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Replacing the amorphous silicon thin layer with microcrystalline silicon thin layer in TOPCon solar cells

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ABSTRACT

In this paper, microcrystalline silicon layer is proposed to replace the amorphous silicon layer in the tunneling oxide passivated contact (TOPCon) solar cell. Both the microcrystalline silicon layer and amorphous silicon layer were deposited by plasma enhanced chemical vapor deposition on quartz substrate and analysed by Raman spectra. The effects of high temperature annealing of TOPCon samples were revealed by scanning electron microscope and dopant profiler. It was observed that, for amorphous silicon layer, high crystallization could be realized by annealing at high temperature, which tends to damage the silicon layer as well as the tunneling silicon oxide. The microcrystalline silicon layer deposited by reducing the silane concentration can achieve higher crystallization at annealing temperature as low as 600 °C. Low temperature annealing avoids the blistering of the silicon layer and the balling-up of the tunneling silicon oxide, resulting in improved passivation. Furthermore, the higher doping efficiency of microcrystalline layer enhanced the performance of TOPCon solar cells, which were investigated by simulation study.

1. Introduction

The solar cell industry is moving toward partial rear contacted (PRC) scheme in order to reduce the recombination loss of carriers by reducing the metal–semiconductor contact area (Weiwei et al., 2016). However, despite of the less than 1% contacted area, the high recombination velocity of $\geqslant 10^5$ cm/s induced by the unpassivated contact hinders the further improvement of open-circuit voltage (V_{oc}) and conversion efficiency (η) Wang et al., 2014. In 2013, Frank Feldmann from Fraunhofer ISE proposed a full area carrier-selective passivated contact as an appealing alternative to partial rear contact and named it TOPCon (Tunnel Oxide Passivated Contact) (Feldmann et al., 2014). The TOPCon structure consists of a doped Si layer and an ultra-thin tunneling SiO_2 layer which is sufficiently thin to enable the tunneling of majority carriers while blocking the transport of minority carriers at the same time. Owing to its excellent passivation and junction properties, remarkable cell efficiency up to 25.1% has been reached, which is the world record for both sides-contacted silicon solar cell (https://www.ise.fraunhofer.de/en/press-and-media/press-releases/press-releases-2015/fraunhofer-ise-achieves-new-world-record-for-both-sides-contacted-silicon-solar-cells).

For the fabrication of TOPCon structure, after the deposition of a Si layer on the tunneling SiO_2 layer, an annealing process is usually needed to increase the crystallization fraction (Feldmann et al., 2014). Highly crystallized Si layer allows more efficient doping, leading to the excellent field passivation and junction property. In this work, microcrystalline silicon (μc-Si) layer was proposed to replace the commonly used amorphous silicon (a-Si) layer to form the TOPCon structure. Both μc-Si layer and a-Si layer were deposited on quartz substrate, annealed and analyzed using Raman spectra. It was found that large amount of hydrogen promotes the crystallization of the Si layer. The μc-Si layer could achieve higher crystallization fraction at lower annealing temperature than a-Si layer. Then high-temperature annealing experiments were conducted. The effects of high temperature on the Si layer and tunneling SiO_2 layer were investigated by SEM and ECV profiler. In addition, the improvements of TOPCon solar cell performance resulting from applying μc-Si layer were explored by device simulation.

2. Experiments and simulation methods

Fig. 1 provides the structure of TOPCon samples used for lifetime measurement. The crystalline silicon substrate is n-type with a resistivity of 5 Ω cm. The ultra-thin tunneling SiO_2 layer was grown in boiled nitric acid for 12 min. The thickness of the

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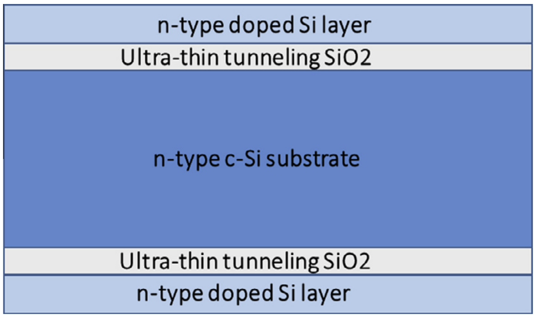

Fig. 1. The structure of TOPCon samples.

tunneling oxide is 1.7 nm obtained by ellipsometer measurement, and it is sufficient for the tunneling of carriers. The silicon layers were deposited using a parallel-plate PECVD (Plasma Enhance Chemical Vapor Deposition) with a ratio frequency of 13.56 MHz. Hydrogen (H_2) and silane (SiH_4) were used as precursor gases. The deposition was done with a chamber pressure of 100 Pa and a deposition temperature of 177 °C. After Si layer deposition, the TOPCon samples were annealed in a tube furnace at different temperature for various time. Lifetime measurements were carried out using the Sinton WCT-120 Lifetime Test Instrument.

The simulated TOPCon solar cell structure is illustrated in Fig. 2. This cell features a front p-type TOPCon emitter and a n-type TOPCon BSF. On the front surface, a layer of ITO is inserted between the Si layer and the front electrode to enhance the transport and the collection of holes. The width of the cell is 400 μm. For front electrode, the width is 25 μm and the thickness is 2 μm. The simulation tool used is the ATLAS simulation package (Michael et al., 2005). The resistivity of c-Si substrate in the simulation is set as 5 Ω cm. And the lifetime is 3 ms. The default parameters of materials used in the simulation are listed in the Table 1. The parameters of c-Si, μc-Si and SiO_2 come from the material library of the simulation tool used (Silvaco, 2015), while the parameters of a-Si are from Klaassen, 1990.

Ray-tracing model has been used to simulate the propagation of light in the solar cell. The photogeneration rate is given by the formula:

$$G = \eta_0 \frac{P\lambda}{hc} \alpha e^{-\alpha y} \tag{1}$$

where η_0 is the internal quantum efficiency, P is the light intensity factor, λ is the wavelength, h is the Planck's constant, c is the speed

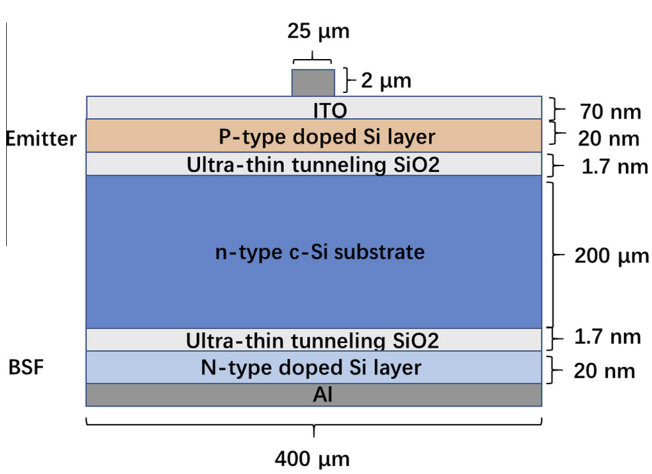

Fig. 2. The structure of simulated TOPCon solar cell.

Table 1
The default parameters of materials used in the simulations.

Material	Electron Affinity	Energy Bandgap	Doping
c-Si	4.05 eV	1.12 eV	1×10^{15} cm^{-3}
a-Si	3.9 eV	1.7 eV	1×10^{21} cm^{-3} (Varied)
μc-Si	4.05 eV	1.12 eV	1×10^{21} cm^{-3} (Varied)
SiO_2	0.9 eV	8.9 eV	None

of light, α is the absorption coefficient, and y is the relative distance from the ray to the specific grid point. The optical parameters of a-Si, μc-Si, crystalline silicon (c-Si) and Aluminum are from SOPRA database. Regarding the recombination mechanisms, Shockley–Read–Hall (SRH) recombination and Auger recombination are applied (Hall, 1952; Shockley and Read, 1952). The SRH recombination rate is given by the following equation (Fossum and Lee, 1982):

$$R_{SRH} = \frac{np - n_i^2}{\tau_p\{n + n_i \exp\left(\frac{E_t}{kT}\right)\} + \tau_n\{p + n_i \exp\left(-\frac{E_t}{kT}\right)\}} \tag{2}$$

where $\tau_p = \frac{\tau_{p0}}{1+\frac{N_{acceptor}}{5.0\times10^{16}}}$ and $\tau_n = \frac{\tau_{n0}}{1+\frac{N_{donor}}{5.0\times10^{16}}}$, τ_{p0} and τ_{n0} are the hole and electron life time, $N_{acceptor}$ and N_{donor} are the concentration of acceptors and donors, n_i is the intrinsic carrier concentration, E_t is the trap level energy with respect to Fermi level, k is the Boltzmann constant, and T is the absolute temperature. Auger recombination rate is defined by (Dziewior and Schmid, 1977):

$$R_{Auger} = C_n(pn^2 - nn_i^2) + C_p(np^2 - pn_i^2) \tag{3}$$

where $C_n = 2.8 \times 10^{-31}$ cm^6/s and $C_p = 9.9 \times 10^{-32}$ cm^6/s are the Auger coefficient for electron and hole, respectively.

In addition, bandgap narrowing effect, Fermi–Dirac carrier statistics and concentration dependent mobility are considered (Slotboom and De Graaff, 1976). Carriers' transport through the ultra-thin SiO_2 layer is modeled by the non-local quantum barrier tunneling model (Steinkemper et al., 2015). In this model, the tunneling current density through a thin insulating layer inserted between two kinds of semiconductor materials is given as:

$$J = \frac{qkT}{2\pi^2 h^3}\sqrt{m_y m_z}\int T(E)\ln\left\{\frac{1+\exp[(E_{Fr}-E)/kT]}{1+\exp[(E_{Fl}-E)/kT]}\right\}dE \tag{4}$$

where m_y and m_z are the effective masses in the lateral direction in the semiconductor, E_{Fl} and E_{Fr} are the quasi-Fermi levels on either side of the insulator barrier, $T(E)$ is the transmission probability. An AM 1.5 G solar spectrum is used for the optical generation to simulate the J–V curve under standard one-sun illumination condition at an intensity of 100 mW cm^{-2}.

3. Results and discussions

3.1. The annealing process of μc-Si and a-Si layer

Two groups of Si layers were deposited on the quartz substrates under the same deposition condition with the only difference being the gas flow ratio between silane and hydrogen. The quartz was chosen as the substrate instead of c-Si wafer in order to eliminate the strong background signal of c-Si. Table 2 shows the gas flow ratio of the two groups. It is noteworthy that the silane used in our lab has already been diluted to 10% with hydrogen.

Table 2
The gas flow ratio of PECVD deposition.

Group	Gas flow (sccm)
A	SiH_4:H_2:PH_3 = 40:10:16
B	SiH_4:H_2:PH_3 = 10:200:4