RRI Case Study

Organic Solar Cell Development for Clean Sustainable Energy

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RESPONSIBLE INNOVATION
COMPASS

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Executive Summary

Nanotechnology is one of the key elements when addressing the worldwide societal challenge of 'secure, clean, and efficient energy'. This challenge accounts for the needed transition towards an optimal and renewable use of energy resources and towards sustainable primary production and processing systems to generate energy with minimal input, environmental impact and greenhouse gas emission, and with enhanced ecosystem service, zero waste and adequate societal value. The objective of our product is to contribute to securing sufficient supplies of clean and sustainable energy. It is fulfilled by developing productive, sustainable and resource-efficient production systems, fostering related ecosystem services, and the recovery of energy diversity, alongside competitive and low silicon supply chains.

The impact achieved by our work has been the development of an innovative, organic solar cells based product, which has high efficiency and a long lifespan. This sustainability aspect of the product is acceptable to users. There is a low level of toxic materials in both the clean sustainable production process and in the product.

To date, silicon based solar cell and thin film (such as cadmium-telluride, gallium-arsenide, etc.), representing the first and second generation of photovoltaic (PV) technologies, respectively, form the majority of the commercial energy market. The applied photovoltaic technologies are mainly silicon-based and are expensive when competing with fossil fuels for electricity production. In addition, silicon, cadmium, tellurium, gallium, and arsenic are environmentally demanding for recycling and disposal.[1] Therefore, the environmental sustainability of these technologies is unclear.

To address these problems, the emerging organic photovoltaic technology offers large cost reductions using inexpensive materials and solution-processing instead of expensive and slow vapour phase deposition, and provides an answer to these problems. The global interest in developing organic solar cells mainly stems from their potential to be flexible and stretchable, low cost, low weight, and semi-transparent.

The basis of the organic solar cell is the use of special organic compounds, donor and acceptor materials, which are sandwiched between two electrodes. One of the electrodes should be transparent which allows the light to penetrate into the device.

There are two major classes of organic solar cell: small molecule and polymer solar cell.

The schematic diagram of a typical polymer solar cell, which is used in this work is shown in figure 1.

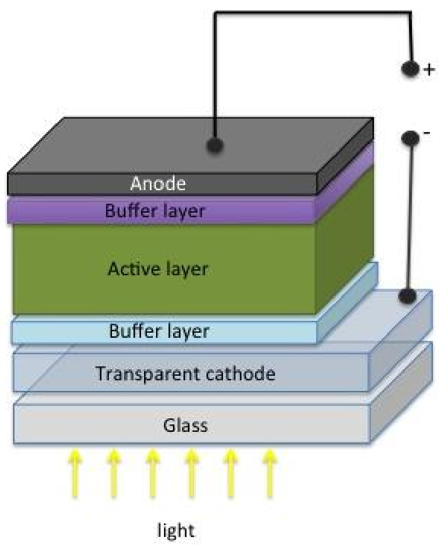

Figure 1 The schematic diagram of organic solar cell.

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Currently however, the low power conversion efficiencies of organic solar cells using the ceramic brittleness and high temperature vacuum deposition of transparent conductive oxides as a transparent conductive electrode, limit their viability and sustainability for cost competitive commercial production, and impede their application in flexible devices.

Transparent conductive electrodes (TCEs) are essential components in optoelectronic devices, such as organic light emitting diodes and organic solar cells. Vacuum deposited indium thin oxide (ITO) film as TCEs have excellent physical properties, such as high optical transmittance and low sheet resistance. ITO films, however, have several drawbacks like fragility, a high refractive index and high processing temperature as well as large wastage of target material during the manufacturing process.[2] Therefore, there is a strong need for alternative materials as TCEs in the next generation of optoelectronic devices. To date, various materials and nano-structures such as conducting polymer hybrid films, graphene, carbon nanotubes, metal mesh, and metal nanowires have been used as alternative to ITO films.

In this work, we developed a periodic ultrathin gold nanowire as an alternative nano-structure for ITO in organic solar cell devices, which gives us both high transparency and low sheet resistance. In addition, the ability of tuning the optical properties of nano-structured metallic film by varying shape, size and material, can enhance the light absorption in the organic active layer, and thus the efficiency of the device. Furthermore, the high electrical conductivity and mechanical elasticity of metallic nano-structures have been a major factor in advancing the application of this technique in a flexible organic solar cell.

The production process is in line with the 2008 European Commission Code of conduct for nanotechnologies and follows the principles related to nanoscience and nanotechnologies. In fact, OPV respects fundamental rights, is safe, ethical and contributes to sustainable development serving the sustainability objectives, and does not harm or create a biological, physical or moral threat to people, animals, plants or the environment, at present or in the future.

Field of Industry or Service

The development of large-area ultrathin gold nanowires as a transparent electrode in organic solar cells is covered by this case study. The periodic ultrathin gold nanowires are prepared from Langmuir-Blodgett films using a lithography method based on the self-assembly of polystyrene nano-spheres. This case study presents the light harvesting ability of periodic gold nanowires and the feasibility of integrating these inexpensive and easily scalable nano-structures into organic solar cells. The presented generic technique is compatible with up-scaling techniques and can easily be applied in various future optoelectronic devices in the energy sector.

Fabrication Methods

This work explains fundamental information about the periodic ultrathin gold nanowires fabrication method, including colloidal mask preparation via nano-sphere lithography, mask modification and metal deposition. In addition, the fabrication of organic solar cells using ultrathin gold nanowires as a transparent flexible electrode, and the optical properties of

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ultrathin nano-structure in organic solar cells and their plasmonic properties are presented. Figure 2 briefly describes the fabrication process of periodic ultrathin gold nanowires.

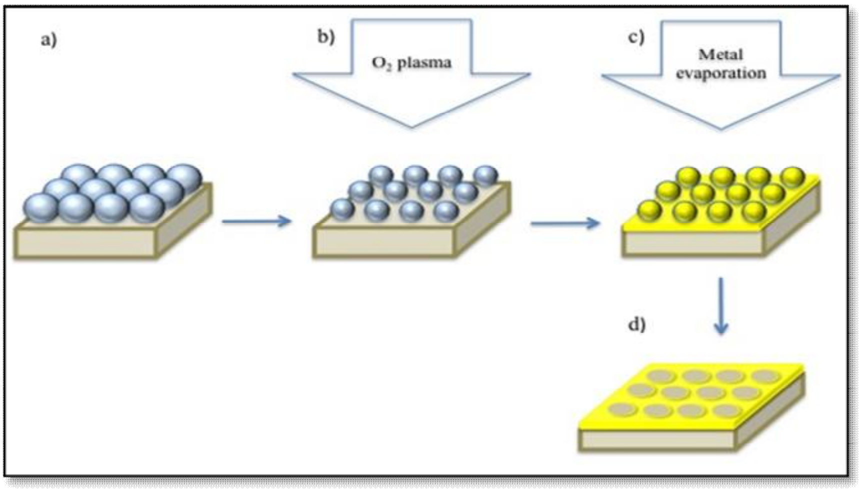

Figure 2 Schematic representation of the procedure for fabricating the periodic ultrathin gold nanowires (a) Monolayer of close-packed PS beads on a PET substrate. (b) Reducing the size of the PS beads through RIE. (c) Deposition of gold thin film onto PS-coated wafers. (d) Removal of PS beads and nanowire formation.

Colloidal mask preparation

In this work a self-assembly of a hexagonal closed-packed monolayer of polystyrene (PS) latex spheres with diameter of 1000 nm are used. The mono-dispersed polystyrene beads are purchased from Sigma Aldrich. The polystyrene solution with a concentration of 2% in ethanol/water is prepared. The prepared solution is slowly applied to the water surface using a syringe. The monolayer of self-assembled PS spheres on the water surface is transferred on a clean piece of glass substrate and dried in air. Figure 3 shows the Langmuir-Blodgett set-up and the scanning electron microscope (SEM) image of the PS monolayer on the glass substrate.

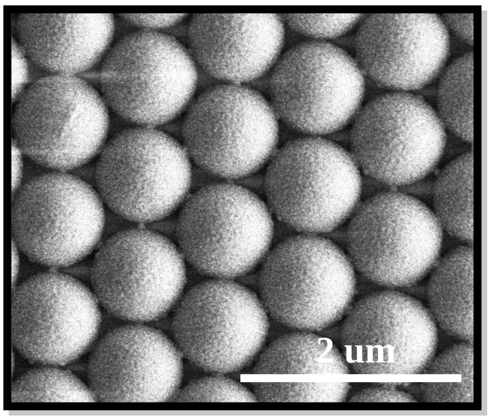

Figure 3 the Langmuir-Blodgett device (image on the left) and SEM image of PS monolayer on glass substrate (right).

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Mask modification

One of the methods to increase the spaces between the polystyrene (PS) spheres and open up the contact area between them is reactive ion etching (RIE).

PS spheres are etched using 30 W power at a pressure of 150 mTorr, while the etching ion-composition includes argon and oxygen. The amount of applied gases can vary depending on the size of the used spheres. Figure 4 shows the results of the etching of the PS sphere.

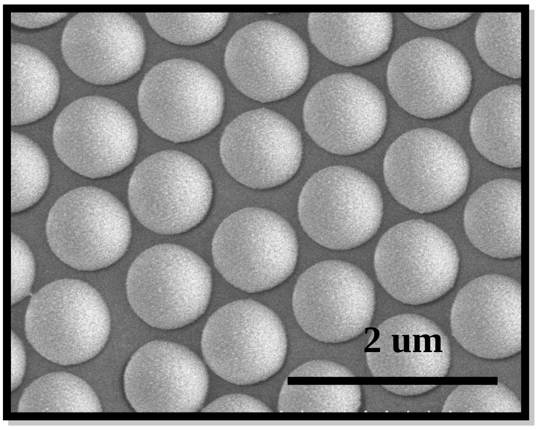

Figure 4 Scanning electron microscope image of the polystyrene nano-sphere after reactive ion etching.

Material deposition

All evaporation processes were done using an e-beam evaporator. A 20 nm thick gold layer was created at 10^{-7} mbar.

Mask lift off

After the metal was evaporated onto the substrate, the PS mask could be removed by lift-off treatment, based on ultra-sonication of the samples in acetone. The lift-off process takes from 30 seconds up to 1 hour depending on the film thickness and type of the structures. After the lift-off process the sample is rinsed several times with 2-propanol or acetone, then in Mill-Q water, and dried in a stream of Nitrogen. Figure 5 shows the resulting ultrathin gold nanowires on glass substrate.

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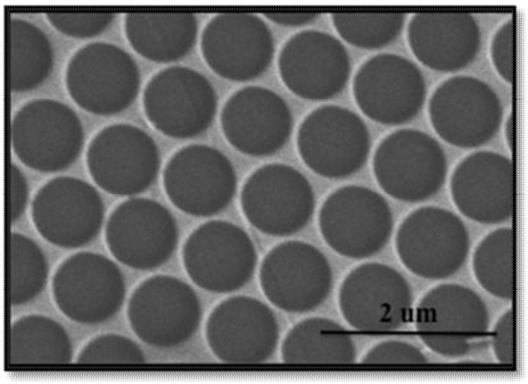

Figure 5 SEM image of ultrathin gold nanowires on glass substrate.

Organic solar cell fabrication

The device is realized on glass substrates containing ultrathin gold nanowires cleaned in an ultrasonic bath with acetone and isopropanol (10 minutes each step). The substrate is covered with poly (3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS-PH1000) via spin coating at 400 rpm for 45 seconds. Subsequently, 35 nm of nanoparticle Zinc oxide (ZnO) (purchased from Genes'Ink) is spin coated onto the PEDOT:PSS layer. Then, a blend of Poly[[4,8-bis[(2-ethylhexyl)oxy]benzo[1,2-b:4,5-b']dithiophene-2,6-diyl][3-fluoro-2[(2ethylhexyl)carbonyl]thieno[3,4-b]thiophenediyl]]:[6,6]-PhenylC71 butyric acid methyl ester (PTB7:PC70BM) (1:1.5 weight ratio- purchased from 1-material: Solenne) dissolved in chlorobenzene and 3%v/v of 1,8-diiodooctane (DIO), is used to form the active layer by spin-coating at 1000 rpm for 120 seconds. The film is treated in a slight vacuum (10^{-1} mbar) for 20 minutes to accelerate the drying process and remove residual DIO from the thin film.

Finally 10 nm of Molybdenum three oxide (MoO_3) and 100 nm of silver are thermally evaporated at 10^{-7} mbar on top of the active layer.

Light harvesting ability of periodic gold nanowires

The absorption spectrum of the device with ultrathin gold nanowires shows broadband enhancement compared to the planar organic solar cells.

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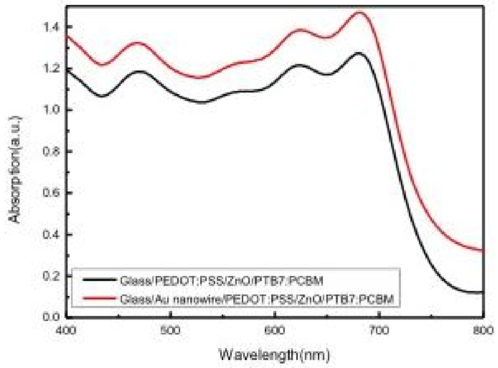

Figure 6 Absorption spectrum of solar cell without gold nanowires (black curve) and solar cell with ultrathin gold nanowires (red curve). The light absorption within the device is enhanced by the factor of 6.6% (average in wavelengths) by integrating the gold nanowires in organic solar cells.

Comparison to the other techniques

In our product, we used nano-sphere lithography to produce the periodic nano-structures, which is a time–efficient and low–cost method in comparison with other lithographic techniques. The recent development of nano-sphere lithography including etching the colloidal mask, using different materials and altering the metal evaporation angle on to the mask, gives us the freedom to produce nano-structures of various shapes. Furthermore, the possibility to be applied on various planar and curved surfaces, and the high throughput of this technique makes this a powerful nano-chemical patterning tool.

The masks' design, their production, and down-scaling to the required feature size usually remains a challenge in conventional mask-assisted lithography techniques. However, nano-sphere lithography embodies a self assembly of mono-dispersed nano-spheres on a targeted substrate and the feature size can easily shrink below 100 nm by reducing the diameter of the nano-spheres.

Events or Activity

Where conventional solar technologies cannot be used, OPV fills the gap. OPV technology benefits from the organic material properties and unlimited molecule design and it can open up several opportunities for this particular market.

The transparency of the organic materials allows us to make semi-transparent photovoltaic devices, which can be used in several applications such as greenhouses, urban furniture, anti-noise walls, bicycle parking and charging stations, shelters for train stations, and for outdoor and indoor decorations.

Using the solar panels to generate electricity decreases the cost of the powering, including the cost of cooling, heating and light. In addition, the ability to make organic solar cells flexible offers a variety of possibilities in terms of how they can be set up; on a tent, backpack, or rolled out on the ground.

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Here are some examples for the application of organic solar cells.

(a)

(b)

(c)

(d)

Figure 6 (a) Semi-transparent coloured solar cell for urban application www.g2e.ch (b) Solar greenhouse on UC Santa Cruz campus www.universityofcalifornia.edu (c) The transparent version of Heliafilm integrated in the building's architecture http://www.heliatek.com/en/applications/buildings (d) Flexible portable solar charger https://infinitypv.com

All advantages at a glance:

- Flexible
- Lightweight
- Thin
- Fast production
- Low cost custom design
- Cost efficient
- Green (no toxic or harmful materials)

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Why does the case study fall under Responsible Research and Innovation (RRI)?

OPV is a new technological approach; it is innovative and at the same time it leverages socially desirable mechanisms and is a sustainable energy solution. OPV offers considerable advantages including completely toxic-free manufacturing processes and low power consumption. A primary advantage of OPV technology over inorganic counterparts is its ability to be utilized in large areas and for flexible solar modules, especially facilitating roll-to-roll (R2R) production. Additionally, manufacturing costs can be reduced for organic solar cells due to their lower cost compared to silicon-based materials and the ease of device manufacturing.

The energy sector reacts by implementing such a sustainable and responsible practice from nanotechnology to grow its business more cleanly, to attract the best talent, and to remain relevant and sustainable to its inventors. OPV as a sustainable innovative product addresses RRI principles from two perspectives: Process and product perspectives.

Conventional silicon cells require ultra-high-purity silicon — of the order of 99.999% pure — and the cells are made via energy-intensive crystal growth and vapour deposition methods. Further adding to their costs, “silicon solar cells use 1,000 times more light-absorbing material than dye-sensitized solar cells and perovskite cells,” [3] says photovoltaics pioneer Michael Grätzel, a chemistry professor at the Swiss Federal Institute of Technology, Lausanne.

OPV cells are made from an assortment of inexpensive materials, including organic polymers and small molecules. And unlike silicon cells, they can be fabricated on flexible supports via inexpensive solution-phase techniques common in plastics manufacturing, such as high-speed roll-to-roll printing. Such development processes will reduce risks. The environmental risks and social issues of the inorganic solar cells are mitigated in OPV, so that its design process creates a competitive advantage by reflecting on the possible social impacts and aims of the product. Moreover, OPVs’ production phase follows a sustainable value creation approach and has engaged different stakeholders into the design process. Close integration and cooperation among engineers, researchers, and companies were required.

Since OPV production processes optimize environmental and social aspects in parallel to other strategic business priorities, and manage financial, environmental and social aspects across all strategic priorities, they demonstrate that sustainability is a driver of the long-term business success.

Accordingly, OPV helps to reduce production costs. Concerning a competitive advantage for such new business, companies and their founders can tap into new markets and remain relevant to a growing number of investors. The amount of money invested in OPV is increasing every year through so-called SRI investment (socially responsible investors). In addition, OPV provides an opportunity to launch new business models in the energy sector.

Altogether, the OPV production process is in line with the 2008 European Commission Code of conduct for nanotechnologies[4] and follows the principles related to nanoscience and nanotechnologies. In fact, OPV respects fundamental rights, is safe, ethical and contributes to sustainable development, thereby serving sustainability objectives. It does no harm or

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does it create a biological, physical or moral threat to people, animals, plants or the environment, at present or in the future. [3, 5]

The industry benefits (Successful application with Ultrathin nanowires - OPV)

An organic solar cell developed in this process can be combined with a great variety of materials, for example flexible substrates, concrete, etc. The flexible organic solar cells can also easily be integrated into concrete. In fact, the future of functional façade systems is the combination of flexible solar cells and concrete. The developed organic solar cell in this case study can be attached directly to the concrete façade without any need for cooling or ventilation systems. In all cases, organic solar cells reduce the operational costs, which helps companies with their sustainability aims.

Organic photovoltaics are the most promising options for solar energy utilization and have several advantages, such as a fast manufacturing process and the possibility to print and coat the device directly onto a flexible substrate by using roll-to-roll coating and printing methods which enables simple handling and low cost production.

In addition, the organic photovoltaic technology avoids the use of rare elements that are in limited supply, and the chemical synthesis of the organic material can be carried out irrespective of the location of manufacturing.

In the work presented, we introduced an inexpensive and easily scalable alternative technique to replace the fragile ITO in organic solar cells. We used the nano-sphere lithography method, which is low cost and compatible with up-scaling techniques. Furthermore, we believe that this process can be applied on flexible substrates and used in flexible OPV technologies.

This technique can be developed easily commercially and addresses the problem of indium scarcity, as indium is the main component in ITO. In addition, it opens up new routes towards ITO-free electrodes in printed electronic devices.

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References

1. Yue, D.; Khatav, P.; You, F.; Darling, S. B., Deciphering the uncertainties in life cycle energy and environmental analysis of organic photovoltaics. *Energy & Environmental Science* 2012, 5 (11), 9163-9172.

2. Barrows, A. T.; Masters, R.; Pearson, A. J.; Rodenburg, C.; Lidzey, D. G., Indium-free multilayer semi-transparent electrodes for polymer solar cells. *Solar Energy Materials and Solar Cells* 2016, 144, 600-607.

3. Jacoby, M, The future of low-cost solar cells. *Chemical & Engineering News Magazine*, May 2, 2016, 94 (18), 30-35

4. European Commission, Commission recommendation on a Code of Conduct for Responsible Nanosciences and Nanotechnologies Research, C (2008) 424, 7 February 2008 - http://ec.europa.eu/research/science- society/document_library/pdf_06/nanocode-apr09_en.pdf

5. Grätzel, M, Recent advances in sensitized mesoscopic solar cells, *Accounts of Chemical Rresearch, American Chemical Society*, 42 (11), 1788-1798. http://pubs.acs.org/doi/abs/10.1021/ar900141y

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