Monolithic Si/perovskite tandem solar cell: advanced designs towards high-efficiency at low-cost

Lead organisation:	Australian National University
Funding Agency:	Australian Renewable Energy Agency (ARENA)
ARENA Project ID:	2020 RND017
Project commencement date:	18 September 2020 **Completion date:** 1 October 2023
Date published:	
Contact name:	Kylie Catchpole
Title:	Professor
Email:	Kylie.catchpole@anu.edu.au
Phone:	02 6125 0874

This Project received funding from ARENA as part of ARENA's Research and Development Program – Addressing end-of-life issues and lowering the cost of solar PV

Table of Contents

Executive Summary

Tandem solar cell has emerged as one of the most promising approaches to further reducing the cost of solar cells by enhancing their efficiency. Among the contenders, the perovskite solar cell stands out as the most promising top cell to partner with silicon (Si) cells in tandem architecture, thanks to its superior optoelectronic properties, impressive efficiency, and the potential for low-cost production. However, the complexities and inclusion of expensive materials and fabrication processes in Si/perovskite tandem architectures, coupled with low material usage during deposition, leads to a substantial increase in manufacturing costs. The pioneering work on the interconnect-free Si/perovskite tandem solar cells led by the ANU team presents an important and promising solution to this challenge.

The objective of this project is to advance Si/perovskite tandem technology towards commercial viability by making significant strides in three key domains: cost, efficiency, and lifetime, building on the simplified tandem cell architecture pioneered by the ANU team. Innovative efforts have been made on both the Si and perovskite subcells, as well as their interfaces. In terms of Si subcells, the project has pioneered a low-cost, double-sided poly-Si/SiO_2 passivating contact cell using industrially-relevant processes, as well as developed and introduced cutting-edge dopant-free Si cell technology for tandem application. For the perovskite subcells, comprehensive material innovations and device optimization having been demonstrated to produce high-quality perovskites and their functional layers, leading to the achievement of high-performance and durable perovskite cells apt for tandem applications at low cost simultaneously. Moreover, meticulous material and interface engineering have been conducted and played a crucial role in simplifying the tandem architecture and realizing the efficient interconnect-free tandem design on various Si technologies. Integrating the subcells with the simplified, interconnect-free tandem architecture leads to state-of-the-art tandem performances of over 29%, the highest for the same type.

To enhance the stability of the Si/perovskite tandem solar cells, both intrinsic strategies—aimed at improving material stability—and extrinsic strategies focusing on robust encapsulation to minimize efficiency loss and prevent moisture and oxygen infiltration have been developed. The encapsulated state-of-the-art tandem cells have met some rigorous industrial benchmarks set for commercial Si solar cell technology. Technoeconomic evaluations have been conducted throughout the project, which not only guides the project's progression but also furnish invaluable insights to the wider community. These achievements significantly elevate the technology readiness level of the Si/perovskite tandem solar cells, setting the stage for commercial readiness and an economically sustainable renewable energy future.

Project Overview

Project Summary

Background

Despite the Si/perovskite tandems' potential for low cost, technoeconomic analysis on high-efficiency, demonstrated Si/perovskite tandem solar cells indicates that current tandem designs add substantially to the cost of standard c-Si cells. So far, little attention has been paid to making tandem designs cost-effective. The ANU team has recently developed a ground-breaking and fundamentally different Si/perovskite tandem structure that considerably reduces the tandem cost by eliminating the commonly-used interconnect layer connecting the two sub-cells, while retaining high-efficiency, and being particularly advantageous for upscaling. The so-called interconnect-free tandem concept has broad applicability, with successful demonstration on commercially relevant homo-junction Si cells and on poly-Si/SiOx passivating contact Si cells, resulting in one of the highest monolithic tandem efficiencies reported in 2018.

Building on this innovation, this project brings together an integrated team of international experts from academia and industry to significantly reduce Si/perovskite tandem solar cell cost. This project will advance the Si/perovskite tandem technology towards commercialisation by making significant advances on all three metrics that are critical for successful commercialisation: cost, efficiency and stability. This will occur by development of new concepts and advanced designs, including double-side poly-Si/SiO_x passivating contact Si cells for tandems, dopant-free Si cell technology to reduce optical losses, ultra-thin transport layer for minimal optical loss, inorganic transport layer for improving tandem stability, etc.

Project Aim

The Project aims to reduce the cost of monolithic Si/perovskite tandem solar cells while achieving high power conversion efficiency and excellent stability. This will be done by developing new concepts and advanced device designs as well as optimising materials and processes, thus providing a pathway to commercialisation for interconnect-free Si/perovskite tandem solar cells.

Development of new concepts and advanced designs will be achieved through four main Project objectives:

Objective 1: Interfacial engineering between the Si front contact and perovskite rear contact to allow minimal optical/electrical losses across the interface and efficient operation of each subcell.

Objective 2: Optimisation of the Si sub-cell (bulk and rear-contact improvement, optics, compatibility with industrial processes) specifically for the interconnect-free tandem, integrating outstanding Si front-contact from objective-1.

Objective 3: Perovskite cell improvement with high-quality and stable perovskite and contact layers.

Objective 4: Tandem stability improvement combining intrinsic (objective-3) and extrinsic strategies (encapsulation).

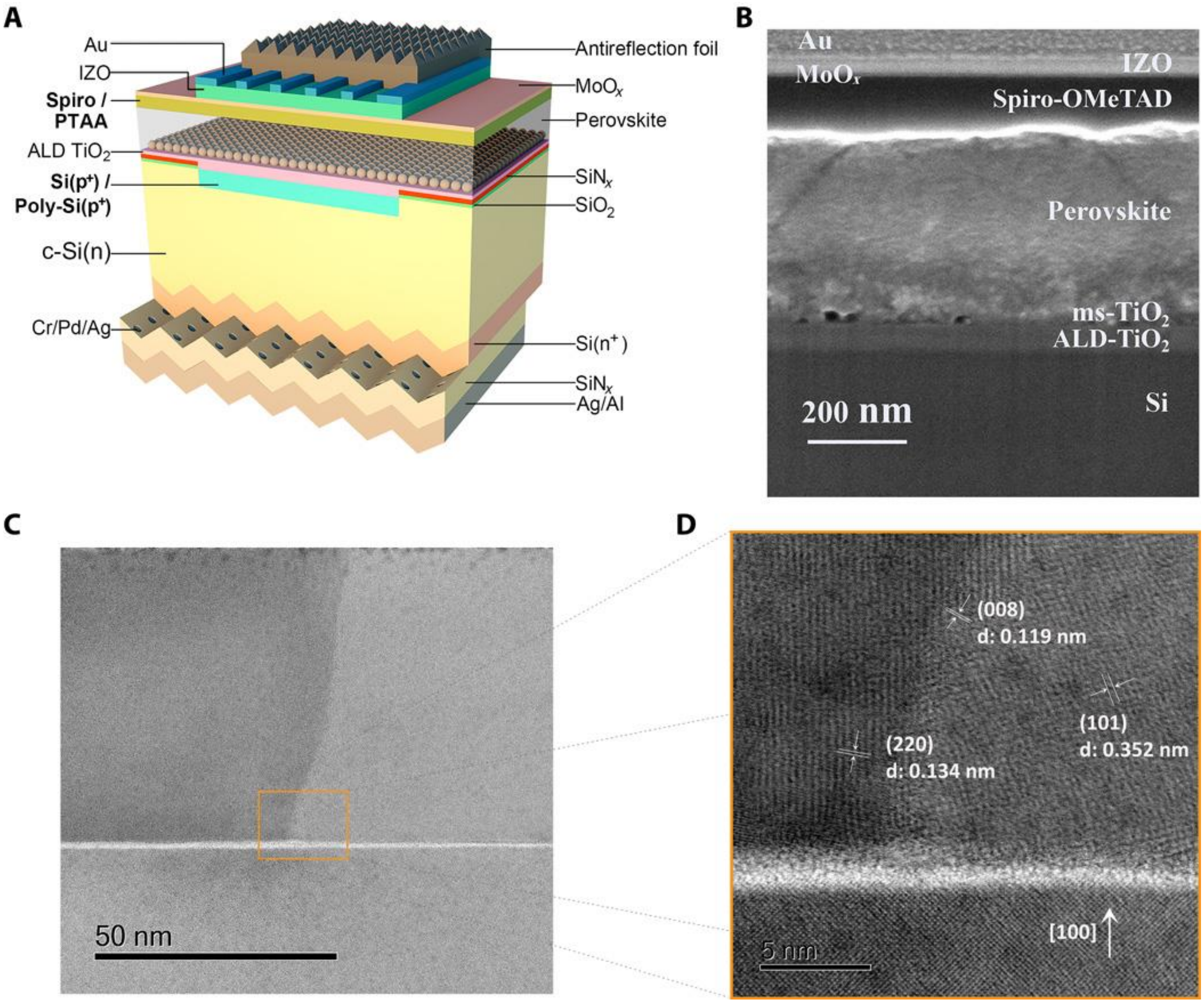

Figure 1 (A) Schematic of the interlayer-free monolithic crystalline-silicon (c-Si)/perovskite tandem solar cell (not to scale). Initial tests were carried out on homojunction Si cells with Spiro-OMeTAD (Spiro) as the top perovskite contact; however, our best performance was obtained with polysilicon (poly-Si) bottom cells and PTAA {poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine]} as the top hole-selective layer. (B) Cross-sectional SEM image of the tandem device based on a Si homojunction subcell from the top surface to the p^+-Si layer [Spiro-OMeTAD is used as a hole transport material]. The antireflection layer was not included because of the large thickness of ~1 mm. (C) Scanning transmission electron microscopy (STEM) bright-field (BF) image, and (D) high-resolution STEM BF image of the TiO_2/p^+-Si interface.

Project Scope

The project has developed several **new concepts and advanced designs for tandem Si/perovskite tandem solar cells**, including double-side poly-Si/SiO_x passivating contact Si cells for tandems, dopant-free Si subcell technology to reduce optical losses and further lower down the manufacturing cost, ultra-thin transport layer to reduce optical loss, stable and dopant-free transport layer, leading to achievement of high-efficiency and excellent stability for Si/perovskites solar cells simultaneously at low cost.

- The project demonstrated high-performance Si/perovskite tandem solar cell based on poly-Si/SiO_2 passivating contact cell. All major Si solar cell technologies have been investigated as the bottom sub-cell, with some of the highest efficiencies achieved on passivating contact Si cells. Si cells based on poly-Si/SiO_2 passivating contacts (poly-Si cells hereafter) with efficiency up to 26% have been reported by several of the world's large PV manufacturers and provide a pathway beyond current PERC technology, while also presenting a promising sub-cell for Si/perovskite tandem solar cells. Poly-Si cells have a significantly lower manufacturing cost per watt than the Si heterojunction cells (HJT), due to the requirement for the latter for large amounts of expensive low-temperature silver paste and a higher depreciation cost of equipment.

  Research on monolithic Si/perovskite tandem solar cells based on poly-Si cells has progressed rapidly, with ANU at the forefront of this research direction. In 2018, the ANU team was the first in the world to report the monolithic Si/perovskite tandem solar cells based on poly-Si cell by developing a simple tandem architecture that bypasses the interconnect layer, leading to a tandem efficiency of 24% for a proof-of-concept device.

  Through this project, ANU has made significant breakthroughs in both the Si and perovskite sub-cells and demonstrated various high-performance tandem structures. One tandem structure was built on an in-house developed high-efficiency double-sided poly-Si cell with an *n-i-p* perovskite top cell, raising the efficiency to >29%, the highest for Si/perovskite tandem technology based on poly-Si cells. Featuring new concepts, this tandem architecture allows concurrent enhancement of efficiency and stability at low cost. A patent application has been lodged for this innovation.

  The other tandem architecture is built on a commercial poly-Si cell (the so-called TOPCon cell) with a *p-i-n* perovskite cell, leading to an efficiency of 27.6%. For this work, a high-quality sputtered NiO_x hole transport layer (HTL) was developed, as well as an electron transport layer (ETL) based on ultra-thin C_{60} covered with an inorganic SnO_2 layer. All are amenable to up-scaling and are particularly suited to the rough surfaces that will be encountered on commercial Si wafers and cells, whether they are textured or not.

- The project demonstrated high-performance Si/perovskite tandem solar cell based on HJT Si cell through the collaborative work by the project partners which encompassed various aspects, including device design, modeling, and fabrication. A low-temperature *n-i-p* perovskite solar cell employing SnO_2 as the electron transport material has been designed and developed, to address temperature constraints imposed by the HJT solar cell. Through this approach, we have achieved an exceptional tandem solar cell performance exceeding 26%, one of the highest for the same type.

- In this project, the project team were the first to demonstrate the potential of utilizing dopant-free Si solar cells in Si/perovskite tandem solar cells through close collaboration with all project partners. A tandem cell, utilising conventional tandem structure, was developed by integrating a dopant-free Si solar cell with a perovskite solar cell using a transparent conductive oxide (TCO) recombination layer. In addition, the project further simplified the tandem architecture by developing low-resistance metal contacts, resulting in an interconnect-free tandem solar cell based on dopant-free Si solar cells.

Stability assessment and improvement: The project has taken a comprehensive approach, focusing on both intrinsic and extrinsic strategies (including encapsulation) to enhance tandem stability while maintaining high efficiencies.

Encapsulated Si/perovskite tandem solar cells, utilizing edge-sealing technology, underwent rigorous accelerated environmental testing to assess their stability. The tandem solar cells based on poly-Si subcell that are developed by this project exhibit stability performances that are among the best stability performance for Si/perovskite tandem solar cells in any architecture.

By applying light-dark cycles throughout a period of 1750 hours, each cycle consisting of 12 hours of 1-sun illumination followed by 12 hours of storage in the dark, no drop in efficiency was observed.

Technoeconomic studies on our high-performance tandem devices have been continuously conducted throughout the project. The ANU team, in collaboration with project partners, utilized a bottom-up cost model to evaluate several established high-efficiency 2-T Si/perovskite tandem cells. These studies not only provide guidance for the project's development of cost-efficient tandem technology but also provide valuable insights for the broader community working on cost-effective tandem solutions.

Outcomes

- Two types of low-resistivity Si and perovskite interfaces have been developed, enabling the successful demonstration of high-performance Si/perovskite tandem solar cells with simplified interconnect-free tandem design. The low-resistivity contact behaviour between the emitter on the front side of the Si subcell and the charge transport layer on the rear side of the perovskite subcell, as well as the compatible fabrication process developed for the perovskite cell with the Si bottom cell, are the major enabler for the simplified tandem structure with high efficiency. Tuning of the material electrical properties, including the doping profile, the energy levels, the defects states has been found to be important to produce contact with outstanding optoelectronic properties, which is delivered by careful material choice, optimising the deposition conditions and post-treatment processes.

- Extensive device optimization led to a significant advancement in poly-Si/SiO_2 passivating contact cells for tandem solar cells, guided by optoelectronic simulation. The project developed a symmetric double-side poly-Si/SiO_2 passivating contact Si solar cell, which are not only silver (Ag)-free but also transparent conductive oxide (TCO)-free. This is achieved by devising and developing an atomic layer deposited titanium oxide (TiO_2) layer, which forms a low-resistivity ohmic contact with both p-type poly-Si and n-type poly-Si layers. The poly-Si cells are fabricated with processes that are highly compatible with mainstream mass-production techniques.

- The project successfully developed high-performance, stable Si/perovskite tandem solar cell, with an efficiency exceeding 29%, based on the interconnect-free tandem architecture, standing as the top-performing cell of its kind. Significant innovation and breakthrough come from integrating an ultra-thin, dopant-free hole transport material into the *n-i-p* perovskite solar cells.

- This project has conducted cost study for Si/perovskite tandem solar cells and produced cost analysis reports that benefit the community by providing guidance for research directions towards low-cost processes and materials in parallel with higher efficiency in the Si-tandem area. Cost analysis points out that the removal of the interconnect layer increases the cost-effectiveness of the tandem solar cell by reducing the manufacturing cost and meanwhile maintaining high efficiency. Developing indium-free transparent conductive material for the top contact of the tandem solar cell can further reduce the material cost, benefiting the expansion of the PV market.

- The project has produced two patents. One patent has provided strong foundation for a recently funded ARENA project titled 'Cost-effective Si/perovskite tandem modules on passivating contact Si cells', which has received substantial financial support from the leading PV manufacturing company to further advance tandem technology towards commercialization. The other has attracted interest from the innovative start-up with the prospect of collaboration in an ARC Linkage project.

- This project has delivered increased skills, capacity, and knowledge relevant to renewable energy technologies through presenting high-quality research findings to the PV research community, industry, and the public.

- This project has also increased Australia’s research capacity and foster the next generation of Australian PV researchers by providing outstanding training opportunities to early-career Post-doctoral Fellows as well as PhD (non-ARENA funded). The project has supported five early career postdoctoral researchers, who have been actively engaged in various facets of tandem technology research. In addition, the project has provided support to one PhD student, who was awarded a Taiwan-ANU PhD scholarship, to conduct research within the project's scope. Additionally, two research assistants who worked on the project and supported by the project have gone on to pursue postgraduate studies in this field.

Transferability

The achievements of this project hold vast potential for both research and the commercialization of perovskite-based optoelectronic device technology, including but not limited to light-emitting diodes, detectors and sensors. Specifically, the innovations in materials for the perovskite and other functional layers in solar cells offer versatility. They are not only poised for integration into industrial solar cell technology but also align with varied perovskite cell designs, including single-junction perovskite solar cells. Furthermore, the meticulously crafted low-resistivity interfaces can be tailored for a spectrum of electronic and optoelectronic devices, including Field-effect transistors (FETs). The device engineering methodologies perfected for Si subcells in tandem solar cells are transferable to commercial standalone Si cells. Additionally, the pioneering solutions and tackled challenges within this project have profound synergy with hydrogen research and development. This alignment has cultivated multidisciplinary partnerships and prompted a subsequent ARENA application in the same domain.

Material and device designs with immense commercial promise developed by this project have been pinpointed and patented. The intellectual property generated from this project has paved the way for a new research alliance with a prominent industry entity, aimed at elevating the technology readiness level from a laboratory scale to a pilot demonstration.

Project partners regularly exchange knowledge and project progress via meetings, seminars, and detailed internal documents. Bi-weekly project meetings have been organized, where members share their findings and advancements. We've also launched a website, perovskitegroup.com.au, spotlighting ongoing projects, the latest discoveries, press announcements, researcher profiles, opportunities, publications, and more.

Chief investigators and fellow researchers consistently participate in both international and domestic conferences, make research institution visits, and deliver presentations to diverse audiences, celebrating our research milestones. The team's innovative strides during this project have been documented in both conference and journal publications. Remarkable achievements, such as setting new world records in efficiency, have also garnered media attention.

Conclusion and Next Steps

This project has demonstrated significant success in achieving both high efficiency and improved stability in simplified Si/perovskite tandem structures, a crucial milestone for advancing this technology towards commercialization. However, it's important to acknowledge that despite this progress, several challenges persist in the commercialization of Si/perovskite tandem solar cell technology.

Si/perovskite tandem solar cells inherit stability concerns from perovskite cells and are additionally susceptible to tandem-specific degradation mechanisms. These challenges encompass issues related to perovskite phase segregation, strain unique difficulties when perovskite films are applied to textured surfaces, and the constraints imposed by current matching. Attaining the long-term stability required for commercialization at both the cell and module levels is a pivotal next step in this field. Besides the accelerated indoor tests, evaluating stability under outdoor conditions is also crucial. The outdoor assessment offers insights into the real-world performance and lifetime of the materials or devices under varying environmental factors.

Furthermore, while Si/perovskite tandem solar cells hold the promise of low-cost manufacturing, it's worth noting that currently, the most high-performing tandem solar cells still rely on high-cost materials and processes. Therefore, it is imperative for the perovskite research community to continue to conduct comprehensive techno-economic analyses and develop high-performance tandem solar cells at low cost. These techno-economic analyses will provide insights into how material and process modifications impact tandem costs and assess their cost-effectiveness relative to dominant photovoltaic technologies in the market. The material, processes and device development efforts for high-efficiency, stable tandem solar cells should be closely guided with the findings from the cost analyses results.

Currently, remarkable efficiencies have been attained for perovskite and tandem solar cells at the laboratory scale. However, a significant challenge persists in the upscaling of this technology to an industrial level, to preserve high efficiency and stability levels and ensure good reproducibility. This scaling process is of paramount importance for the practical deployment of Si/perovskite tandem solar cells within the renewable energy landscape.

Addendum

Patent Applications

[1] 'PHOTOVOLTAIC CELL AND METHODS OF FABRICATING SAME', Heping Shen, Pheng Phang, Kylie Catchpole, Daniel Macdonald, James Bullock, Di Yan, et al. Provisional patent P117920.AU

[2] "TANDEM PHOTOVOLTAIC CELL", Heping Shen, Leiping Duan, Kylie Catchpole, Provisional patent; P117603.AU

Journal Publications

[1] Leiping Duan, et al. "Stability challenges for the commercialization of perovskite–silicon tandem solar cells", Nature Reviews Materials, 2023, 8, 261–281. DOI: https://doi.org/10.1038/s41578-022-00521-1

[2] Yiliang Wu, et al. “27.6% Perovskite/c-Si Tandem Solar Cells Using Industrial Fabricated TOPCon Device”, Adv. Energy Mater. 2022, 2200821. DOI: https://doi.org/10.1002/aenm.202200821

[3] The Duong, et al. “Bulk Incorporation with 4-Methylphenethylammonium Chloride for Efficient and Stable Methylammonium-Free Perovskite and Perovskite-Silicon Tandem Solar Cells”, Adv. Energy Mater. 2023, 13, 2203607. DOI: https://doi.org/10.1002/aenm.202203607

[4] Naeimeh Mozaffari, et al. “Above 23% Efficiency by Binary Surface Passivation of Perovskite Solar Cells Using Guanidinium and Octylammonium Spacer Cations”, Solar. RRL 2022, 6, 2200355. DOI: https://doi.org/10.1002/solr.202200355

[5] Grace Tabi, et al. “LiI doping of mixed-cation mixed-halide perovskite solar cells: Defect passivation, controlled crystallization and transient ionic response”, Materials Today Physics 2022, 27, 100822. DOI: https://doi.org/10.1016/j.mtphys.2022.100822

[6] Md Arafat Mahmud, et al. “Combined Bulk and Surface Passivation in Dimensionally Engineered 2D-3D Perovskite Films via Chlorine Diffusion”, Adv. Funct. Mater. 2021, 31, 2104251. DOI: https://doi.org/10.1002/adfm.202104251

Conferences and seminars

- Kylie Catchpole: Plenary presentations at the International Photovoltaic Science and Engineering Conference 2021
- Kylie Catchpole: Invited speaker at iCANx, a global series of talks that attracts an audience of typically 20,000-30,000
- Heping Shen: Invited speaker at ACS Fall meeting 2023.
- Heping Shen: Invited speaker at Europe Material Society Research Meeting 2023, France.
- Heping Shen: Invited speaker for school seminar at University of New South Wales, May 2023.

Media coverage

- Renewable Economy, “Australian researchers beat their own record for next-gen solar cell efficiency” https://reneweconomy.com.au/australian-researchers-beat-their-own-record-for-next-gen-solar-cell-efficiency/
- Energy Matters, “Australian Researchers Obtain Perovskite-Silicon Tandem Solar Cell With 30.3% Efficiency” https://www.energymatters.com.au/renewable-news/australian-researchers-obtain-perovskite-silicon-tandem-solar-cell-with-30-3-efficiency/
- PV Magzine, “ANU team break 30% efficiency in tandem solar cell” https://www.pv-magazine-australia.com/2023/02/08/anu-team-break-30-efficiency-in-tandem-solar-cell-hitting-australias-2030-stretch-goal/
- Renewable Economy, “Australian researchers smash efficiency record for ‘tandem solar cells” https://reneweconomy.com.au/australian-researchers-smash-efficiency-record-for-tandem-solar-cells-58712/

Lesson Learnt

Lessons Learnt Report: Technical knowledge regarding interfacial properties: electrical and optical coupling between subcells

Project Name: **Monolithic Si/perovskite tandem solar cell: advanced designs towards high-efficiency at low-cost**

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	Canberra

Key learning

Interfacial properties, encompassing both electrical and optical aspects between subcells, play a pivotal role in constructing high-performance tandem solar cells with an efficient and simplified design. Through comprehensive material engineering and modelling in this project, we discerned the essential physical parameters (doping density, doping species, and energy levels) that determine these properties. We also solidified the foundational knowledge that bridges process engineering with material characteristics, which in turn influences the interfacial attributes. This understanding not only lays the groundwork for further improvements but also facilitates the investigation of new materials, potentially leading to novel tandem architectures and other advanced optoelectronic devices.

Implications for future projects

The insights acquired and the techniques devised for optimizing materials to achieve targeted optoelectronic characteristics serve as invaluable contributions to the fields of material science and device engineering, especially in contexts where interfaces are prevalent. Beyond solar cell applications, the innovative materials produced during this project hold potential for a myriad of other optoelectronic device developments.

Background

Objectives or project requirements

Traditional monolithic tandem solar cells incorporate an interlayer, either a recombination layer or a tunnelling junction, to connect the subcells. These interlayers, while essential, absorb light and add extra steps to the fabrication process, which, in turn, diminishes the cost-effectiveness of the tandem solar cells. As a result, there's a compelling need to develop a more simplified tandem architecture.

Process undertaken

The project was conducted with a focus on material engineering, specifically by optimizing fabrication processes to allow optimal interfaces between the two subcells with minimal optoelectronic losses. By optimising the fabrication processes, such as deposition temperature and choice of precursor, we were able to fine-tune the doping density and energy levels of the contact materials. This was done to ensure that they not only form low-resistivity, ohmic contact interfaces but also possess superior charge extraction properties for each subcell. Consequently, the contact properties and their performance in each subcell were evaluated concurrently. In addition, an innovative approach was adopted to segregate charge transport from the surface passivation of the absorbers, thereby minimizing interfacial energy losses in these devices.

Lesson Learnt

Lessons Learnt Report: Learnings from optoelectronic modelling and loss analysis results

Project Name: **Monolithic Si/perovskite tandem solar cell: advanced designs towards high-efficiency at low-cost**

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	Canberra

Key learning

Through this project, we have set up cutting-edge optoelectronic modelling systems that span from the material level to the device level (both single junction and tandem). The model elucidates a roadmap for tapping into the real efficiency potential of Si/perovskite tandem solar cells and highlights pivotal areas for further enhancement. The modelling is consistently carried out to steer our material, process, and device optimization efforts, especially when integrating new designs.

Implications for future projects

Optoelectronic modelling and loss analysis are critical for all kinds of solar cells. The carrier loss mechanism analysis platform developed in this project could be widely used for many types of solar cells. The strategies used to develop this platform are also valuable intellectual property for the development of other analysis platforms.

Background

Objectives or project requirements

Si/perovskite tandem solar cells have exhibited efficiencies that exceed the individual performance records of each subcell. To fully unleash the superior potential of these tandem cells, it's essential to rigorously optimize every layer and interface to minimize the optoelectronic losses. Such optimization endeavours should be steered by advanced optoelectronic modelling. Moreover, as we delve deeper into exploring new material properties, unforeseen phenomena emerge that necessitate the use of modelling to aid in comprehension.

Process undertaken

We employed the SunSolve Ray tracer for optical modelling and the Quokka simulation to evaluate electrical properties. We expanded the Quokka simulation from standalone Si cells to the Si structure for a tandem design. Furthermore, we adapted the Quokka simulation for perovskite solar cells, which includes modelling the charge-carrier transport in the perovskite absorber using the semiconductor drift-diffusion equations. Iterative modelling processes were undertaken, and the results were compared with experimental data to validate our modelling system. The modelling results provide guidance for us for further experimental optimization.

Lesson Learnt

Lessons Learnt Report: Realising High Efficiency and Excellent Stability of Si/perovskite Tandem Solar Cells through Effective and Efficient Approach

Project Name: **Monolithic Si/perovskite tandem solar cell: advanced designs towards high-efficiency at low-cost**

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	Canberra

Key learning

High-efficiency performance of tandem solar cells relies on the high performance of each subcell, the excellent interface property as well as efficient optical coupling between the subcells. The tandem solar cells have many more layers than the single-junction solar cell design, indicating a more complicated system to optimise and more uncertain factors to occur during the device fabrication. To ensure fast progress, strategies including testing on the interface level before the cell level, conducting simulation and experiment simultaneously, as well as optimising the tandem efficiency in parallel with improving the efficiency for each subcell will help. In addition, stability testing of the solar cell under various aging condition is a time-consuming process. To plan the measurement early as well as set up systems for high throughput measurement will be helpful for make fast progress.

Implications for future projects

The advancements in achieving high efficiencies and enhanced stability elevate the technological readiness of perovskite and tandem solar cells for commercialization. The systematic and efficient methodologies, encompassing testing structures and understanding degradation mechanisms, offer valuable insights for continued refinement towards the ultimate commercial rollout of tandem technologies. The primary upcoming challenges and strategies for the large-scale manufacturing of Si/perovskite tandem solar cells revolve around maintaining high performance at an industrial scale and ensuring stability on par with Si cells, ideally spanning a lifetime of at least 10-15 years, which is a major focus of our current research work.

Background

Objectives or project requirements

This project aims to establish multiple high-performance Si/perovskite tandem solar cells with simplified architecture to reduce the performance. Achieving this necessitates extensive material screening and design optimization at both the single cell and tandem cell levels. Coordinating these experimental efforts with modelling tasks is a significant undertaking that demands considerable time. Moreover, stability tests are time-intensive, often spanning hundreds to thousands of hours. A substantial number of cells must undergo these tests to ensure consistent and reproducible results.

Process undertaken

This project has implemented a streamlined testing structure, enabling efficient deposition and testing procedures to make informed decisions for the development of high-performance devices. This testing framework provides accurate predictions for their potential performance in tandem solar cells with the aid of the modelling. Moreover, stability evaluations were initiated early in the project, beginning with single-junction perovskite solar cells. This approach helped identify degradation mechanisms, facilitating improvements in materials and device design before their integration into tandem cells.