# A Review of Materials Science Research Pathways for Building Integrated Photovoltaics

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**Abstract:** Buildings account for a large part of the world's usage of energy. Hence, there is a growing interest for renewable and non-polluting energy sources for utilization in buildings, both for existing and new buildings. A promising energy technology for buildings are building integrated photovoltaics (BIPV), which are part of or replace the traditional exterior building skin, e.g. roof and facades, and at the same time are being able to harvest the solar radiation and convert it to electricity in their solar cell elements. Thereby, for BIPV the properties and requirements for both the solar cell technology and the climate protection screen will be important to address, e.g. aspects like solar cell efficiency, power output and performance ratio as well as rain tightness, robustness, durability and building physical issues such as heat and moisture transport in the building envelope. This work presents from a materials science perspective the possible research pathways and opportunities for the BIPV of tomorrow. These pathways include sandwich, wavelength-tuned, dye sensitized, material-embedded concentrator, flexible, thin amorphous silicon, quantum dot, nanowire, brush-paint and spray-paint solar cell material technologies, different surface technologies and various combinations of these.

**Keywords**: Building integrated photovoltaics, BIPV, Solar cell, Materials science, Review.

## 1. Introduction

The interest and demand for energy-efficient and energy-harvesting buildings is continuously increasing, thus initiating the exploration of various solutions like e.g. building integrated photovoltaic (BIPV) systems which represent a powerful and versatile tool for achieving the 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. The building integrations of photovoltaic (PV) cells are carried out on sloped roofs, flat roofs, facades and solar shading systems, thereby replacing the outer building envelope skin and thus serving simultanously 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. 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 objective 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 future BIPV solutions.

## 2. The State-of-the-Art of BIPV

BIPV systems represent a wide product range and 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, thereby not replacing the traditional building parts as BIPV systems do. As an example, BIPV tiles on building roofs are shown in Fig.1. For an overview and detailed information of state-of-the-art BIPV products it is referred to earlier studies (Jelle et al. 2012b, Jelle and Breivik 2012a).

Fig.1. Examples of BIPV tiles on building roofs, Solar Thermal Magazine (left) (2010) and Applied Solar (right) (2010).

## 3. Materials Science Research Pathways for Possible Utilization in BIPV

### 3.1. PV Development and its Impact on BIPV

The ongoing development of PV materials and corresponding technologies may have a strong impact on the BIPV development and their possible building applications in the years to come, which will especially be valid if one from the PV based research will be able to tailor-make solar cell materials and solutions for building integration (Jelle and Breivik 2012b, Jelle 2016, Jelle et al. 2016b). Important in this respect is the timeline for reported best research-cell efficiencies which depicts all verified records for different PV conversion technologies as given in Fig.2, including crystalline Si, thin film, single-junction GaAs, multijunction and emerging technologies, collected from solar companies, universities and national laboratories.

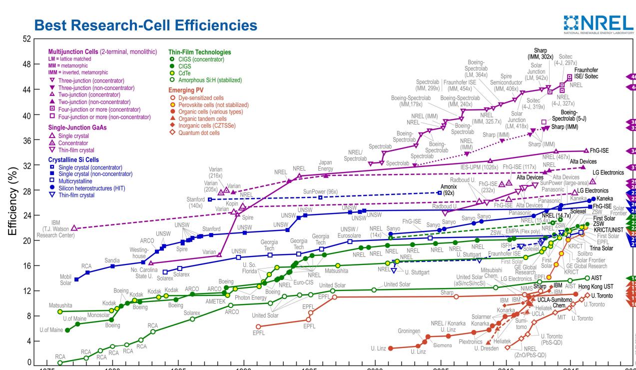


Fig.2. Best research-cell efficiency timeline (enlarge digitally to see details) (NREL 2016).

### 3.2. High-Performance Solar Cells

High-performance solar cells with efficiencies up to 25-40 % have been produced by research laboratories for many years. 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. Moreover, textured surfaces and buried contacts with minimal shading reduce optical losses. The total production is very expensive. Furthermore, 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.2).

### 3.3. Visible versus Non-Visble Solar Radiation

A solar radiation harvesting system has been developed, applying 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.3), hence resulting in a solar cell able to produce electricity while still allowing people to see through a clear glass with no colour distortions (Mourant 2014). Thus, solar energy may be harvested by windows which apparently look like normal and clear windows.

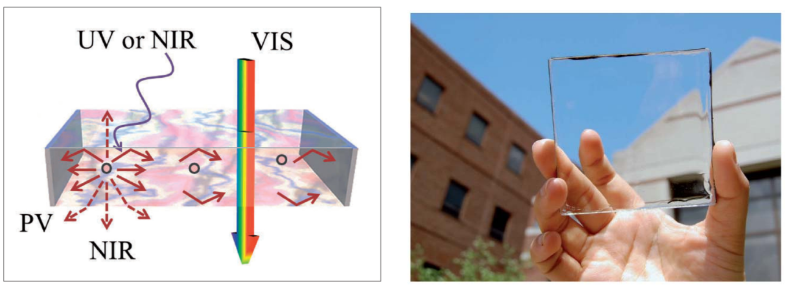


Fig.3. Solar harvesting tuned to absorb specific non-visible wavelengths of solar radiation and letting visible solar radiation pass straight through (Mourant 2014).

### 3.4. Sandwich Solar Cells

Sandwich or stack solar cells utilize 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, a triple solar cell 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 (DGS 2008). Thereby, a much larger portion of the solar radiation may be utilized.

### 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 (except for DSSC) was 6.5 % in 2007 and has now reached 11.5 % in 2016 (Fig.2). Noteworthy, polymer solar cells are more sensitive to degradation, where ultraviolet solar radiaion 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 ($TiO_2$) substrate material like in the Grätzel solar cell. 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 $TiO_2$ 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.

### 3.7. Antenna-Sensitizer Solar Cells

Solar cell ”antennas” may harvest several wavelengths, i.e. a much broader spectrum of the solar radiation, where 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.” (Amadelli et al. 1990).

### 3.8. CIGS and CdTe Solar Cells

CIGS (copper indium gallium selenide) and cadmium telluride (CdTe) as flexible and lightweight solar devices are shown in Fig.4, and have yielded an active area efficiency of 14.7 % and 9.4 %, respectively (Buecheler et al. 2011). 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.” (Buecheler et al. 2011).

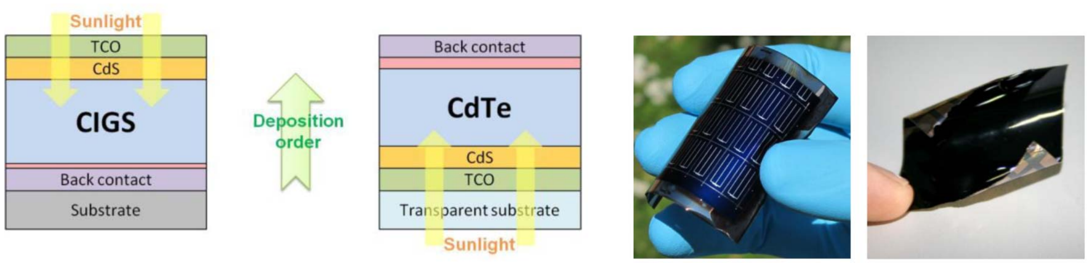


Fig.4. Principle configuration build-up and photos of flexible CIGS (nos. 1 and 3 from left) and CdTe (nos. 2 and 4 from left) thin film solar cells (Buecheler et al. 2011).

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” (Stuart 2012).

### 3.9. Quantum Dot Solar Cells

Experimental investigations carried out by Semonin et al. (2011) 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. For further details, including charge transfer processes between CdS and $TiO_2$ in a quantum dot nanowire based solar cell, it is referred to the review by Badawy (2015). 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.

### 3.10. Solar Cell Concentrators

One may 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 (Jelle et al. 2012).

Importantly, for solar cell concentrators to be applied as BIPV, both for new buildings and retrofitting of existing ones, 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.5, 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) (Baig et al. 2015).

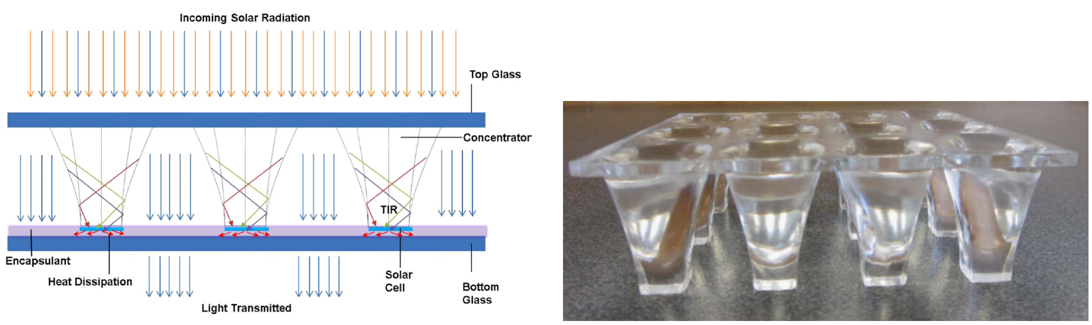


Fig.5. Schematics of a solar concentrator utilizing total internal reflection (TIR) in order to guide the incoming solar radiation to the active solar cell parts (left) and actual concentrator element array made of polyurethane (right) (Baig et al. 2015).

### 3.11. Inverted Pyramid Texturing

Inverted pyramid geometry texturing (Smith and Rohatgi 1993) 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. Attention should also be paid to the study by e.g. Kang et al. (2015) where an asymmetrically textured structure for efficient solar radiation trapping in BIPV was designed.

### 3.12. <u>Integration of PV in Concrete</u>

A possible future option 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 (Prasad and Snow 2005, SolarPower 2011). As 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. Moreover, 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 (DysCrete 2015ab).

### 3.13. <u>Solar Cell Paint</u>

Thin laminate and paint layer solar cell materials represent another future option for the PV sector. Clearly, 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.

Javier and Foos (2009) fabricated a complete photovoltaic cell by applying a handheld airbrush, dilute solutions of cadmium selenide (CdSe) and cadmium telluride (CdTe) nanorods, commercially available silver paint, and transparent-conducting-electrode-coated glass. The suitability of using a handheld airbrush to create high-quality films was explored, and they 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 (Javier and Foos 2009). In this respect, see also the study by Lee et al. (2013).

A patternable brush painting process for fabrication of flexible polymer solar cells was investigated by Heo et al. (2011), where their flexible polymer solar cell is depicted in Fig.6. Moreover, schematics of a brush painting process to prepare brush-painted flexible organic solar cells are also shown in Fig.6, where highly transparent and flexible Ag nanowire electrodes with low sheet resistance were utilized (Kang et al. 2014). It is referred to the available literature for other examples of investigations carried out on brush painting, spray coating and flexible solar cells.

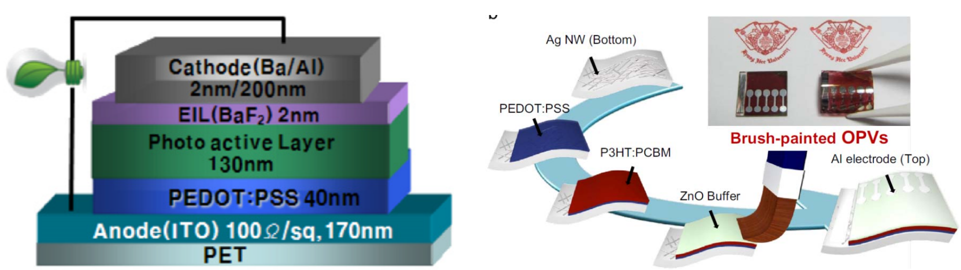


Fig.6. (Left) Device structure of a flexible polymer solar cell (Heo et al. 2011). (Right) Schematics depicting a brush painting process of preparing brush-painted flexible organic solar cells. The inset photo shows the flexibility of the brush-painted flexible organic solar cells (Kang et al. 2014).

### 3.14. Hybrid Solar Cells

Hybrid solar cells combine miscellaneous 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. Various 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.

### 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 with PV materials in completely new and innovative devices. Thus, 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.” (Jelle et al. 2012a). Hence, 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 (Ahn et al. 2007, Deb et al. 2001, Gao et al. 1999, Lampert 2003). Thus, electricity will be produced while the windows block the solar radiation. In addition, for the building industry electrochromic windows with no external electrical wiring may at the moment be the 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 might also be utilized 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 ($TiO_2$) 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 (2013). According to their operational state when purchased, the commercial self-cleaning products may be divided into factory- and user-finished products. Various strategies are applied and pursued for achieving a self-cleaning effect, where these may be categorized into different surface characteristics as (a) photocatalytic hydrophilic surfaces, (b) superhydrophobic or ultrahydrophobic surfaces, and (c) microstructured or nanostructured surfaces. 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. 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. Hydrophobicity is an often used measure of the repellent nature of a surface, and then especially to repel water. 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 (Xue et al. 2010, Yao and He 2014). Several examples of natural water-repellent leaf surfaces and artificially fabricated superhydrophobic surfaces are given in Fig.7. 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 include microscale roughness, nanoscale roughness and hierarchical roughness (combination of both micro- and nanoscale) (Xiao and S. Chaudhuri 2012).

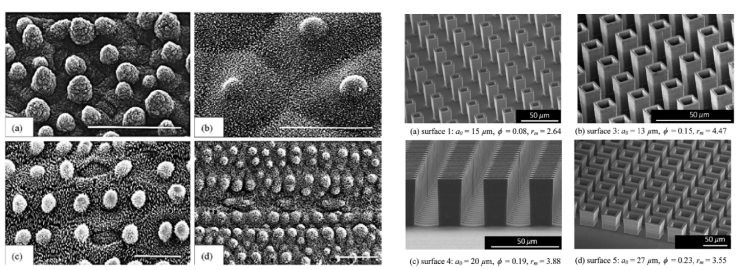

Fig.7. Micromorphologies for water-repellent leaf surfaces of (a) Nelumbo nucifera and (b) Lupinuspolyphyllos (scale bars = 50 μm), and (c) Gladioluswatsonioides and (d) Sinarundinaria nitida (scale bars = 20 μm) (left four photos) (Hsu et al. 2011). Images of four artificially fabricated hollow hybrid superhydrophobic surfaces (scale bars = 50 μm) (right four photos) (Dash et al. 2012).

Micrographs of various surface structures for icephobicity are shown in Fig.8, depicting nanocones, nanopits, micropillars and micropillars with embedded nanotextures. In addition, Fig.8 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.

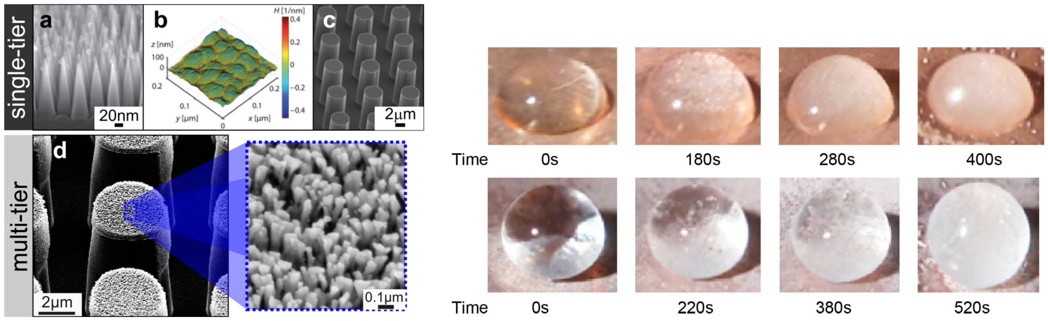


Fig.8. (Left) Micrographs with relevant length scales and structures in single-tier and multi-tier structures for icephobicity: (a) etched Si nanocones, (b) etched $SiO_2$ nanopits, (c) etched $SiO_2$ micropillars, and (d) etched Si micropillars/nanotextures with the nanotexture depicted in the inset image (Schutzius et al. 2015). (Right) Icing process of a water droplet on a plain copper surface (top) and a nano-fluorocarbon coated surface (bottom) (Wang et al. 2012).

Moreover, 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 will still be 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 satisfactorily achieved.

A very 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). Thus, one has to ask what kind of force field this could be, which in addition is (ideally) not using any 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 (Jelle.2013, Jelle et al. 2016a).

Furthermore, natural, biological superhydrophobic surfaces like e.g. plant leaves and insect wings when damaged may regenerate their surfaces by biological growth processes and are thus able to maintain their superhydrophobicity over their whole lifetime. Hence, 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 (Jelle et al. 2016a).

### **3.18. <u>End Notes</u>**

Following the development of new building materials and components, including BIPV materials, it is of major importance to study the durability of these materials, which may be achieved by e.g. carrying out accelerated climate ageing in the laboratory (Jelle 2012). Moreover, conducting a robustness assessment of these materials and components may also be found to be beneficial (Jelle et al. 2014). As a final remark, 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.*” (Mourant 2014).

## 4. Conclusions

A review has been presented where miscellaneous research pathways and opportunities for building integrated photovoltaics (BIPV) from a materials science viewpoint have been explored. The continued research and development within both PV and BIPV materials and technologies will improve the BIPV solutions in the years to come, e.g. with respect to solar cell efficiency, environmental aspects, robustness, long-term durability versus climate exposure, production costs and various building integration aspects. Among different future visions for BIPV one should note easily applicable and flexible solutions like e.g. paint applications of PV cells and bendable solar cells.

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