Super-Efficient Coloured PV for Vehicles

Yuanxun Liao[1], Mark Keevers[1], N.J. Ekins-Daukes[1], Martin Green[1], Yajie Jiang[1]*

[1]School of Photovoltaic and Renewable Energy Engineering of University of New South Wales, Sydney, NSW, 2052, Australia
yuanxun.liao@unsw.edu.au; mark.keevers@unsw.edu.au; nekins@unsw.edu.au; m.green@unsw.edu.au; yajie.jiang@unsw.edu.au

The key elements for the development of vehicle-integrated photovoltaics (VIPV) include at least sufficiently high efficiency, reasonable price, and certain aesthetics. Highly efficient solar cells enable cars to achieve meaningful driving range on a limited surface area. The price of these high-efficiency solar cells must be within the range that people can afford. Solar panels should have different colors to blend with the colors of cars. High-efficiency triple-junction III-V solar cells could be available at affordable prices. However, changing their color without a significant loss of efficiency remains a challenge. Here, we show that a simplified optical notch filter can effectively change the color of III-V solar cells with less than 3% efficiency loss. Thus, colored super-high-efficiency solar cells with efficiencies over 31% have been demonstrated, meeting VIPV requirements.

Introduction

The cost of III-V solar cells is presently high, around $100/Wp (USD) for space arrays and marginally lower for CPV systems. There is no fundamental reason for this high III-V cell cost, other than the relatively low manufacturing volumes. A recent study conducted by NREL showed cost reduction strategies that could reduce costs below $1/Wp [1]. Although this is still an order of magnitude higher than present Si-based technology, there are valuable markets for III-V PV where efficiency holds a premium. Vehicle-integrated PV (VIPV) is a particularly good application, with the technical requirement that the cells are highly efficient and the social requirement that the cells be coloured. Toyota recently demonstrated a 56 km/day solar range from a Prius PHEV equipped with 34% III-V-based solar cells. A recent study of consumer attitudes towards electric vehicles and PV electric vehicles has shown that potential PV-EV drivers are willing to pay $2000 for integrated PV charging and a high premium on colour, with the survey showing a 'willingness to pay' at least $7,000 extra for colour, amounting to a capacity cost of $9/Wp [2].

A range of attractive coloured PV products already exist to serve the building integrated PV (BIPV) market, but their colour comes with the penalty of significantly reduced efficiency. This is tolerable for BIPV where the building surface area is large, but the available area on a vehicle is very restricted so this work demonstrates means for achieving colour on highly efficient multijunction solar cells whilst maintaining electrical power conversion efficiencies above 30%.

The perception of colour arises from the stimulation of cone light receptors in the eye. Conventional PV cells and modules are usually designed to minimize reflection and therefore have a dark appearance to the eye. However, selectively reflecting a narrow light beam from the module will result in the perception of colour, which may just slightly decrease efficiency and keep the efficiency limit of single-junction solar cells still above 30% [3].

Main text

Specifically, the triple-junction III-V solar cell used in this work is illustrated in Figure 1A, with an efficiency of about 34% under one sun condition. The product of one-sun photon flux and solar cell EQE is shown in Figure 1B, and the top cell covers almost all the visible solar spectrum. The effect of selectively reflecting a narrow light beam is to dig a trench in the product of the top cell, as demonstrated in Figure 1B, which will decrease Jsc and thus the efficiency. If the selective reflectance is around 50% and the beam linewidth is less than 50 nm, like those in Figure 1C, the calculated efficiency loss is less than 3%, which means the triple-junction solar cells can still maintain efficiency above 30%.

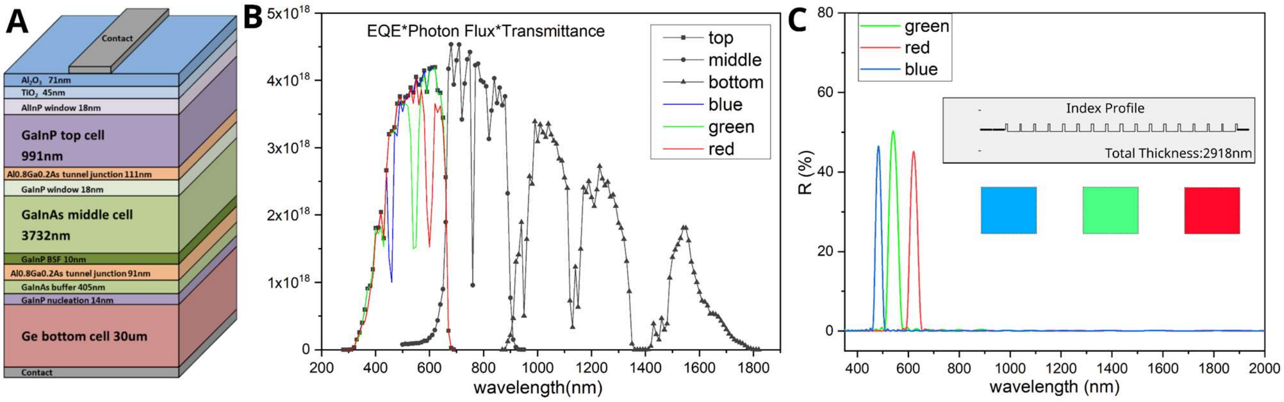

Figure 1. (A) Schematic diagram of the triple-junction III-V solar cells. (B) The product of one-sun photon flux and solar cell EQE for the III-V solar cell; and the effects of filters are included by further multiplying the transmittance of the filters. (C) The designed reflectance and colors of the filters. A typical filter structure has been shown as an inset, which consists of high and low index layers with a total thickness of about a few microns.

The key challenge is how to achieve this at a low cost. The selective reflection shown in Figure 1C can be achieved with an optical notch filter, an expensive optical component that can cost tens to hundreds of dollars for a few square inches. As shown in the inset of Figure 1C, we significantly simplify the notch filter design, which keeps the narrow linewidth but substantially decreases the layers and total thickness of thin films, at the cost of reducing the reflectance from near unity to about half. In this way, the cost of adding colours to a car with a surface of 3 square meters of solar cells could decrease to less than 600 dollars, amounting to a capacity cost of $0.1/Wp, much lower than the survey cost that people are willing to pay [2].

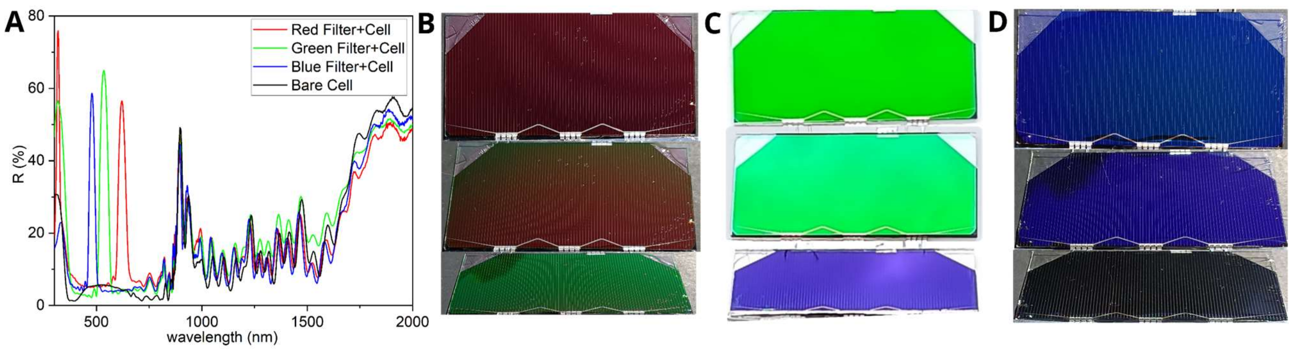

Figure 2. (A) Measured reflection spectra for bare and filter-encapsulated III-V solar cells. The colour effects of the filter-encapsulated solar cells at different angles under sunlight. (B)-(D) represent colours of red, green, and blue, respectively. For (B)-(D), from top to bottom, photos are taken at three different angles: 0-10 degrees, 30-40 degrees, and 70-80 degrees.

The measured reflection spectra of solar cells and filters are illustrated in Figure 2A. In comparison with the bare solar cell, sharp selective reflections are achieved at 476 nm, 536 nm, and 623 nm for blue, green, and red, respectively, with linewidths of 27 nm, 38nm, and 34 nm. And the impacts on the middle and bottom cells are small.

The visual effects of the filters on solar cells are shown in Figure 2B to 2D. The original black colour of the solar cells has been completely masked by the filter in outdoor conditions. However, the colors are blue shifting with view angles, since the optical path lengths are angular dependent. The colour change is not visually prominent until about 40 degrees, which is a problem for colour purity but can also be used for colour-changing purposes. The angular dependence can be improved by glass textures that can provide similar optical path lengths at different angles.

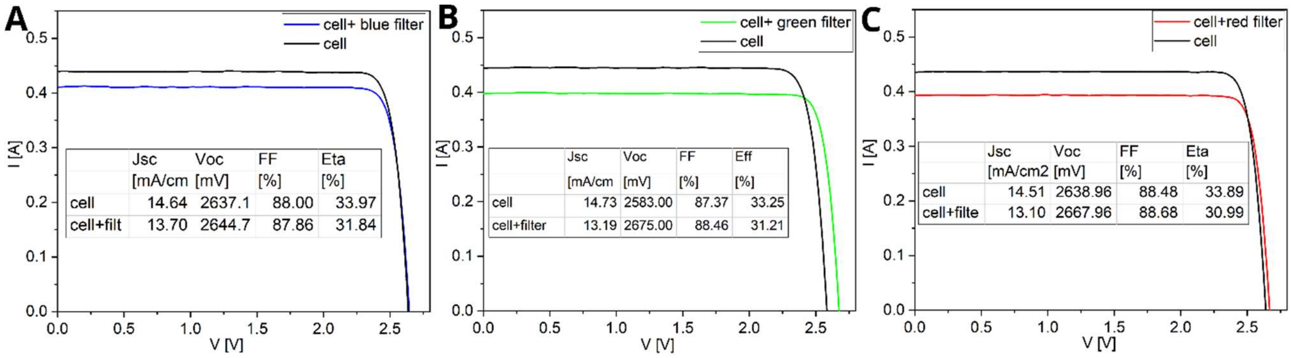

Figure 3. I-V curves measured at 1 sun conditions for encapsulated solar cells with (A) blue filter, (B) green filter, and (C) red filter and for the associated original solar cells. The measured parameters are shown as inset.

The I-V curves of original and filter-encapsulated solar cells are illustrated in Figure 3. First, the efficiencies of colored solar cells are above 30%, which has successfully achieved our targets. It is worth noting that such high efficiency is achieved by completely shading the pristine black, which has not been reported so far. Second, the efficiency loss is less than 3% for a triple-junction, which hints at an even smaller loss for a single-junction cell like Si cells. Third, the efficiency loss is due to reduced Jsc caused by the reflection, with Voc and FF almost the same, which is consistent with our analysis above. Finally, there is still room for optimization, and it is very possible to control the efficiency loss within 2%.

Summary

Super-efficient coloured solar cells are likely to drive the VIPV market as it enables both considerable solar mileage range and aesthetic appearance. We demonstrate how to achieve this with low-cost optical notch filters, which not only completely shade the original black colour of solar cells but also maintain a very high efficiency of above 30%. Considering that there is no other comparable technology, it is worth further research.

References

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