**Project 12: Cell Design for Window and Skylight Applications**
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## Introduction and Background

During the last 20 years there has been an increased tendency towards the use of transparent facades in commercial buildings, in which windows cover 60-70% or more of the facade area. This trend is expected to continue as daylight and view to the outdoors are associated with enhanced productivity and well being. However, it has been shown[1] that modern facades only require a certain transparency ratio to achieve both optimal levels of transmitted daylight and views to the exterior. Windows and skylights are complex elements which need to be designed in an integrated manner by taking into account, among others, the following important requirements:

1. Provision of adequate daylight and view to the outdoor environment: daylight can be provided by both transparent and translucent glazing, but a clear view is only provided by transparent glazing. Diffuse daylight is generally preferred in an office environment in order to avoid glare problems.
2. Impact on building energy performance: reduction of heat transfer from/to the exterior environment so as to reduce energy consumption for space cooling and heating, and possibly energy production.
3. Thermal and visual comfort for the space occupants: thermal comfort depends on the temperature of the indoor window glass layer, while visual comfort primarily relates to glare prevention and light quality.

In most office buildings, where reduction of cooling energy costs is a major consideration, double glazing is generally utilized with a low-emissivity coating on one of the two surfaces facing the cavity to reduce heat transfer by longwave thermal radiation. The outer glass layer often includes a tint to reduce transmission of solar radiation. Rather than having a tint or using ceramic frit on the outer glass to reduce solar transmittance, a layer of semitransparent photovoltaics (STPV – the term will be used to cover both transparent and partly transparent PV) may be utilized to achieve the twin purpose of reducing solar heat gains while generating solar electricity, thus possibly turning a facade into a net energy generator. This potential has been recognized and some products have begun appearing incorporating thin film PV such as Photovol[2]. However, the additional cost of the facades is significantly higher than that of PV modules with the same output. Thus, further research is required to bring down costs of fenestration with STPV.

It has been shown that STPV can provide significant energy savings[3]. STPV can contribute to electricity savings when comparing artificial lighting replaced by daylight through the window[4] and for cooling-dominant areas they can be used in place of tinted glass as a tool for reducing cooling loads[5]. Li, *et al*[6] showed that for Hong Kong, including $CO_2$ trading, the simple monetary payback for STPV alone was 102 years but when combined with an appropriate lighting control strategy it could be reduced to 15 years. For modern highly glazed facades, it has been shown[7] that just a portion of the transmitted daylight is adequate to meet indoor lighting requirements, particularly when a controlled dimmable lighting system is employed in conjunction with automatically controlled motorized shading. As shown in Fig. 23, L. E. Robinson and A. K. Athienitis[8] studied a 3-section facade concept - the bottom third being opaque, the middle portion clear and the top third covered by glazing with spaced cells or STPV, and found that when both savings in lighting energy consumption and electricity generation are taken into account, a facade that incorporates STPV has the potential to be a net generator of energy. However, the detailed impact on comfort and cooling loads needs to be studied in more detail with different STPVs.

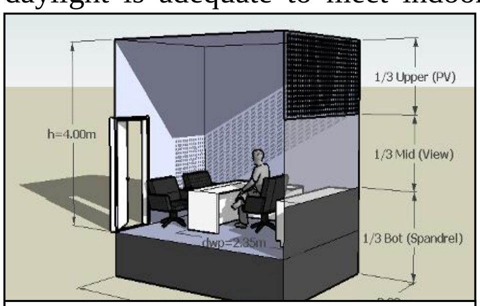

**Fig. 23**: 3 section façade with STPV

**Objective**: The project will study two ways to enhance the cost effectiveness of innovative fenestration designs with STPV: first by developing high efficiency transparent bifacial Silicon-based cells that harness as much solar radiation as possible while achieving adequate visible transmittance properties; secondly through low cost organic cells. An integrated energy model (electricity plus heat plus daylight) of STPV fenestration will provide direction to the development of the new designs.

**Development of Optimal Designs for Integration of STPV in Fenestration (AKA)**
We will investigate through modelling and computer simulations optimal configurations and designs for windows and skylights with semitransparent PV, taking into account electricity generation, reduction in electricity consumption for lighting, cooling energy consumption and comfort considerations. It will provide input to the design of cost effective solar cells with high efficiency and appropriate visible transmittance tuned in properties and suited to different orientations (generally between southeast and west facing in the Northern Hemisphere). Prototype windows with the transparent solar cells will be built and tested in collaboration with industry partner Unicel Architectural, a Canadian manufacturer of fenestration products (see attached support letter).

Activities planned in this subproject by the team of A. K. Athienitis at Concordia are as follows:
1. Literature and technology review. Development of detailed multilayer glazing energy model that incorporates semitransparent PV; development of appropriate performance indices for electricity generation, visible transmittance and solar heat gain coefficient. (Year 1)
2. Development of detailed daylighting and lighting model for typical office with 3-section facade and performance of simulations for different glazing area ratios and orientations, as well as STPV properties; provision of initial feedback to the design of inorganic and organic cells. (Year 2)
3. Development of mathematical model for integrated energy analysis of typical office space, taking into account electricity generation and energy consumption for lighting and cooling plus heating. Performance of extensive simulations for different climates, building types and orientations. Provision of revised feedback to design of transparent cells. Development of a small scale prototype with Silicon cells and evaluation of performance. (Years 3-4)
4. Development of prototypes and testing in collaboration with industry partner Unicel; comparison with simulation results. Provision of final feedback to cell design and its integration into windows and skylights. Development of prototype incorporating organic materials. (Years 4-5)

**Silicon-Based STPV Cells for Windows and Skylights (SS )**
We will develop Silicon-based STPV cells with high efficiencies. The tasks are listed below:
1. *Formation of spherical Silicon crystals:* Sphere-shaped Si crystals will be formed from powdered Si feedstock[9] materials and from crystalline substrates. Crystals with improved electronic quality will be a focus to obtain high-efficiency solar cells[10]. Work will also include structural and electrical characterization of the crystals, as well as testing of spherical diodes with diffused p-n junctions. (Years 1-3)
2. *Formation of nano-porous Si layers on spherical diodes:* An electrochemical etching (ECE) process with HF circulation will be developed for the formation of nano-Porous Si (nano-PS) films on spherical surfaces. Nano-PS films, due to the quantum confinement, show interesting luminescence[11] properties which can be exploited to obtain higher PV efficiencies through photon-shifting. Optimally luminescent nano-PS will be developed. The films will be studied by scanning electron microscopy (SEM), atomic force microscopy, transmission electron microscopy, transmission electron diffraction and X-ray diffractometry (XRD). (Years 1-3)
3. *Formation of RF-sputtered zinc oxide (ZnO) thin films on plastic substrates:* The wide band gap[12], high chemical stability, high transparency, and good electrical conductivity (with proper dopants) make ZnO an interesting transparent conductive oxide. Al-doped ZnO films are cost-efficient. RF-sputter deposition of ZnO films on plastic substrates will be developed using Al and ZnO targets.

AC sputtering will also be investigated for high deposition rates. Crystallinity and morphology will be investigated by XRD and SEM. (Years 2-4)

4. *Process integration for cell fabrication:* The developed process steps will be integrated in a cell fabrication sequence. Key steps will be: p-n junction formation on spherical crystals by thermal diffusion, diode mounting onto transparent polyethylenetelephthalate polymer substrate[13], controlled nano-PS layer formation, via opening by mechano-chemical etching, coating of transparent polymeric dielectrics, deposition of ZnO films, and formation of electrodes. Tests for electrical & optical properties, mechanical reliability, and stability (accelerated tests) will be carried out. (Years 2-5)
5. *Investigation of transparent conductive polymers:* In order to lower the production costs, transparent conductive polymers[14] will also be separately studied and investigated for integration with PET substrates. This will provide better adhesion, mechanical reliability, and improve carrier transport to the ZnO layers. (Years 4-5)
6. *Investigation on Integrated Electronics:* Considering the recent progress of flexible electronics[15], the integration of simple power-conditioning circuits at the module level will be investigated. Circuit design and testing will first be separately carried out, and the developed technology will be integrated to the cell/module fabrication process. (Year 5)

*Key Features of the Proposed Technology:* Cells are of bifacial nature: increased electric output; high conversion efficiency; efficient light absorption; the tiny spheres absorb light from different directions, including diffused light. Transparency: different transparencies can be obtained by adjusting the size and packing density of spheres. UV absorption: The PET-like polymers have a high UV absorption. Flexible nature: The mechanically flexible modules can be integrated into skylights and windows.

**Low-Cost Organic Semitransparent Solar Cells (ML)**

In parallel, polymer-based semitransparent solar cells will also be investigated. This activity is complementary to Project 5.4.2 led by M. Leclerc. Indeed, polymer bulk heterojunction (BHJ) solar cells based on composites of an electron-donating conjugated polymer and an electron-accepting fullerene offer great promise for realization of low-cost solar cells[16,17,18]. During the past decade, research has focused on regio-regular poly(3-hexylthiophene) (P3HT) as the standard electron-donating material in polymer BHJ solar cells with important progress in understanding the device science and associated improvements in the device efficiency. Relatively high performance polymer BHJ solar cells made from a mixture of P3HT and [6,6]-phenyl C61 butyric acid methyl ester (PCBM) have been reported with maximum power conversion efficiencies of $\eta_e$ = 4-5%[19,20,21]. Although approaches to improving the efficiency of P3HT/PCBM cells are still being reported, the relatively large band gap of P3HT (~1.9eV) limits the fraction of the solar spectrum that can be harvested, and the relatively small energy difference between the top of the $\pi$-band (highest occupied molecular orbital, HOMO) of P3HT and the lowest unoccupied molecular orbital (LUMO) of the fullerene acceptor results in a low open-circuit voltage, $V_{OC} \approx 0.6V$. These fundamental energies defined by the electronic structure of the semiconducting polymer (the energy gap and the HOMO energy) must be decreased in order to achieve polymer BHJ solar cells with power conversion efficiencies of 6% and higher.

Recently several classes of low-band gap polymers have been developed to better harvest the solar spectrum with deeper HOMO energies that can potentially increase $V_{OC}$[22,23,24]. These polymers are designed to exploit internal charge transfer from an electron-rich unit to an electron deficient moiety within the fundamental repeat unit. Among them, alternating copolymers developed in Canada and based on poly(2,7-carbazole) derivatives[25], with a suite of electron deficient moieties to choose from, are particularly fascinating. The different electron deficient moieties can be used to tune the electronic energy gap of the semiconducting polymer while the deep HOMO of the carbazole leads to higher values for $V_{OC}$[26]. The implied flexibility in the synthesis can lead to both a smaller bandgap that enables the harvesting of a larger fraction of the solar radiation spectrum, and a deeper HOMO energy that increases the open circuit voltage of the photovoltaic device. Recently, M. Leclerc and collaborators have reported a semi-transparent polymeric material that demonstrates power conversion efficiency up to 6% from a BHJ cell with $V_{OC}$ approaching 0.9 V.

On the basis of these promising results, the research team will develop different poly(2,7-carbazole) derivatives with different band gaps and electronic properties. These new copolymers will be designed following the calculations performed at Concordia. They will be characterized and integrated in different solar cell configurations (as with the Silicon-based SPTV designs). More precisely, the team will:

1. Synthesize different poly(2,7-carbazole) derivatives with bandgaps ranging from 1.2-1.9 eV (Yr 1-2)
2. Evaluate their physical properties (Molecular weights, Absorption, HOMO-LUMO levels, hole and electron mobilities) (Year 2-3)
3. Evaluate their performance in different BHJ solar cells when blended with fullerenes (Year 4)
4. Develop and test functional solar cells. Evaluation of their stability (in collaboration with S. Sivoththaman) (Year 5)

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