



A Review of Materials Science Research Pathways and Opportunities for Building Integrated Photovoltaics

光伏建筑一体化之材料科学研究途径与机遇述评

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Accepted for publication on 3rd August 2016

Abstract - Building integrated photovoltaics (BIPV) represent a powerful and versatile tool for achieving the ever increasing demand for energy-efficient and energy-harvesting buildings of the near future. The BIPV systems offer an aesthetical, economical and technical solution to integrate solar cells harvesting solar radiation to produce electricity being an integral part of the climate envelopes of buildings. Building integration of photovoltaic (PV) cells are carried out on sloped roofs, flat roofs, facades and solar shading systems, where the BIPV systems replace the outer building envelope skin, thus serving simultaneously as both a climate screen and a power source generating electricity. Hence, BIPV may provide savings in materials and labour, in addition to reducing the electricity costs. Nevertheless, in addition to specific requirements put on the solar cell technology, as the BIPV systems act as the climate protection screen it is of major importance to have satisfactory requirements on rain tightness and durability, where various building physical issues such as heat and moisture transport in the building envelope also have to be considered and accounted for. Research within materials science in general and within PV technology in particular may enable and accelerate the development of highly innovative and efficient BIPV materials and systems. Sandwich, wavelength-tuned, dye sensitized, material-embedded concentrator, flexible (e.g. copper indium gallium selenide CIGS and cadmium telluride CdTe), thin amorphous silicon, quantum dot, nanowire, brush-paint and spray-paint solar cells, different surface technologies and various combinations of these are examples of possible research pathways for PV and BIPV. From a materials science perspective, this work presents a review bridging the path from the current state-of-the-art BIPV to possible research pathways and opportunities for the future BIPV.

Keywords - building integrated photovoltaics, BIPV, solar cell, materials science, surface.

I. INTRODUCTION

The demand for energy-efficient and energy-harvesting buildings is growing, hence initiating the exploration of miscellaneous solutions. Building integrated photovoltaic (BIPV) systems are increasing in popularity and usage as they represent a powerful and versatile tool for achieving the ever increasing demand for zero energy and zero emission buildings of the near future, hence providing an aesthetical, economical and technical solution to integrate solar cells to become an integral part of the exterior climate envelopes of buildings.

Building integrations of photovoltaic (PV) cells are carried out on sloped roofs, flat roofs, facades and solar shading systems, thus replacing the outer building envelope skin and hence serving simultaneously as both a climate screen and a power source generating electricity.

That is, BIPV may provide savings in materials and labour, in addition to reducing the electricity costs. Nevertheless, in addition to specific requirements put on the solar cell technologies, it is of major importance to have satisfactory requirements on rain tightness and durability, where various climate exposure factors and building physical issues such as heat and moisture transport in the building envelope also have to be considered and accounted for.

The aim of this work is to present from a materials science perspective an overview and bridge the path from the state-of-the-art BIPV systems of today to possible research opportunities for making the BIPV solutions of tomorrow.

II. STATE-OF-THE-ART BIPV SYSTEMS

The BIPV product range is very wide, and the BIPV products or systems may be categorized in different ways, e.g. as foil, tile, module and solar cell glazing products. On the other hand, building attached (applied/added) photovoltaics (BAPV) are regarded as add-ons to the buildings, thus not replacing the traditional building parts as BIPV systems are doing. Examples of BIPV tiles on building roofs are shown in Fig.1 [1,2]. Furthermore, two different BIPV products are depicted in Fig.2 [3,4]. For an overview and detailed information of state-of-the-art BIPV products it is referred to earlier studies [5,6].



Fig.1. Examples of BIPV tiles on building roofs, Solar Thermal Magazine (left) [1] and Applied Solar (right) [2].

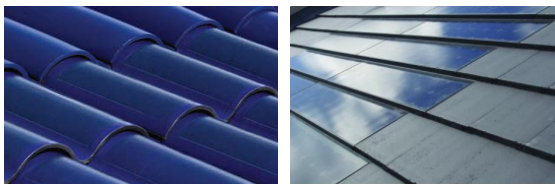


Fig.2. BIPV tile products, SRS Energy (left) [3] and Solar Century (right) [4].

III. MATERIALS SCIENCE RESEARCH PATHWAYS

3.1. IMPACT ON BIPV FROM PV DEVELOPMENT

The development of PV materials and their technologies may have an even stronger impact on the BIPV development in the years to come. This will especially be valid if one from the PV based research is able to tailor-make solar cell materials and solutions for building integration [7,8]. In Fig.3 there is given a timeline for reported best research-cell efficiencies, depicting all verified records for different PV conversion technologies [9].

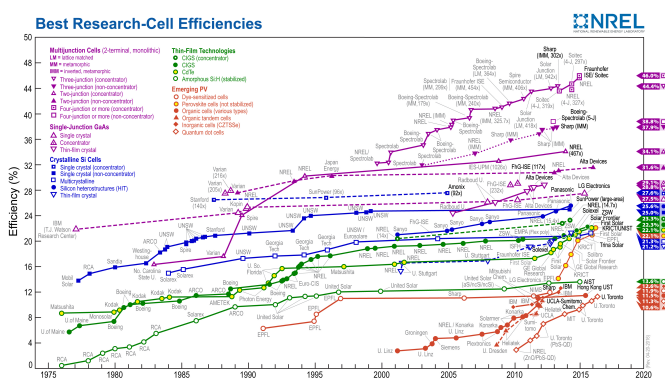


Fig.3. Timeline for reported best research-cell efficiencies (enlarge digitally to see details) [9].

The miscellaneous PV conversion technologies given in the overview in Fig.3 include crystalline Si, thin film, single-junction GaAs, multijunction and emerging technologies, and are collected from solar companies, universities and national laboratories [9].

Ongoing experimental studies range from those with more focus on pure materials science, e.g. quantum dots [10], to the more device focused ones, e.g. ceramic tiles [11].

3.2. HIGH-PERFORMANCE SOLAR CELLS

Research laboratories have for many years produced high-performance solar cells with efficiencies up to 25-40%. One approach is to use materials with higher purity and to eliminate the impurities along in the process. The back surface can be passivated with silicon oxide and amorphous silicon to minimize recombination losses at the surfaces and contacts. Furthermore, textured surfaces and buried contacts with minimal shading reduce optical losses. The total production is very expensive.

High-performance solar cells may also be made as solar cell concentrators or concentrated photovoltaic (CPV) cells. The highest solar cell efficiency for a CPV cell is currently 46.0% in 2016 (see Fig.3).

3.3. ABSORBING NON-VISIBLE SOLAR RADIATION

A system for harvesting solar radiation has been developed, using small organic molecules that are tuned to absorb specific non-visible wavelengths (i.e. ultraviolet and near infrared) of solar radiation and letting the visible solar radiation pass straight through (Fig.4), thus resulting in a solar cell able to produce electricity while still allowing people to see through a clear glass with no colour distortions [12]. Thereby, solar energy may be harvested by windows which apparently look like normal and clear windows.

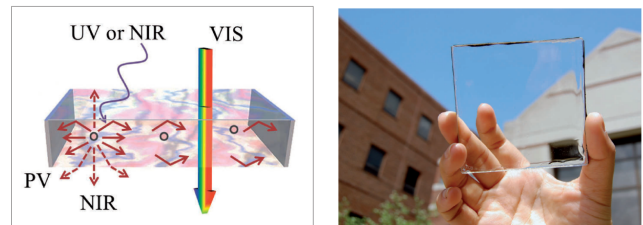


Fig.4. Solar harvesting tuned to absorb specific non-visible wavelengths of solar radiation and letting visible solar radiation pass straight through [12].

3.4. SANDWICH SOLAR CELLS

Sandwich or stack solar cells use several different material layers and cells with different spectral absorbances to harvest as much as possible of the solar radiation in a wide wavelength range. As an example, Fig.5 [13] shows a triple solar cell that has a top cell layer which absorbs the blue light and allows the other wavelength parts of the solar radiation to pass through. The green and yellow light ranges are then absorbed by the middle cell layer, and the red light is absorbed by the bottom cell layer. Hence, a much larger portion of the solar radiation may be utilized.

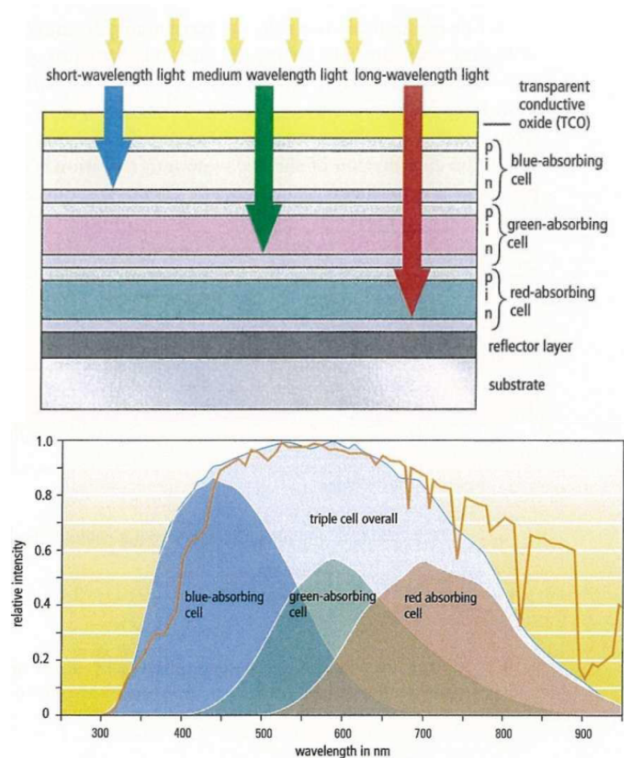


Fig.5. A triple solar cell with its configuration (top) and spectral responses (bottom) [13].

3.5. POLYMER SOLAR CELLS

Ultra-low cost and low-medium efficiency organic based modules are based on dye sensitized solar cells (DSSC), extremely thin absorbers, organic polymer cells and others. Organic semiconductors are less expensive than inorganic ones. The highest reported efficiency for an organic solar cell (with the exception of DSSC) was 6.5 % in 2007 and has now reached 11.5 % in 2016 (see Fig.3). However, polymer solar cells are more sensitive to degradation, where ultraviolet solar radiation and oxygen from the atmosphere may oxidize the organic layer.

3.6. DYE SENSITIZED SOLAR CELLS

Dye sensitized solar cells (DSSC) have solar radiation absorbing dyes usually deposited onto a titanium dioxide (TiO₂) substrate material like in the Grätzel solar cell. The schematic structure and band diagram for DSSC are depicted in Fig.6 [14,15].

The DSSC technology is often compared with and stated to imitate the photosynthesis, and is by Grätzel called "the artificial leaf". The cells absorb across the visible spectrum and therefore lead to an increased efficiency ranging from 7 % under direct solar irradiation (AM1.5) and up to 11 % in diffuse daylight. The TiO₂ material is a renewable and non-toxic white mineral, thus giving smaller environmental impacts, where an easy manufacturing process contributes to lower costs. The reduced production costs and the decreased environmental impacts result in shorter energy and economical payback time, and therefore makes the DSSC technology very promising. The market share for this

technology is still very small, but it is expected to rise and may achieve a great influence in the future.

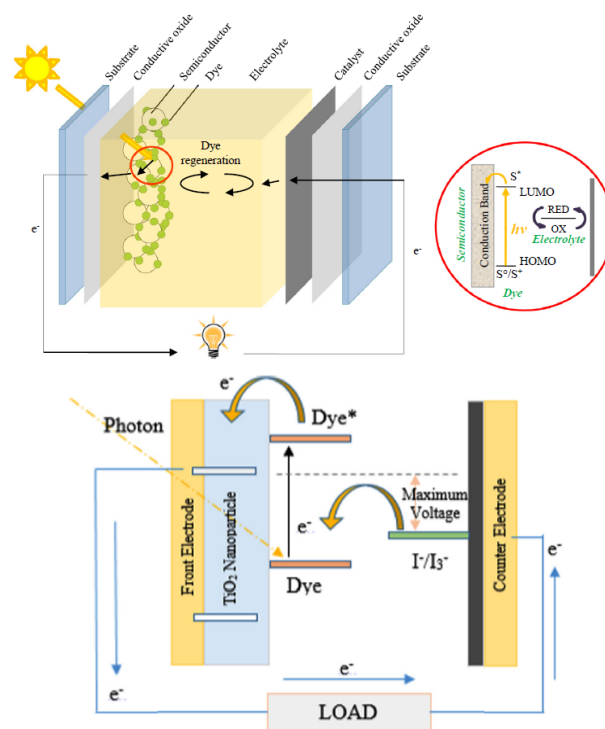


Fig.6. DSSC schematic structure (top [14]) and band diagram (top [14] and bottom [15]).

3.7. ANTENNA-SENSITIZER SOLAR CELLS

So-called solar cell "antennas" may harvest several wavelengths, i.e. a much broader spectrum of the solar radiation. This technology concept may also be compared to the more "traditional" sandwich solar cells. "The use of antenna-sensitizer molecular devices may constitute a viable strategy to overcome problems of light harvesting efficiency in the spectral sensitization of wide-bandgap semiconductors." [16]. A principle drawing of an antenna-sensitizer solar cell example is depicted in Fig.7 [16].

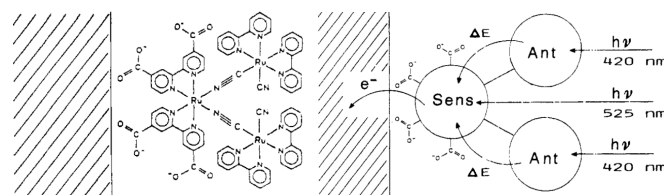


Fig.7. Illustrative representation of the adsorption mode of the trinuclear complex on the TiO₂ surface (left) and block diagram showing the function of the trinuclear complex as an antenna-sensitizer molecular device (right) [16].

3.8. CIGS AND CdTe SOLAR CELLS

Flexible and lightweight CIGS (copper indium gallium selenide) and cadmium telluride (CdTe) solar devices are shown in Fig.8 (principle configuration drawings) and Fig.9 (photos of actual devices), and have yielded an active area efficiency of 14.7 % and 9.4 %, respectively [17]. These flexible and lightweight devices increase the integration

flexibility and allow building integration in structures which can not take the additional load of heavy and rigid glass laminated solar modules. "The flexible solar modules can be laminated to building elements such as flat roof membranes, tiles or metallic covers without adding weight and thus, the installation costs can be reduced significantly." [17].

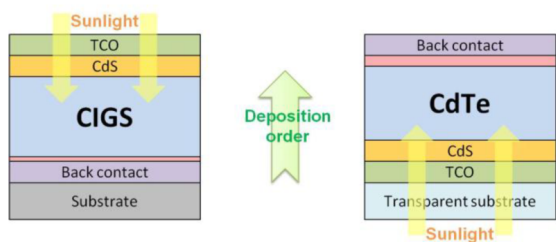


Fig.8. Schematic configuration build-up of CIGS (left) and CdTe (right) thin film solar cells [17].

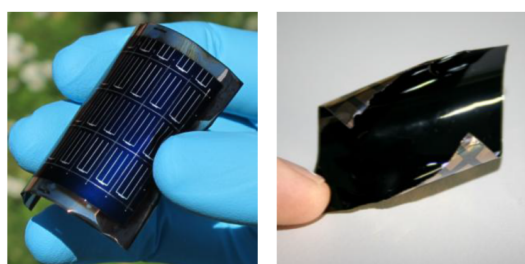


Fig.9. Photos of flexible CIGS (left) and CdTe (right) solar cells on polyimide substrates [17].

The flexibility of CIGS solar cells is also noted by others, e.g. quoting "Thanks to flexible lamination, CIGS solar cells now have the ability to both realize their potential as the most efficient thin film technology and to dominate the building-integrated photovoltaics (BIPV) market in the future" [18]. A bending test carried out on a CIGS solar cell on flexible borosilicate ultra-thin glass substrate (100 μm) is shown in Fig.10 [19].

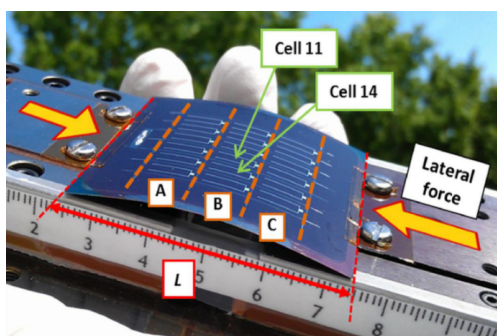


Fig.10. Bending test of a CIGS solar cell on flexible borosilicate ultra-thin glass substrate (100 μm) [19].

3.9. QUANTUM DOT SOLAR CELLS

Experimental investigations carried out by Semonin et al. [10] have reported photocurrent quantum efficiencies exceeding 100 % in a quantum dot solar cell, being enabled by multiple exciton generation (MEG). The MEG process may occur in semiconductor nanocrystals or quantum dots where absorption of a photon with at least twice the bandgap energy

creates two or more electron-hole pairs. In Fig.11 there are shown scanning electron microscope images of TiO₂ nanorods and cadmium sulfide (CdS) quantum dots [20]. For further details, including charge transfer processes between CdS and TiO₂ in a quantum dot nanowire based solar cell, it is referred to the review by Badawy [20]. Hence, miscellaneous new and exciting discoveries within solar cell research may with time find its way into the PV and BIPV systems for the buildings of tomorrow.

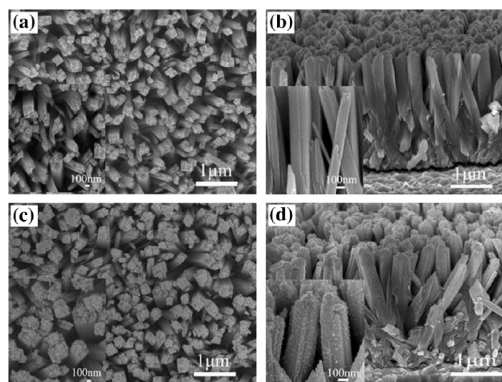


Fig.11. Field-emission scanning electron microscope (FESEM) images of (a) TiO₂ nanorod array (top view), (b) cross-sectional SEM image of TiO₂ nanorod array grown on FTO (fluorinated tin oxide), (c) top and (d) cross-sectional view of CdS quantum dots coated on a TiO₂ nanorod array [20].

3.10. SOLAR CELL CONCENTRATORS

It is possible to envision to be able to make an exterior surface capable of harvesting as much solar energy as if the whole exterior surface was covered with a PV material, while in fact the actual PV material surface is considerably smaller and located somewhat beneath the exterior surface, hence reducing the PV material costs. This may be viewed as a special built-in concentrator system integrated within the PV surface. Hence, the idea may then be to fabricate a "solar concentrator" at a microscopic material level embedded in the solar cell surface and beneath [5].

A luminescent solar concentrator (LSC) example is depicted in the illustrations given in Fig.12 [21], where first dye-doped polymethylmethacrylate (PMMA) plates were prepared by an in-situ polymerization method and thereafter crystalline silicon solar cells were mounted to the as-prepared dye-doped PMMA plates.

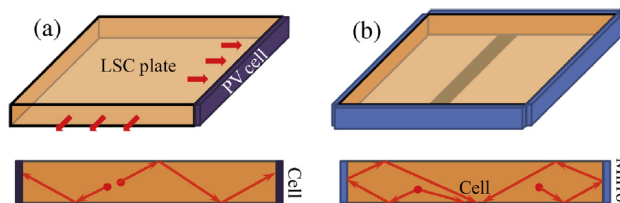


Fig.12. Illustration of a luminescent solar concentrator with (a) side-mounted and (b) bottom-mounted solar cells [21].

Naturally, for solar cell concentrators to be applied as BIPV, it is crucial to make the concentrator dimensions as small as possible, e.g. with respect to the total thickness.

An example still at a macroscale, but nevertheless being part of the ongoing process of reducing the dimensions of solar concentrators, is shown in Fig.13, where the height of the polyurethane (PUR) concentrator element is as small as 25 mm, thereby entitling the authors to name their system as building integrated concentrating photovoltaics (BICPV) [22].

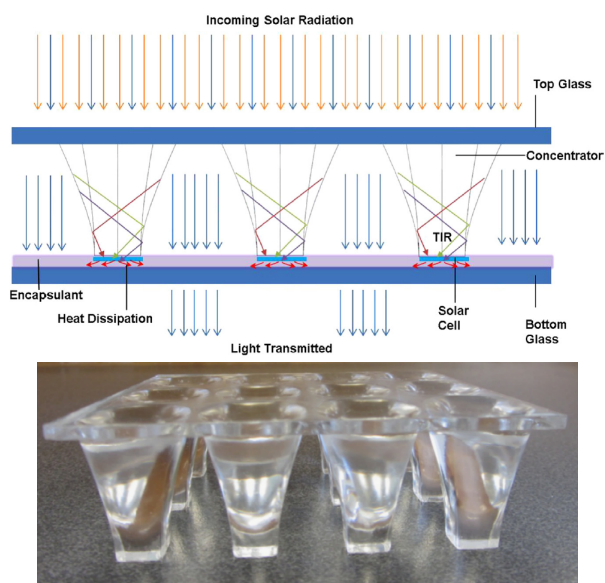


Fig.13. Schematics of a solar concentrator utilizing total internal reflection (TIR) in order to guide the incoming solar radiation to the active solar cell parts (top) and actual concentrator element array made of polyurethane (bottom) [22].

3.11. INVERTED PYRAMID TEXTURING

An illustration of inverted pyramid texturing utilized to harvest more of the incident solar radiation is depicted in Fig.14 [23].

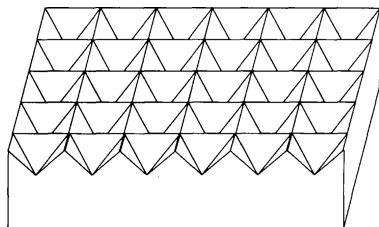


Fig.14. Inverted pyramid geometry texturing utilized for light trapping on Si solar cells [23].

Inverted pyramid geometry texturing of a solar cell surface allows a more effective solar radiation trapping due to the following three effects: (a) reduced front surface reflectance by providing the opportunity for a portion of the incoming solar rays to undergo a triple bounce, (b) increased path length of the solar ray through the cell, thus absorbing a larger fraction of the solar rays which has entered the cell before exiting the cell, and (c) increased amount of solar rays reflected from the back surface, by total internal reflection at the front surface/air interface by making the incident angle greater than the critical angle. Note also the work by e.g. Kang et al. [24] where they have designed an asymmetrically textured structure for efficient solar radiation trapping in BIPV.

3.12. INTEGRATION OF PV IN CONCRETE

A possible option for the future that e.g. Enecolo and SolarPower Restoration Systems Inc. have looked into is to integrate the PV cells in materials at an early stage, e.g. in prefabricated concrete plates [25,26]. Since concrete is one of the most widely used construction materials in the world, and the integration of PV with concrete surfaces has remained largely undeveloped, this research field has a huge potential. Furthermore, note also the BIPV product DysCrete using an organic dye on a concrete surface to harvest solar radiation and generate electricity, the name origin from dye sensitized solar cells and concrete [27,28].

3.13. SOLAR CELL PAINT

Thin laminate and paint layer solar cell materials represent another future option for the PV sector. Obviously, such materials have a huge potential for BIPV applications. Considerably reduced material usage, extremely easy application like brush or spray painting and the fact that nearly any building may easily be coated on any surface are crucial advantages that hold the potential of changing the way photovoltaics are being integrated in buildings. Wear and tear and reduced durability of the solar cell paint layers may be compensated by more frequent maintenance intervals, i.e. repainting, if the costs will be kept sufficiently low for the emerging solar cell paint systems we are just merely catching the very first glimpses of today.

A complete photovoltaic cell was fabricated by Javier and Foos [29] using a handheld airbrush, dilute solutions of cadmium selenide (CdSe) and cadmium telluride (CdTe) nanorods, commercially available silver paint, and transparent-conducting-electrode-coated glass, as illustrated in Fig.15. They explored the suitability of a handheld airbrush to create high-quality films and were able to form ultra smooth surfaces from 20 to 500 nm in thickness. The current estimated efficiency is very low, but the research demonstrates the variety in the potential of PV cells [29]. In this respect, see also the study by Lee et al. [30].

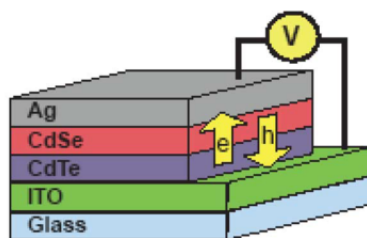


Fig.15. Illustration of a PV cell configuration composed of ITO-coated glass, CdTe and CdSe nanorods, and silver paint. Electrons (holes) are preferentially pushed towards the Ag (ITO) electrode as depicted by the arrows [29].

Moreover, a patternable brush painting process for fabrication of flexible polymer solar cells was investigated by Heo et al. [31], their flexible polymer solar cell being depicted in Fig.16. Furthermore, schematics of a brush painting process to prepare brush-painted flexible organic solar cells are shown in Fig.17, where highly transparent and flexible Ag nanowire electrodes with low sheet resistance were utilized [32]. It is

referred to the available literature for other examples of investigations carried out on brush painting, spray coating and flexible solar cells [33-36].

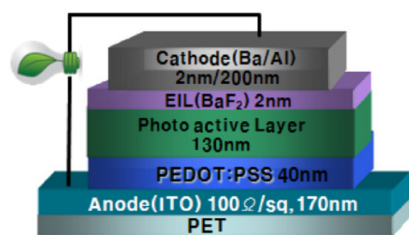


Fig.16. Device structure of a flexible polymer solar cell [31].

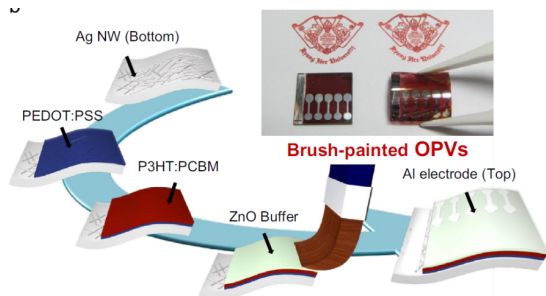


Fig.17. Schematics depicting a brush painting process of preparing brush-painted flexible organic solar cells. The inset photo shows the flexibility of the brush-painted flexible organic solar cells [32].

3.14. HYBRID SOLAR CELLS

Hybrid solar cells are combining various properties of different materials. Typically, they consist of both organic and inorganic semiconductors, where the organics absorb the solar radiation and the inorganics function as the electron transporter. The structure and interface types are of crucial importance for the hybrid solar cells. Often an increased interfacial surface area between the organic and inorganic materials is desired in order to facilitate charge separation and increase the efficiency.

Miscellaneous nanoscale structures like mesoporous inorganic films mixed with organics, alternating inorganic-organic lamellar structures and nanowire structures may be made. Hybrid solar cells exist in many variations and combinations and hence constitute a very broad group of solar cells, where e.g. nanoparticle, nanowire, quantum dot, graphene, carbon nanotube, conjugated polymer, silicon, cadmium telluride, cadmium sulfide, perovskite, titanium dioxide and dye sensitized materials among others are being applied in various devices [37-51].

3.15. ELECTROCHROMIC PV DEVICES

Solar cell glazing products available today have potential for optimization, e.g. the solar radiation utilized in a solar cell cannot be exploited as daylight in the buildings. One possible optimization pathway may be to incorporate electrochromic materials [52-62] with PV materials in completely new and innovative devices. Hence, we may pay attention to the following quote: "Nevertheless, various optimizing schemes of the key properties in these fenestration types have to be chosen and carried out, e.g. the solar radiation utilized in a solar cell and converted into electricity cannot be exploited as

daylight in the buildings. One might also envision incorporating solar cells or photovoltaics with electrochromic materials in completely new fenestration products, where the photovoltaic and electrochromic material or materials cover the whole glazing area. However, normal windows still need a transparent (in some cases translucent) state, and when in this state such windows cannot produce electricity from the visible part of the solar spectrum as the visible light is transmitted through the window." [52].

The National Renewable Energy Laboratory (NREL) of Golden (USA) has built self-powered photovoltaic electrochromic devices up to 25 cm² [60]. For these self-powered PV electrochromic devices, "...the main concerns for future large-area applications are the possible loss of the energy generated by the PV device for larger dimensions, a small range of optical modulation and rather low transmittances in the clear state." [60].

Thus, integrating PV with electrochromics or other smart window (colour switching) technologies in a way so that the PV-electrochromic elements will provide shading when there is need for it is yet another research path [63-67]. Thereby, electricity will be produced while the windows block the solar radiation. Moreover, in the building industry electrochromic windows with no external electrical wiring may at the moment be most desirable.

3.16. SELF-CLEANING SURFACES

Self-cleaning window glass panes already exist commercially, which are supposed to decrease the need for manual cleaning substantially. This technology may also be used for the glass surfaces of PV and BIPV systems. Most of these self-cleaning glass panes function by applying a photocatalytic coating like e.g. titanium dioxide (TiO₂) on the outer glass surface, where the incident ultraviolet (UV) solar radiation reacts with this coating to break down organic dirt. Thereafter, rain water spreads evenly over the hydrophilic surface and runs off in a "sheet" taking loosened dirt with it, thus drying quickly without leaving stains or streaks. A state-of-the-art review on commercially available self-cleaning glazing products along with a study on future research pathways are presented by Midtdal and Jelle [68].

According to their operational state when purchased, the commercial self-cleaning products may be divided into factory- and user-finished products [68]. Factory-finished products cover all factory produced glazing products (e.g. windows) where a self-cleaning surface is already operational when purchased. User-finished (user-do-it-yourself) products involve liquid products, either in form of a spray or a roll-on applicator, which can be applied by the user to existing glass surfaces to obtain a self-cleaning coating or film on top of the regular glass pane or any other material.

Various strategies are applied and pursued for achieving a self-cleaning effect, where these may be categorized into the following different surface characteristics:

- (a) Photocatalytic hydrophilic surface.
- (b) Superhydrophobic or ultrahydrophobic surface.
- (c) Microstructured or nanostructured surface.

Commercial factory-finished self-cleaning products are most often based on photocatalytic hydrophilic coatings or surfaces, whereas user-finished self-cleaning products are normally based on the creation of hydrophobic coatings on the desired surfaces.

In the following we will learn that there exists an important correlation between superhydrophobicity and a structured coarseness of a surface, whereupon the term icephobicity will also be discussed. As a general rule of thumb, the coarseness dimensions of the structured self-cleaning surface should be smaller than the dirt particles to be removed by the self-cleaning effect.

3.17. SUPERHYDROPHOBIC AND ICEPHOBIC SURFACES

Superhydrophobicity, icephobicity and similar aspects on how to avoid snow and ice formation on the solar cell surfaces will be among the important issues to address. In Fig.18 [69,70] this challenge is shown, as depending on the climate conditions, snow and ice may stick to smooth glass surfaces for large inclination angles and even for vertical surfaces.



Fig.18. Snow/ice slab firmly sticking to the glass surface of an insulated window pane even at an inclination angle of 90° during a laboratory experiment (left). Snow covering a solar cell panel at an inclination angle of 70° (right) [69,70].

Hydrophobicity is an often used measure of the repellent nature of a surface, and then especially to repel water. A completely hydrophobic surface has a water contact angle of 180°, whereas a completely hydrophilic surface has a water contact angle of 0°. A surface is considered as hydrophilic for water contact angles below 90°, hydrophobic above 90°, superhydrophilic below 5° (within 0.5 s or less) and superhydrophobic above 150° [71-74].

The hydrophobicity of a surface will be dependent upon (i) the micro- and nanoscale coarseness of the surface, and (ii) the surface energy of the surface, where the former one may be considered as a mechanical property and the latter one as a chemical property, respectively. In general, a micro- or nanoscale coarse surface and a low surface energy will give a hydrophobic surface. A low surface energy can be achieved by use of reactive molecules mainly classified into four categories, i.e. fluorinated molecules, alkyl molecules, non-fluorinated polymers and silicon/silane compounds [73,75].

A surface's coarseness on a micro- and nanoscale has a direct influence on its repellent and hydrophobic properties. The wetting states of a liquid drop placed on a surface are illustrated in Fig.19 depicting a smooth surface (where contact angle measure is shown), the Wenzel state, the Cassie-Baxter state and a combined state [76], where the Cassie-Baxter state represents the superhydrophobic state where liquid drops are

repelled as spheres from the surface (large contact angle). In the Wenzel state the liquid (water) drops are impaled by the nanorods (or similar structure) on the surface, while in the Cassie-Baxter state the liquid drops are resting on top of the nanorods with trapped air pockets beneath between the nanorods.

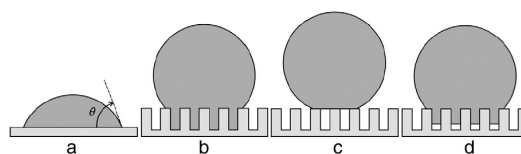


Fig.19. Wetting states of a liquid drop to a surface: (a) drop on a smooth surface (contact angle measure is illustrated), (b) Wenzel state, (c) Cassie-Baxter state, and (d) combined state [76].

In Fig.20 there is given an overview of the timeline of major advances in the area of liquid repellency, including advances in theory, polymer and surface chemistry, development of superhydrophobic surfaces (SHS), slippery liquid-infused porous surfaces (SLIPS), polydimethylsiloxane (PDMS) and polytetrafluoroethylene (PTFE) [77].

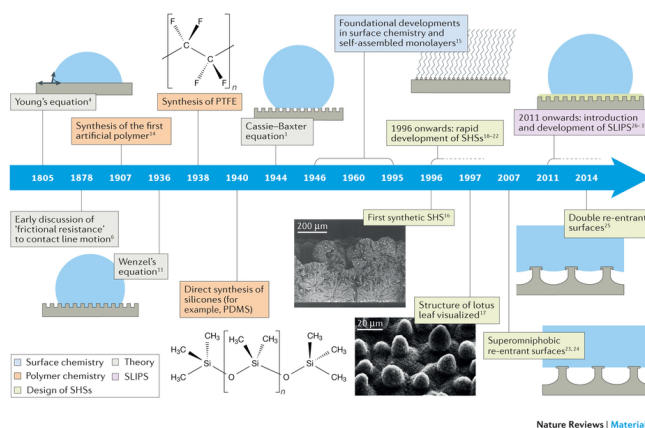


Fig.20. Timeline of major advances in the area of liquid repellency (enlarge digitally to see details) [77].

Examples of natural water-repellent leaf surfaces and artificially fabricated superhydrophobic surfaces are given in Fig.21 [78,79].

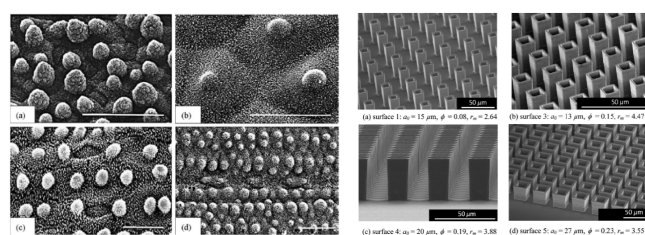


Fig.21. Micromorphologies for water-repellent leaf surfaces of (a) *Nelumbo nucifera* and (b) *Lupinus polyphyllus* (scale bars = 50 μm), and (c) *Gladiolus watsonioides* and (d) *Sinarundinaria nitida* (scale bars = 20 μm) (left four photos) [78]. Images of four artificially fabricated hollow hybrid superhydrophobic surfaces (scale bars = 50 μm) (right four photos) [79].

Several of the same principles may be applied for anti-icing investigations as for self-cleaning aspects, in particular superhydrophobicity and structured surface coarseness effects,

hence the term icephobicity has been introduced and is now in common usage. Anti-icing coating design cases with various roughness scales, including microscale roughness, nanoscale roughness and hierarchical roughness (combination of both micro- and nanoscale) are illustrated in Fig.22 [80].

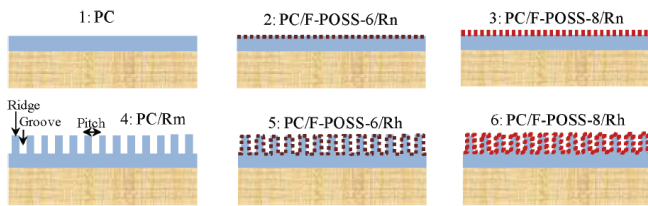


Fig.22. Anti-icing coating design cases with roughnesses Rn nanoscale, Rm microscale, and Rh hierarchical [80].

In Fig.23 there are shown micrographs of various surface structures for icephobicity, depicting nanocones, nanopits, micropillars and micropillars with embedded nanotextures [81]. Furthermore, Fig.23 also shows the effects of a nano-fluorocarbon coating on icing processes, where the water droplets on the coated surface have a much smaller contact area to the superhydrophobic surface, i.e. water spheres due to the large contact angle caused by the superhydrophobicity, resulting in a much longer starting time for icing and also a much longer total time needed to complete the whole icing process for the superhydrophobic surface than for the non-coated plain surface [82].

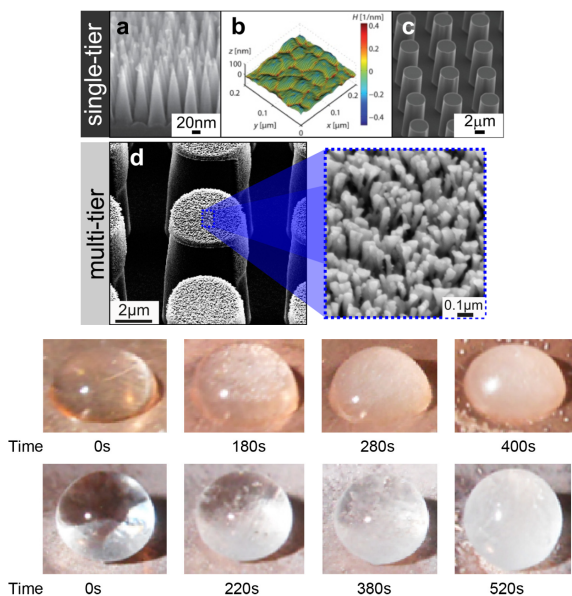


Fig.23. (Top) Micrographs showing relevant length scales and structures utilized in single-tier and multi-tier structures for icephobicity: (a) etched Si nanocones, (b) etched SiO₂ nanopits, (c) etched SiO₂ micropillars, and (d) etched Si micropillars/nanotextures with the nanotexture depicted in the inset image [81]. (Bottom) Icing process of a water droplet on a plain copper surface (top) and a nano-fluorocarbon coated surface (bottom) [82].

The task of preventing snow and ice formation involves other crucial aspects than merely removal of dirt and water from these surfaces. Freezing of water below 0°C represents a huge obstacle or challenge in this respect, which in some cases is further complicated by in general possible moisture

condensation from surrounding air and subsequent freezing on the surfaces. Although many promising results have been achieved, e.g. for prolonged freezing delays on superhydrophobic surfaces, there is still much research to be carried out before practical and efficient snow and ice avoiding/repelling surfaces for a full range of outdoor weather exposure conditions have been accomplished.

An interesting research pathway may be to investigate if it is possible to make some sort of force field solution. That is, to envision a force field which could repel all snow crystals already before they are impacting onto the solar cell surfaces, in addition to prevent any ice formation on the exterior surfaces (e.g. rain which freezes, and condensation and freezing processes from moisture in the ambient air). Hence, one has to ask what kind of force field this could be, which in addition is (ideally) not using extra energy. An electric or magnetic force field, or a combination of these, either static or dynamic, may be investigated. Or could something entirely different be envisioned? In order to be able to repel the snow crystals one may explore if the dipolarity in water molecules may be taken advantage of and utilized, even in solid state as snow and ice and not as liquid water, or the various transition states (gas, liquid and solid state) at the solar cell surfaces.

Natural, biological superhydrophobic surfaces like e.g. plant leaves and insect wings when damaged may regenerate their surfaces by biological growth processes and are therefore able to maintain their superhydrophobicity over their whole lifetime. Thus, one may ask if it could be possible to make artificial superhydrophobic surfaces which would continuously regenerate their surface patterns and thereby retain their superhydrophobic properties, i.e. self-healing, self-repairing or self-regenerating superhydrophobic surfaces.

3.18. FINAL REMARKS

As new building materials and components are being developed, including BIPV materials, it is of major importance to investigate the durability of these materials, e.g. by carrying out accelerated climate ageing in the laboratory [83]. Furthermore, conducting a robustness assessment of these materials and components may also be found to be beneficial [84]. Finally, it seems appropriate to end this with the following vision from Richard Lunt at Michigan State University: "Ultimately, we want to make solar harvesting surfaces that you don't even know are there." [12].

IV. CONCLUSIONS

Various research pathways and opportunities for building integrated photovoltaics (BIPV) from a materials science viewpoint are explored. Continued research and development within both PV and BIPV materials and technologies will improve the BIPV solutions in the coming years, e.g. with respect to solar cell efficiency, environmental aspects, robustness, long-term durability versus climate exposure, production costs and miscellaneous building integration aspects. Easily applicable and flexible solutions like e.g. paint applications of PV cells and bendable solar cells are among the future visions for BIPV.

ACKNOWLEDGEMENTS

This work has been supported by the Research Council of Norway and several partners through the research projects "Building Integrated Photovoltaics for Norway" (BIPV Norway) and "The Research Centre on Zero Emission Buildings" (ZEB).

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