Project 12: Project Scientific Progress – Fall 2009 to Fall 2015

The project studied the performance of full-scale STPV window, through testing and simulation (see **On STPV windows for façade and skylight applications**). The optical and thermal properties of the STPV window, and the presence of low emissivity coatings or suspended films have a direct impact on operating temperatures, window electrical performance and durability. Issues such as heat management, visual and thermal performance as well as cost and durability are as important as STPV electricity production. E.g. the selection of STPV optical properties has a direct impact on STPV electrical performance, solar heat gains and daylight availability within the building. A deeper understanding of these interactions and the ability to measure and predict key properties such as the solar heat gain coefficient (SHGC) and thermal conductance (U-value) allow PV researchers and the window industry to provide the necessary PV materials and designs for high performance STPV window. Focus was given to two promising STPV cell technologies: transparent a-Si/nc-Si PV films (see "**On Silicon-based STPV cells"**) and low cost organic PV films (see "**On organic STPV cells**") with tunable optical properties. The project developed, refined and fabricated processes, materials and STPV devices (TRL1 to TRL4) to enhance the performance of STPV technologies, suited for window and skylight applications.

On STPV windows for façade and skylight applications: The research on STPV windows focused into 3 major components.

- Study of the potential benefits of STPV windows on the building energy, daylighting and thermal performance through the selection of the STPV optical properties. An integrated simulation model (thermal, electrical and daylighting) was developed and verified with experimental data. The potential performance of Poly-Si, a-Si/μc-Si and organic (OPV) PV technologies was studied for a perimeter office, utilizing various façade designs. The selection of the optical properties was shown to be sensitive on the daylight and lighting controls applied on the building and the photovoltaic cell technology integrated into the STPV window (figure 1). A STPV module with 30% visible effective transmittance (integrated as the outer layer of a double glazed window, incorporating a low emissivity coating on surface-3) was ideal in providing sufficient daylight conditions throughout the year and resulting to an annual end-use electricity consumption of as low as 30 kWh/m^2/yr. STPV visible transmittance higher than 30% should be avoided as it will result in reduced annual PV electricity yield and undesirable solar gains. In addition, simulation results suggested that high cell operating temperatures of up to 64°C could occur that might cause accelerated degradation when organic thin film technologies are used.

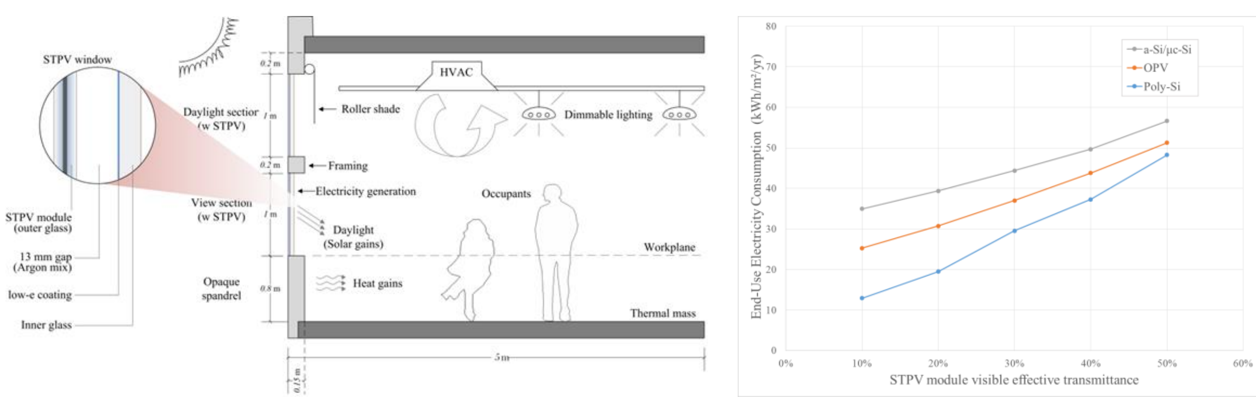

Figure 1. A schematic of major interactions between the STPV windows, the office space and the occupants (left) and the annual end-use electricity consumption of three STPV cell technologies (right),

for a typical perimeter office.

- Full–scale prototyping of STPV windows. Several STPV prototype modules were fabricated, utilizing opaque crystalline Si PV cells arranged in such a way as to allow light to pass through the resulting space between the cells or a-Si/μc-Si "see-through" thin film. Various degrees of transparency were achieved (6%-48% of effective visible transmittance) with various electrical efficiencies. The STPV modules were integrated as the outer layer of multi-glazed insulating units (double or triple-glazed incorporating low-emissivity coatings) (Table 1). The thermal, electrical and daylighting performance of the STPV windows were studied to better understand the impact of various design parameters on the STPV window performance. The experimental data generated was used to verify the integrated simulation model developed for STPV windows. It was found that the reduction of the STPV window thermal conductance (from 2.5 W/m^2K to 0.81 W/m^2K) can result into an increase of up to 10°C on the PV cell operating temperature. The use of a low emissivity coating or suspended film can result an increase of up to 7°C on the cell while the location of the coating or film within the STPV window assembly has little impact on the cell temperature (less than 0.5°C). Finally, the average STPV window temperature is strongly affected by the effective transmittance of the STPV module (outer layer): The lower the transmittance (which in return results to higher absorbance and electrical efficiency), the higher the average STPV window temperature.

Table 1. Electrical, optical and thermal properties of representative STPV window prototypes, developed under the project. Note that the name of the prototype indicates its transmittance under visible spectrum (e.g. STPV6% has an effective transmittance of 6%).

Name of window	PV technology	η_{mp}	P_{mp} W	V_{oc} (A)	I_{sc} (A)	$\mu_{P,mp}$ %/°C	Solar Transmittance	Visible transmittance	Thermal conductance (W/m^2K)
STPV6%	Poly-Si	0.15	294.10	45.2	8.56	-0.43	0.046	0.058	2.013
STPV17%		0.13	240.40	37.61	8.52		0.136	0.172	
STPV29%		0.10	187.90	29.98	8.57		0.225	0.286	
STPV40%		0.07	133.30	22.28	8.48		0.314	0.399	
STPV5%	a-Si/μc-Si	0.09	139.77	168.45	1.039	-0.28	0.033	0.049	1.068
STPV7%		0.09	142.94	169.94	1.047		0.058	0.068	1.883

- The determination of solar heat gain coefficient (SHGC) for STPV windows. An experimental methodology was developed to determine the SHGC and overcome the lack of commercially available simulation tool or standard testing procedure able to estimate the SHGC of STPV windows with applied load (electricity produced by the STPV window is consumed by an electronic load operating at the maximum power point). The methodology utilized an indoor solar simulator and calorimeter facility (figure 2). A SHGC reduction from 2% to 20% was estimated, when the STPV windows were tested with no-load and with load applied at maximum power point. The reduction was dependant on the electrical efficiency of the module; the higher the efficiency, the higher the reduction on the SHGC. In addition, STPV window operating temperatures of up to 55.3°C were also observed, under irradiance of 1000 W/m^2 and ambient air temperature of 21°C. In the case of STPV windows utilizing opaque crystalline Si PV cells, a temperature differential of up to 13°C was observed between parts of the window covered with PV cells and with encapsulant only (no PV cells). Such differential temperatures were specific to poly-Si STPV windows and there were not apparent on the STPV windows utilizing a-Si/µc-Si "see-through" thin film with uniform optical properties.

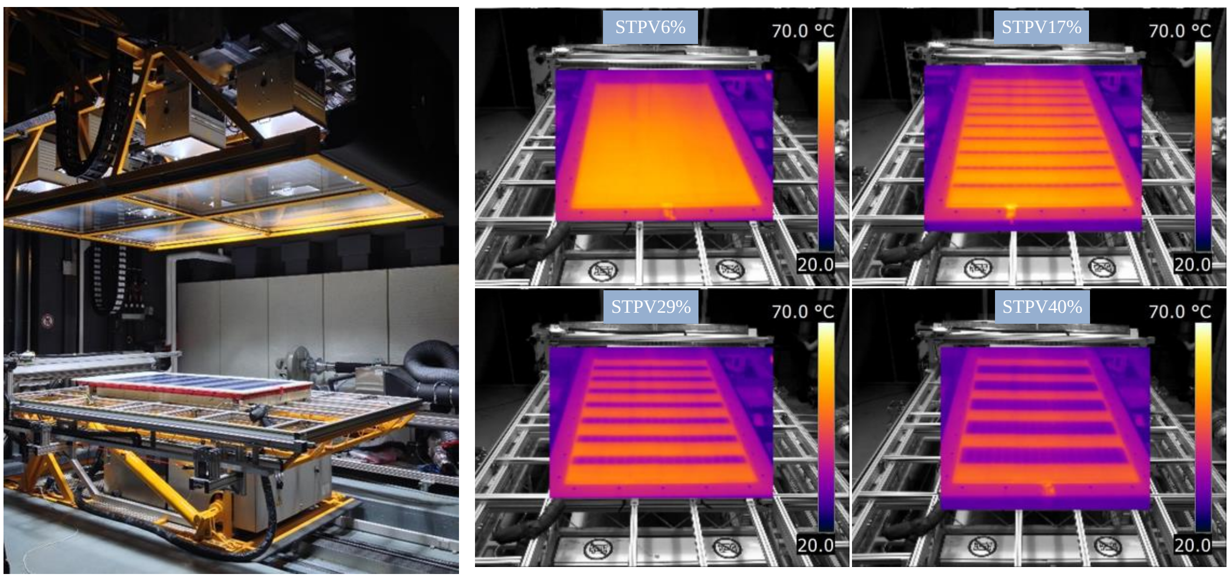

Figure 2. STPV window tested under the Concordia University solar simulator laboratory (left) and temperature profile for four STPV prototype windows, under 1000W·m^{-2} and ambient air temperatures of 21°C (right).

On Silicon-based STPV cells. The research on Silicon-based STPV cells focused into 3 major components.

- Development of transparent amorphous Si and nanocrystalline Si thin films to function as active parts of the STPV device (n-doped a-Si, p-doped nc-Si, and intrinsic). The films were optimized for electronic properties, optical absorption, and high transparency on visible region, using a new PECVD system. As a result, the fabrication of a nc-Si layer in the range of 150nm - 200nm with the efficiency of 4-5% in device integration and transparency of above 50% was possible (figure 3).

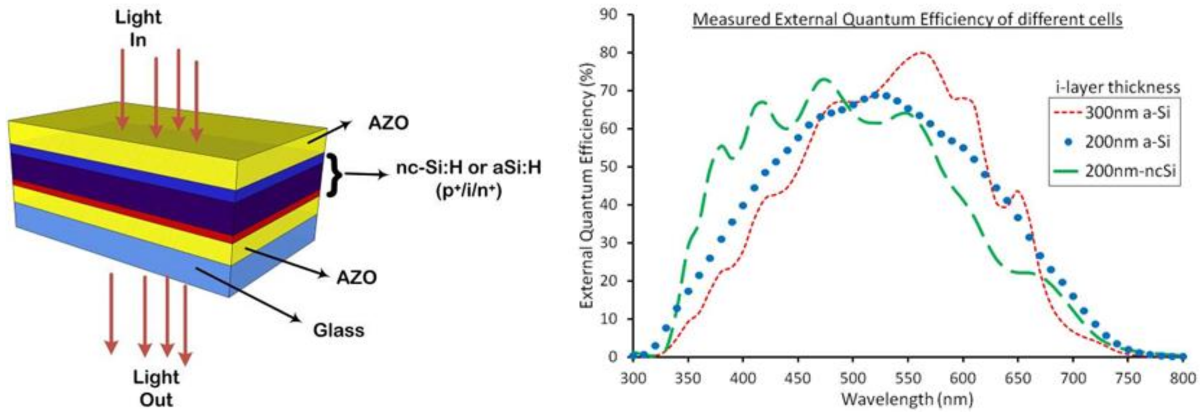

Figure 3. Schematic of the Glass/AZO/a-Si ($n^+/i/p^+$)/AZO solar cell structure on glass (left) and EQE of developed cell with 200nm nc-Si in compare to previously developed 300nm and 200nm a-Si absorber layer (right).

- A process was developed to deposit Al-doped ZnO films by RF-sputtering that resulted to high transparency and low resistivity (as low as 0.3 mΩ·cm by post annealing in vacuum at 300^0C) of the transparent oxide films (TCO). The purpose was to completely eliminate the metal grid in the cell structure. In order to further enhance the performance of the device, an advanced light trapping transparent conductive layer was designed and fabricated (figure 4). A nanoplasmonic metallic nano-island with silver on transparent AZO coated glass improved the conductivity in TCO, and improved light absorption by guiding incoming light to appropriate coupling mode of absorbing layer (nc-Si).

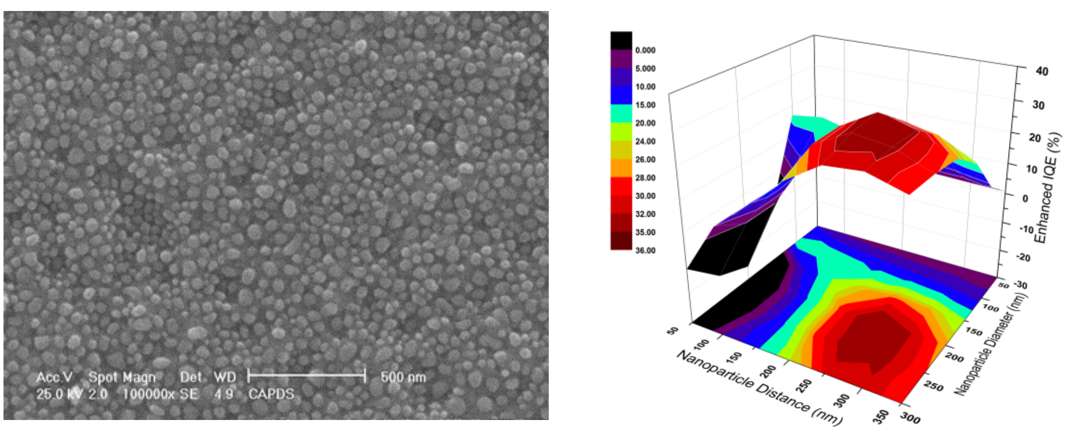

Figure 4. Silver nano-island fabrication after thin film deposition and nanofabrication on glass coated with sputtered AZO (left) and Internal Quantum Efficiency (IQE) silver nano-island on top of proposed nc-Si:H solar cell as a function of different parameters, through FDTD simulation (right).

- Integration of the individually optimized process steps made possible the fabrication of a STPV thin-film on glass and plastic substrates. Prototype a-Si/nc-Si solar cells were fabricated and tested under a flash solar simulator (standard AM1.5). Electrically isolated (by reactive ion etching) 0.25 cm^2 device area was used for probing, achieving electrical efficiencies of up to 6.53% (figure 5).

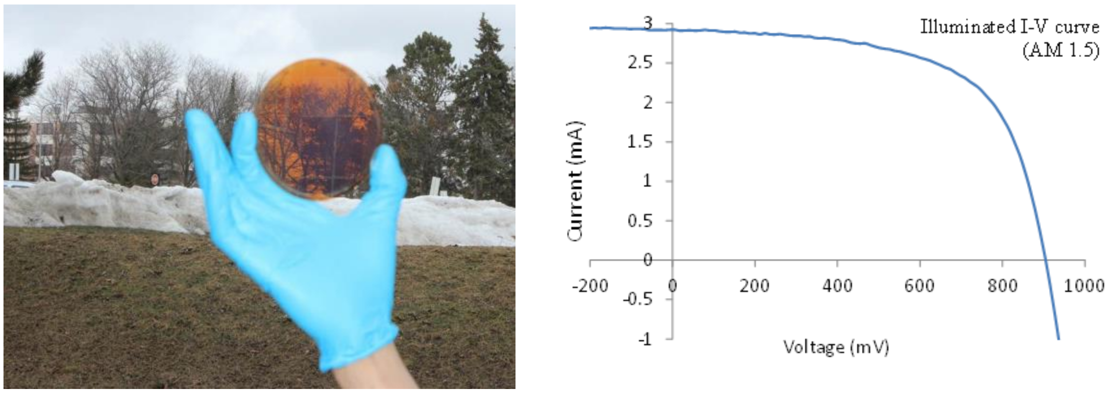

Figure 5. Image of the complete Glass/AZO/a-Si (n^+/i/p^+)/AZO solar cell prototype (left) and illuminated I-V characteristic of the cell (right).

On organic STPV cells. The research on organic STPV cells focused on the synthesis and evaluation of several copolymers. The most promising candidates for STPV window applications were tested in bulk heterojunction (BHJ) solar cells and tandem solar cells. Major results are summarized below:

- Several grams of PCDTBT, a 2,7-carbazole-based copolymer were prepared (figure 6) following a reliable synthetic procedure. This material is among the most efficient polymers studied in polymeric solar cells reaching power conversion efficiency of up to 7.2% and expected lifetime up to 7 years.

- Two TPD-based materials — namely PBDTTPD and AP079 — were synthesized using Stille cross coupling reaction or direct heteroarylation polymerization, respectively (figure 4). The latest method is a cheap, green and efficient polymerization that led to high molecular weights materials. Using the donor-acceptor (*push-pull*) architecture, the polymers demonstrated power conversion of 7.1% (for PBDTTPD) and 6.2% (for AP079).

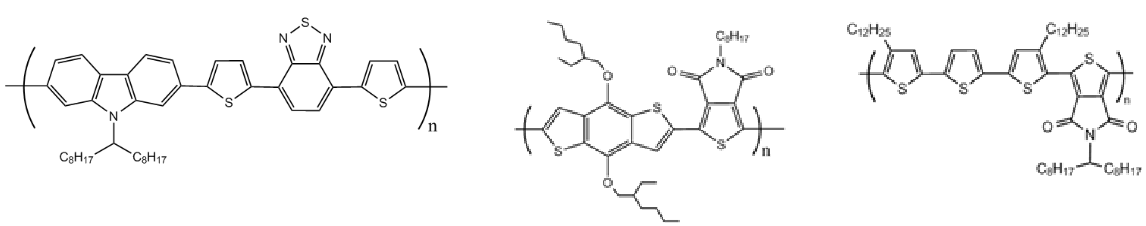

Figure 6. Chemical structure of PCDTBT (left), PBDTTPD (middle) and AP079 (right).

- In-depth investigation of Thieno-thiazole, Furo and selenopheno[3,4-c]pyrrole-4,6-dione-based copolymers (TTz, FPD and SePD) was undertaken (figure 7). Several FPD and SePD copolymers were synthesized and evaluated, with P7 reaching power conversion efficiencies up to 6.1%, in single layer BHJ solar cells (optimized devices); for TTz power conversion up to 4.38% was reached, for P4.

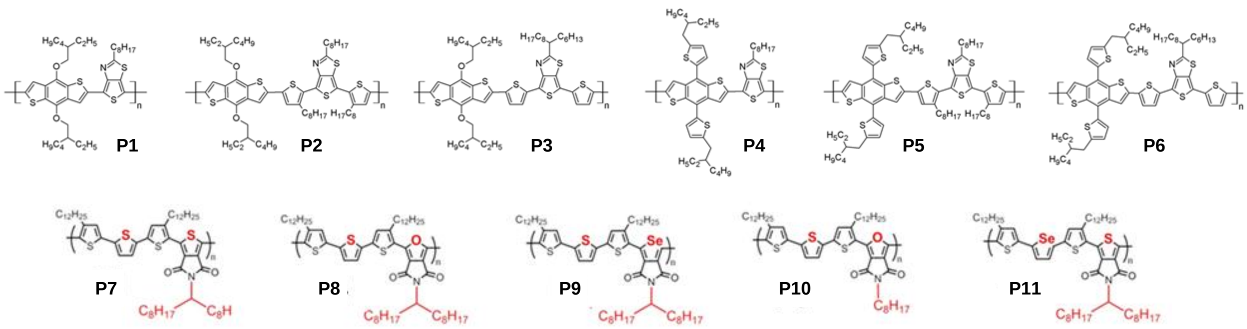

Figure 7. TTz copolymers (P1 to P6) and, FPD and SePD copolymers (P7 to P11), synthesized and characterized under this project.