HETEROJUNCTION SOLAR CELL EFFICIENCY IMPROVEMENT ON VARIOUS C-SI SUBSTRATES BY INTERFACE RECOMBINATION MODELLING

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ABSTRACT

High efficiency Si heterojunction (HJ) solar cells must exhibit low interface recombination, as it limits the cell open circuit voltage (V_{OC}). The study of the interface recombination of various a-Si:H/c-Si lifetime test samples gives insight into the recombination mechanisms, which are found compatible with an amphoteric recombination model [1]. We find that there is a trade-off between reduced interface defect density, yielding high-V_{OC} cells (713mV), and increased field effect passivation resulting in higher efficient cells (19.1%) on flat wafers. Predicted V_{OC}s of 725mV are reached for optimally textured *n*- and *p*-type c-Si wafers passivated by intrinsic a-Si:H, but the V_{OC}s of the cells are lower. The injection-level dependence of the surface recombination identifies the efficiency limiting factors of HJ solar cells. Such measurements are thus a powerful indicator to achieve highly efficient devices.

1. INTRODUCTION

Based on the University of Neuchâtel's experience in VHF-PECVD thin film silicon solar cell deposition, a research program on amorphous/crystalline heterojunctions was started in our laboratory two years ago. Achieving high efficiency HJ solar cells requires a good surface passivation of the crystalline silicon (c-Si) by the overlaying hydrogenated amorphous silicon (a-Si:H), as the device's open circuit voltage (V_{OC}) is ultimately limited by interface recombination. The introduction of an interface recombination model based on the amphoteric nature of silicon dangling bonds with the consequential insight into the a-Si:H/c-Si interface led us to a fast development of HJ emitters and back surface fields (BSF) that have both high conductivities and excellent surface passivation properties.

2. A-SI:H/C-SI LIFETIME TEST STRUCTURES

The Sinton lifetime (LT) tester [2] allows measuring the effective carrier lifetime τ_{eff} over a wide range of injection levels *ECD* (excess carrier density). a-Si:H layers are grown by VHF-PECVD in a single chamber.

2.1 High-quality interface passivation

The passivation quality of intrinsic (*i*) a-Si:H is compared to that of state of the art silicon dioxide (SiO_2) [3] in Fig. 1. *i* a-Si:H passivates c-Si dangling bonds efficiently as shown by the LT of 7ms measured on lightly doped *n*- and *p*-type c-Si.

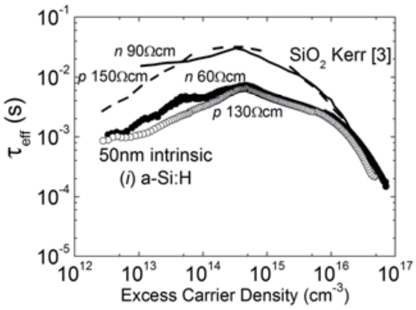

Fig. 1 Passivation by *i* a-Si:H and SiO_2.

2.2 Interface recombination modelling

Injection-level dependent LT measurements on LT test samples consisting of various combinations of a-Si:H (intrinsic, microdoped, intrinsic plus doped) and c-Si (doping type and level) led us to the introduction of an interface recombination model based on the amphoteric nature of Si dangling bonds [1]. Fig. 2 shows as an example the passivation of a $2x10^{15}cm^{-3}$ phosphorous doped c-Si wafer. It shows that fitting our model to experimental curves yields good accordance. We conclude that the growth of *i* a-Si:H passivates efficiently c-Si dangling bonds on all kind of c-Si, while the magnitude of additional field effect passivation can be tuned by further doped a-Si:H layer capping.

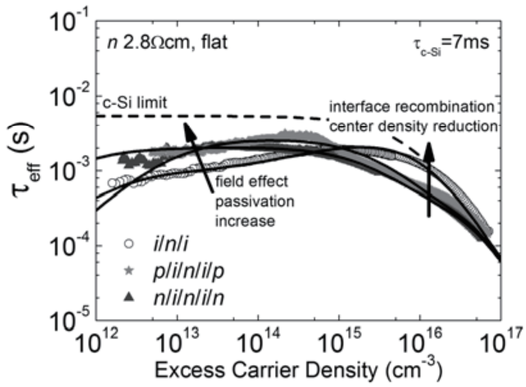

Fig. 2 Modelling a-Si:H/c-Si interface passivation.

3. SI HETEROJUNCTION (HJ) SOLAR CELLS

In addition to the V_{OC} limitation given by interface recombination, contacting the HJ structure (TCO) can limit the fill factor (*FF*) by resistive losses, but it can also increase the interface recombination by negatively influencing the field effect passivation of insufficiently doped a-Si:H layers. By comparing the results of standard 1-sun *IV* and external quantum efficiency measurements (*EQE*) on individual HJ solar cells with the LT measured in the non-contacted state, we are able to determine what limits the measured efficiency. The HJ solar cells whose *IV* curves are shown in Fig. 3 are contacted by ITO layers and have a size of ~0.5x0.5cm^2 without front metallization.

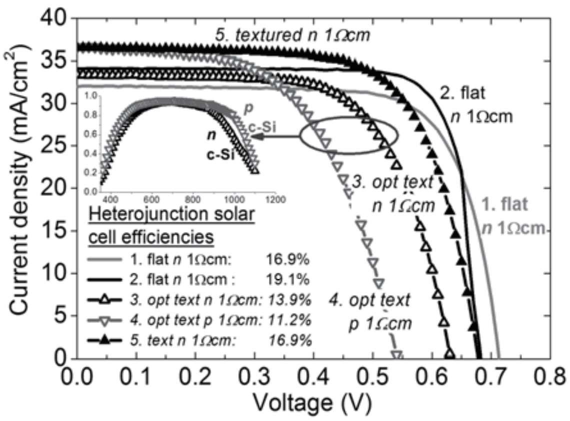

Fig. 3 1-sun *IV* curves of various a-Si:H/c-Si HJs.

3.1 Trade-off between V_{OC} and *FF* on flat wafers

The highest V_{OC} we measured (1. in Fig. 3) is 713mV, which reaches the V_{OC} value predicted by LT measurement analysis of the device without the ITO layers. By reducing the a-Si:H layer thicknesses, we achieve an efficiency of 19.1% (2. in Fig. 3), but with a lower V_{OC} value, limited by increased interface recombination. The high *FF* of 82% is obtained thanks to highly conductive doped layers.

3.2 Layer growth on textured wafers, TCO contact

For textured c-Si, the simple HF-dip performed on flat c-Si is not sufficient as surface pre-treatment prior to a-Si:H deposition. Optimally preconditioned textured c-Si surfaces, as prepared at HMI [4], exhibit LTs of >1ms resulting in predicted V_{OC}s of 725mV on 1Ωcm *n*- and *p*-type c-Si when passivated with *i* a-Si:H layers. LT measurements on HJ solar cell precursors out of both of these optimally prepared textured wafers in the non-contacted state predict V_{OC}s of 665mV. This loss in predicted V_{OC} is due to growth problems of our *i*/*n*-stack, as shown by the comparison of the long-wavelength *EQE* of both cells (inset in Fig. 3). The *n*-layer on the flat substrate is growing at the transition to microcrystalline Si (μc-Si:H), and transmission electron micrographs (TEM) show a bad epitaxial growth in the pyramid valleys. The much lower V_{OC}s (3. and 4. in Fig. 3) finally measured after contact formation are linked mainly to unoptimized ITO layers.

3.3 Trade-off between interface recombination center density reduction and field effect increase for textured HJ cells

Textured *n*-type wafers with a less optimal surface preconditionning show lower predicted V_{OC}s of 680mV when passivated by *i* a-Si:H layers. Further on the *i*/*n*-stack passivation limits the predicted V_{OC} to 630mV. Growing the *n*-layer the same conductive but more amorphous lowers interface recombination but results in a loss of field effect passivation, as shown by the corresponding LT curve comparison (the influence of interface state density reduction and field effect passivation on LT curves is shown in Fig. 2). The field effect passivation, linked to the thickness of the *i*-layer and the doping of the *n*- and *p*-layers, facilitates the carrier transport from the bulk and leads thus to a higher *FF*. Due to this trade-off between field effect passivation and low interface recombination center density, in our textured cells, up to now the *FF* loss (5. in Fig. 3) is still so large that it is not compensated by the current gain due to light trapping, so that the efficiency remains at 16.9%.

4. CONCLUSIONS

Modelling and analysis of carrier lifetime data measured by QSSPC on non-contacted devices allows a classification of the factors limiting the 1-sun efficiency of completed solar cells. Increased surface recombination linked to growth problems of the a-Si:H stacks, insufficient conduction of the doped a-Si:H layers, and losses due to the TCO contact have thus been identified in our devices. A cell V_{OC} of 713mV and an efficiency of 19.1% are reached on flat *n*-type c-Si.

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