Passivation at the interface between liquid-phase crystallized silicon and silicon oxynitride in thin film solar cells

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Summary

The passivation quality at the interface between liquid-phase crystallized silicon (LPC-Si) and a dielectric interlayer (IL) stack is investigated by means of high-frequency capacitance-voltage (C-V) measurements, which reveal the defect state density at the interface \(D_i\) as well as the effective charge density in the IL \(Q_{IL,eff}\). We developed a metal-insulator-semiconductor (MIS) structure based on a molybdenum layer sandwiched between the glass substrate and the IL/LPC-Si stack, which is compatible with C-V measurements. \(D_i\) and \(Q_{IL,eff}\) results are correlated with measured open circuit voltages \(V_{oc}\) and internal quantum efficiencies (IQE) of corresponding LPC-Si solar cells on glass, both for n-doped and p-doped LPC-Si. We varied the nitrogen and hydrogen content in the amorphous silicon oxynitride \((a-SiO_N_x:H)\) layer adjacent to the LPC-Si and applied an additional hydrogen plasma treatment (HPT) at 400 °C for 30 min. A Gaussian-like defect distribution at around 0.1 eV above the mid gap energy is significantly reduced by the additional HPT. With additional HPT, the lowest \(D_i\) and highest \(Q_{IL,eff}\) for p-doped LPC-Si at mid gap, i.e. \(D_i = (3.5 \pm 0.7) \times 10^{11} \text{ eV}^{-1} \text{cm}^{-2}\) and \(Q_{IL,eff} = (1.6 \pm 0.3) \times 10^{12} \text{ cm}^{-2}\), correspond to the passivation by an \(a-SiO_N_x:H\) layer with a low nitrogen and high hydrogen content. The \(D_i\) and \(Q_{IL,eff}\) results demonstrate that the IL/LPC-Si interface can achieve similar passivation properties as reported for similar dielectric layers on silicon wafers.

Purpose of Work

Single junction thin film silicon solar cells on glass with conversion efficiencies of up to 12% can be achieved by melting 5 – 20 µm thick silicon absorbers with a heat source such as a laser or an electron beam on glass substrates [1, 2, 3]. The LPC-Si converts into highly crystalline material which leads to solar cells with open circuit voltages of 618 mV for p-type absorbers and 657 mV for n-type absorbers [3, 5]. It was found, that the interface between the IL and the absorber has a major impact on the cell performance [2, 5, 6]. The purpose of our work is to analyze the passivation quality at this interface. The focus lies on \(D_i\) (in eV\(^{-1}\)cm\(^{-2}\)) as well as \(Q_{IL,eff}\) (in cm\(^{-2}\)), which are crucial parameters affecting the chemical and field-effect passivation [7]. We study the influence of the hydrogen and nitrogen content in the \(a-SiO_N_x:H\) layer adjacent to the LPC-Si absorber on \(D_i\) and \(Q_{IL,eff}\). In addition, we investigate the influence of an additional direct HPT for 30 min at 400 °C on \(D_i\) and \(Q_{IL,eff}\). Measured \(D_i\) and \(Q_{IL,eff}\) results are compared with solar cell parameters, i.e. the open circuit voltage and the internal quantum efficiency. Overall, our work provides a better understanding of the passivation properties at the IL/LPC-Si interface for further optimization in the future.

Approach

Our approach is to prepare samples consisting of a molybdenum layer, a plasma-enhanced chemical vapour deposited (PECVD) interlayer stack composed of amorphous silicon oxide \((a-SiO_x:H)\), amorphous silicon nitride \((a-SiN_x:H)\) and \(a-SiO_N_x:H\) and a LPC-Si layer, both n-doped and p-doped, on glass substrates and split each sample into two halves: One half is prepared for high-frequency C-V measurements in order to determine \(D_i\) and \(Q_{IL,eff}\) while the other half is processed into solar cells in order to measure the open circuit voltage and the internal quantum efficiency (see Fig. 1 in the explanatory
In the developed MIS structure, which is compatible to C-V measurements, molybdenum functions as metal gate contact [8]. In order to study the influence of the nitrogen and hydrogen content in the a-SiO\textsubscript{x}N\textsubscript{y}:H layer adjacent to the LPC-Si absorber on \(D_\text{fi}\) and \(Q_{\text{IL,eff}}\), we prepared samples with four different a-SiO\textsubscript{x}N\textsubscript{y}:H layers (see Table 1 in the explanatory pages). In order to study the effect of an additional HPT at 400 °C for 30 min on \(D_\text{fi}\) and \(Q_{\text{IL,eff}}\), half of the LPC-Si samples, i.e. one of a pair with the same a-SiO\textsubscript{x}N\textsubscript{y}:H layer, were subjected to the additional HPT.

**Scientific Innovation and Relevance**

The scientific innovation and relevance of our work lies in the development of a MIS structure based on IL/LPC-Si stacks on glass, which allows the quantification of \(D_\text{fi}\) as well as \(Q_{\text{IL,eff}}\) via the C-V technique. Both parameters are crucial for the analysis of the passivation quality at the IL/LPC-Si interface. The development of the MIS structure is realized by a molybdenum layer, which functions as metal gate contact, sandwiched between the glass substrate and the IL/LPC-Si stack. The direct analysis of the IL/LPC-Si interface in our work is in contrast to earlier work which focused on the indirect analysis of the IL/LPC-Si stack based on the solar cell parameters open circuit voltage and internal quantum efficiency. The positive effect of the HPT on the LPC-Si solar cell performance was shown before [4, 5], but up to now the effect of this treatment on the IL/LPC-Si interface is not fully understood. With our work we are able to demonstrate that the HPT decreases \(D_\text{fi}\) at the IL/LPC-Si interface.

**Results and Conclusions**

We investigate \(D_\text{fi}\) at the interface between a dielectric IL stack and LPC-Si as well as \(Q_{\text{IL,eff}}\) in the IL via high-frequency C-V measurements which give direct insight into the quality of the chemical and field-effect passivation of such a system. C-V measurements on the IL/LPC-Si stacks on glass are enabled by the preparation of MIS structures. Molybdenum is used as metal sandwiched between the glass substrate and the IL/LPC-Si stack, without adversely affecting the laser-crystallization process. For p-doped LPC-Si, we find a Gaussian-like defect distribution at about 0.1 eV above the mid gap energy. This defect state density is significantly reduced by an additional direct HPT at 400 °C and 30 minutes duration. The effect is pronounced for a low hydrogen content in the a-SiO\textsubscript{x}N\textsubscript{y}:H. The variation of the nitrogen content in the a-SiO\textsubscript{x}N\textsubscript{y}:H layer had only little effect on \(D_\text{fi}\) and \(Q_{\text{IL,eff}}\). After the additional HPT for p-doped LPC-Si, the interface with a low nitrogen and a high hydrogen content in the a-SiO\textsubscript{x}N\textsubscript{y}:H layer resulted in the lowest \(D_\text{fi}\) and the highest \(Q_{\text{IL,eff}}\), i.e. \(D_\text{fi} = (3.5 \pm 0.7) \times 10^{11} \text{eV}^{-1}\text{cm}^2\) and \(Q_{\text{IL,eff}} = (1.6 \pm 0.3) \times 10^{12} \text{eV}^{-1}\text{cm}^2\). The \(D_\text{fi}\) and \(Q_{\text{IL,eff}}\) results demonstrate that the IL/LPC-Si interface has similar passivation properties as reported for similar dielectric layers on silicon wafers.
**Table 1:** Process gas flow rates during the plasma-enhanced chemical vapor (PECVD) deposition of the amorphous silicon oxynitride (a-SiO$_x$N$_y$:H) layers with corresponding nomenclature used in our work.

<table>
<thead>
<tr>
<th>nomenclature</th>
<th>N$_2$ (sccm)</th>
<th>H$_2$ (sccm)</th>
</tr>
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<tbody>
<tr>
<td>N rich, H rich</td>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>N rich, H poor</td>
<td>500</td>
<td>400</td>
</tr>
<tr>
<td>N poor, H rich</td>
<td>200</td>
<td>0</td>
</tr>
<tr>
<td>N poor, H poor</td>
<td>200</td>
<td>400</td>
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**Fig. 1:** (a) Sketch of the simple, bifacial test structure for the measurement of the open circuit voltage ($V_{oc}$) and the internal quantum efficiency (IQE) of liquid-phase crystallized silicon (LPC-Si) solar cells on glass, exemplary for p-doped LPC-Si. (b) Sketch of the metal-insulator-semiconductor (MIS) structure based on LPC-Si layers prepared for capacitance-voltage (C-V) measurements, exemplary for p-doped LPC-Si. (b) Cross-section image of a LPC-Si sample in a MIS structure acquired by secondary electron microscopy (SEM).
Fig. 2: Defect state density ($D_{it}$) at the interface between amorphous silicon oxynitride (a-SiO$_x$N$_y$:H) and p-doped liquid-phase crystallized silicon (LPC-Si) over the silicon band gap energy relative to the mid gap energy ($E_{MG} \approx E_i$). For $E - E_i > 0$ the conduction band edge is approached, for $E - E_i < 0$ the valence band is approached. The $D_{it}$ results of samples with three different a-SiO$_x$N$_y$ layers (see table 1) with and without the additional hydrogen plasma treatment (HPT) are compared. The $D_{it}$ data were deduced from measured high-frequency capacitance-voltage (C-V) curves. Each $D_{it}$ curve corresponds to the average values of four curves.

References


