Nano Technology Low Cost Outperforming Solar Panels

The Future of the Global Solar Industry

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Abstract

Solar Bankers patented new generation of solar modules employs a nano-structured polymer foil on their cover glass, which refracts and concentrates specific wavelengths of light to improve module performance. The optical device refractive abilities allow it to separate absorbable, or "desirable", wavelengths of solar radiation from efficiency-lowering wavelengths, such as infrared and other short-wave light. The foil then also acts as a lens and concentrates the separated spectra of light onto different areas on the module.

Long wavelengths of light, like infrared, are usually dispersed on the solar cell in the form of heat, which significantly reduces cell efficiency. Our nano-structured foil "light-splitting" effect allows efficiency-lowering radiation to be concentrated away from the actual cell, so that cell efficiency remains unaffected by incoming heat.

In parallel, the foil is able to concentrate "desirable" wavelengths directly onto the cell. This concentration – regardless of the efficiency of the cell used – increases the amount of absorbable solar radiation received by the cell per unit area by up to 40%.

Hence our foil significantly improves cell/module performance with the double-effect of A) protecting cells from efficiency-lowering light while B) increasing the amount of convertible solar energy arriving at the cell per unit area.

Our second-generation module can even use the heat energy refracted away from the cell to also produce electricity, further improving module efficiency.

This means modules using the foil can reduce the size of the cell – and the amount of silicon! – they employ by up to 90% while producing the same output as before. Given silicon solar cell is the module's most expensive component, the described effect can reduce module unit production costs to an unprecedented degree. In terms of cost-efficiency, we quote Mr. Ban Ki-Moon, Secretary General of the UN "Low cost solar energy for all"

Introduction

Solar photovoltaic (PV) is the fastest-growing energy technology in the world today and a leading candidate for renewable electricity generation for the years to come[1]. PV has evolved in the last two decades from a niche market of small-scale applications to a mainstream electricity source, with about 83% of the overall capacity installed in the last five years[2]. As a consequence, the cost of solar energy declined significantly due to improvements in technology and economies of scale, to the point that PV is today the most inexpensive technology for renewable energy generation in many regions of the world.

Global PV deployment is dominated by Silicon (Si) technologies, both mono and polycrystalline, which benefit from abundant materials and mature manufacturing processes. Measured under standard conditions of 25°C and 1000 W/m^2, commercial Si solar cells have power conversion efficiencies (PCE) ranging from 10 to 23%[3], which translates to less than a quarter of the sunlight energy being converted into electricity. Of the remaining sunlight energy, over 80% is converted into heat[4], which has a negative impact on solar cell performance. The consequence of increased operational temperature is an average efficiency loss of 0.6%/°C[5, 6], and this results in a sensible reduction in power output when solar modules are exposed to hot environments with high levels of irradiance. In order to compensate for these losses, leading PV companies heavily invested in R&D to improve solar cells performance by focusing mainly on material quality[7] and solar cell design[8]. Although these efforts resulted in a small increase in PCE, the problem of heat generation in solar cells still remains and continues to hinder module performance on field applications.

In this paper we present the first commercial solar PV module that uses only desirable wavelengths of light, eliminating the efficiency-lowering portion of the solar spectrum and thus drastically reducing solar cell heating. Solar Bankers patented module employs commercial Si solar cells and a glass-integrated low-cost nano-structured polymeric foil capable of spatially separating different wavelengths of light. The optical foil concentrates the part of the spectrum suitable for PV conversion onto high-efficiency Si cell stripes, while the infrared light, which causes undesirable panel overheating, is bended away from the active PV converter. The combination of spectral separation and concentration traduces in a decrease in panel overheating of 36% compared to standard modules and in a reduction of solar cell area requirement by up to 90%. The result is a highly efficient PV panel with lower unit cost compared to standard Si modules.

Photovoltaic conversion

The most relevant figure of merit of solar cells is the PCE, which measures the portion of solar energy converted into electricity. Commercial Si solar cells, for example, have PCEs in the range 10-23%, where differences are attributed to material quality and manufacturing processes[3]. Solar cells PCE is evaluated under internationally recognized standard conditions, which correspond to an irradiance of 1000 W/m^2 and a temperature of 25°C. In commonplace applications however, solar modules are exposed to much harsher environmental conditions. In regions like the Middle East and North Africa (MENA), India and other parts of Asia, where solar PV is considered a very promising technology due to high annual irradiance, outside temperature can overpass 50°C. In addition, heat generation within the solar modules translates in operational temperatures of up to 80°C[5], that greatly differ from the 25°C under which solar modules are tested. At higher operational temperatures, solar cells experience a reduction in performance, which is generally measured with a parameter denominated temperature coefficient. The temperature coefficient indicates the relative decrease in PCE that a solar cell undergoes when its temperature increases by one degree. Commercial Si cells have temperature coefficients ranging from 0.35 to 0.9%/°C depending mainly on material quality[6]. For example, an average temperature coefficient of 0.6%/°C, a solar cell with nominal PCE of 20% (at 25°C) operating at 80°C exhibits an efficiency of only 13.4%, meaning that a panel with nominal power output of 300 W delivers instead only 201 W. As observed, the effective power output can be reduced by more than 30%, and therefore it is critical to understand what are the factors that influence solar modules thermal conditions in order to limit their effect and ultimately reduce associated energy losses.

Operating temperature and heat losses in Silicon Solar Cells

There are several factors that need to be accounted for to determine the operating temperature (OT) of a solar cell. The first one is the outside or environmental temperature, which represents the baseline to calculate the OT. Unless cooling systems are integrated, which are most of the time economically inconvenient, solar cells operate always at a greater temperature than that of the surrounding air. The reason for this is that the sunlight energy that is not converted into usable electricity is partially turned into heat and, as a consequence, the OT of the solar panel increases. The main heat generation mechanisms that take place in a solar cell and conduce to module heating are thermalization, Joule heating and low-energy photon absorption by contacts:

- Thermalization is a physical mechanism where free electrons release their excess energy, determined as the difference between the energy of the incoming photon and that of the semiconductor band gap, as heat. As a consequence, high-energy photons are only partially converted into electricity and their excess energy is dissipated by generating heat;
- Joule heating, also known as ohmic heating, is the generation of heat that takes place when an electric current passes through a material with finite resistivity. The amount of heat released is proportional to the square of the current, the materials resistivity and the transversal area;
- Finally, low-energy photons are not absorbed by semiconducting materials and are almost entirely transmitted. However, they are absorbed by metallic contacts and converted into heat. As the thermal resistance between a metal and semiconductor is generally very low, heat is transferred to the latter, causing the temperature of the solar cell to increase.

Calculations performed for an ideal Si solar cell, which has a theoretical PCE of 33%, indicate that these three heat generation mechanisms account for over 80% of the unconverted energy[4]. Their individual contributions are clearly indicated in Fig. 1. As explained before, the energy associated with these physical mechanisms is converted into heat, increasing the module OT and consequently reducing their nominal PCE. It follows then that hindering or reducing one or more of these heat generation mechanisms would have a beneficial effect on solar cells performance.

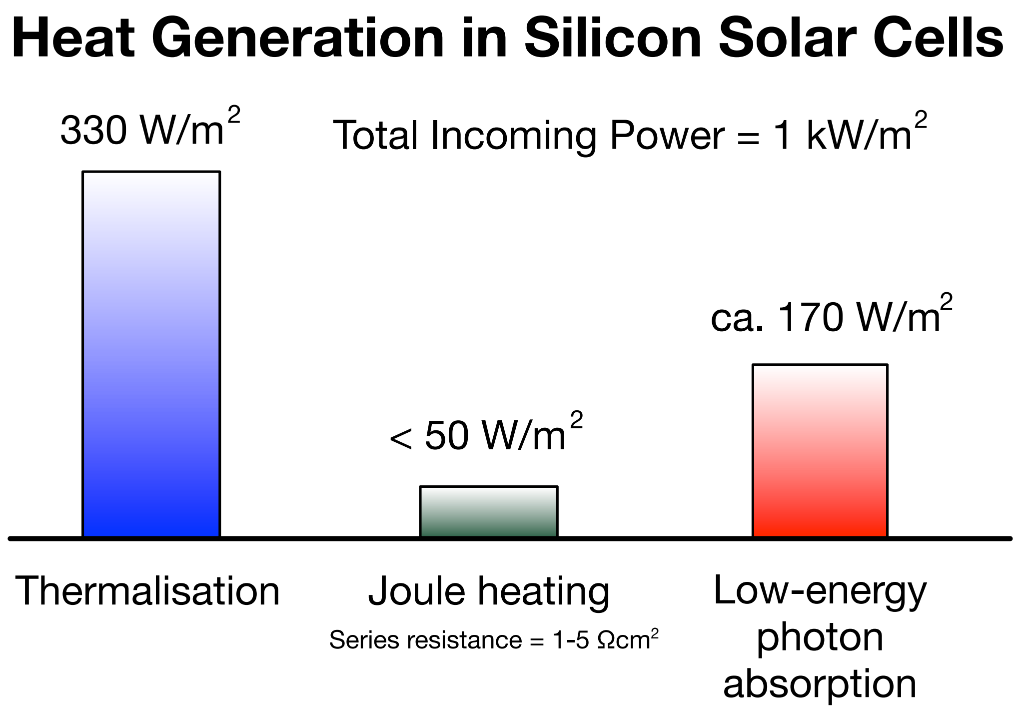

Fig. 1 Mechanisms of heat generation in solar cells and related energy contributions calculated for the ideal case of a 33%-efficient Silicon solar cell.

Solar Bankers New Generation Solar Module

Solar Bankers patented solar module drastically reduces OT by eliminating the contribution of low-energy photons to heat generation and allows therefore for increased power output in field applications compared to standard modules. Fig. 2 shows a representation of the module, which features a glass-integrated nano-structured optical foil and high-efficiency back-contact Si solar cells. The optical foil is a holographic grating that concentrates the light along one axis and separates the different wavelengths into two separate beams. The part of the spectrum suitable for PV conversion is concentrated on Si cell stripes, obtained by laser cutting commercial solar cell wafers, while the remaining wavelengths are bended away from the active converter. As a result, the heat generated within the cells is reduced, as low-energy photons, which only cause panel overheating, are bended away. In addition, solar cell area requirement is sensibly diminished, as photons suitable for conversion are concentrated on a very small area.

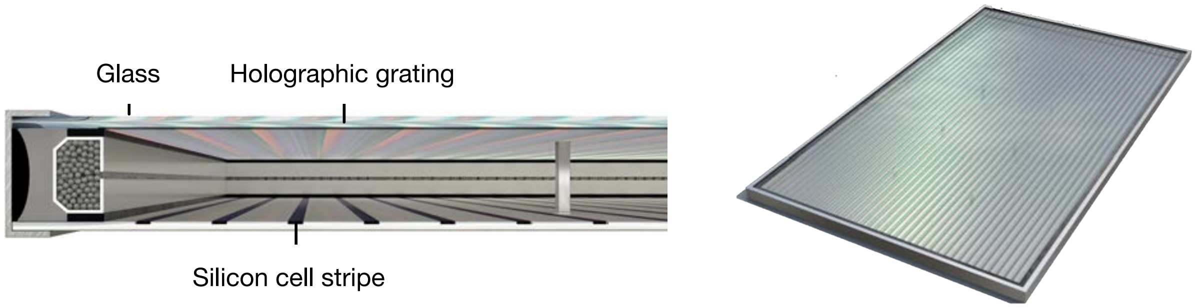

Fig. 2 Representations of Solar Bankers' PV module, which is comprised of a glass, a holographic grating and high-efficiency, back-contact Si solar cells. The thickness of the module is 4.6 cm and the internal volume is filled with nitrogen to prevent polymer degradation.

Solar Bankers solar module key component is the optical foil pictured in Fig. 3. The device is a micrometric-thick polymeric layer that diffracts the light and separates its colors. Its surface is patterned with nanometer-size steps that selectively interact with the different wavelengths of light, causing color separation. The foil is made of Poly(methyl methacrylate) (PMMA), a transparent, highly durable thermoplastic, and is printed on glass, which prevents from UV degradation by reflecting short wavelengths. The device is fabricated with a roll-to-roll imprinting machine, which consists of an imprint roller that transfers its nano-patterned surface onto a flexible substrate. The master is fabricated by electron-beam lithography and the nanostructures are transferred onto the flexible substrate on a 1-to-1 scale. Roll-to-roll imprinting enables large-scale and low-cost manufacturing: one machine can produce up to 20 m^2 per minute and production costs are limited as the imprint roller, which is the most expensive component, can be re-used for thousands of cycles.

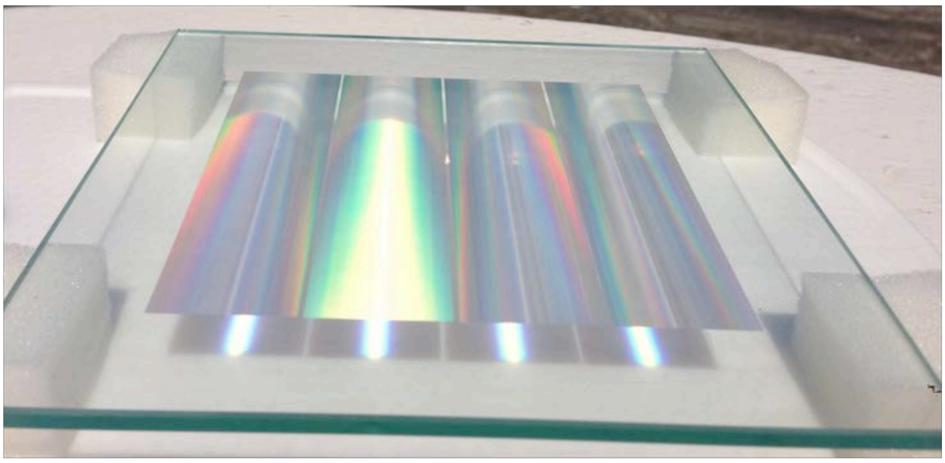

Fig. 3 Picture of Solar Bankers' holographic grating. It consists of a micrometric-thick polymeric layer that separates light colors and concentrates only wavelengths suitable for PV conversion.

The optical properties of the polymeric foil were tested by the Fraunhofer Center for Silicon Photovoltaics CSP. Fig. 4a, which shows the transmittance of the device measured over the spectral range 300-1100 nm, reports an average value of 97.5%, meaning that the incoming light is almost entirely transmitted and that, therefore, optical losses are negligible. Fig. 4b shows a picture of the light pattern transmitted by the foil when illuminated with white light. Light beams are concentrated at a distance of approximately 3 cm, which is, by definition, the focal length of the device. To quantify such figure and determine the optical concentration factor of the device, the lateral size of the transmitted light pattern was measured at different distances, the results of which are shown in Fig. 4c. Using an initial spot size of 20 mm, a minimum beam diameter of 500 μm was obtained at 3.25 cm, corresponding to a maximum concentration factor of 40x. In order to investigate the spectral separation properties of the foil, the device was illuminated with a solar simulator and the spectral content of the first light beam (the one containing visible light) was measured at the focal plane. Fig. 4d, which reports the optical efficiency of the device, obtained normalizing the spectral irradiance of the transmitted light beam with that of the incoming light, shows a sharp spectral separation in correspondence of 1200 nm, with an in-band efficiency greater than 95%. This figure confirms the foil capability of selecting wavelengths suitable for PV conversion as Si solar cells can absorb only photons below 1200 nm.

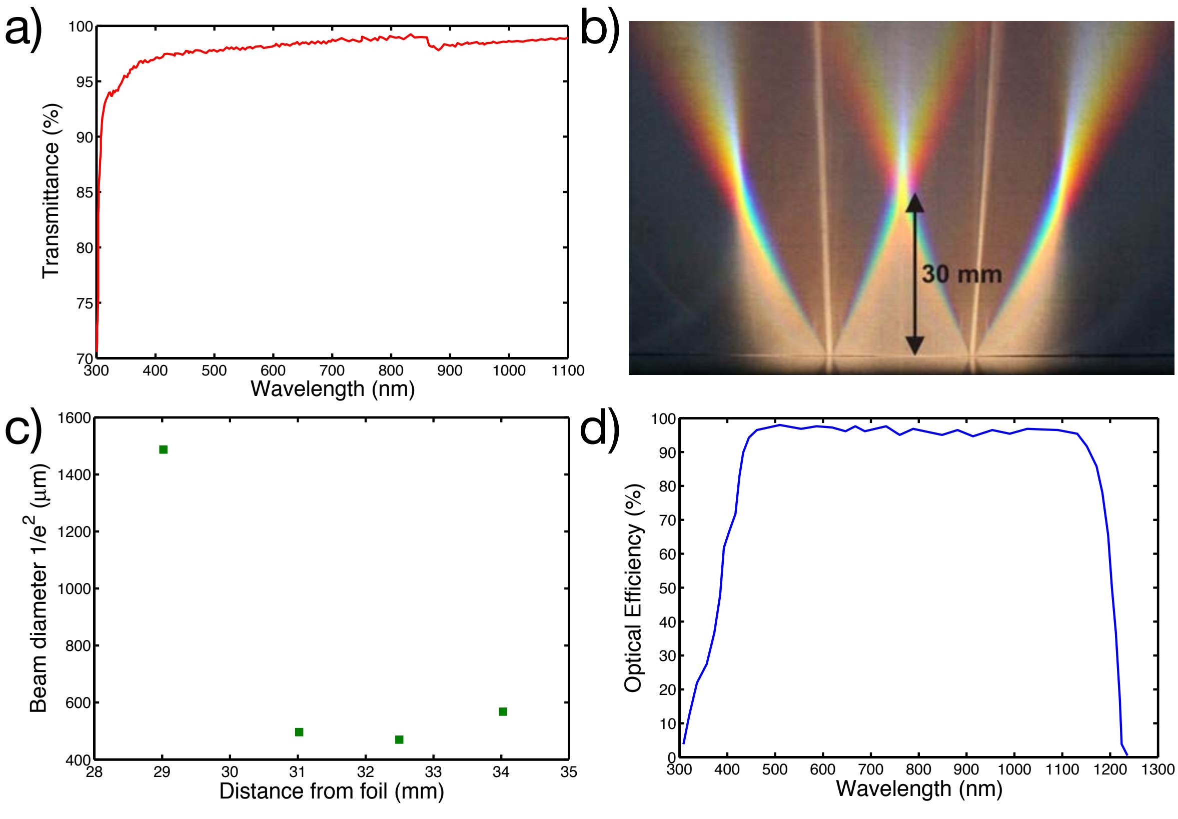

Fig. 4 a) Transmittance of the optical grating measured in the spectral range 300-1100 nm; b) Picture of the light pattern transmitted by the optical film when illuminated with a white, halogen lamp; c) Diameter of the light beam

transmitted by the optical film versus distance. The incident spot had a diameter of 20 mm; d) Optical Efficiency of the optical film measured in correspondence of the PV converter.

At the focal plane of the optical foil, Solar Bankers module implements commercial metal wrap through (MWT) Si cells. Unlike standard solar cells, MWT solar cells are interconnected on the backside[9]. The front grid is contacted by metallized vias that lead the current onto the backside. This innovative layout not only reduces light shading, but also decreases ohmic losses. The MWT architecture thus achieves higher PCEs and allows reducing the cost of cell interconnections as inexpensive pre-designed conductive back sheets can be used. MWT Si cells are cut in small, 7-mm-wide stripes, to fit with the size of the light pattern projected by the foil. For this process laser cutting is used, which is a relatively inexpensive manufacturing process with very high yields, generally close to 100%[10]. Due to light concentration, up to 90% solar cell area savings are achieved compared to standard modules. This characteristic in combination with the abovementioned inexpensive solar cell interconnection traduces in a reduction of 50% of solar module manufacturing costs compared to standard products.

Solar Module Characterization

Table I shows the technical specifications of Solar Bankers module. It has a surface of 1.5x1 m^2 and a maximum power output of 300 W, resulting in a PCE of 19.8 %, which can be further increased by using higher performing MWT cells.

Electrical Specifications	
Maximum Power Output	300 W
Power Tolerance	$\pm$ 5 W
Max-Power Voltage	32.4 V
Max-Power Current	9.3 A
Open Circuit Voltage	39.4 V
Short Circuit Current	9.8 A
Module Efficiency	19.8%
Mechanical Specifications	
Solar Cells	MWT Si solar cells
Front Glass	High-transmission tempered glass

Junction Box	IP65 & IP67
Frame	Anodized aluminum alloy/silver/clear
Dimensions	1500 mm x 1000 mm x 46 mm

Table I Electrical and mechanical specifications of Solar Bankers PV module.

Solar Bankers module features high performance at elevated temperatures because of its optical foil. To verify the effect of Solar Bankers optical foil on the in-field module OT, the module working temperature was measured at different light concentration factors and compared to the OT of the same module without featuring our proprietary foil (for the module without foil, concentration was achieved with a standard through concentrator). Results are reported in Fig. 5, where it can be observed that Solar Bankers proprietary foil helps to effectively reduce the module delta temperature (OT-$T_{ambient}$, where $T_{ambient}$= 45 °C) by 36% as a consequence of the spectral separation that bends away low-energy, heat-generating photons. This reduction in OT traduces in a net increase in power output of approximately 7%, which corresponds to 21 W out of 300 W. If we analyze this result in terms of temperature coefficient, which measures the efficiency loss per degree of temperature, we can say that the use of the optical foil reduces its effective value by 36%, allowing then to produce extra power output at high temperatures.

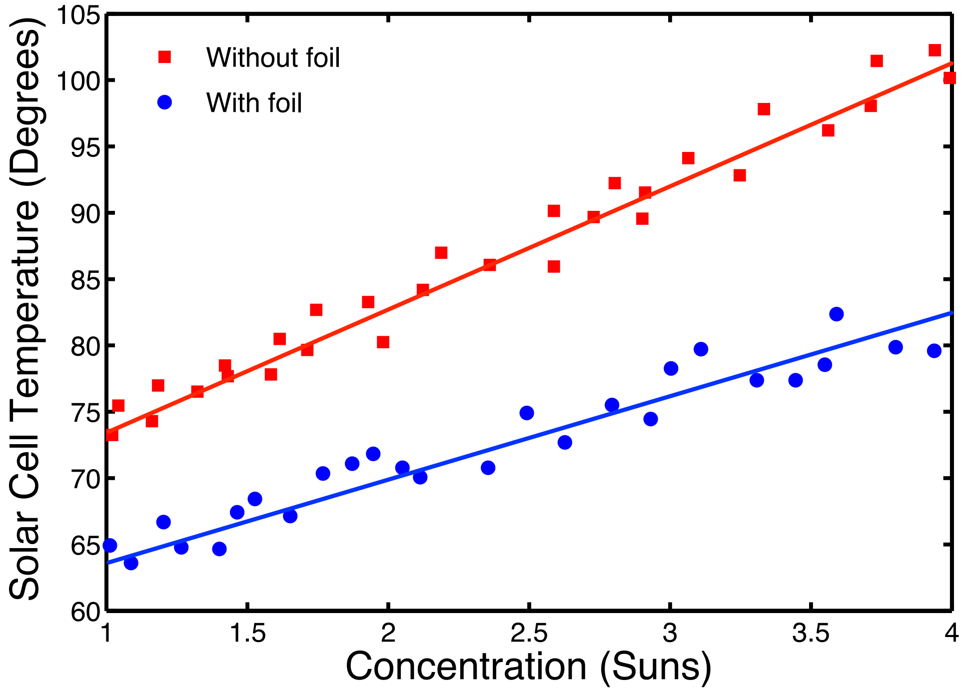

Fig. 5 Solar Cell temperature measured versus concentration with and without Solar Bankers optical grating. The measurement was carried out in field, with an outside temperature $T_{ambient}$ of 45 °C. The concentration of 1 Sun

corresponds to approximately 700 W/m^2.

Conclusions

In this paper we have presented the first commercial, high-efficiency PV module that reduces solar cell OT compared to standard modules by eliminating the spectral components of light that only produce heat. The module features a glass-integrated low-cost nano-structured polymeric foil, which selects the wavelengths of light suitable for PV conversion and concentrates them on MWT Si solar cell stripes, obtained from commercial wafers. The foil is fabricated with a roll-to-roll machine, which allows for large-scale and low-cost manufacturing, and was tested by the Fraunhofer Center for Silicon Photovoltaic, which certified an in-band optical efficiency greater than 95% and sharp spectral separation. The module was finally tested in field and we verified an average decrease in delta temperature of 36% compared to standard modules, which traduces in a net increase in power output of over 7%. Solar Bankers PV module and its high-tech optical foil represent a low-cost solution to reduce thermal losses and to increase the power output of solar panels and are particularly recommended in high-temperature environments.

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