ALD based TOPCon-type solar cells on textured silicon wafer

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1 – Purpose

- **Main objective:** Fabrication of a **front and rear TOPCon-type structure** using p-type and n-type Poly-Si/SiOx stacks for crystalline silicon solar cells on **textured surfaces**.
- **Ultrathin SiOx** layer realized by **ALD**: precise control of the thickness at **atomic scale** to manage layers **below 2 nm** for the tunneling transport of carriers.

TOPCon structure [1]

Target structure: Front & rear poly-Si/SiOx stack on textured surface

Challenges: Keep **high passivation properties**, especially for the **p-type poly-Si/SiOx stack** at the front, and on **textured surface**.
This work:
- Underlines the **roles of H atoms** for p-type poly-Si/SiOx stack, and the **stability**. Method proposed: **cyclic dehydrogenation-rehydrogenation** (D-R).
- Present **solar cells characteristics** using the target structure.

[1] A. Richter et al., *SOLMAT* **173** (2017) 96-105.

2 – Experimental details

Fabrication processes:
- **Wafers**: (n-type) Fz-Si <100>, 280 µm, 1-5 Ωcm.
- **Cleaning**: 4-step chemical process [2]
- **Texturization**: KOH self-heated at 80°C for 15 min.
- **SiOx layers**: deposited by **ALD**.
- **a-Si:H layers**: deposited by **PECVD**.
- **High-T annealing** (**high-TA**): 820 °C for 1 h.
- **Hydrogen plasma treatment** (HPT): 300 °C, 1 min

Characterization techniques:
- Minority carrier lifetime (MCLT) measurement at 1×10^{15} cm^{-3} injection level (quasi steady-state photoconductance, **QSSPC**)
- Thickness and bandgap of the films deposited (Spectroscopic ellipsometry, SE)
- Study of Si-H bindings at wavelength 2000-2100 cm^{-1}, and Si-O bindings at 1050 cm^{-1} (**FTIR**)
- Stoichiometric ratio x of SiOx (**FTIR**)
- Crystallinity of amorphous silicon layers after thermal annealing (**Raman** spectroscopy)

- For D-R cyclic method: characterizations done after **low-TA** (450 °C), **high-TA** (850 °C), and after HPT.

Atomic Layer Deposition (ALD) Process: Oxford Instruments FlexAL system
- Substrate holder: **300°C**
- Spectroscopic ellipsometry **in situ** using **Cauchy Model**
- Inductively Coupled Plasma (ICP) with RF frequency: **13.56 MHz**

SiOx deposition
Step 8 - 3DMAS dose
Step 9 - 3DMAS purge
Step 10 - Plasma gas stabilization
Step 11 - O₂ plasma dose (O₂ 60 sccm)
RF power 250 W / Pressure 15 mTorr / Time 3 s
Step 12 - Post plasma purge

Amorphous layers of: Si / O / Si / …

- Precursor 3DMAS: **Tris (dimethylamino) silane**
Residuals N-(CH₃)₂ purged

[2] S. N. Granata et al., *Energy Procedia* **27** (2012) 412-418.

3 – Thickness control at atomic scale

- Precise control of the thickness of SiOx : **linear dependence** with the **number of cycles** during ALD process [3].

[3] M. Lozac'h et al., *SOLMAT* **185** (2018) 8-15.

4 – Cyclic Dehydrogenation-Rehydrogenation Method (D-R cycles)

Structure used for cyclic D-R method:
(p) poly-Si 20±2 nm
c-Si → SiOx 0.8±0.1 nm
(p) poly-Si 20±2 nm

- Low-TA: boron diffusion not activated.
- Depletion and reintroduction of H can not explain the lifetime difference after the 1st HPT and 4th-5th D-R.
- Passivation process involves 2 roles of H: DBs termination and H-related field effect.
- After high-T, **SiOx stoichiometry** is **1.7** [3].
- Lifetime recovery is a stretched exponential [4]: relaxation of a disordered system, i.e. **dispersive nature** of (p) poly-Si/SiOx stack due to non-stoichiometric ratio.

M. Lozac'h et al., *Jpn. J. Appl. Phys.* **58** (2019) 050915. [3] M. Lozac'h et al., *SOLMAT* **185** (2018) 8-15. [4] S. De Wolf et al., *Appl. Phys. Lett.* **93** (2008) 032101.

5 – After high-T annealing: passivation property, and doping profile

- Only **ALD** allows good passivation for symmetric (n) poly-Si/SiOx stack: because the **passivation very sensible to SiOx thickness**.
- (p) poly-Si/SiOx stack is less sensible.

- **TEM images**: excellent **conformal** thickness for SiOx, poly-Si is well underlined by XRD.
- SIMS profiles: Boron diffusion controlled by boron flow and (i) poly-Si layer. H accumulates at interfaces.

6 – Lifetime recovery

- **I-V characteristics** of TOPCon-like solar cell on textured c-Si wafer:

I-V characteristics of TOPCon-like solar cell on textured c-Si wafer:
- **Jsc over 39 mA/cm²** (EQE)
- Optimized boron flow of 50 sccm allows best **PCE** of **18.8 %** with **FF** of **78%**.
- TLM reveals ρ_c at 1 Ωcm².

[5] J. Melskens et al., *IEEE J. Photov.* **8** (2018) 373-388.

7 – Summary

- **Cyclic dehydrogenation-rehydrogenation method** is proposed to underline the roles of H atoms for the passivation of **(p) poly-Si/SiOx stack** and show the good thermal stability with τ_{eff} remaining at 1.2 ms after 1 D-R cycle.
- Successive D-R cycles does not modify the bonds configuration, the **stoichiometric ratio of SiOx remains at 1.7**. It does not activate the boron diffusion. Only the H atoms are involved, which underlines **two roles**: one is the DBs termination, and the H-field effect related. => H induces positive charging for SiOx with x < 2 [6].

- **ALD-SiOx double sided TOPCon-like solar cells** efficiency is presented on textured c-Si wafer with best PCE about **18.8 %**, J_{sc} of **39 mA/cm²** (for front grid) and FF of 78 %.
- The V_{oc} is about 639 mV and could be improved by using efficient hydrogen source.
- Further improvements in term of PCE are expected by optimizing the **ohmic contacts**, and decreasing the **saturation current density** (J_0), still about 300 fA/cm².

[6] W. L. Warren, *Appl. Phys. Lett.* **68** (1996) 2993.

8 – Acknowledgments