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

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ABSTRACT

Research within materials science photovoltaics (PV) technologies may enable and accelerate the development of highly innovative and efficient building integrated photovoltaics (BIPV) materials and systems. Sandwich, wavelength-tuned, dye sensitized, material-embedded concentrator, flexible (e.g. copper indium gallium selenide CIGS and cadmium telluride CdTe), crystalline silicon on glass (CSG), thin amorphous silicon, quantum dot, nanowire, brush-paint and spray-paint solar cells and various combinations of these are examples of possible research pathways for PV and BIPV. Furthermore, other surface technologies may also be very interesting and promising for utilization on solar cells, e.g. light-trapping geometries, anti-reflection, self-cleaning, superhydrophobic and icephobic surfaces. From a materials science perspective, this work presents a review and bridges 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, material, science.

1 INTRODUCTION

BIPV systems represent a powerful and versatile tool for achieving the ever increasing demand for zero energy and zero emission buildings of the near future, thus offering an aesthetical, economical and technical solution to integrate solar cells to become an integral part of the climate envelopes of buildings. Building integrations of 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 simultanously 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 building physical issues such as heat and moisture transport in the building envelope also have to be considered and accounted for.

2 STATE-OF-THE-ART BIPV

Examples of BIPV tiles on building roofs are shown in Fig.1 [1,2]. Many different BIPV systems exists, and they may be categorized in various 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 are doing. 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].

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

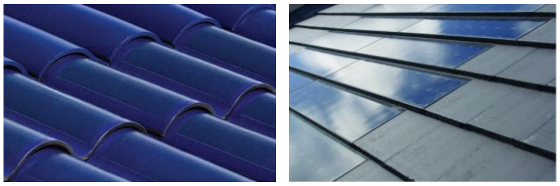

Figure 2: BIPV tile products, SRS Energy (left) [3] and Solar Century (right) [4].

3 BIPV MATERIALS SCIENCE PATHS

3.1 PV Development and Impact on BIPV

PV materials development 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].

A timeline for reported best research-cell efficiencies is given in Fig.3, depicting all verified records for various PV conversion technologies, including crystalline Si, thin film, single-junction GaAs, multijunction and emerging technologies, collected from solar companies, universities and national laboratories [9]. The 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].

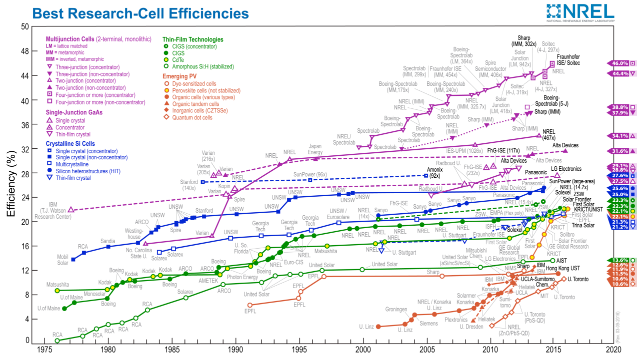

Figure 3: Timeline for reported best research-cell efficiencies (enlarge digitally to see details) [9].

3.2 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 a triple solar cell may have 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 is then absorbed by the middle cell layer, and the red light is absorbed by the bottom cell layer. Thus, a much larger portion of the solar radiation is utilized.

3.3 Absorbing Non-Visible Solar Radiation

A solar harvesting system 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), thereby resulting in a solar cell able to produce electricity while still allowing people to see through a clear glass with no colour distortions [12]. Thus, solar energy may be harvested by windows which apparently look like normal and clear windows.

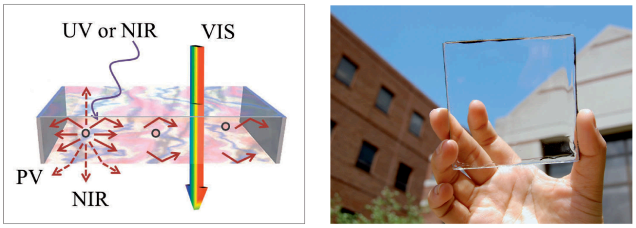

Figure 4: Solar harvesting tuned to absorb specific non-visible wavelengths of solar radiation and letting visible solar radiation pass straight through [12].

3.4 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 2015 (see Fig.3). However, the polymer solar cells are more sensitive to degradation, where ultraviolet solar radiaion and oxygen from the atmosphere may oxidize the organic layer.

3.5 Dye Sensitized Solar Cells

Dye sensitized solar cells (DSSC) usually have a titanium dioxide (TiO_2) substrate material like in the Grätzel solar cell. The 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.

3.6 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. Also the back surface can be passivated with silicon oxide and amorphous silicon to minimize recombination losses at the surfaces and contacts. 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 % (Fig.3).

3.7 Antenna-Sensitizer Solar Cells

Solar cell ”antennas” can harvest several wavelengths, i.e. a much broader spectrum of the solar radiation. This may 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.” [13].

3.8 CIGS and CdTe Solar Cells

Flexible and lightweight CIGS (copper indium gallium selenide) and cadmium telluride (CdTe) solar devices have yielded an active area efficiency of 14.7 % and 9.4 %, respectively [14]. These lightweight devices 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.” [14].

”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” [15]. Figure 15 shows a bending test of a CIGS solar cell [16].

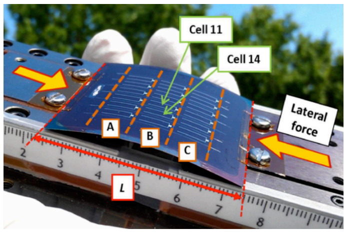

Figure 5: Bending test of a CIGS solar cell on flexible borosilicate ultra-thin glass substrate (100 μm) [16].

3.9 Quantum Dot Solar Cells

Photocurrent quantum efficiencies exceeding 100 % have been reported in a quantum dot solar cell, being enabled by multiple exciton generation (MEG) [10]. 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. Scanning electron microscope (SEM) images of cadmium sulfide (CdS) quantum dots coated on TiO_2 nanorods are shown in Fig.6 [17].

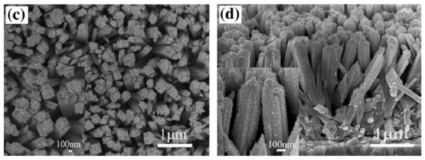

Figure 6: CdS quantum dots coated TiO_2 nanorods [17].

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 might be viewed as a special built-in concentrator system integrated within the PV surface. Thus, the idea may then be to fabricate a ”solar concentrator” at a microscopic material level embedded in the solar cell surface and beneath [5]. An example still at a macroscale, but nevertheless being part of the ongoing process of reducing the dimensions of solar concentrators, is depicted in Fig.7, where the height of the polyurethane (PUR) concentrator element is as small as 25 mm, thus entitling the authors to name their system as building integrated concentrating photovoltaics (BICPV) [18].

Figure 7: Solar cell PUR concentrator element array [18].

3.11 Inverted Pyramid Texturing

Inverted pyramid geometry texturing of a solar cell 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.

3.12 PV Integration in Concrete

An option for the future is to integrate the PV cells in materials at an early stadium, e.g. in prefabricated concrete plates. 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.

3.13 Solar Cell Paint

Thin laminate or paint layer (brush or spray) solar cell materials represent another future option with a very high potential, also for BIPV applications. Different materials are being utilized, both inorganics like e.g. CdSe and CdTe and various organics (e.g. [19,20]).

3.14 Hybrid Solar Cells

Hybrid solar cells exist in many variations and 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. Often an increased interfacial surface area between the organic and inorganic materials is desired in order to facilitate charge separation and increase efficiency.

3.15 Self-Cleaning and Icephobic Surfaces

Self-cleaning aspects and how to avoid snow and ice formation on the solar cell surfaces will also be important issues to address. Figure 8 illustrates this challenge as depending on the climate conditions snow and ice may stick to smooth glass surfaces for large inclination angles and even for vertical surfaces. Thus, in order to find solutions for these challenges investigations on superhydrophobic and icephobic surfaces are being conducted [21-24], where anti-icing coating design cases with microscale and nanoscale surface roughnesses are illustrated in Fig.9.

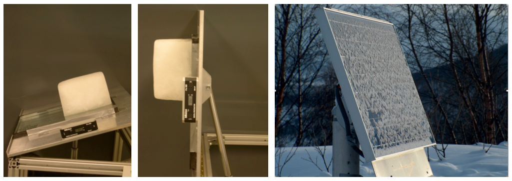

Figure 8: Snow/ice slab firmly sticking to the glass surface of an insulated window pane even at an inclination angle of 90° during a laboratory experiment (left). Snow covering a solar cell panel at an inclination angle of 70° (right) [21].

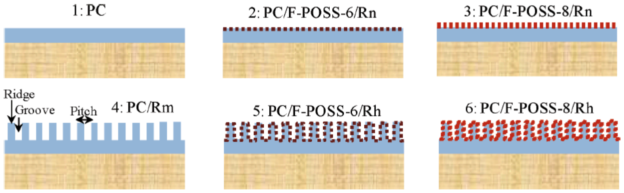

Figure 9: Anti-icing coating design with nanoscale (Rn), microscale (Rm) and hierarchical (Rh) roughness [23].

3.16 Ending Notes

During development of new building materials and components, including BIPV materials, it is of major importance to investigate the durability, e.g. by carrying out accelerated climate ageing in the laboratory [25]. Thus, performing a robustness assessment of these materials and components may also be found to be beneficial [26].

We may 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].

4 CONCLUSIONS

Miscellaneous research pathways and opportunities for BIPV from a materials science viewpoint are addressed. 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 building integration. Easily applicable solutions like e.g. paint applications of PV cells are among the future visions.

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