MONASH University

Bringing all-polymer solar cells closer to commercialization

Project results and lessons learnt

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Project partners:	Flinders University, Macquarie University
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Executive Summary

Polymer solar cells have the potential to contribute to renewable energy generation, being utilised in installations and situations for which conventional silicon solar cells are not suited. In particular their light weight nature, mechanical flexibility, colourfulness and transparency may see them utilised in portable power applications, built-in photovoltaics, and situations where absolute cost of manufacture is the main concern. Limiting the development and commercialization of polymer solar cells is their relatively low efficiency and poor stability. This project seeks to address issues facing the commercialization of solar cells based on blends of semiconducting polymers by developing materials that are stable and that can be manufactured at scale. This project also seeks to employ novel techniques for the rapid screening of new materials foreshortening the development cycle.

This report describes progress and lessons learnt from the second half of the project. Specific outcomes from the second half of the project include: (i) Assessment of the thermal stability of polymer solar cells, (ii) Upscaling and optimisation of the synthesis of photovoltaic polymers, and (iii) Upscaling of the fabrication of polymer solar cells to the cm^2 scale.

Project Overview

Project summary

Solar panels are based on photovoltaic (PV) cells that convert sunlight directly into energy. While silicon is the mostly widely used material for making PV cells, other materials can be used which have different properties. Polymer solar cells use light absorbing and electrically active polymers as the active material in PV cells instead of silicon. While solar cells based on silicon are commercially available and can be found on many rooftops across Australia, they are brittle, require heavy protective casings, and are opaque. Polymer solar cells on the other hand are light-weight, flexible, colourful, and can be easily manufactured. Polymer solar cells could see application in portable power applications, as semitransparent windows incorporated into buildings, and in general applied in situations where silicon solar panels are ill-suited.

However there are a number of challenges facing the commercialization of polymer solar cells including efficiency and lifetime. This project seeks to address these challenges by understanding stability issues and developing new materials for high efficiency polymer solar cells.

Project scope

To aid in the development of polymer solar cells, higher efficiency materials need to be developed. However efficiency is not the only parameter relevant to commercialization. Also of relevance are material cost, lifetime, and manufacturability. Hence the goal of this project is to develop new materials that are also stable and can be scaled up in synthesis and be processed at scale.

Solar cells operate under direct sunlight. As such, they can experience temperatures up to 85 °C during the day and freezing temperatures overnight. The thermal stability of the solar cell is therefore paramount to ensure long term operation. Polymer solar cells rely on a blend of two materials, and under elevated temperature these two materials can "de-mix" resulting in a loss in efficiency. Characterisation of the thermal stability of different polymer solar cells types is essential in order to select the most stable materials going forward.

Solar polymers are prepared using chemical synthesis – the linking of smaller chemical subunits into long chain molecules. For large-scale industrial application, this chemical synthesis needs to be both scalable and sustainable. Instead of only being able to make milligrams worth of material for basic laboratory experiments, gram-scale quantities need to be produced to enable scale up for pilot manufacturing studies. Also, the chemical reaction should avoid the use of toxic compounds due to environmental concerns. New synthetic strategies are thus required to ensure that polymer solar cells are truly "green."

Translating laboratory-based discoveries to the factory, so-called "lab to fab" can sometimes be challenging. In the laboratory, solar cell devices are typically fabricated which are much smaller (< 0.1 cm^2) than the solar panels that are employed on roof tops and in solar farms (~ 1 m^2). Sometimes the fabrication techniques used for laboratory-based devices do not scale up. This means that the efficiency of small, laboratory-scale cells cannot be replicated using the fabrication techniques needed for commercial manufacture. For polymer solar cells, the process of "spin-coating" is typically used for making small, laboratory-scale cells. This process works by dispensing the solution to be coated onto the surface of the substrate to be coated and then spinning at high speeds. This spinning spreads the liquid uniformly across the substrate and results in a uniform, thin film when the solution dries. While this works fine on a small scale, scaling up to anything larger than a dinner plate is essentially impossible. A lot of solution and material is also wasted when it is ejected at the edges during the spin-coating process. The production of large area polymer solar cells instead uses coating techniques that work similar to the printing of a newspaper: a long flexible support layer is fed by rollers through a coating machine which deposits a thin layer of solar material. Differences between how long it takes for films to dry in this "roll-to-roll" coating process compared to spin-coating can mean that good efficiencies achieved using spin-coating are sometimes not realised when large area coating processes are used. To ensure this is not a problem, a third focus of the project was to make all laboratory-scale cells using a coating technique that mimics the coating conditions used in a manufacturing environment.

In summary, this project seeks to develop new materials (polymers) with high efficiency that are stable and that can be manufactured at scale.

Outcomes

Outcomes from the second half of this project include:

(i) The thermal stability of polymer solar cells has been assessed.
(ii) The reaction conditions for the green synthesis of solar polymers have been optimised.
(iii) Upscaling of the fabrication of polymer solar cells has been realised with cm^2 cells produced via blade coating.

<u>Thermal stability of polymer solar cells</u>

There are different "flavours" of polymer solar cells based on the nature of the two materials blended to make the photoactive layer. All types of polymer solar cell use at least one polymer in the mix, with some using fullerene derivatives based on C_{60} or C_{70} molecules ("polymer:fullerne" solar cells), some using other types of small molecules ("polymer:non-fullerene" solar cells) and some using a blend of two polymers ("all-polymer" solar cells). Blends of two materials are not necessarily stable, especially when placed under elevated temperature like what can be experienced under direct sunlight. All-polymer solar cells may have a strategic advantage due to the long chain-like nature of their molecular structure which causes entanglements that arrests de-mixing. We have assessed the thermal stability of different types of polymer solar cells using standard thermal cycling experiments, where the solar cells have been heated up to 85 °C and then cooled to room temperature simulating a daily cycle.

Figure 1 compares the thermal stability of these three classes of polymer solar cells. Encouragingly the all-polymer solar cell shows superior thermal stability, with power conversion efficiency (PCE) only dropping by 5% after 500 cycles. In contrast, the other two types of polymer solar cells show a rapid drop in efficiency after only a few cycles. This result indicates that blends of large molecular weight polymer chains is an effective way to arrest demixing of the active layer in polymer blend solar cells.

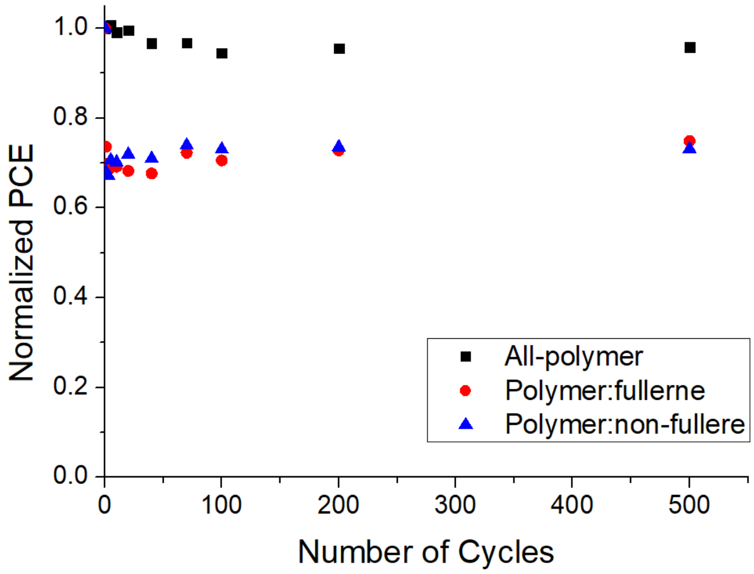

Figure 1. Comparison of the thermal stability of three classes of polymer solar cells.

<u>Optimisation of polymer synthesis reaction conditions</u>

Over the lifetime of the project over 100 batches of solar polymers have been synthesised. To be practical, synthesised quantities on the gram-scale are required with minimal toxic waste. To this end, the environmentally friendly polymerisation method, direct arylation, was investigated and the reaction conditions optimised to upscale the synthesis of both polymer donors and acceptors. The synthesis of polymers on the gram scale has been realised with high yields and high molecular weights avoiding the used of toxic organotin compounds. Our results demonstrate a green way of upscaling the synthesis of conjugated polymers.

<u>Upscaling of solar cell fabrication</u>

In the laboratory spin-coating has been used to prepare layers of solar polymers for use in polymer solar cells with active area of < 0.1 cm^2. To enable translation to high-throughput manufacturing processes such as roll-to-roll printing, other coating techniques which better replicate the conditions of large area coating should be used. To this end, we have used the technique of blade coating that enables cells to be produced on the laboratory scale, with coating conditions that are translatable to the manufacturing scale. We have realised cm^2 sized cells fabricated using blade coating (see Figure 2) with only modest reduction in cell efficiency compared to smaller lab-scale cells.

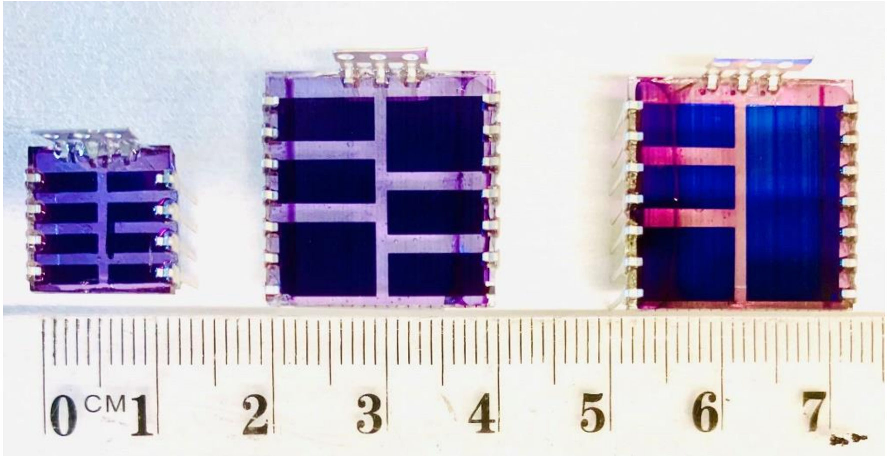

Figure 2. Evolution in device size. Left: spin-coated 0.045 cm^2 cells. Middle: blade-coated 0.21 cm^2 and 0.36 cm^2 cells. Right: blade-coated 0.21 cm^2, 0.36 cm^2 and 1.0 cm^2 cells.

Transferability

Knowledge regarding the stability of solar polymers will be relevant for application in other types of organic solar cells, and the application of these materials in other organic optoelectronic devices. Knowledge gained may be also transferrable to the development of large area photodetectors.

Knowledge gained is being shared through communication of results at national and international meetings such as at the annual symposium of the Australian Community for Advanced Organic Semiconductors and the Asia-Pacific Solar Research Conference. Detailed technical reports are being made available through the research repository Bridges, see:

https://bridges.monash.edu/projects/Bringing_All-Polymer_Solar_Cells_Closer_to_Commercialization/65450

We have also commenced roll-to-roll printing trials with the Flexible Electronics Laboratory at CSIRO in Clayton which has an activity in printed solar cells funded through ARENA. These printing trials have been disrupted due to COVID-19-related lab closures and restrictions, however there are plans to restart when restrictions ease.

Conclusion and next steps

This project has demonstrated that some of the obstacles to the commercialisation of all-polymer solar cells can be surmounted. Materials can be produced on the gram-scale using environmentally friendly processes. All-polymer solar cells show promising thermal stability under thermal cycling. They can also be produced on the cm^2 scale using scalable coating processes. There are challenges which remain including relatively poor photochemical stability and the development of robust encapsulation strategies to mitigate environmental degradation.

In the long run the realisation efficient, robust polymer solar cells will enable photovoltaic technology employed in areas and applications currently off limits to traditional silicon solar cells. The knowledge gained from this project will also in general assist the international organic solar cell community in bringing organic solar technology closer to fruition.

Lessons Learnt

Lessons Learnt Report: Thermal stability of polymer solar cells

Project Name: *Bringing All-Polymer Solar Cells Closer to Commercialization*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	SA, NSW and Victoria

Key learning

The thermal stability of all-polymer solar cells based on blends of two semiconducting polymers was found to be superior to other types of polymer solar cells, with the entanglement of long chain polymer molecules and effective way to suppress demixing under thermal cycling.

Implications for future projects

For polymer solar cells to be a commercially viable technology they need to demonstrate good thermal stability when benchmarked against established standards. While power conversion efficiency is the focus of most academic studies, high efficiencies do not always correlate with high thermal stability. Polymer solar cells that employ small molecule acceptors are susceptible to thermal degradation under standard thermal cycling experiments, and larger molecular weight materials should be preferred to ensure good thermal stability over a reasonable operational lifetime.

Knowledge gap

Most academic studies focus on developing new materials for high efficiency with little emphasis placed on environmental stability. Good data on the thermal stability of different systems according to established standards is lacking.

Background

Objectives or project requirements

The objective of this part of the project was to measure the thermal stability of a series of polymer solar cells according to the ISOS-T-1 protocol. Different types of polymer solar cells (all-polymer, polymer:fullerene, polymer:non:fullerene) were tested, as well as different material combinations.

Process undertaken

12 different polymer solar cells types were fabricated and subjected to thermal cycling according to the ISOS-T-1 protocol, which involves cycling between room temperature and 85 °C. Thermal cycling was performed in a nitrogen environment to exclude the influence of other environmental factors.

10 different all-polymer solar cell types were screened, along with representative polymer:fullerene and polymer:non-fullerene cells. Cell efficiency was measured after 1, 3, 5, 10, 20, 40, 70, 100, 200 and 500 cycles.

Supporting information

Full technical details can be found in the technical report "Stability of all-polymer solar cells," published on Monash University's research repository Bridges: DOI: 10.26180/15185976, and available online at:

https://bridges.monash.edu/articles/report/Stability_of_all-polymer_solar_cells/15185976

MONASH University

Lessons Learnt Report: Upscaling of polymer synthesis

Project Name: *Bringing All-Polymer Solar Cells Closer to Commercialization*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	SA, NSW and Victoria

Key learning

The direct arylation polymerisation method is appropriate for the environmentally friendly synthesis of solar polymers with high yields, high molecular weights on the gram-scale avoiding the use of toxic organotin compounds.

Implications for future projects

The large-scale manufacture of semiconducting polymers for the industrial production of polymer solar cells will require synthetic strategies that can be (i) produce the amount of material required and (ii) minimise the amount of toxic waste produced. The synthetic route of direct arylation polymerisation has been shown to be a promising strategy to this end, and the optimum reaction conditions identified will provide assist future projects to produce large quantities of polymers for printing trials.

Knowledge gap

Semiconducting polymers for solar applications are typically produced on the milligram scale and screened for efficiency with little concern for how easy the synthetic protocol can be upscaled and how much waste toxic produced. New synthetic pathways that enable gram-scale quantities to be produced that are environmentally friendly are required.

Background

Objectives or project requirements

While the new materials that can be realised by organic synthetic chemistry is essentially limitless, there are limits on the how easily certain materials can be produced. The objective of this part of the project was to develop synthetic pathways that enable in the environmentally friendly synthesis of solar polymers on the gram scale to provide proof of principle for further upscaling of all-polymer solar cell manufacture.

Process undertaken

Traditional polymerisation methods to synthesise high molecular weight solar polymers generally rely on transition-metal-catalyzed cross-couplings, especially Stille coupling that requires the use of toxic organotin compounds. To synthesise polymers in a more environmentally friendly way, we have explored the reaction conditions for direct arylation polymerisation, avoiding the use of organotin compounds. Over 100 polymer batches have been synthesised, and we have optimized the reaction conditions permitting the gram-scale synthesis of materials while minimising the amount of toxic waste generated.

Supporting information

Full technical details can be found in the technical report "Upscaling and optimisation of the reaction conditions for direct arylation polymerisation," on Monash University's research repository Bridges:

https://bridges.monash.edu/articles/report/Upscaling_and_optimisation_of_the_reaction_conditions_for_direct_arylation_polymerisation/15238539

Lessons Learnt Report: Upscaling of polymer solar cells

Project Name: *Bringing All-Polymer Solar Cells Closer to Commercialization*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	SA, NSW and Victoria

Key learning

Blade coating is suitable for the fabrication of cm^2 sized all-polymer solar cells, with good retention of efficiency compared to small cells and low leakage current.

Implications for future projects

The large-scale manufacture of polymer solar cells requires high throughput manufacture over large areas. The successful demonstration of the blade-coating of all-polymer solar cells on the cm^2 scale paves the way for larger trials using roll-to-roll printing. All-polymer blends may provide distinct advantages for roll-to-roll printing such as fewer pinholes and easier processing compared other formulations (polymer:fullerene, polymer:non-fullerene).

Knowledge gap

Prior to this project, most upscaling studies have focused on other types of organic solar cells (e.g. polymer:fullerene, polymer:non-fullerene). The potential for all-polymer blends to be fabricated using scalable coating processed on the cm^2 scale was still to be fully explored.

Background

Objectives or project requirements

In order to make sure laboratory-scale solar cell results were translatable to the large area manufacture of polymer solar cells, we sought to implement a laboratory-scale coating technique whose conditions were relevant to large area manufacture. Blade coating was identified as a promising technique that uses a blade (such as a glass slide, silicon wafer or knife edge) to coat a layer of solution across a substrate. The coating and drying conditions for blade coating are similar to large area printing techniques such as slot-die coating, so that if good efficiencies can be achieved in the laboratory they can be translated to larger area coating processes.

Process undertaken

After initial efficiency screening using small scale cells (0.045 cm^2) on 12 mm by 12 mm substrates, a new substrate size (19 mm by 19 mm) was adopted which enabled cells of varying size to be realised. Blade coating conditions were then optimised with cell size increasing from 0.21 cm^2 to 0.36 cm^2 to 1.0 cm^2. Encouragingly, low dark currents which reflect a high film uniformity with low pin-hole density were observed. Systematic decreases in fill factor with increasing active area were seen, which are related to the increased series resistance of the cells. In future, strategies to mitigate series resistance in large area cells will enable higher efficiency of large area devices

Supporting information

Full technical details can be found in the technical report “Stability of all-polymer solar cells,” published on Monash University’s research repository Bridges: DOI: 10.26180/15186003, and available online at:

https://bridges.monash.edu/articles/report/Upscaling_of_polymer_solar_cells/15186003