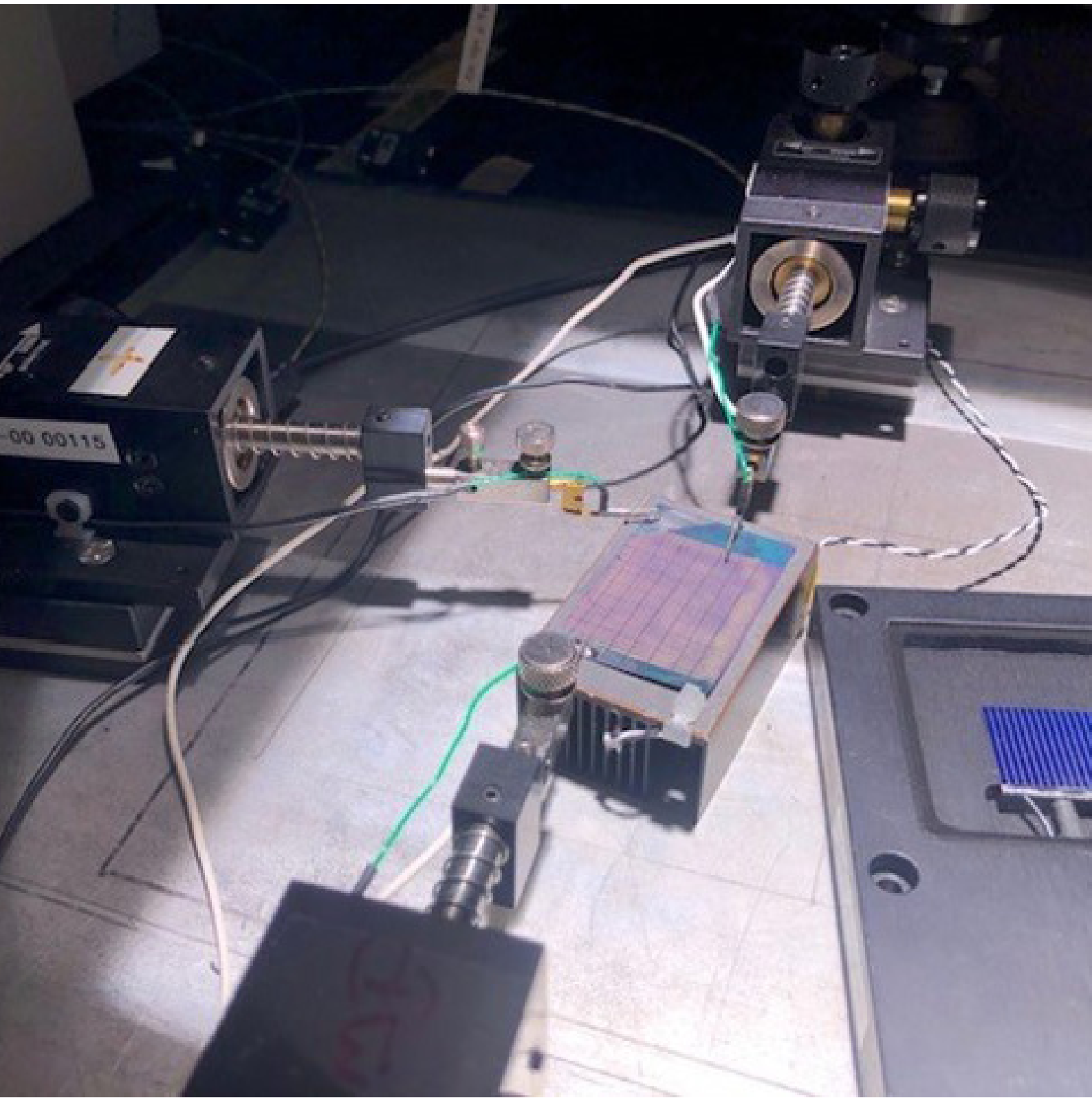


## 64020-1088 PLATECELL ELECTROPLATING OF CZTS ABSORBER FILMS FOR FLEXIBLE SOLAR CELLS

Final report  
September 2024



## 1. Project details

<b>Project title</b>	PlateCell
<b>File no.</b>	64020-1088
<b>Name of the funding scheme</b>	EUDP
<b>Project managing company / institution</b>	DTU Electro
<b>CVR number</b> (central business register)	30060946
<b>Project partners</b>	Elplatek, IPU, Sunplugged and DTU Nanolab
<b>Submission date</b>	21 October 2024

## 2. Summary

### Project summary:

The project addressed the need for sustainable, cost-effective, and flexible solar cell solutions by developing CZTS thin-film solar cells using electrodeposition. The technology was demonstrated on industrial substrates, marking a significant step towards scalable, low-cost production.

The project realized the following results

- The project successfully developed a process for producing CZTS solar cells using electroplating on flexible substrates, achieving a baseline efficiency of 2%.
- This was the first demonstration of CZTS solar cells produced through electroplating in an industrial setting, providing a proof of concept for scalable, low-cost production.
- Collaboration between Sunplugged, Elplatek, and research partners ensured the optimization of each step in the process, leading to the adaptation of industrial processes to CZTS technology.
- The project identified key technical challenges and mapped solutions that could lead to improved efficiencies in future developments.
- Future work will focus on further increasing efficiency through ongoing R&D efforts and seeking additional funding to advance the technology readiness level.
- The expected effects of this technology include providing a sustainable and cost-efficient alternative to traditional silicon and CIGS solar cells, especially for applications requiring flexible and lightweight panels, such as building-integrated photovoltaics.

### Projektresumé

Projektet adresserede behovet for bæredygtige, omkostningseffektive og fleksible solcelleløsninger ved at udvikle CZTS tyndfilmssolceller ved brug af elektroplatering. Teknologien blev demonstreret på industrielle substrater og markerede et væsentligt skridt mod skalerbar og billig produktion.

I projektet opnåedes følgende resultater

- Projektet udviklede med succes en proces til at producere CZTS-solceller ved elektroplatering på fleksible substrater og opnåede en baseline-effektivitet på 2%.
- Dette var den første demonstration af CZTS-solceller produceret gennem elektroplatering i et industrielt miljø, hvilket gav et proof of concept for skalerbar og billig produktion.
- Samarbejdet mellem Sunplugged, Elplatek og forskningspartnere sikrede optimering af hver del af processen, hvilket førte til tilpasning af industrielle processer til CZTS-teknologi.
- Projektet identificerede nøgleudfordringer og kortlagde løsninger, der kan føre til forbedrede effektivitet i fremtidige udviklinger.
- Fremtidigt arbejde vil fokusere på yderligere at øge effektiviteten gennem fortsat forskning og udvikling samt søge yderligere finansiering til at fremme teknologiens TRL.
- Teknologien forventes at kunne tilbyde et bæredygtigt og omkostningseffektivt alternativ til traditionelle silicium- og CIGS-solceller, især til applikationer, der kræver fleksible og lette paneler, såsom bygningsintegrerede solceller.

### 3. Project objectives

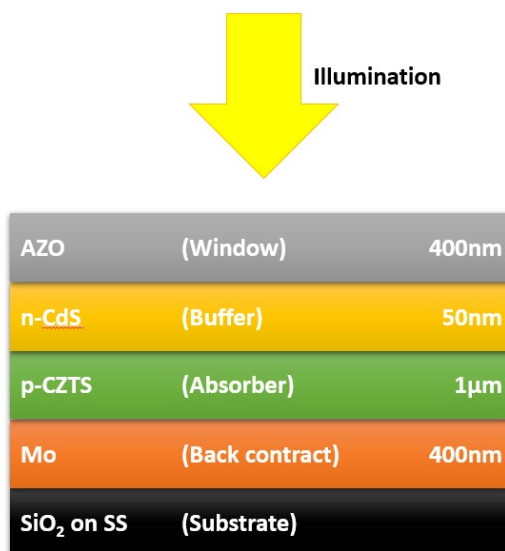
#### 3.1 What was the objective of the project?

The thin-film solar cells are merging into the solar cell market, and currently about 7 % of the accumulated operating solar cells are thin-film cells. These cells have recently become economically competitive to crystalline silicon, and there are strong reasons to expect a much higher fraction of thin-film cells in the near future. These cells are robust, can be bent and while the dominant cell type silicon is approaching its theoretical maximum in efficiency, the most common thin-film cells, CdTe and CIGS (CuInGaSe) are not yet close to their maximum.

Another promising thin-film cell is CZTS (copper, zinc, tin and sulfur) which recently has reached 15.84% efficiency (adding a bit of selenium) and which consists exclusively of non-toxic and Earth-abundant elements (when not adding selenium) in contrast to CdTe and CIGS. The absorber in CZTS solar cells is only 1 μm thick (in contrast to silicon absorbers of thickness 150 -200 μm), and cells of CZTS can thus be fabricated on flexible substrates.

The objective of the PlateCell project was to develop and demonstrate thin-film solar cells using CZTS as the absorber material on flexible substrates, produced through an electroplating process. The project aimed to start a Danish initiative where using electroplating as the vehicle towards production of solar cells and in the long term achieve a solar cell efficiency of at least 8% on flexible substrates and to demonstrate that CZTS solar cells produced through electrodeposition could reach efficiencies comparable to the best results achieved through other techniques, such as sputtering, which has achieved efficiencies up to 12.6% (when no selenium is added).

In the project period the aim was to realize 2% efficiency in first a small scale research setup and afterwards in an industrial setting the CZTS produced by Danish Elplatek and later on finalized by the Austrian company, Sunplugged, building the last parts of the solar cell stack as shown below:



**Figure 1:** Schematic of the thin-film solar cell fabricated in this thesis on Moly foil substrates.

Sunplugged is working with roll-2-roll CuInGaSe (CIGS) and the purpose of the project was to swap the CIGS layer with CZTS produced by Elplatek and realize a solar cell production with stable efficiency results which

was achieved for the promised 2% in the project plan though the attempts for going for higher efficiencies failed.

### **3.2 Which energy technology has been developed and demonstrated?**

The energy technology developed in this project is based on CZTS solar cells, a promising thin-film solar cell technology composed of non-toxic and Earth-abundant elements. The project focused on scaling up the electroplating process for large-area production, aiming to produce low-cost, flexible solar panels that could be used in a variety of applications, including building-integrated photovoltaics (BIPV) and product-integrated photovoltaics (PIPV)

## 4. Project implementation

### 4.1 How did the project evolve?

The project group worked very well together which is key to such a rather highly ambitious project where new ground is broken. Electroplating of CZTS has only been done by a few research groups internationally and not in an industrial setting as this project set out to do. The project met many setbacks and was prolonged for 1 year to be able to meet the milestones. Overall, the project was well run and even though the project partners were hoping for higher efficiencies beyond the 2% achieved, a strong baseline was achieved which can be used to work towards the ultimate goal of making an electroplating based roll-2-roll production of CZTS in Denmark. Results from the PV community will assist in the process of achieving this goal, as new results have recently brought the efficiency of CZTS solar cells out of stagnation around 12% to <15% (adding small amounts of Se though) making them very close to a commercial threshold for being interesting for mass production. The plating results achieved in the PLATECELL project can most likely benefit from these results and “just” add annealing in an atmosphere containing small amounts of selenium, as well as other benefits outside of the plating processes will spill over to raise the efficiency to much higher levels than obtained in this project.

### 4.2 Describe the risks associated with conducting the project.

The biggest challenge in the project was the flexible stainless steel substrates used at Sunplugged which is treated with SiO<sub>2</sub> as a diffusion barrier before sputtering a layer of Mo being the real solar cell substrate. When annealed at 580°C the SiO<sub>2</sub> diffuses into the CZTS layer making the stack useless for finalizing the solar cell. The substrate doesn't meet these high temperatures when doing the roll-2-roll CIGS solar cells which they are making for, and the mitigation for use in the PLATECELL project prolonged the project considerably and it is still the biggest problem in going forward.

### 4.3 Did the project implementation develop as foreseen and according to milestones agreed upon?

The project followed the plan though with the need for an overall 1 year extension to make the results fit to the plan made for the project.

### 4.4 Did the project experience problems not expected?

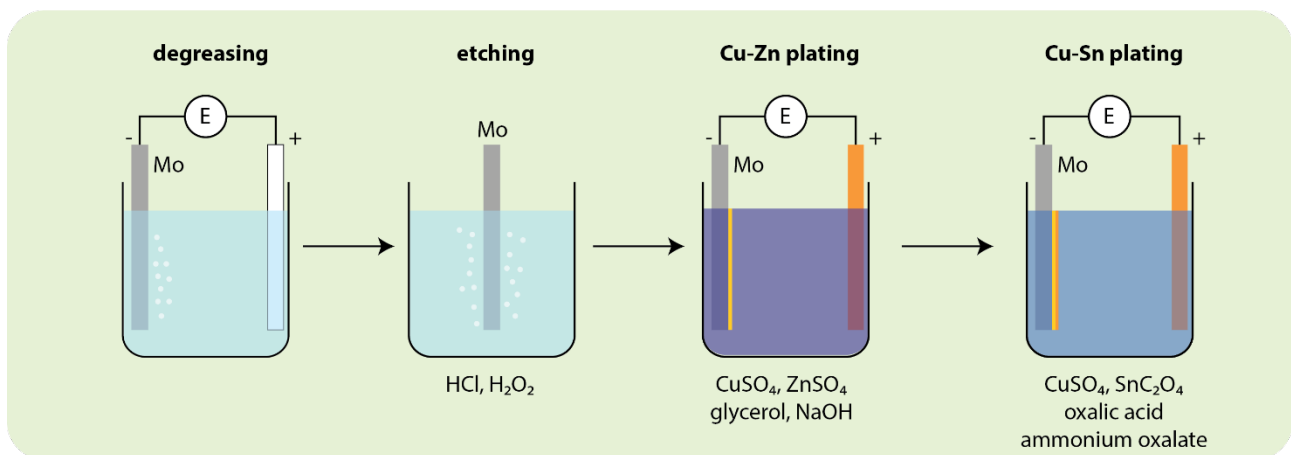
As described above it was not expected that the substrate should be more challenging than the CZTS active layer, but that is the nature of research especially when trying to upscale in an industrial setting. The stainless steel substrate was chosen as it can handle the high temperature needed for the CZTS annealing where the traditional polyimide used in flexible CIGS production would not be feasible.

## 5. Project results

The work was divided into the following work packages:

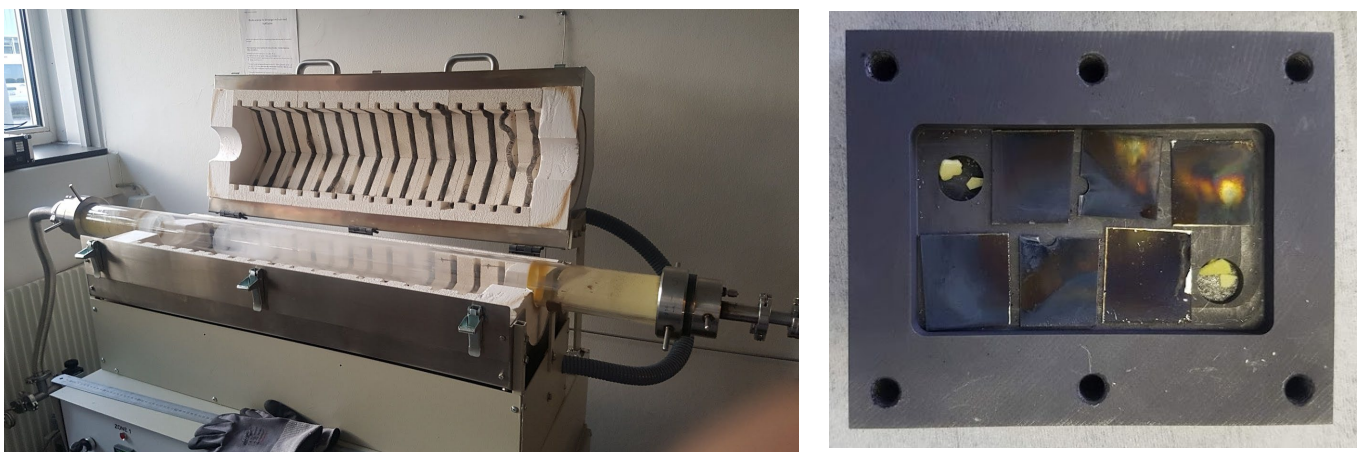
- Work Package 1: Project Management
- Work Package 2: Preliminary Film Deposition
- Work Package 3: Characterization and Cell Production
- Work Package 4: Cell Production under Industrial Conditions
- Work Package 5: Production of Cells by Roll-to-Roll Technique
- Work Package 6: Commercial Track

For all CZTS experiments molybdenum was used as substrate and some kind of process flow like the below was used:



**Figure 2:** Steps in the electroplating process of the absorber layer

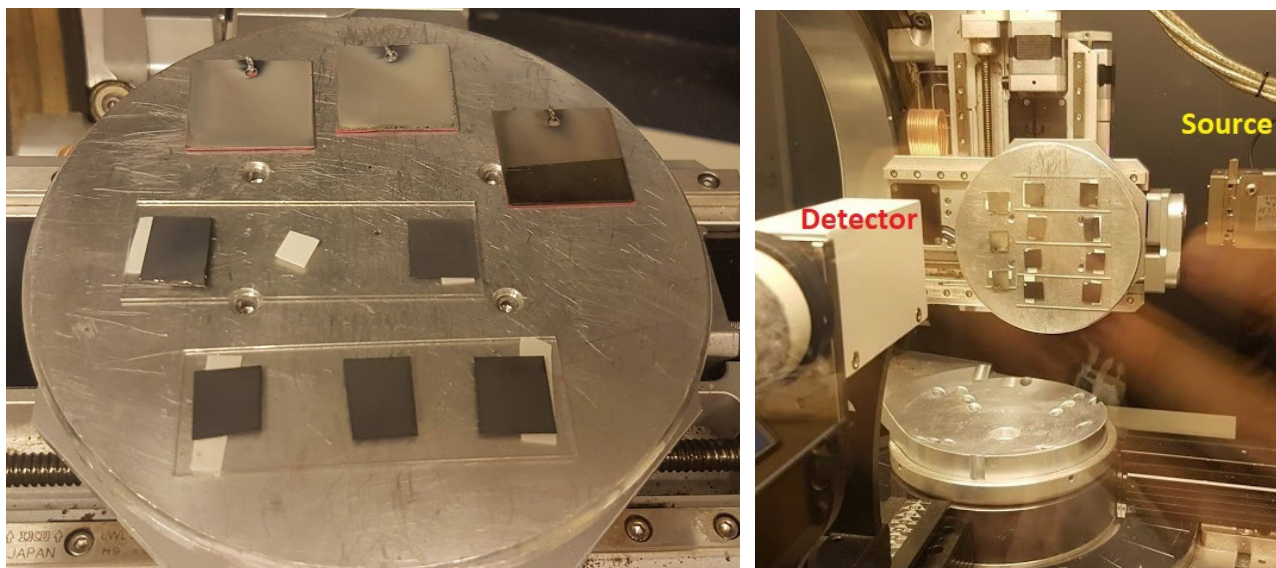
The substrate was cleaned from organic materials (like fingerprints) by a degreasing process followed by etching to remove oxide layer on the molybdenum. The absorber layer (CZTS) was subsequently deposited by one or more electroplating processes. The sulphur is afterwards incorporated into the layer by heat treatment in a sulphur-rich atmosphere in an oven as shown below.



**Figure 3:** Left: Oven with sulphur atmosphere. Right: Graphite box where 6 samples can be placed for heat treatment.

During the heat treatment at 585°C the CZTS is formed, and crystals of the material grow. The project mainly revolved around this part of the solar cell as the rest of solar cell stack are known from CIGSs solar cells where it has reached high efficiencies.

For the characterization of the CZTS samples after deposition (as-deposited), several methods were used. For compositional analyses, XRF (X-ray Fluorescence) was used on all samples, with SEM (Scanning Electron Microscopy) / EDX (Energy Dispersive X-ray Spectroscopy) used for imaging and compositional analysis on some of the bulk Mo and Moly foil samples that were picked for further processing. The same samples (or different parts of the same samples) were also taken for XRD (X-ray Diffraction) and Raman characterization for phase analysis. For XRD, Raman, and SEM/EDX, the characterization would typically be done on different pieces of the same sample in the same setting, with some pieces being as-deposited and the rest after sulfurization.



**Figure 4:** Left: Bulk Mo samples attached to XRD holder, large samples in the top are as-deposited, small samples on glass are after sulfurization. Right: XRD setup, during an ongoing measurement. Stationary source for GI measurement, with only the detector rotating around the sample.

The rest of the layers in the CZTS solar cell stack are CdS and AZO. CdS are deposited by chemical bath deposition and AZO by sputtering. These processes are standard and was done in a research environment at DTU Nanolab and in an industrial setting at Sunplugged towards the end of the project.

Below is describe the project results in chronological order.

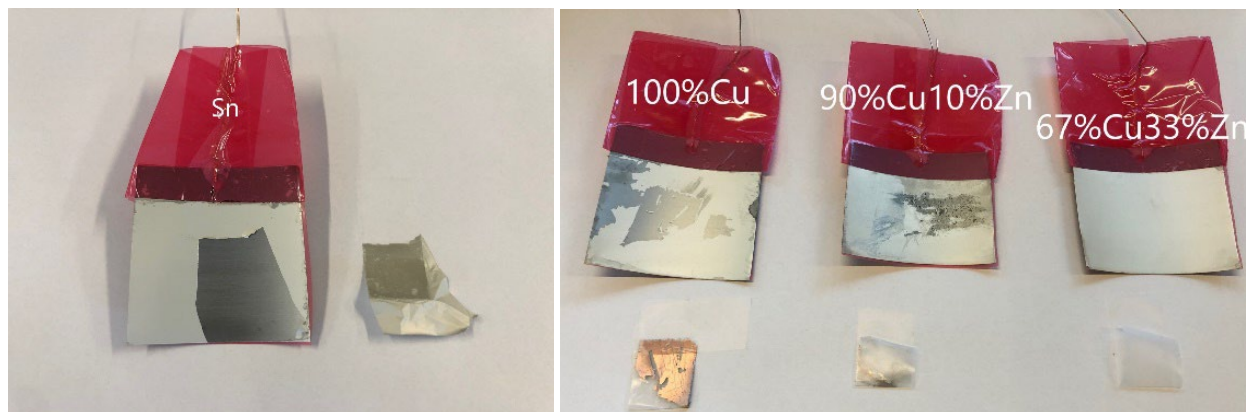
## 5.1. Preliminary film deposition

### 5.1.1 Development of a method for improving the adhesion to the molybdenum substrate

Molybdenum is a typical substrate for CZTS solar cells, but it is also a difficult substrate for electroplating, since molybdenum is not stable in air or water but quickly develops an oxide layer which leads to delamination of the electroplated material – sometimes even during the deposition process.

All attempts to deposit the pure metals (Cu, Zn or Sn) from acidic or alkaline (typically cyanide based) electrolytes were not successful due to massive hydrogen evolution on the substrate. Cyanide is strong complex agent for all three metals and increases the deposition potential (a higher potential

is required to release the metal ions from the cyanide complex), leading to more co-deposition of hydrogen - even in an alkaline solution. Pyrophosphate or glycerol/sodium hydroxide electrolytes facilitate electroplating on Mo because less strong complexes are formed. The use of Cu, CuZn and Sn as adhesive layer onto molybdenum substrates has been investigated. Simple tape tests demonstrated that only a brass alloy (67%Cu and 33%Zn) coating completely survives the test, while Sn, Sn on Cu and Sn on 90%Cu10%Zn delaminated (see figure 5).



**Figure 5:** Photos of tape tested samples. Sn electrodeposited directly on Mo (left) and Sn coated on Cu or CuZn alloys, electrodeposited on Mo (right).

Tin has higher electrodeposition potential than hydrogen, and hydrogen evolution could interfere with tin adhesion to the substrate. Regarding copper-molybdenum adhesion, the phase-diagrams of the Cu-Mo system [1] indicates bad affinity between copper and molybdenum, while the phase diagram of the Zn-Cr system (chromium is similar to molybdenum) [2] indicates a higher affinity for mixing. These considerations lead to the conclusion, that the best option for fabrication of CuZnSn precursor alloys is to use two electroplating steps; first direct deposition of CuZn onto the Mo substrate, followed by electroplating of pure Sn.

### 5.1.2 Optimization of electrolyte for Sn electroplating

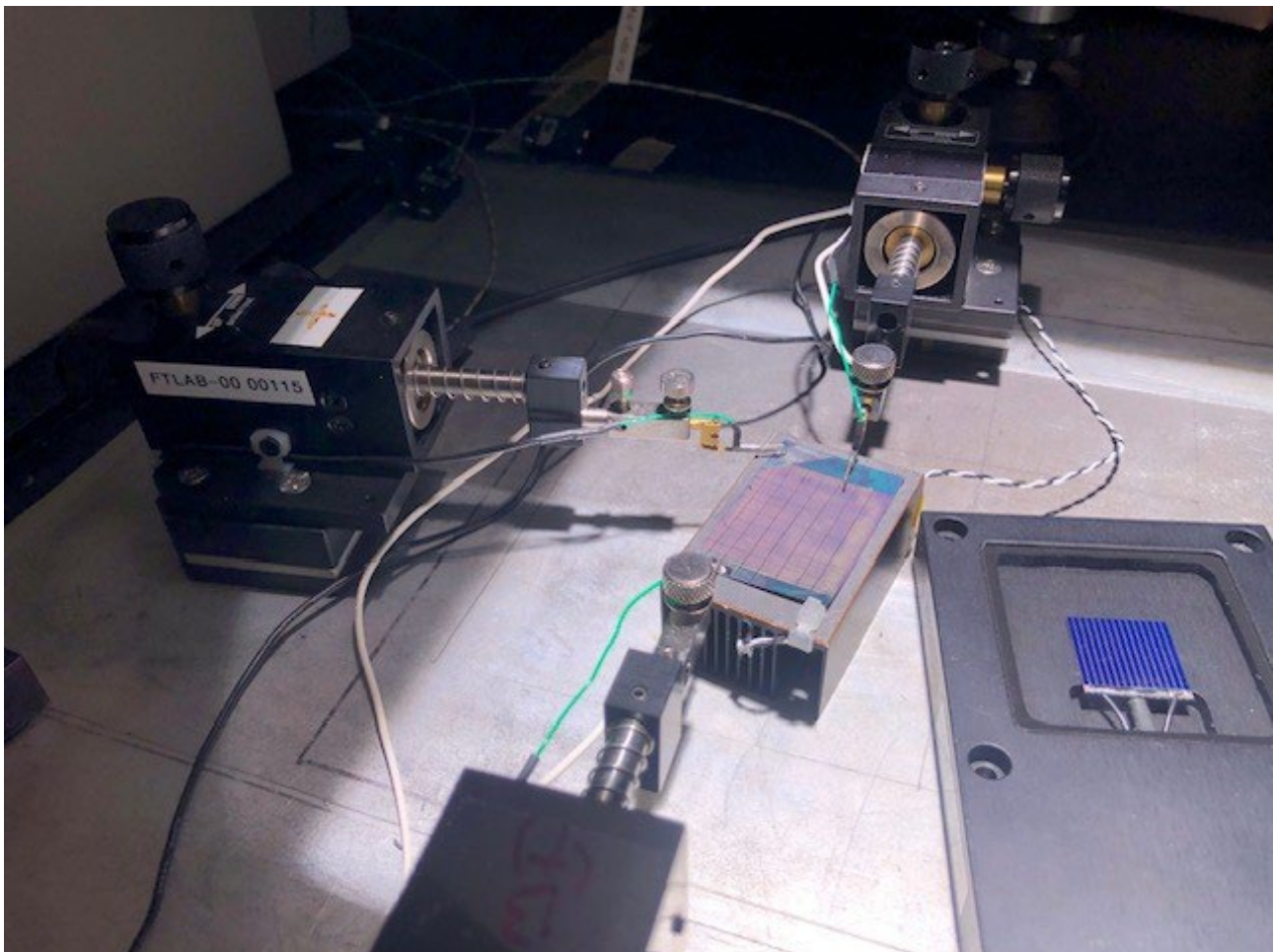
Tin electrolytes in general, except for alkaline cyanide Sn(IV) electrolytes, have a problem of stability due to oxidation of Sn(II) to Sn(IV). This effect will lead to instability and potentially also delamination. Oxalate and pyrophosphate Sn(II) based electrolytes give rise to variation in chemical composition of the alloys as a function of solution aging, while the more stable Sn(IV) cyanide electrolytes cause delamination of the already deposited CuZn from the Mo substrate. Both commercial tin electrolytes tested results in massive hydrogen evolution during electroplating. The pyrophosphate tin electrolyte is the most balanced one with regards to both stability of chemicals and appearance of the coating (see Table I). By adding sulfosalicylic acid as complexing agent for Sn(II) and dipotassium phosphate as pH buffer, the stability of this Sn electrolyte has been improved.

**Table I:** Features of pure tin electrolytes

Electrolyte type	Advantages	Disadvantages
Cyanide, <u>Sn(IV)</u>	Commercial, stable	Delamination
Acidic, sulfate <u>Sn(II)</u>	Commercial, relatively stable	Delamination
Pyrophosphate, <u>Sn(II)</u>	Good adhesion, good appearance	No commercial solution exists

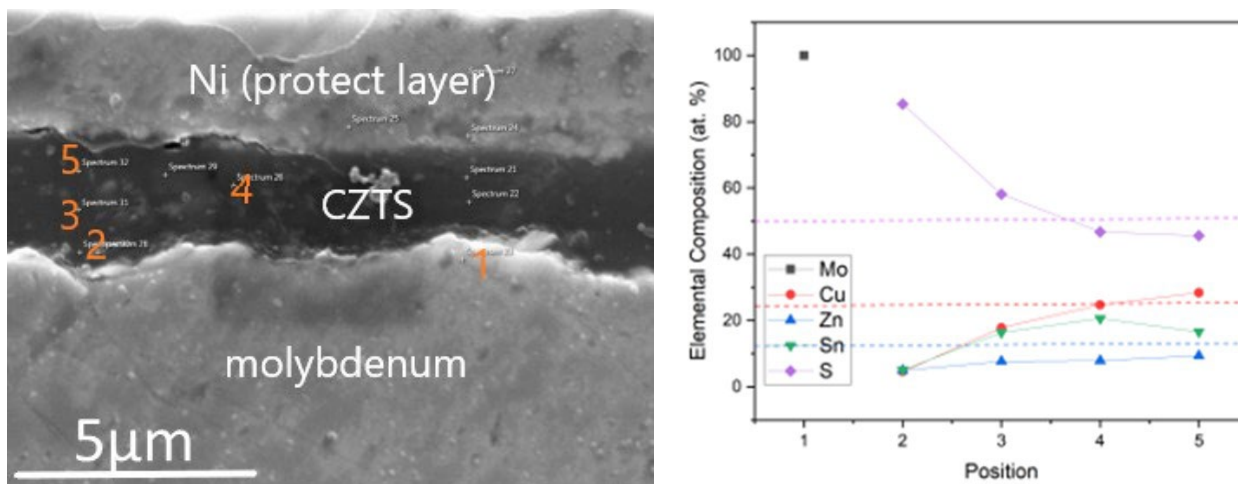
## 5.2. Characterization and cell production

CuZnSn deposited samples were prepared by electroplating as a combination of CuZn and pure tin plating. For fabrication of the CZTS absorber, the electroplated CuZnSn precursors were annealed in a graphite box placed inside a temperature-controlled quartz tube in an inert atmosphere by vacuuming and purging with nitrogen gas. The pressure inside the tube was 175 mbar at the start of each annealing. The temperature was raised at a rate of 20 °C/min. and kept at 585 degrees for 15 minutes. For sulfurization, 50 mg sulfur powder is placed inside the graphite box holding the CuZnSn precursors. The fabrication into solar cells was done by chemical bath deposition of a CdS buffer layer on top of the CZTS, then RF sputtering was used to deposit a thin (~50 nm) resistive layer of i-ZnO, and finally a thicker (~300 nm) conductive window layer of AZO (Al-doped ZnO). The fabricated cells were divided into 3 mm by 3 mm squares through manual scribing with a thin needle for IV curve measurement (Fig. 6).



**Figure 6:** Photos of IV curve measurement of a CZTS solar cell

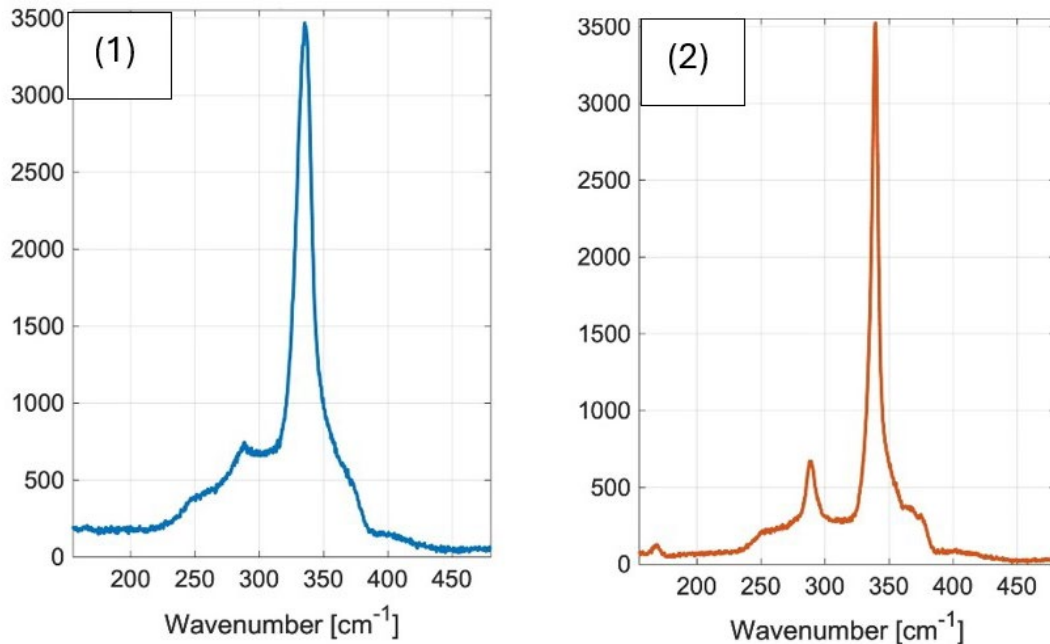
The solar cell efficiency of the CZTS absorber fabricated never reached more than 0.02%. A polished cross-section of the CZTS fabricated from a precursor of Sn/CuZn electrodeposits was examined by Scanning Electron Microscopy (SEM) and shows another phase between the molybdenum substrate and CZTS layer. The EDS analysis indicates higher sulphur content and lower copper content close to the molybdenum. This indicated formation of MoS, which could – at least partly – explain the low efficiency. J. Scragg described [2] that the presence of copper in the region close to molybdenum gives rise to the formation of voids and suggested stacks with copper at the top to minimize the risk. The EDS result indicates copper diffuse away from the interface.



**Figure 7:** SEM image and EDS profiles of a cross-section of CZTS absorber layers fabricated by sulfurization of precursors of electrodeposited Sn/CuZn on a molybdenum foil. A nickel layer was added on top of the stack by electroplating to protect the CZTS mechanically during polishing.

Thus, adding a copper top coating and lowering the copper content in the CuZn alloy used as adhesive layer on the molybdenum substrate, have been introduced to mitigate the undesired diffusion observed in Fig. 7. SEM images of CZTS from Sn/CuZn and Cu/Sn/CuZn look similar, however, there is a slight difference in the composition with 54.4%S-21.9%Cu-9.5%Zn-14.2%Sn versus 50.7%S-24.4%Cu-12.2%Zn-12.7%Sn, respectively.

The Raman spectra show differences between the absorbers from two different precursors (Fig. 8). Especially the peak at 287  $\text{cm}^{-1}$  associated with CZTS appears clearly in the spectrum of CZTS from a precursor of Cu/Sn/CuZn. The shoulder of the peak around 300  $\text{cm}^{-1}$  in the spectrum of CZTS from Sn/CuZn could include peaks of  $\text{SnS}_2$  at 312  $\text{cm}^{-1}$  and of SnS or  $\text{MoS}_2$  at 288  $\text{cm}^{-1}$ . The shoulder around 400  $\text{cm}^{-1}$  in the spectrum of CZTS from the Sn/CuZn precursor could be associated with  $\text{MoS}_2$  at 410  $\text{cm}^{-1}$ . The higher tin/sulfur content at the interface found in the EDS analysis indicates the presence of secondary phases of molybdenum sulfide and tin sulfides.



**Figure 8:** Raman spectra of CZTS absorber layers fabricated by sulfurization of precursors of electroplated Sn/CuZn (1) and Cu/Sn/CuZn (2) on molybdenum.

The solar cell with the CZTS absorber from Cu/Sn/CuZn achieved an efficiency of 0.42% (Table II). Especially the open circuit voltage of the cell from Cu/Sn/CuZn is almost ten times greater than the one from the Sn/CuZn precursor, due to reduction of the resistance of the CZTS and less MoS<sub>2</sub> secondary phase. The low current could be caused by poor current transport between CZTS and molybdenum.

Liu described [4] that a MoO<sub>3</sub> layer on the surface of molybdenum back contact improves the photovoltaic performance. The oxide works as a barrier against the reaction of molybdenum with sulfur leading to decomposition of CZTS, and the MoO<sub>3</sub> can provide favourable band alignment to CZTS compared to molybdenum. Therefore, attempts were made to form an oxide layer on the molybdenum foil by applying an anodic potential at 5 V in an alkaline bath for 5 seconds. Before this treatment cathodic degreasing was used to remove oil and dirt from the substrate, a treatment that also removes the original oxide layer. The color changed (Fig. 9) and became gradually darker by anodizing with time, as the oxide layer increased in thickness.



**Figure 9:** Photo of molybdenum sheet after anodizing treatment

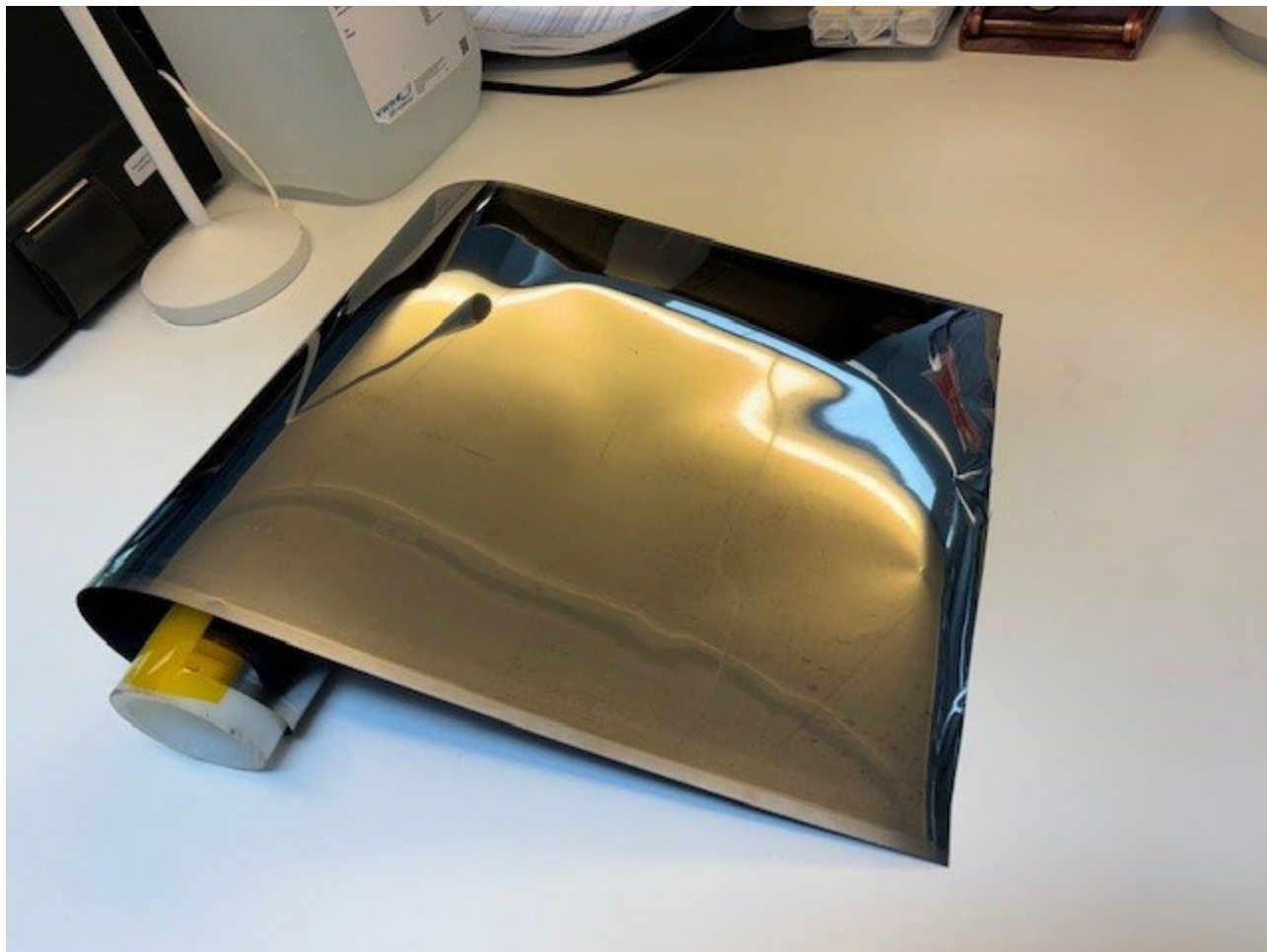
The adhesion of the CuZn layer directly electrodeposited on molybdenum treated by anodizing is good. The treatment raised the efficiency of the solar cell to 1,0% (Table II). The short circuit current increased, while the open circuit voltage and the fill factor are similar with ones of the solar cell on molybdenum with no anodizing treatment. That could be caused by modification of the band alignment of the CZTS/Mo, not by improvement of CZTS formation.

Table II: Performance of solar cells

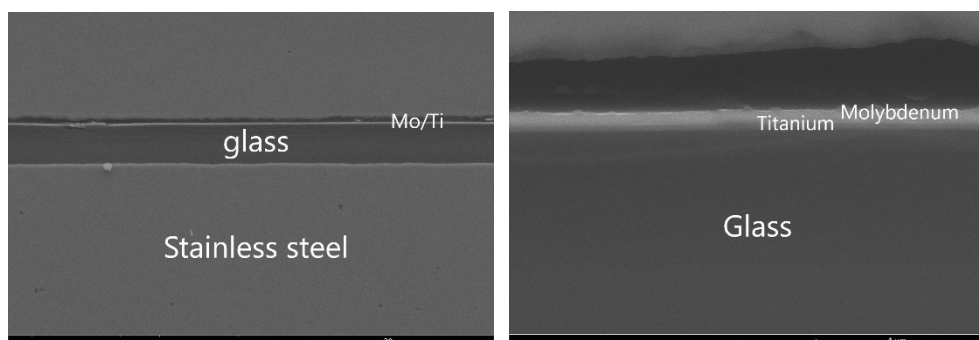
<b>precursor</b>	$I_{sc}$ mA	$V_{oc}$ V	$P_{max}$ $\mu W$	Fill factor %	Efficiency %
Sn/CuZn/Mo	0,3	0,028	2,2	26,2	0,02
Cu/Sn/CuZn/Mo	0,7	0,24	50,2	29,8	0,42
Cu/Sn/CuZn/anodized Mo	1,4	0,29	119	29,6	1,0

### 5.3. Cell production under industrial conditions

Flexible substrates of stainless-steel foil with 300 nm molybdenum back contact layer, titanium adhesive layer and glass barrier layer were prepared by Sunplugged GmbH (Fig. 10). Cross-sections of the substrate are shown in Fig. 11.

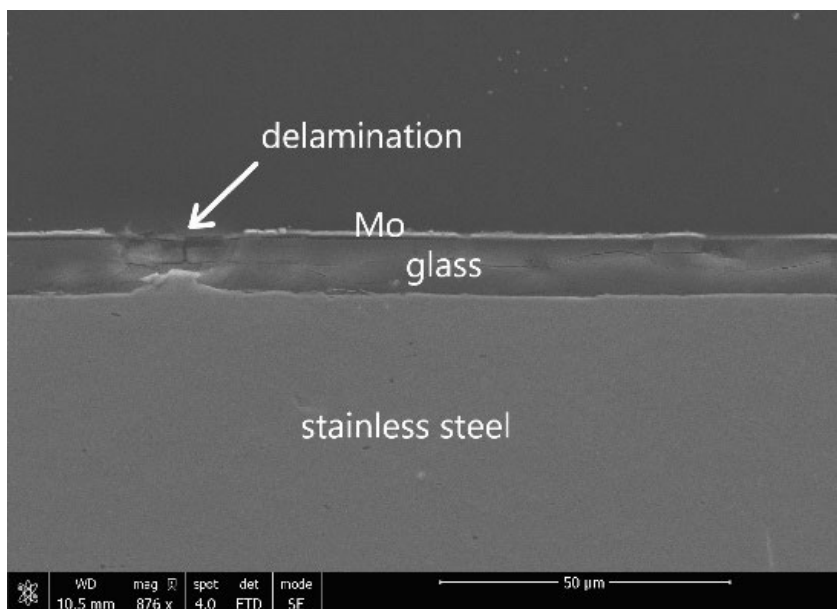


**Figure 10:** Photo of molybdenum/titanium/glass coated stainless-steel foil manufactured by Sunplugged GmbH



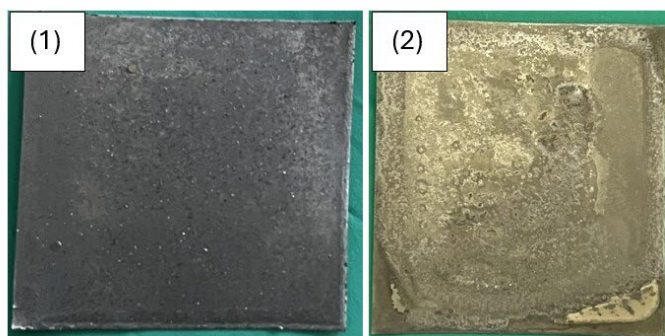
**Figure 11:** SEM images of a cross-section of molybdenum/titanium/glass coated stainless-steel foil substrate.

Thin film CZTS precursors of electroplated Sn/CuZn and Cu/Sn/CuZn on the Mo/glass coated stainless-steel foil were fabricated by combining with annealing of the metallic stacks, CdS deposition and AZO/ZnO sputtering (similar to the cells fabricated on pure molybdenum substrates), however, the efficiency never reached more than 0,3%. The SEM image (Fig. 12) of the cross-section shows that the glass coating gives rise to a problem with partial delamination of the molybdenum coating under annealing at 585 degree.



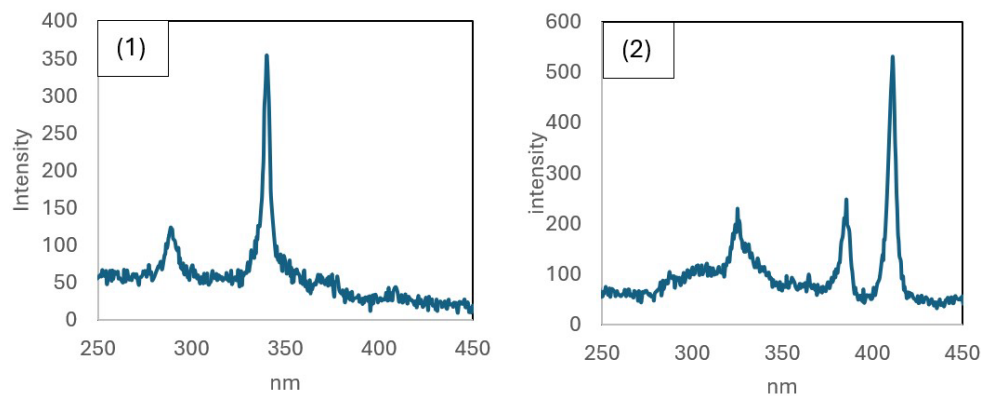
**Figure 12:** SEM images of a cross-section of molybdenum/titanium/glass coated stainless steel foil substrate annealed at 585 °C.

Attempts to fabricate cells using a stainless-steel substrate without a glass layer (but still having a Ti/Mo top layer) were made, but the substrate with no glass coating never allowed CZTS formation during sulfurization. The photos show a difference in the appearance of sulphurized CuZnSn electrodeposited on the two different foils with and without glass coating (Fig. 13).



**Figure 13:** Photos of Cu/Sn/CuZn electrodeposited on molybdenum/titanium/glass coated stainless steel foil substrate (1) and molybdenum/titanium coated stainless steel foil substrate (2) after annealing at 585°C.

The Raman spectrum of the CZTS on foil without glass coating mainly showed molybdenum sulfide phases and no phases containing iron, chromium or titanium (Fig. 14).



**Figure 14:** Raman spectra of CZTS absorber layers on molybdenum/titanium/glass coated stainless steel foil substrate (1) and molybdenum/titanium coated stainless steel foil substrate (2) after annealing at 585°C.

## 5.4. Dissemination results

We have made the following disseminations as part of the project:

- Io Mizushima, Sara Engberg, Kristoffer Bentsen, Torben Tang, Karen Pantleon, Peter Westermann, Peter Poulsen, Stela Canulescu, “fabrication of CZTS absorber layer by electrodeposition for thin-film solar cells”, in 12nd Kesterite Workshop, February 9-11, 2022, Kongens Lyngby, Denmark
- Io Mizushima, Peter Torben Tang, Alexander Holm and Jørgen Schou, “Development of fabrication process for electroplated CZTS absorber”, in 40<sup>th</sup> European Photovoltaic Solar Energy Conference and Exhibition, September 18-22, 2023, Lisbon, Portugal
- Io Mizushima, Peter Torben Tang, Alexander Holm and Eduard Llorens Balada, “Development of fabrication process for thin-film cell with electroplated CZTS absorber”, in 52<sup>nd</sup> IEEE Photovoltaic Specialist Conference, June 9-14, 2024, Seattle, USA
- Io Mizushima, Peter Torben Tang, Christoph Kammerlander, Andreas Zimmermann, “Flexible thin-film CZTS solar cell based on electroplated metallic precursor deposited on a molybdenum/glass coated stainless steel foil”, in 41st European Photovoltaic Solar Energy Conference and Exhibition, September 23-27, 2024, Vienna, Austria

### References

- [1] H. Okamoto, Desk Handbook Phase Diagrams for Binary Alloys, Materials Park, Ohio (2000)
- [2] H. Okamoto, J. phase Equilibrium and Diffusion 33, 246-247 (2012)
- [3] J. Scragg, “Copper zinc tin sulfide thin films for photovoltaics,” Ph.D. thesis, ISSN 2190-5053, Springer, 2011
- [4] L. Liu, T. Lau, L. Huang, S. Wang and X. Xiao, “Modification of Mo back contact with MoO<sub>3-x</sub> layer and its effect to enhance the performance of Cu<sub>2</sub>ZnSnS<sub>4</sub> solar cells” Solar RRL, 2, pp1800243, 2018

## 6. Utilisation of project results

The project is part of a long-term vision to realize a plating based thin film PV production company in Denmark potentially as a joint venture between Sunplugged and Elplatek. The PLATECELL project has set the foundation and a stable 2% efficiency has been achieved of CZTS solar cells produced on Sunplugged produced substrates – electroplated at Elplatek – and finalized at Sunplugged again and therefore a end-to-end commercial setting. CZTS is a very complex technology and it is impressive in itself to realize this base-line efficiency adapting all the processes at the company sites supported by research at DTU and IPU. It is though clear that a higher efficiency is needed for commercialization and the project partners will pursue research project funding for advancing in the TRL chain. The challenges are though pretty clear and mapped out by the project partners and the new results in the CZTS research community makes the PLATECELL project team optimistic that these “tricks” easily be implemented bringing the efficiency close to state-of-the-art if the needed investments are obtained to break down these barriers. The project started at a rather low TRL and even though this is the first project to produce CZTS by electroplating in an industrial setting, it is still too low on the TRL ladder to realize commercial turnover.

The flexible solar cell market is competitive, with several established players like Ascent Solar and Flisom already offering solutions based on other thin-film technologies such as CIGS and organic photovoltaics. These competitors have gained market traction due to their efficiency and flexibility. However, the PlateCell project's approach to using earth-abundant and environmentally benign CZTS presents a unique value proposition. This technology addresses concerns related to the toxicity and scarcity of materials used in other thin-film solar cells, offering a sustainable and potentially lower-cost alternative.

By providing an alternative to traditional silicon-based and CIGS solar cells, CZTS technology can support the expansion of renewable energy sources, help lower carbon emissions, and facilitate the transition to a greener energy economy. A higher efficiency are though needed than what was realized in the PLATECELL project. It is though a matter of cost and less on efficiency as 10% efficiency can be plenty if the cost is low enough and the electroplating at least in theory enable for a very low cost CZTS solution. Product and building integration are the first markets to be addressed if this can be achieved as silicon doesn't fit fore these markets.

The project involved a PhD student at DTU Nanolab and several PostDocs at DTU Electro. The findings and advancements have been integrated into educational curricula at partnering universities, fostering knowledge dissemination and training the next generation of solar technology researchers. Additionally, the results are being shared through conferences and publications, ensuring the broader scientific community can benefit from the innovations developed during the project.

## 7. Project conclusion and perspective

The PlateCell project successfully demonstrated the feasibility of producing CZTS solar cells through an end-to-end industrial process using electroplating. While the achieved baseline efficiency of 2% marks a significant milestone, it is recognized that higher efficiencies will be essential for commercialization. The project has laid a strong foundation by establishing and optimizing processes at company sites such as Sunplugged and Elplatek, with the support of research institutions like DTU and IPU. This marks the first time CZTS solar cells have been produced via electroplating in an industrial setting, proving the viability of this approach.

One of the key conclusions from the project is that, despite the challenges associated with CZTS technology, it is possible to develop a scalable, environmentally friendly, and cost-effective thin-film solar solution. The project's focus on utilizing earth-abundant and non-toxic materials provides a sustainable alternative to traditional silicon-based and CIGS solar cells, addressing concerns about material scarcity and environmental impact. The success of the project has helped to map out the technical challenges that need to be overcome to achieve competitive efficiencies, making the project partners optimistic about future developments.

The next steps for the PlateCell technology include seeking additional research funding to advance the technology readiness level further up the development chain. The project partners plan to address the identified challenges by implementing new techniques and insights from the CZTS research community, which have emerged during the project's timeline. The goal is to improve the efficiency of the solar cells to closer to state-of-the-art levels (around 10-12%) while maintaining the cost benefits associated with electroplating. Achieving this will require continued collaboration between industry and academia, leveraging the groundwork established by the PlateCell project.

Moreover, future research will focus on refining the deposition process, optimizing the materials and interfaces, and conducting extensive testing to ensure the stability and reliability of the solar cells under real-world conditions. If these developments are successful, the technology will be well-positioned to enter the market, particularly in niche applications such as building-integrated photovoltaics and product-integrated photovoltaics, where flexibility and low cost are critical advantages.

The PlateCell project has demonstrated the potential of CZTS-based solar technology as a viable alternative to existing thin-film solutions. With its focus on sustainable, low-cost production, the project has the potential to revolutionize how solar cells are manufactured, reducing the reliance on scarce or toxic materials and supporting the global transition to renewable energy. If future efforts succeed in increasing efficiency while maintaining cost-effectiveness, this could pave the way for broader adoption of CZTS technology, especially in markets where traditional silicon panels are less suitable.

Additionally, the success of the PlateCell project may inspire further research and development in the field of electroplating for solar cell manufacturing. The ability to produce flexible, lightweight solar cells at lower costs could open new markets and applications, driving innovation in product design and integration. This could lead to new business opportunities for companies involved in the production, installation, and integration of solar technology, potentially boosting employment, exports, and private investment.

Overall, the PlateCell project has provided valuable insights and practical advances that will serve as the basis for future developments in CZTS solar technology. The continued efforts of the project partners will be crucial in overcoming the remaining technical barriers and bringing this promising technology closer to commercial viability.