron density. The second parameter is the resonance frequency of the equivalent circuit. When the resonance frequency approaches generator frequency, the plasma draws more current and the amount of RF power dissipated increases [25,26]. A number of additional parameters are recorded by
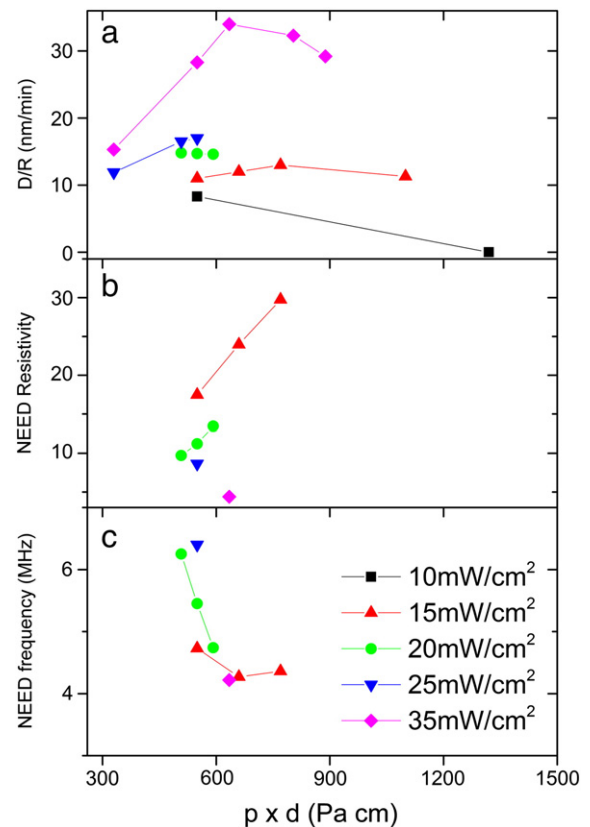

Fig. 1. Deposition rate D/R for different deposition power densities as a function of pressure. Lines are guides for the eye.

Fig. 3. Deposition rate D/R, NEED resistivity and NEED resonance frequency for different deposition power densities as a function of p × d. The lines are guides for the eye.