SILANE PLASMA DIAGNOSTICS FOR HIGH-EFFICIENCY SILICON HETEROJUNCTION SOLAR CELLS

SUMMARY

In silicon heterojunction solar cells, the passivation of the crystalline silicon wafer surfaces and fabrication of emitter and back surface field are all performed by intrinsic and doped amorphous silicon thin layers, usually deposited by plasma-enhanced chemical vapor deposition (PECVD). By using *in-situ* diagnostics during PECVD, it is found that the passivation quality of such layers directly relate to the plasma conditions, especially on the silane depletion fraction. Good interface passivation is indeed obtained from highly-depleted silane plasmas. Based upon this finding, layers deposited in a large-area very high frequency (40.68 MHz) PECVD reactor were optimized for heterojunction solar cells, yielding V_{oc}'s up to 727 mV and aperture efficiencies up to 20.7% on 4 cm^2 cells.

1. INTRODUCTION

Silicon heterojunction solar cells have a high conversion efficiency potential, up to 23% to date [1]. The passivation of the crystalline silicon (c-Si) wafer surfaces is usually performed by very thin intrinsic amorphous silicon (a-Si:H) layers, deposited by RF plasma-enhanced chemical vapor deposition (PECVD) or similar methods. The emitter and back surface field of the cell are generally also formed with PECVD doped a-Si:H layers. It has been shown that a-Si:H can provide excellent passivation of c-Si surfaces. However, to produce high-efficiency devices, it is crucial to control the properties of the a-Si:H layers during deposition. In this context, plasma diagnostics are very useful giving fundamental insight into deposition mechanisms. Properties of a-Si:H layers have already been studied *in-situ* with optical methods. Here, a novel infrared laser-based plasma diagnostic tool is used in order to measure *in-situ* the silane (SiH$_4$) depletion fraction during deposition. The influence of the silane depletion on a-Si:H layers used for c-Si wafer passivation is studied. Based on this, heterojunction solar cells were optimized.

2. EXPERIMENTAL SETUP

Amorphous silicon layers were deposited at 200°C in an automated large-area (electrode size 50 x 60 cm^2) parallel-plate PECVD reactor powered at VHF (40.68 MHz), using mixtures of SiH$_4$, H$_2$, PH$_3$ and B(CH$_3$)$_3$. This reactor is equipped with a plasma impedance probe, with a laser light scattering (LLS) system measuring the presence of powder in the discharge, and with an optical emission spectrometer (OES). In addition, an infrared laser-based spectrometer is also installed for silane density measurements. The silane density is deduced from light absorption measurements. Silane molecules have many rotovibrational absorption lines in infrared, therefore a light source emitting in this region is required to perform such measurements. In this work a quantum cascade laser (QCL) is used, whose wavelength can be tuned between 2241 and 2245 cm^{-1} allowing us to reach much higher resolution than Fourier transform infrared spectroscopy (FTIR), as shown in figure 1. The monochromatic infrared light is focused and injected through the reactor, and the light intensity is measured on the other side. Measurements of light intensities through the pumped reactor (base vacuum level), through the reactor filled with silane at working pressure before ignition, and through the reactor during the steady-state discharge allow us to deduce the silane depletion D, which is defined by $D = 1 - (n_{SiH4} / n^0_{SiH4})$, where n^0_{SiH4} and n_{SiH4} are the silane densities in the reactor before plasma ignition and during the
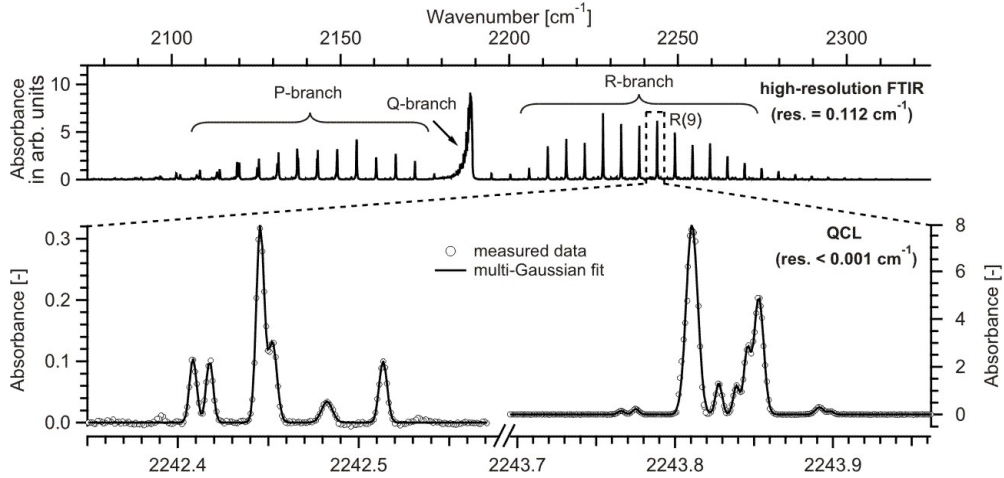
plasma steady state, respectively.

FIG. 1. The ν_3 absorption band of SiH_4 acquired by a high-resolution FTIR (upper part, [2]), the Doppler-resolved R(9) multiplet of SiH_4 acquired by the QCL-based spectrometer (lower right part), and some weak unassigned absorption lines of SiH_4 that only appear in the spectrum acquired by the QCL-based spectrometer (lower left part).

The structure of the 2 x 2 cm^2 heterojunction solar cells was as follows: Ag front grid / ITO 80 nm / p^+ a-Si:H 10 nm / i a-Si:H 5 nm / textured FZ n c-Si 250 μm wafer / i a-Si:H 5 nm / n^+ a-Si:H 10 nm / ITO 50 nm / Ag back metallization. Both ITO layers and the back metallization were deposited by DC magnetron sputtering (in a Roth & Rau Switzerland tool). A front grid was stencil-printed with a low temperature silver paste. All the fabrication steps are fully compatible for cell production at an industrial scale.

3. RESULTS

Figure 2 shows the silane depletion fraction D, the active power P_{ac} (steady-state values), the deposition rate R and the effective minority carrier lifetime τ of passivated FZ wafers with 18 nm i a-Si:H as a function of the three main process parameters, namely the VHF input power, the silane flow and the total pressure. It can be seen that D depends strongly on the process parameters, going from 0.5 to 0.9 in the range of discharge regimes explored here. D increases with the power because the silane dissociation rate is in first approximation proportional to the power, and D decreases (increases) with the flow (pressure) because the SiH_4 residence time in the reactor is decreased (increased) [3]. The minority carrier lifetime τ of as-deposited and annealed passivated wafers follows the same trend as D in the power, silane flow, and pressure series. High lifetimes were obtained from highly-depleted silane plasmas. In other words, passivation is improved with layers deposited close to microcrystalline regimes [3]. This result can be linked to other silicon thin-film solar cell studies, where it is found that the best a-Si:H material quality is reached just before the a-Si:H to μc-Si:H transition. Thus, contrary to other plasma properties such as P_{ac} or R for example, a relevant parameter to characterize the passivating quality of a-Si:H layers appears to be the silane depletion. The optimization of passivating layers is thus greatly facilitated and accelerated if one knows the silane depletion, since the three main process parameters can be reduced to only one, which in addition can be measured *in-situ* during deposition.

Based on the results presented in the previous section, carrier lifetimes up to 7.8 ms have been reached on solar cell precursor (*in* and *ip* a-Si:H stacks on textured wafer), as

shown in figure 3a. This demonstrates that layers deposited at relatively high deposition rates (> 0.6 nm/s) with VHF can provide excellent passivation. The best 2 x 2 cm^2 cell obtained with our plasma-based optimization shows a high open-circuit voltage (V_{oc}) of 724 mV, giving a conversion efficiency of 20.7% (aperture area), as shown in figure 3b. The highest V_{oc} measured in a cell reaches 727 mV. The cells use a standard ITO as front antireflection and conductive layer, and a silver front grid made by stencil-printing.
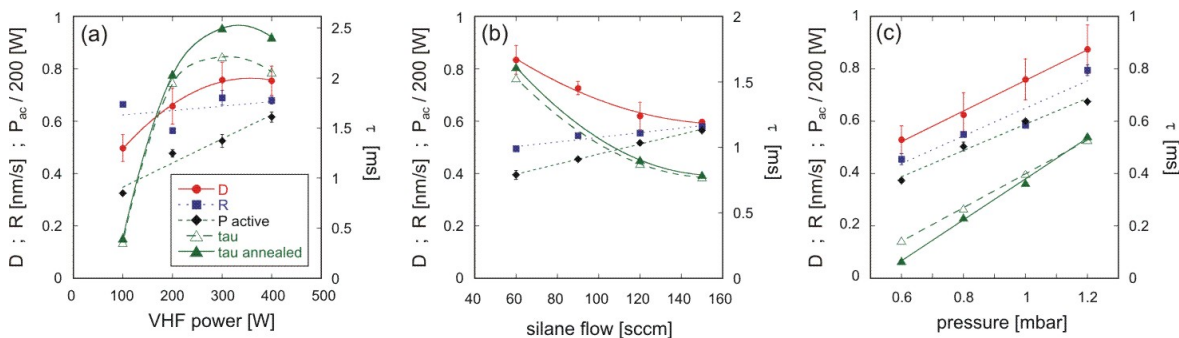

FIG. 2. Depletion fraction D, deposition rate R, active power P_{ac} and minority carrier lifetime τ at 10^{15} cm^{-3} as a function of (a) the VHF power (120 sccm SiH$_4$, 0.8 mbar); (b) the silane flow (200 W, 0.8 mbar); (c) the total pressure (200 W, 120 sccm SiH$_4$). Wafers are passivated with 18 ± 3 nm intrinsic a-Si:H layers and are annealed at 180°C for 90 minutes. Lines are guides for the eye.
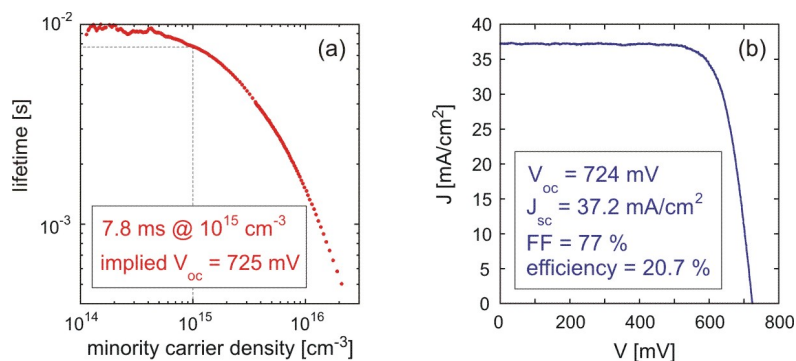

FIG. 3. (a) Lifetime measurement of a solar cell precursor (a-Si:H *in* and *ip* stacks on a FZ textured wafer), as-deposited; (b) Illuminated-IV curve of the finished 2 x 2 cm^2 heterojunction solar cell made with the precursor of figure 3a, measured under standard test conditions (in-house measurement).

4. CONCLUSIONS

In summary, the use of plasma diagnostics during PECVD is not only useful for a better understanding and control of the process, but it is also highly valuable for the optimization of devices. We have shown that a-Si:H layers used for c-Si wafer passivation can be efficiently tuned knowing the silane depletion fraction during deposition. Indeed, it appears that the depletion is a much more relevant parameter than other plasma properties. In the discharge regimes explored here, good passivating layers were obtained from highly-depleted plasmas. Produced in a large area industrial VHF PECVD reactor, medium-sized silicon heterojunction solar cells were optimized using this approach, yielding 20.7% efficiencies.

[1] M. Taguchi *et al.*, Proceedings of the 24th EU-PVSEC, Hamburg, Germany, 2009, pp. 1690-1693.

[2] S.W. Sharpe *et al.*, Appl. Spectrosc. 58 (12), 1452-1461 (2004).

[3] B. Strahm *et al.*, Plasma Sources Sci. Technol. 16, 80 (2007).