# Powersail project: Executive Summary Report

# Disruptive PV Power Array Technology to Enable Economic Viability of SPS "POWERSAIL"

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# Introduction

The goal of the Powersail project is to demonstrate the potential of amorphous silicon (a-Si) deposited on ultralight space-grade polyimide for solar power satellites (SPS). State of the art solutions are III-V compound semiconductor triple junction-based PV modules, which are 100 times too expensive and one order of magnitude too heavy to build a competitive SPS with terrestrial microwave energy collection infrastructure. Despite its lower power conversion efficiency (PCE) than state-of-the-art multijunction solar cells, and even mainstream crystalline silicon (c-Si), a-Si for solar is a thin-film technology requiring minute amount of material and is adapted for low-cost large-area deposition, which is compatible with inexpensive/flexible substrates. Furthermore, a whole industrial platform has already been established for module fabrication.

In the work performed during the Powersail project, two established technology materials and processes are merged into one fully integrated novel PV array architecture, combining space rated thin film Polyimides from NEXOLVE Holding Company LLC (NXLV) USA and thin film a-Si PV module technology from CSEM Switzerland. Very small ultra-lightweight demonstrator cells on polyimide have been demonstrated previously, but the demonstration of a laser interconnected solar module is still lacking to demonstrate the scalability of the technology to large areas. The final goal of the project is therefore to fabricate a medium area (10×10 $cm^2$) ultra-lightweight laser processed demonstrator module. This will allow to assess the potential of this technology for SPS, in terms of W/kg performances. The simplicity of the laser process (litho-free) will potentially enable cost < 1$/W, which is impossible to reach with competing technologies (c-Si or III-V).

In this report, the findings and technology achievements obtained in the framework of the Powersail project will be summarized, and conclusions on the potential of this technology will be presented.

# Thin-film solar module description and process flow

## Thin-film module interconnection

As stated in the introduction, the focus is on leveraging amorphous silicon module technology, known for its low-cost nature and successful large-scale industrial production. To minimize the resistive losses for large area, thin-film solar cells need to be divided in smaller segments interconnected in series. In this context Figure 1(a) provides a schematic cross view description of an exemplary 3-segment amorphous silicon solar module. This exemplifies how the interconnection is performed with P1/P2/P3 lines:

- P1 insulates the front electrode of the first segment to the one of the second segment thanks to the high resistivity of the solar absorber.
- P2 connects the back electrode of segment 1 to the front one of segment 2.
- P3 insulates the back electrodes of segment 1 and 2.

Similarly, P2/P3 lines on the left side connect the front electrode to the front contact and a P1 line for the back contact insulates the front electrode of segment 3 from the contact area. A P4 line insulates the solar module from the layers outside the module design area.

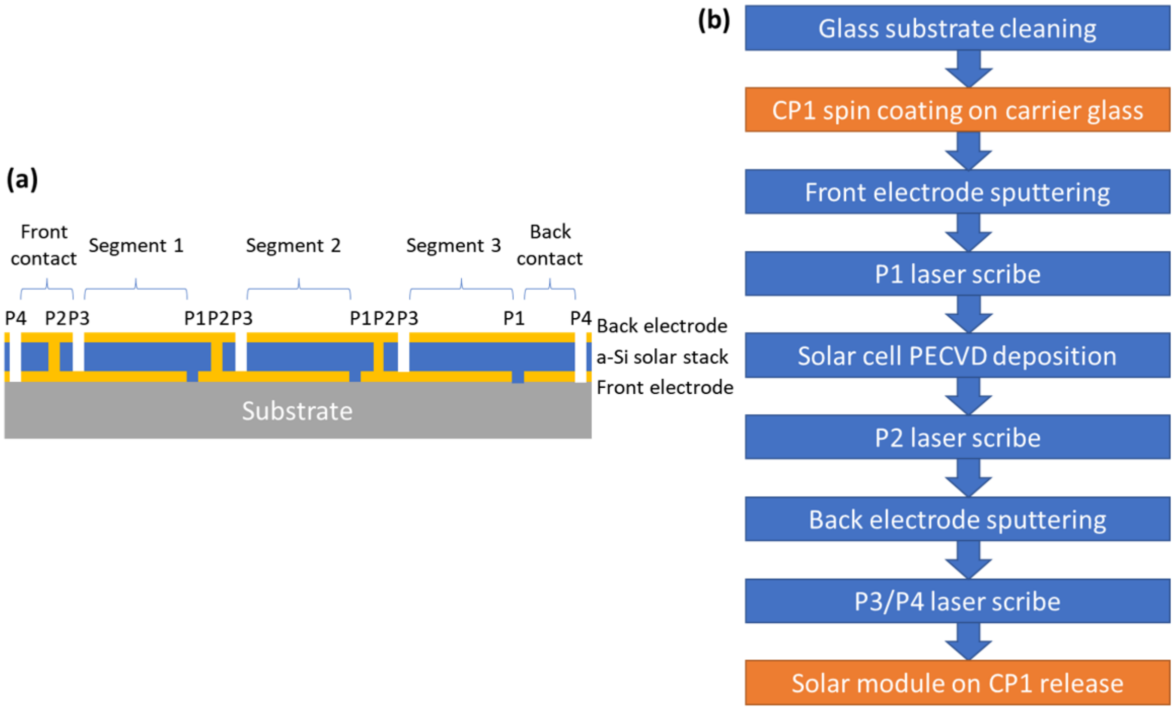


*Figure 1: (a) Cross section schematic of a typical 3 segment module design (b) Process flow for solar module fabrication. Steps in blue are standard for production on glass and steps in orange are specific to fabrication on polymer substrates.*

## Process flow description

The full Powersail module process flow is reported in Figure 1(b), and quickly covered here.

To fabricate an ultra-lightweight module for application in space, the substrate used to support the active layers must be thin. It also must be resistant to the harsh conditions encountered in space, and finally a flexible and lightweight substrate is desirable to be used in deployable structures. In this context, the substrate of choice is CP1 from NXLV, which is certified for long-duration space application [CP1 has been tested and is rated for a 10-year life in geosynchronous earth orbit (GEO)]. Thicknesses ranging from 3 µm to 25 µm were used. As the handling of free-standing substrate coupons is not realistic, the CP1 was coated onto cleaned glass carrier substrates. It will be possible to release the CP1 from the substrate at process end.

The first deposition step consists in sputtering a transparent and conducting oxide layer structure to form the solar module front electrode. This electrode is then ablated by P1 laser scribing. This process will remove the electrode material, ensuring insulation between the different segments.

After that, *p-i-n* a-Si layers are deposited by plasma enhanced chemical vapor deposition to form the solar module active region. Then the P2 laser scribing is performed, the parameters are chosen to ablate the a-Si layers while leaving the transparent conducting front electrode intact. The subsequent deposition of the metallic back electrode will then provide a connection to the front electrode through the ablated a-Si. Then the P3 laser scribing will remove the back electrode and a-Si insulating adjacent segments by the back electrode, completing the interconnection. Finally, a P4 laser scribe will ablate all the layers in order to define the module area.

The ultralight weight module is then ready to be removed from the carrier glass substrate.

## Project results

### Process developments

Standard module process on glass substrates is mastered at CSEM, however moving to the thin CP1 coated substrates raised several challenges.

- CP1 polymer must be coated to the glass substrate: initially we procured such samples directly from NXLV. Due to procurement issues and problems with customs, we developed our own spin-coating process.
- Laser scribing on CP1: as presented in the process flow description, laser processes must be tuned to specifically remove individual layers. Adding CP1 means that the laser processes must not damage it. This step was identified as the main challenge to overcome before project execution. P1 and P4 being the most aggressive processes, they are expected to be the most critical ones. Indeed, using our base process heavy damage was observed [Figure 2(a)]. An optimization using higher repetition rate but smaller power allowed to successfully remove the front electrode [Figure 2(b,c)], while keeping CP1 damage minimal (only visible with multiple passes).
- CP1 polymer must be released from carrier substrate at process end. This is achieved by soaking the assembly in DI water and waiting for the substrate to release. This approach worked well during initial tests without the full process, but at process end release proved more challenging, probably due to the thermal budget endured. This could be solved by longer soaking time, substrate scoring close to the edge, and CP1 protection under polyimide tape close to the scored edge.

The other process steps were implemented without major difficulties and the planned demonstrators could be fabricated.

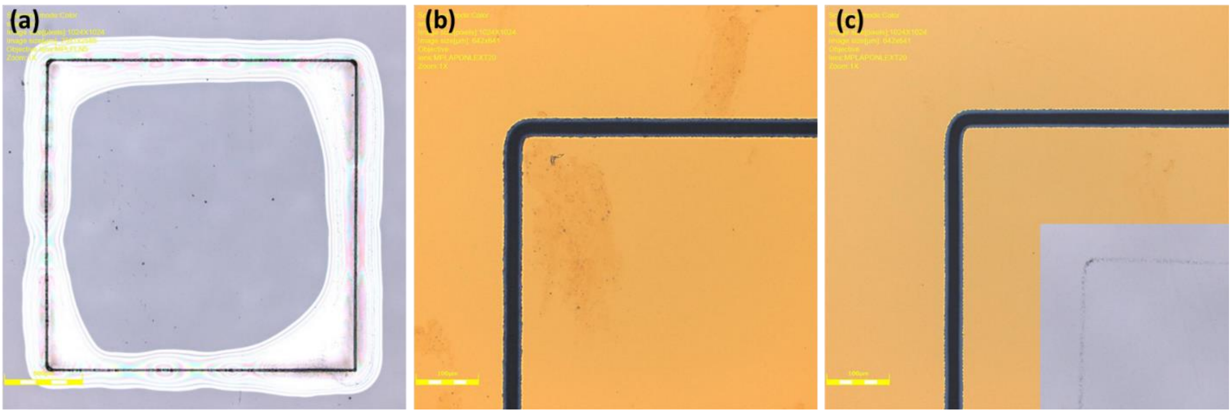


*Figure 2: (a) Scribe on CP1 using standard P1 parameters. (b) Scribe on CP1+electrode highest repetition rate, lowest power 1 pass. (c) Scribe on CP1 optimized 1 pass. Inset: scribe with same parameters but 3 passes on CP1 only.*

### Demonstrator results

With the individual processing steps validated, it was possible to fabricate ultra-lightweight devices. Over the course of the project several test devices were designed, fabricated and tested as intermediate steps towards the demonstrator module:

- Single test solar cell
- Single interconnect test structure
- 4×3 $cm^2$ active region test module

Results on these structures were instrumental for the successful realization of the final demonstrator, but are not discussed here.

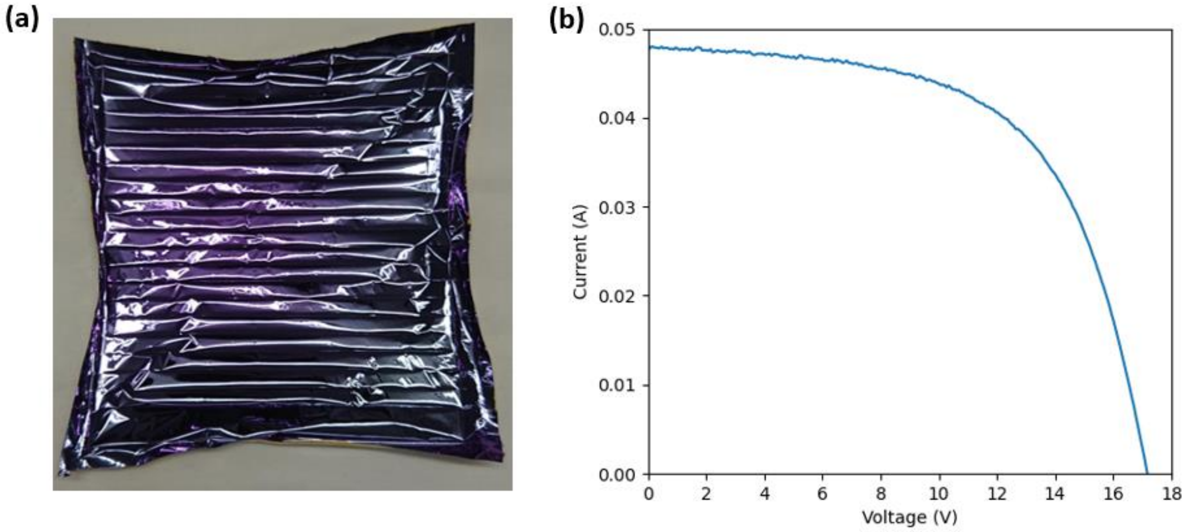


*Figure 3: (a) Picture of a released demonstrator module. (b) Current voltage curve of the best module fabricated.*

The layout of the final design was chosen relatively conservatively: significant spacing between the scribe lines will minimize the risks of shunts in case of improper alignment, and a large (20) number of segments would ensure low resistive losses. The demonstrator had a 10×10 $cm^2$, active area and a 11×10 $cm^2$ one including the contacts. A picture of the released minimodule is displayed on Figure 3(a). Performances were pushed by using very thin CP1 layer and optimizing the front electrode. Several working devices were produced, the best one having the properties reported in the table below after current voltage measurements under AM1.5g (terrestrial) illumination [Figure 3 (b)]:

| $V_{OC}$ [mV] | $I_{SC}$ [mA] | $J_{SC}$ [mA/cm²] | $J_{SC}$ segment [mA/cm²] | FF [%] | Eta [%] | $P_{MPP}$ [W] | Weight [mg] | W/kg perf [W/kg] |
|---|---|---|---|---|---|---|---|---|
| 17.18 | 47.91 | 0.48 | 9.58 | 59.81 | 4.92 | 0.49 | 88 | 5591 |

Solar simulators tuned for AM0 (space) illumination were not available at CSEM, therefore a study was performed to evaluate the performances of the demonstrator in space, considering the illumination spectra and the cell spectral response. A 6927 W/kg output was calculated.

This demonstrates that it is possible to reach close to 7000 W/kg performances in space despite using a relatively low efficiency technology. The module produced exhibited efficiencies below 5%, and the key to achieve such power per weight figures was working with an ultra-thin substrate. The efficiency demonstrated here is still low compared to state-of-the-art thin film silicon technology, where values well in excess of 10% for multijunction a-Si/a-SiGe/µc-Si thin-film solar cells. Even for single junction a-Si cell, we can produce in-house devices with >9% efficiency using advanced light trapping schemes. It would be tempting to consider that implementing this approach to the Powersail technology would be highly beneficial. However, we estimated that the efficiency gains might be significantly or even completely offset by weight gains for W/kg performances.

While the scope of Powersail was the development of the ultralight weight module only, for the full system the figure of merit should include the weight of the deployment mechanism. In this context, for a device having an efficiency like current demonstrator, a larger deployment system will be required to achieve the same power than one using a more efficient solar panel. The efficiency will thus have a bigger impact compared to when considering the solar module alone. Improving the efficiency is therefore important for the development of the Powersail technology.

## Conclusion

In the Powersail project a process has been developed to fabricate 10×10 $cm^2$ demonstrator ultra-lightweight solar modules. The long-term goal is to apply this technology to solar power satellites with terrestrial microwave energy collection. The device combines space-certified CP1 polyimide from NXLV with thin film a-Si silicon solar technology. To achieve this, several new process steps were developed. This was combined with the existing knowledge on a-Si solar module processing to allow the successful fabrication of the demonstrator. Despite a relatively low power conversion efficiency inherent to a-Si solar cells, with a measured 4.92 % value under AM1.5g, the weight of the demonstrator is only 88 mg for 0.49 W resulting in a very high power density. The performances under AM0 were estimated considering the spectral response of the cells and the differences between AM0 and AM1.5g. The generated power would increase to 0.61 W for the device, increasing the power density, despite a reduced 4.4% efficiency due to the blue shifted spectrum. The weight value is for the solar panel only and the relevant figure should include the booms and deployment system. Due to the relatively low efficiency of the demonstrator, a very large area is needed to compensate which will increase the weight of the system. As a result, efficiency improvements are required to demonstrate the full potential of the technology for SPS. The subsequent steps for the development of this technology - beyond the Powersail project- would be to improve efficiency, assess the reliability in space environment, study deployment systems for such large area structures, and upscale it for large-area production, in a roll-to-roll process.