

DEVELOPMENT OF N-TYPE SILICON HETEROJUNCTION SOLAR CELLS BY USING NOVEL LINEAR REMOTE RF PECVD A-SI:H DEPOSITION

Y. Wu, K. Boulif, C. Devilee, M. Dissel, M. S. Dorenkamper, W. J. Soppe, A. W. Weeber, L. J. Geerligs
ECN Solar Energy, PO Box 1, 1755 ZG Petten, The Netherlands, e-mail:wu@ecn.nl

ABSTRACT: We report on n-type silicon heterojunction (SHJ) solar cells made using novel pilot scale deposition equipment. We investigated the possibility to apply a simplified cell structure without a passivating intrinsic amorphous silicon buffer layer [a-Si:H(i)]. The doped amorphous silicon layers [a-Si:H (n/p)] were deposited by using a novel remote plasma enhanced chemical vapor deposition system (PECVD) with a linear radio frequency (rf) source. Processes for thin (10-20nm) doped a-Si:H layers with useful conductivity and surface passivation were developed and applied in the formation of the SHJ cell. A total recombination velocity of less than 40 cm/s on (100) surface was obtained. An efficiency of 13.2% of several untextured SHJ cells with an area of 21.1cm² was established.

1. INTRODUCTION

The silicon heterojunction solar cell, well known for its high conversion efficiency (up to 23.0% [1]), has been widely studied by many groups. The core element of the HIT structure is a very thin (< 6-7 nm) intrinsic amorphous silicon (a-Si:H(i)) layer, which can provide a superior surface passivation to greatly reduce the charge recombination at the interface. In reality, to produce such kind of a-Si:H thin layer is not trivial because: 1) to achieve a high-quality surface passivation, a special surface cleaning process has to be established in order to minimize the surface defect density and surface micro-roughness [2]; 2) the process window for a high quality a-Si:H (i) layer needs to be established, to create by PECVD a sharp interface of the amorphous/crystalline Si structure, and to obtain an effective saturation of dangling bonds by hydrogen atoms [3]; 3) the passivating quality of the thin a-Si:H (i) layer has to be kept stable in the subsequent deposition of doped a-Si:H layers and contacts [4].

In 2006, K. V. Maydell et al. [5] reported a work in which they achieved good performance of silicon heterojunction solar cells on n- and p-type Si wafers without using the a-Si:H(i) buffer layer. They found that, with an optimal doping concentration (dopant/SiH₄=2000 ppm) in the deposited a-Si:H layer, there was an obvious decrease of surface recombination compared to those obtained at other doping concentration and it resulted in an enhanced V_{oc} in the corresponding cell measurement. Compared to the conventional HIT cell, this structure provides a simplified cell processing. Furthermore, degradation of the a-Si:H (i) layer due to the deposition of the doped layer can be avoided [4]. However, without using a-Si:H(i), a good surface passivation has to be accomplished by the doped layers, which shall have the combined properties of surface passivation, as well as junction formation and charge transportation.

In this work, we apply a new deposition method, remote linear radio frequency plasma-enhanced CVD (rf-PECVD) to produce high quality, very thin doped a-Si:H layers directly on n-type mono-crystalline float zone silicon (100) wafers. A concept SHJ cell with a simple structure was established without using the a-Si:H(i) layer. For this proof-of-concept we did not apply surface texturing. The surface passivation by doped a-Si:H layers, as a function of layer thickness and deposition temperature, was investigated. SHJ cells with a size of ~21 cm² were fabricated. Cells with efficiency of 13.2%, fill factors of ~72% and Voc of ~635 mV were obtained.

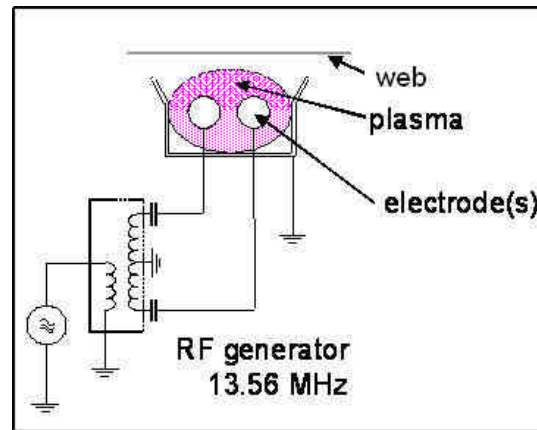


Figure 1. Schematic drawing of the remote linear radio frequency plasma enhanced CVD system. The web carries the wafers (face down).

2. EXPERIMENTS

Mirror-polished N-type float zone silicon (100) wafers (diameter of 100 mm) with a thickness of 300 μm and a resistivity of 2.3 Ωcm were used as the substrates for the amorphous silicon layer depositions. Prior to the deposition, chemical cleaning and a short HF dip were performed. After the HF dip, the wafer is transported into the vacuum chamber of the rf-PECVD, with only a short delay, to avoid surface degradation.

The surface passivation by individual a-Si:H(p) and a-Si:H(n) layers was investigated as follows. We deposited a thick, passivating a-SiN_x:H layer [6] on one side of the wafer by a separate Microwave PECVD system. This assures a good surface passivation, which normally yields τ_{eff} > 1 ms, at one side of the Si wafer. The a-SiN_x:H layer deposition was followed by additional wafer cleaning and HF-dip. Then, an a-Si:H(p)/(n) layer was deposited on the other side for effective lifetime measurement.

The PECVD layout is shown in figure 1. The a-Si:H(p)/(n) layer deposition was carried out in a rf-PECVD system equipped with rf plasma sources (13.56 Mhz) [7]. The PECVD source is able to deposit layers in a regime of low ion energy, which avoids damage to the wafer surface by ion bombardment. Furthermore, the generated plasma is below the wafer surface, by which dust deposition on the wafer surface can be prevented. Diborane (B₂H₆) mixed with hydrogen gas was used as doping gas in the deposition of a-Si:H(p)

whereas phosphine (PH₃) mixed with hydrogen gas was used as doping gas in the deposition of a-Si:H(n).

In the formation of the cell structure [a-Si:H(p)/c-Si(n)/a-Si:H(n)], depositions were carried out with two different sequences: a) first a-Si:H(p) emitter layer, next a-Si:H(n) BSF layer; b) first a-Si:H(n) BSF layer, next a-Si:H(p) emitter layer. The nominal thickness of the doped a-Si:H layers was fixed at 15 nm, and was estimated from the growth rate measured for thicker layers. ITO layers were sputtered on the a-Si:H layers at both front and rear sides of wafer using a sputtering tool. Metal contacts (Pd/Ti/Ag) were evaporated on the rear of wafer as a fully covered blanket contact and on the front in an H-pattern through a contact mask.

The effective lifetime (τ_{eff}) of single doped layers as well as of cell precursors were measured by Sinton WCT120, and are reported at a charge carrier density of $10^{15}/\text{cm}^3$. The amorphous structure of the layers, particularly for those deposited at high temperature, was characterized by Raman spectroscopy. Electrical measurements of a-Si:H(p) layers deposited at various temperatures on glass substrates, with evaporated aluminum contacts, were carried out using a Keithley 595 Quasistatic CV Meter. The optical band gap of the optimized a-Si:H(p) layer, which was later used as emitter layer in the cell, was extracted by fitting a Tauc plot. The performance of the fabricated SHJ cells was analyzed by J-V and spectral response measurements.

3. RESULTS AND DISCUSSION

The upper graph of figure 2 plots the effective minority charge carrier lifetime of n-type FZ wafers as a function of deposition temperature. Keeping a constant layer thickness of ~50 nm, the effective lifetime is increased with increasing the deposition temperature. In this series of experiments, the highest τ_{eff} is ~ 800 μs and ~ 1150 μs obtained for a-Si:H (p) and (n) layers, respectively, deposited at temperature of ~ 210°C, which is rather higher than those used for a-Si:H (i) depositions in previous studies [8, 9].

Possibly the benefit of the high deposition temperature applied in this work can be considered as an in-situ annealing process simultaneous with the process of the layer deposition. As early as the formation of first several atomic layers, hydrogen diffusion is probably initiated and the probability of passivating the dangling bonds at interface of a-Si/c-Si is increased. Consequently, the surface passivation is enhanced. Also due to the relatively high temperature, dopants may be effectively distributed in a very thin layer to improve the electronic properties (conductivity, doping efficiency). However, dopants may disturb the surface passivation due to the presence of dopant-related defects.

In the lower graph of figure 2, the effective lifetime decreases with reducing the layer thickness, indicating a similar trend as reported by S. Olibet et al. [10]. For the layer with a nominal thickness of ~15 nm, the effective lifetime is >400 μs , which approximately corresponds to a recombination velocity of ~40 cm/s.

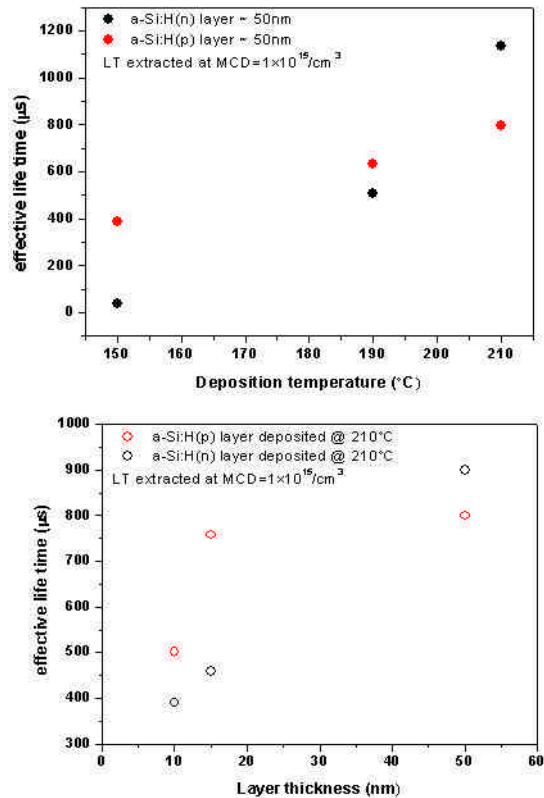


Figure 2. Effective minority charge carrier lifetime of single a-Si:H(p)(n) layers as a function of deposition temperature (upper graph); and as a function of layer thickness (lower graph).

The effective lifetime of cell precursors of the type a-Si:H(p)/c-Si(n)/a-Si:H(n) was also investigated because this allows to estimate the surface passivation quality on the finalized SHJ cell. Layers as seen in the upper schematic drawing of figure 3 were deposited in two different deposition sequences: (a) deposition of a-Si:H (p) before a-Si:H (n); (b) deposition of a-Si:H (n) before a-Si:H (p).

To check the surface recombination of the individual layers, each layer was simultaneously deposited at 210°C on a reference wafer, which had one side coated by a passivating SiN_x layer, as described previously. All such reference wafers had similar τ_{eff} as those tested in the single layer studies as shown in figure 2, indicating a good reproducibility.

In the middle graph of figure 3, a large degradation of surface passivation is observed as a reduced τ_{eff} for those cell precursors in which a-Si:H (p) layer was deposited at first. We obtain a very low τ_{eff} of ~60 μs that is far less than minimum τ_{eff} of single layer shown in figure 2. However, by depositing a-Si:H (n) layer as first layer, instead of a-Si:H (p), a higher τ_{eff} of ~450 μs has been approached as seen in the lower graph of figure 3. This value corresponds to the previous results very well. This suggests that the huge difference of τ_{eff} originates from a different deposition sequences.

In the deposition sequence (a) the a-Si:H (p) layer is post-annealed during deposition of the a-Si:H (n) layer. There may be a temperature gradient from rear to

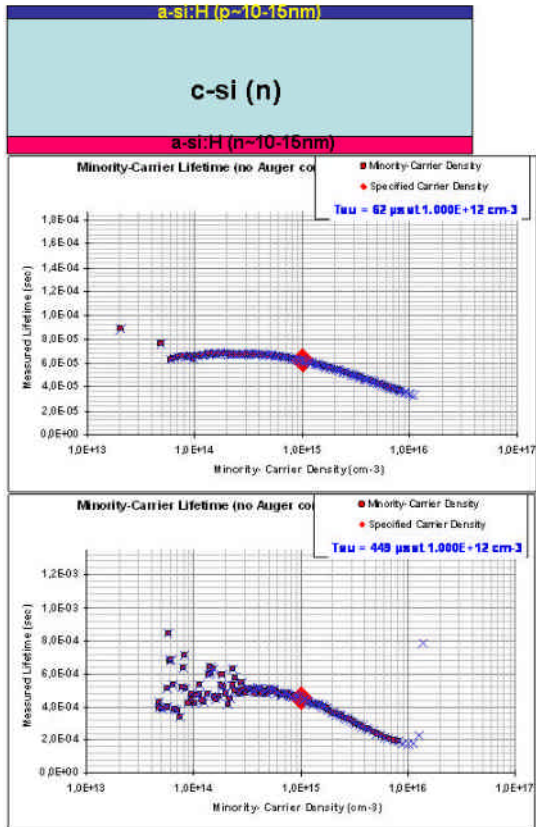


Figure 3. schematic drawing of SHJ cell (top); effective lifetime of cell precursor formed by deposition of a-Si:H (p) prior to a-Si:H (n) (middle); effective lifetime of cell precursor layer formed by deposition of a-Si:H (n) followed by a-Si:H (p), on n-FZ wafer (bottom).

front of the wafer, meaning that the (p) layer is at slightly increased temperature. Thus, thermally induced degradation of surface passivation may occur [11]. On the contrary, the better τ_{eff} obtained in the deposition sequence (b) indicates that a-Si:H (n) is much less sensitive to the thermal impact than a-Si:H (p).

To confirm the amorphous structure of the deposited layers, we applied Raman spectroscopy measurements on doped a-Si:H layers deposited at a temperature of $\sim 210^\circ\text{C}$. The upper graph of figure 4 shows that layers of both doping types are amorphous, based on the characteristic peaks at $\sim 480\text{ cm}^{-1}$ [12]. There is not any obvious indication of existence of microcrystalline phase in these layers.

The efficiency of the boron doping process for the a-Si:H (p) layers deposited at different temperatures is evaluated by electrical measurements. Dark conductivity (σ_d) of a-Si:H (p) layers is shown in figure 5. The layer thickness is within the range of 30-50 nm, which is thicker than the layers really applied in the cell. It shows that σ_d of the p-type layers increases with increasing deposition temperature. The highest σ_d of $\sim 6 \times 10^{-6}\text{ S/cm}$ is achieved for deposition at 210°C and it is about two orders of magnitude higher than that deposited at 150°C . This result is in agreement with the work reported by H. S. Ray et al. [13] indicating that, when using constant dopant gas flow rate, high doping

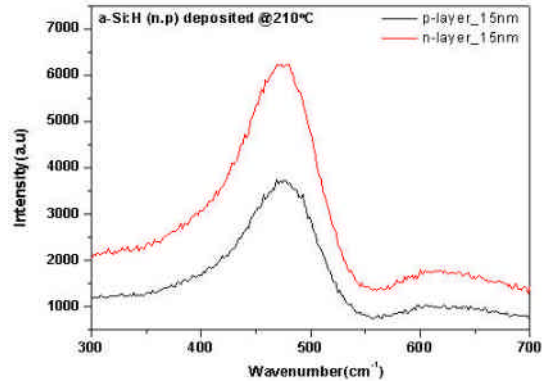


Figure 4. Raman spectra indicating a typical amorphous structure of the deposited a-Si:H (p)/(n) layers.

concentration is relatively easy to be achieved in the deposition at a high temperature.

In the inset of figure 4, an activation energy of $\sim 450\text{ meV}$ for the layer deposited at 210°C is derived from the slope of the linear section in the Arrhenius plot, between 130 and 60°C . This result implies reasonably effective boron doping in the thin a-Si:H (p) layer.

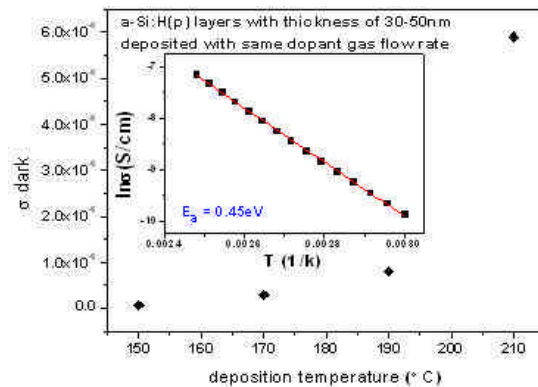


Figure 5. Dark conductivity of a-Si:H(p) layers on glass as a function of deposition temperature. The inset shows the Arrhenius plot and activation energy for a layer deposited at 210°C .

Furthermore, the optical band gap of the optimized a-Si:H (p) layer has been determined by Tauc plot as shown in figure 6, which is based on optical measurement. The derived optical bandgap is $\sim 1.73\text{ eV}$. This indicates again the layer is a typical amorphous silicon, which has a larger optical bandgap than crystalline Si.

The completed structure of the finalized SHJ cell is shown in the schematic drawing of figure 7. Following the a-Si:H deposition, ITO layers and metal contacts (titanium/ palladium/silver) were deposited on top of the doped a-Si:H layers at each sides of the wafer. The performance of the SHJ cells with a size of $\sim 21\text{ cm}^2$ was evaluated by J-V measurement carried out under AM

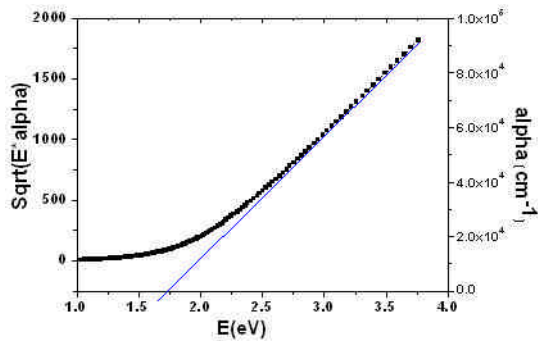


Figure 6. Tauc plot of the optimized aSi:H (p) film, deposited at 210°C. The optical bandgap is about 1.73 eV.

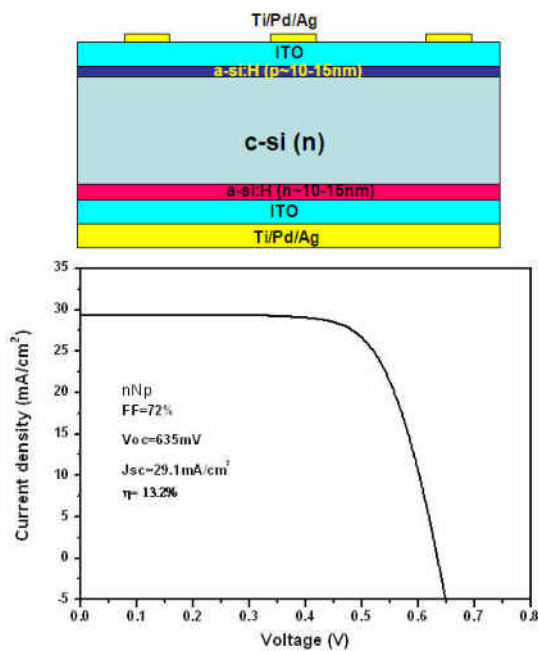


Figure 7. Schematic drawing of SHJ cell structure (top); corresponding results of J-V measurement (bottom).

1.5 illumination. Figure 7 shows a measured J-V curve, with a fill factor of 72%, short circuit current density J_{sc} of ~ 29.1 mA/cm², open circuit voltage V_{oc} of ~ 635 mV and cell efficiency of 13.2%.

Detailed analysis based on spectral response and transmission/reflection measurements shows that the low J_{sc} is mostly caused by the non-textured surface, by optical losses due to absorption in the a-Si and ITO, and by imperfect surface passivation. The obtained V_{oc} is limited by imperfect surface passivation. Nevertheless, it is close to that in the work reported by K. von Maydell et al. [5], who used a similar heterojunction structure. However, the lower fill factor implies the existence of series resistance, which is probably due to 1) the a-Si layer still not being thin enough and 2) the energy barriers at the interfaces of ITO/a-Si:H (p)/c-Si(n) not being low enough [14]. As checked from voltage modulated lock-in thermography at reverse bias voltage of 5V there is no indication of significant shunt in the SHJ cell. In addition, an “S” shape curve is not observed in our case. This may

indicate that 1) there is no apparent insulator at the interface of a-Si:H (p)/c-Si wafer in the cell [15]; 2) a well-doped a-Si:H (p) layer reduces the energy barrier for charge carrier transportation at this interface to a sufficient extent [14].

4. CONCLUSIONS

We have developed a thin doped a-Si:H (p) layer, which combines both surface passivation and good electrical conductivity, and applied it as an SHJ emitter on n-type FZ-Si(100) wafer, using a pilot scale remote linear rf-PECVD. Although the deposition is at a relatively high temperature of ~ 210 °C, the layers indicate an amorphous structure with a good conductivity and a desirable optical bandgap. The order of layer depositions has a great influence on the surface passivation by the a-Si layers. A lower recombination velocity, of ~ 40 cm/s, has been achieved based on the optimized deposition process by depositing a-Si:H (n) prior to a-Si:H (p). Silicon heterojunction solar cells with an area of 21.1cm² have been successfully fabricated with a resulting cell efficiency of 13.2%.

5. ACKNOWLEDGEMENT

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6. REFERENCES

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