Rapid Laser Annealing of Transparent Conductive Oxides for Temperature-Sensitive Solar Cell Structures

A. Münzer, M. Bivour, L. Tutsch, F. Meyer, S. W. Glunz[1]
Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany
Phone +49 761/4588-2168, anna.muenzer@ise.fraunhofer.de
[1] INATECH, University Freiburg, Emmy-Noether-Str. 2, Freiburg, Germany

In this work we address the challenge of reducing the sheet resistance R_{sheet} of transparent conductive oxide (TCO) thin films on temperature (T-) sensitive solar cell substrates. We demonstrate ultraviolet (UV) pulsed nanosecond (ns) laser annealing processes, leading to a significantly reduced R_{sheet} for different TCOs on silicon heterojunction (SHJ) substrates without compromising the implied open circuit voltage iV_{OC}. These processes offer a fast and cost efficient alternative to classical annealing processes, potentially enabling indium free TCO types on more sensitive solar cell types such as perovskite solar cells.

Motivation

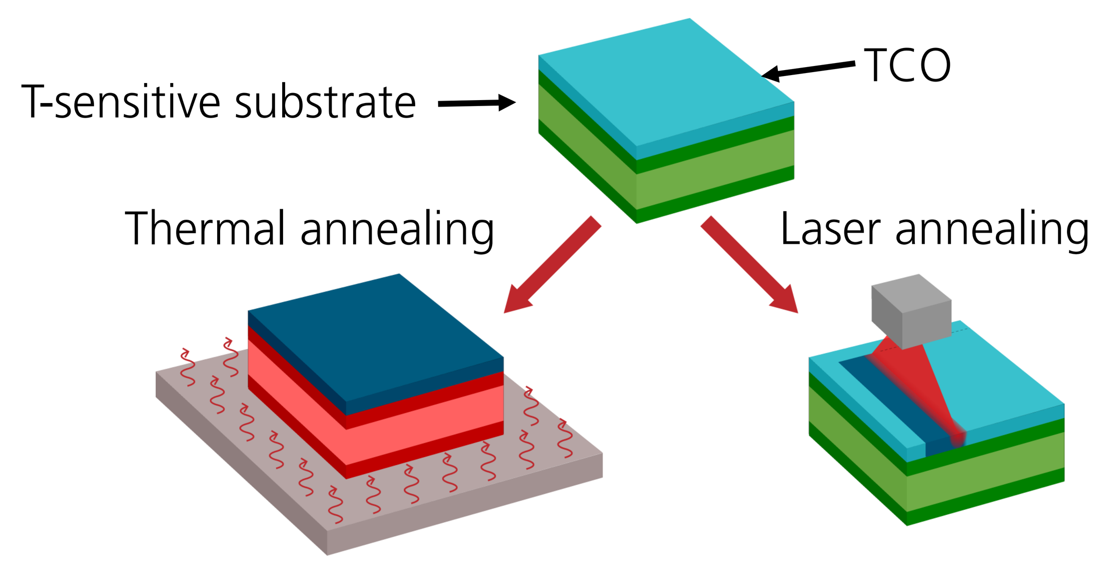


Fig. 1: Thermal annealing versus laser annealing for TCO thin films on a temperature-sensitive substrate.

Challenge:

- Annealing the TCO thin film on T-sensitive solar cells [1]
- Optimizing TCO properties [2]
- Avoiding degradation and efficiency losses

Approach:

- Rapid, depth selective laser annealing
- Surface near layer modification
- Protecting substrate from thermal impact [3]

Experimental Approach

Sample Structure

- Planar n-type SHJ substrates
  - Front side intrinsic / p-type doped amorphous silicon layer stack a-Si:H (i/p)
- **TCO Variation**:
  1. Oxygen-rich indium tin oxide (ITO)
  2. Aluminum doped zinc oxide (AZO)

Annealing

- Pulsed ns-laser processes at three different wavelengths (photon energy ≈ TCO bandgap energy):
  1. λ = 248 nm
  2. λ = 308 nm
  3. λ = 343 nm
- Hotplate: 10 min at temperatures from 50°C to 400°C

Characterization

- Modulated photoluminescence (PL) [4]→ iV_{OC}
- Four point probe measurements → R_{sheet}

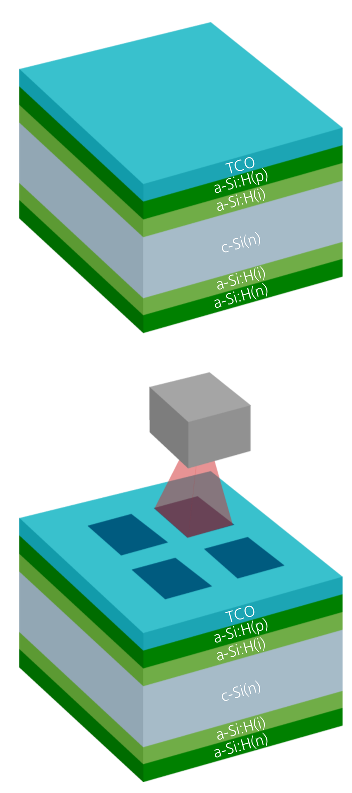
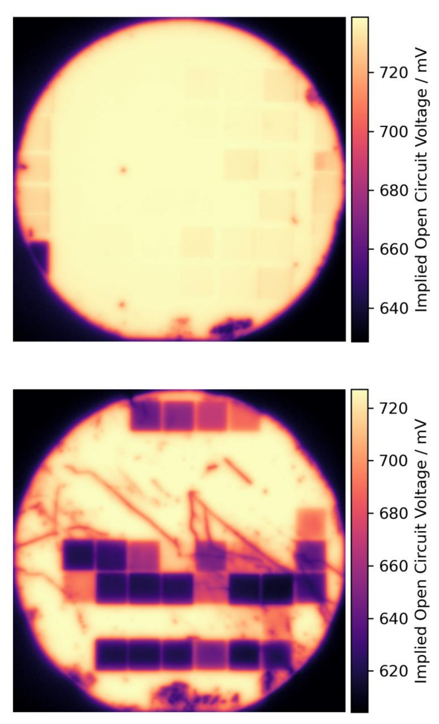


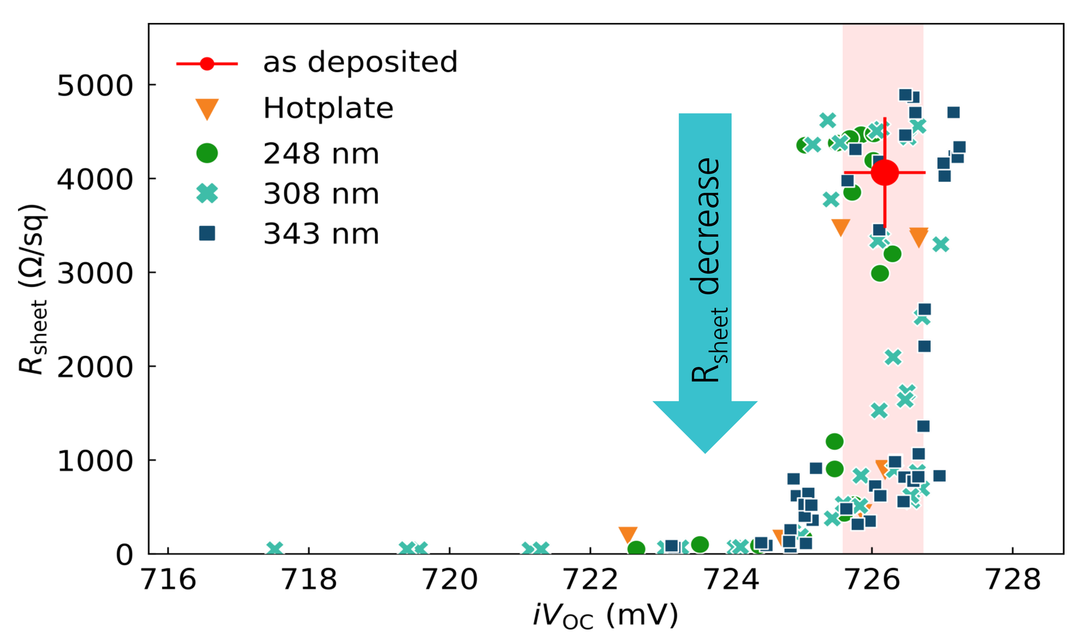
Fig. 2: Schematic illustration of sample structure and laser annealing experimental procedure.

Results

a) PL images of lasered samples



b) ITO: R_{sheet} as a function of substrate iV_{OC}



c) AZO: R_{sheet} as a function of substrate iV_{OC}

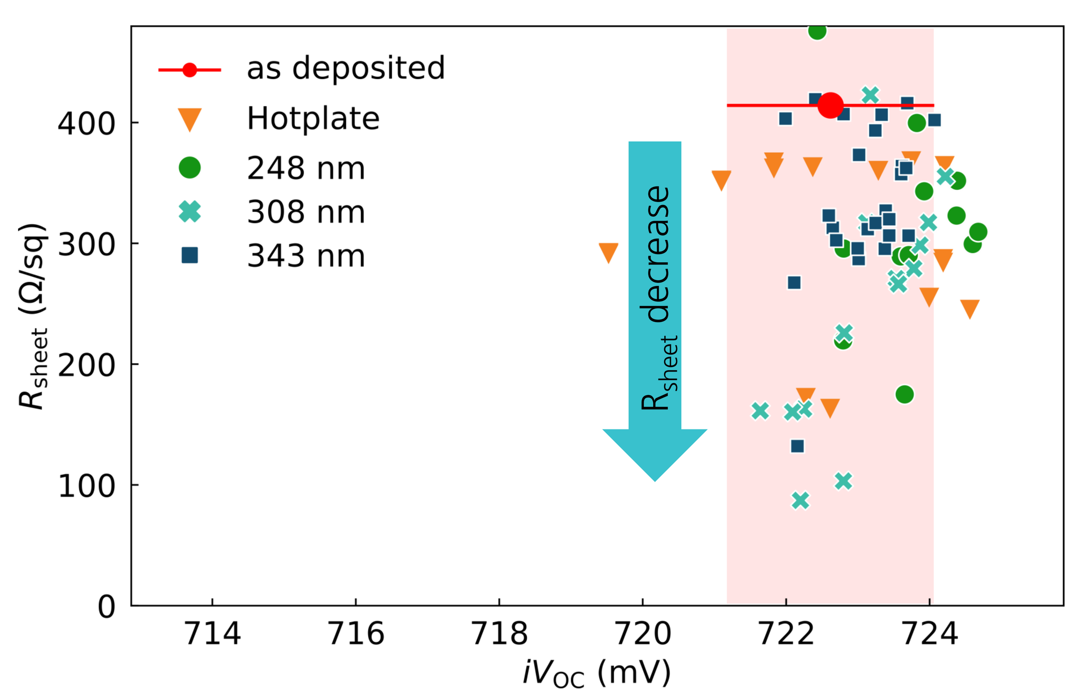


Fig. 3: a) Exemplary PL images showing areas of no/minor degradation (top) and strong degradation (bottom) of the a-Si:H layer after laser annealing. Measurements of TCO R_{sheet} in combination with iV_{OC} for b) substrates with ITO and c) the AZO thin film. Measurements after annealing by the three different UV wavelengths as well as for the hotplate annealing are shown.

- UV ns-laser anneal leads to significant R_{sheet} decrease for different TCO types:
  - ITO: R_{sheet} = 4060 Ω/sq → 50 Ω/sq
  - AZO: R_{sheet} = 414 Ω/sq → 90 Ω/sq
  - Significantly reduced R_{sheet} while maintaining initial iV_{OC} level
  - Comparable to hotplate annealing
- ➢ Fast alternative process to conventional thermal processes
- ➢ Potential of enabling indium free TCOs, requiring higher annealing temperatures for solar cells [5]
- ➢ Potential for TCO annealing on more temperature sensitive substrates (e.g. perovskite solar cells)

Summary and Conclusion

- Reduction in R_{sheet} of ITO and AZO layers on temperature sensitive SHJ substrates by UV ns-laser annealing
- R_{sheet} is reduced significantly without compromising the iV_{OC}
- **Damage free laser annealing of TCO thin films**
- Laser processes as **fast alternative** to hotplate annealing
- Potential of enabling **indium-free TCOs** for solar cells
- Potential of enabling TCO anneal on T-sensitive **perovskite solar cells**

[1] C. Messmer, et al., *Prog. Photovoltaics* (2022)
[2] L. Tutsch et al., *Prog. Photovoltaics* (2021)
[3] J. Nomoto et al. NPG Asia Materials (2022)
[4] J. M. Greulich et al., *AIP conference proceedings* (2022)
[5] W. Yang et al., *Thin Solid Films* (2010)

link to Fraunhofer ISE contributions of the 40th EU PVSEC, available as of 20.09.2023

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