CALIFORNIA ENERGY COMMISSION

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

High-Efficiency Perovskite Tandem Modules with Resilient Interfaces

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

This report describes the development of perovskite-on-silicon tandem solar cells. Tandem solar cell technology has the potential to achieve an efficiency that improves upon today's solar panels by up to 50 percent relative, thereby reducing the cost of solar installations and lowering the cost of solar for California ratepayers. Advancements were also made in developing a mechanically compliant conductive adhesive for silver-free shingling of cells into robust modules. The cell and architecture advances hold promise to enhance energy yields of solar installations when the sun is not shining directly overhead, raise overall system efficiency, and reduce the cost and resource-intensity of solar. This technology contributes significantly to California's mandated energy goals to reduce greenhouse gas emissions, meet renewable energy targets, and promote a cleaner environment

Keywords: Solar cell, tandem, perovskite, silicon, shingle module, conductive polymer

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Background

Transitioning away from fossil fuels to a renewable energy future is perhaps the single greatest challenge faced by humanity today. As a major economic power, the state of California can exert significant influence in adopting renewable energy technologies. It has already leveraged this weight with legislation such as Senate Bill 350 (De León, Chapter 547, Statutes of 2015) and Senate Bill 100 (De León, Chapter 312, Statutes of 2018), the latter of which mandates a transition to a 100 percent renewable energy supply by 2045. Executive Order (B-55-18, 2018) also requires California to transition to carbon neutrality by 2045.

Solar, specifically photovoltaic (PV), cells can play a significant role in helping California reach its ambitious renewable energy mandates. Developing more efficient solar cells is one way to address a long-standing problem with solar energy: cost. By increasing efficiency, solar power can become more affordable for all stakeholders. The current leading solar technology relies on a single light-absorbing material, silicon, which is plateauing at its upper performance limits of 22–26 percent conversion efficiency, with a theoretical limit of approximately 30 percent.

This project explored the use of multiple materials in a solar cell to absorb the sunlight, each capturing different parts of the solar spectrum, to push the efficiency boundaries beyond the current plateau. The project team's goal was to create innovative solar cells with two light-absorbing layers that can achieve a power conversion efficiency of 32 percent and a levelized cost of electricity of $0.031 per kilowatt-hour. These new modules, when commercialized, are expected to reduce electricity costs to California ratepayers and investor-owned utilities by boosting PV module power and energy over time, particularly in space-constrained distributed generation scenarios such as rooftop installations.

Project Purpose and Approach

Historically, tandem modules, or those that combine two different solar absorbing materials in a PV module, allow a conversion efficiency of greater than 30 percent. These modules have been made from materials and use fabrication methods that are prohibitively expensive, primarily due to the purity and high temperatures required. The University of California, San Diego research team explored several key technologies, including materials and processes, to reduce the costs of tandem PV modules and increase their production and use.

The project team developed perovskite-on-silicon tandem (PoSiT) modules, a multi-layer solar module using an unconventional cell architecture designed to minimize power losses. Traditional module architectures arrange cells adjacent to each other, resulting in lateral gaps between the solar cells where no power is produced. This project used shingled modules to reduce these losses. Shingled modules consist of solar cells overlapping like roof shingles with cell interconnections occurring at the overlapping edges. This arrangement eliminates the gaps between cells and enables the use of smaller cells, eliminating bulky copper ribbons and reducing shading losses. This new arrangement, however, requires an adhesive to join the cells. This adhesive must be conductive and flexible to avoid degrading the tandem cells as they experience thermal expansion and contraction. The project team developed an innovative silver-free and mechanically compliant conductive adhesive (MCCA), which may offer a significant advancement for the sustainability and cost of solar cell production. Silver consumption by the solar industry makes up about 15 percent of the global silver demand. Reducing silver use not only significantly decreases costs, but also lowers the environmental impact of solar panel production and waste disposal.

To achieve the project purpose, the team took the following approach:

1. Developed an innovative MCCA polymer technology to achieve low-loss, resilient contact interfaces in a high-power "shingled" module and novel lab techniques for the large-area processing of the MCCA polymer.
2. Using solution-processing methods, conducted conformal assembly of the perovskite top cell onto textured silicon cells produced in a commercial manufacturing line. The use of textured silicon bottom cells facilitates the absorption of light from a wide variety of angles, which is important as the sun shifts in the sky and during cloudy days.
3. Integrated MCCAs into shingled silicon modules in a lab setting.
4. Conducted reliability testing of the tandem modules via International Electrotechnical Commission-standard accelerated environmental testing, including damp heat testing, thermal cycle testing, and outdoor rooftop testing to assess reliability and stability.

To facilitate the project approach, the project team custom-built an innovative perovskite solar cell assembly line (PASCAL) robot to automate fabrication while demonstrating improved precision and repeatability for tandem photovoltaic applications.

Key Results

The project team produced fundamental scientific knowledge results related to perovskite materials, their interfaces, and technological advancements for the design and assembly of solar modules. Three main areas of technology and knowledge include advancing perovskite absorbers on textured silicon cells, integrating wide-bandgap perovskites with improved chemistry, and developing MCCA polymer technology for shingled modules.

The team successfully developed PoSiT cells and a shingled module architecture using silver-free conductive adhesives, moving the technology towards a realizable efficiency of greater than 32 percent.

Using the custom-built automated perovskite solar cell assembly line robot, the project team optimized material properties, such as what light is absorbed and the stability of the material against degradation under high temperatures. These experiments were complemented by simulations to optimize perovskite solar cell design. The perovskite materials were deposited using solution coating methods atop commercially available silicon solar cells. The project team demonstrated the viability of this solution-processing technique to deposit high quality perovskite films on the rough surfaces of commercial silicon solar cells. Deposition of perovskite onto commercially available silicon cells is a significant step toward scaling the technology from the lab.

Integration of the PoSiT devices aimed to avoid capital-intensive processes such as atomic layer deposition, a manufacturing method commercialized by the semiconductor industry. Despite multiple alternative approaches, no other deposition method proved capable of enabling the perovskite to be coated with a transparent top contact necessary to allow light into the cell. Ultimately, the project team adopted an atomic layer deposition process to deliver functional tandem devices.

The prototype PoSiT devices achieved greater than 19 percent efficiency. This result is without additional layers that can improve the flow of current at interfaces. Results show that substantial efficiency gains toward the project goal of greater than 32 percent are feasible. Notably, any efforts to further increase efficiency must also maintain operational durability. With a focus on the operational durability of the perovskite absorber in this project, the project team identified perovskite compositions that have been underexplored and found that many offer substantial promise for durable performance. To emphasize this, the team performed degradation testing on these tandem devices via exposure to hundreds of hours of damp heat and thermal cycling accelerated degradation conditions as well as weeks of real-world outdoor testing, where the devices demonstrated comparable optoelectronic quality before and after testing.

While it is difficult to estimate the levelized cost of electricity impacts of a tandem technology that is not yet commercialized, it is notable that most, if not all, major photovoltaic manufacturers have identified perovskite-silicon tandems on their technology roadmaps. The industry shift towards tandem technology will lead to substantial levelized cost of electricity improvements by leveraging the higher efficiencies.

Possibly the most important takeaway for the technological sector is the viability of using conducting polymers to enable a massive reduction in silver consumption by the solar industry, which makes up roughly 15 percent of global silver demand. This is relevant for traditional silicon photovoltaics even if adoption of perovskite-on-silicon tandem cells do not reach large-scale commercial viability. Replacing silver would significantly reduce costs because silver is relatively scarce and expensive. Common formulations of silver-based electrically conductive adhesive cost approximately $1.50 to $2.00 per gram, compared to copper at $0.50 per gram. Preliminary analyses suggest an approximate 75 percent cost reduction may be achievable for conductive adhesives relative to today’s state of the art silver-based adhesives.

In addition, reduced mining activity will contribute to a lower environmental impact (for example, deforestation, groundwater and atmospheric contamination, habitat and landscape destruction) associated with solar panel production.

For MCCA development, a conductive polymer was designed as the primary conductive material in the silver-free adhesive. The polymers were used as a conductive adhesive in shingled modules that were tested in accelerated degradation conditions and for mechanical strength. The performance of the MCCAs was compared against commercially available adhesives, which rely on high loadings of silver (for example, 70 to 80 percent weight). While the commercially available adhesives generally outperformed the MCCAs in terms of mechanical strength, the MCCAs achieved comparable electronic performance and reliability, all using materials of significantly lower cost enabled through the silver-free approach. The MCCAs survived hundreds of hours of damp heat and thermal cycling tests without encapsulation and without showing substantial degradation.

Knowledge Transfer and Next Steps

The project team disseminated project findings to key stakeholders, including state agencies such as the California Energy Commission and the California Public Utilities Commission, the PV research and development community including university research groups across the country, and the PV industry including California companies developing perovskite tandem cells. The knowledge transfer for this project will continue through professional meetings, such as the Fall Materials Research Society meeting and the Institute of Electrical and Electronics Engineers Photovoltaic Specialists Conference, and discussions with other for-profit and non-profit entities in the PV community. In addition, manuscripts are being prepared for submission to peer-reviewed journal publications such as *Advanced Materials* and the *American Chemical Society Energy Letters*.

Future research and next steps to advance this technology towards commercialization should focus on further improving MCCAs to enhance their electrical conductivity, mechanical flexibility, and longevity. Exploring new materials and innovative manufacturing techniques can lead to even more reliable and cost-effective solutions. Research institutions and industry collaborations should be encouraged to continue exploring the possibilities of MCCAs in various applications.

For perovskite-silicon tandem solar cells, next steps include additional research efforts with a focus on operational durability in accelerated cycles of learning across scales — from lab-scale cells to large area modules. Achieving high fill factors at large areas remains a challenge. The project team also recommends additional strategies such as surface passivation of the perovskite layer to further improve the carrier lifetimes toward effectively increasing the open circuit voltages of the device. Furthermore, engaging development of the selective contacts toward optimizing band alignments while achieving durable performance are recommended.

CHAPTER 1: Introduction

The transition from fossil fuels to cleaner energy sources is not just a global necessity but also a local one. It affects everything from the environment to the economy. As one of the world's largest economies, California is uniquely positioned to lead the way in making this transition smoother and more affordable. The legislature has enacted a variety of policy initiatives such as Senate Bill 350 (De León, Chapter 547, Statutes of 2015) and Senate Bill 100 (De León, Chapter 312, Statutes of 2018), the latter of which mandates a transition to a 100 percent renewable energy supply by 2045. Executive Order (B-55-18, 2018) also requires California to transition to carbon neutrality by 2045.

The project's goal was to develop more efficient tandem photovoltaic (PV) solar cells as a solution to a long-standing problem with solar energy: cost. By increasing the efficiency of these cells, solar power can become more affordable for all stakeholders. The current leading solar technology relies on a single absorber material, silicon (Si), which has its limitations. The project explored the use of multiple materials, each capturing different parts of the solar spectrum, to push the efficiency boundaries beyond the current plateau.

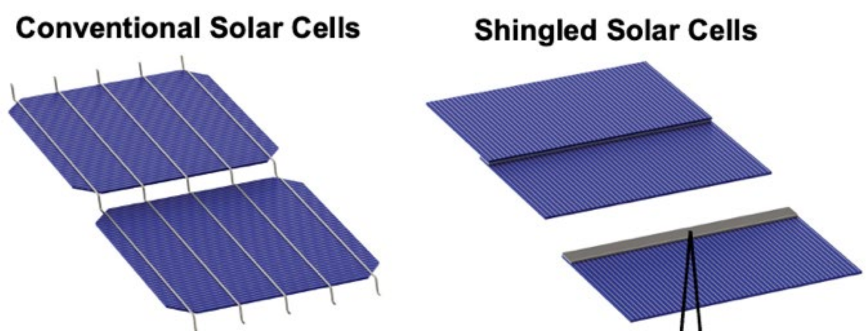
This project took on the challenge of making solar power more cost-effective by achieving a module efficiency of 32 percent and a levelized cost of electricity (LCOE) of $0.031 per kilowatt-hour (kWh). The key to this lies in developing tandem solar cells with higher efficiencies and, in concert, enabling module architectures that minimize losses that exist by necessity in standard module designs. It is important to optimize improvements in both because, for solar power, many aspects of the total system cost, such as external framings, scale not with power output but rather with module area. Hence, power conversion efficiency is the most powerful lever that can be used to reduce the LCOE. Improvements in efficiency mean ratepayers and utility companies will benefit as solar power becomes more accessible.

The existing utility-scale solar technology primarily uses silicon. While these devices are quite efficient, they are limited by the fact that they only use one main material as the absorber, which wastes much of the energy found in the solar spectrum. By combining multiple materials as absorbers, it is possible to capture different parts of the solar spectrum, allowing for a stepwise improvement in cell efficiency.

The heart of the project was the development of innovative perovskite-on-silicon tandem (PoSiT) solar cells integrated into a shingled module architecture. While PoSiT cells exist in the literature, these are overwhelmingly developed with silicon cells fabricated at the laboratory scale. This means that these lab silicon cells are incomplete models of the cells produced in a real-world manufacturing line. For example, such devices will be made using lapped and polished silicon wafers that lack the surface irregularities (saw damage) that are present in manufacturing line wafers, and that can pose a real processing challenge when depositing the perovskite top cell.

Additionally, traditional solar modules have inefficiencies in their layout, such as "dead zones," where space is wasted due to the need for soldered interconnects between cells, as well as busbars that result in shading that leads to power loss. The project addressed these issues by making use of a shingled architecture where, like roofing shingles, the cells are stacked and connected edge-to-edge, eliminating the interconnect "dead-zone" and enabling the use of smaller cells, further eliminating the need for thick, opaque busbars. Figure 1 shows schematics of busbar and shingled architectures. While shingled modules are not new, they are normally enabled by the usage of adhesives that have an insulating polymer matrix that encases an interconnected network of silver particles. These adhesives typically have loadings on the order of 70 to 80 percent silver by weight, increasing what is already a huge demand on this scarce resource by the PV industry. The project team's innovation in this area was the development of a silver-free and mechanically compliant conductive adhesive (MCCA).

Figure 1: Busbar vs. Shingle Module Architecture



Traditional module integration (left) uses tabbing wires soldered to busbars to carry current from the back contact of one cell to the front contact of the next cell to wire the cells in series. A shingled module lay-up (right) overlaps the front and back contacts of the cell and connects them with an electrically conductive adhesive.

Source: UC San Diego

This project aimed to accelerate the adoption of these technologies into real-world manufacturing lines. This is reflected in the use of manufacturing-line silicon cells, demonstrating ease of integration, as well as ensuring that the materials involved are processed using scalable techniques, up to the square-meter area. Lastly, the project aimed to validate the reliability of these innovations through accelerated degradation testing using standards in the solar community, as well as real-world outdoor testing.

By increasing the efficiency of solar cells and reducing costs, the project sought to make a genuine impact for Californians and the environment. This project focused on practical solutions for California's journey towards a cleaner, more sustainable future.

CHAPTER 2: Project Approach

The University of California, San Diego team proposed to develop perovskite-on-silicon tandem PV modules that would achieve a power conversion efficiency of greater than 32 percent during the project period using low-cost manufacturing approaches that could scale to meters squared (m^2) products with a projected levelized cost of electricity of $0.031/kWh.

Historically, tandems with greater than 30 percent efficiency have been formed using compound semiconductors made predominantly from gallium and arsenic and using fabrication methods that are prohibitively expensive, primarily due to the material purity required and high temperatures involved. Decades and millions of dollars of research into compound semiconductors has failed to produce substantial cost reductions for use in terrestrial PV. This project aimed to change this limitation through the development of several key technologies, including materials and processes, to enable the widespread adoption of tandem photovoltaic technology for power production at a wide variety of scales, from individual consumers to industry- and utility-scale adoption in California and beyond.

To overcome lingering cost barriers to widespread PV, the project team pursued the development of high-efficiency tandem solar cells because the strongest lever to reduce LCOE is to increase efficiency. The dominant commercialized silicon PV technology has plateaued at 22-26 percent conversion efficiency, and the theoretical limit for any single-absorber solar cell under standard “1-sun” operating conditions is 30.5 percent. While other absorbers such as perovskites have attracted significant attention in recent years, the price of Si modules has fallen by 45 percent in the last three years to $0.36 per watt, leaving minimal margin or market for nascent single-absorber technology that can only ever achieve similar efficiency. The project team aimed to create a step change reduction in the LCOE of PV by creating innovative PoSiT solar modules with a power conversion efficiency greater than 32 percent while paving the way for modules that could, in theory, reach greater than 40 percent efficiency.

The project team advanced this paradigm change in PV technology from single absorber to tandem solar cells by reaching multiple key milestones during this project, including the following:

1. Introduced innovative MCCA polymer technology to achieve low-loss, resilient contact interfaces in a high-power “shingled” module.
2. Developed several novel techniques for the large-area processing of the MCCA polymer.
3. Integrated perovskites with improved chemistry onto pyramidally textured silicon cells produced in a real-world manufacturing line.
4. Integrated MCCAs into shingled silicon modules which were tested under a variety of electronic, thermal, and mechanical degradation conditions.

5. Conducted accelerated degradation tests that showed that the perovskite retained comparable optoelectronic quality across most testing conditions, with the exception of damp-heat testing, the most aggressive of all testing scenarios.

To develop high-efficiency PoSiT modules, the team advanced innovative polymer technology to create resilient contacts to the perovskite. The mechanical compliance of the contacts enhanced module reliability — a critical success factor for perovskite technology — and reduced costly silver use. The team developed the MCCA layers that serve two purposes in the module: (1) to make charge-collecting finger contacts on the front side of the mechanically sensitive perovskite absorbers, and (2) enable cell-to-cell interconnection in high-power "shingled" cell modules.

Additionally, a variety of novel solid-phase polymer processing methods were developed for use with the MCCA. These techniques were meant to address some of the novel challenges that arise with the development of perovskite cells in tandem with textured silicon, with the added benefit of being widely applicable to other polymer technologies. Unlike conventional processing methods from either liquid or vapor phases, these solid-phase processing methods begin with the formation of a pre-solidified thin film atop a liquid substrate. Once the film is formed, it can be manipulated or used in a wide variety of ways. One technique allows for the deposition of highly conformal polymer thin films on micron-scale features (such as the light trapping pyramids on Si cells). The other technique has the film fully removed from the water surface and then transferred onto the desired surface, allowing for the applications of these films in a manner devoid of solvents, which is particularly important for solvent-sensitive perovskites.

The project used shingled modules to reduce the electrical losses inherent in traditional module architecture where lateral gaps between cells produce "dead-zones" where module area needs to be devoted to the soldered interconnects between cells, effectively wasting valuable space. Shingled modules, akin to roofing shingles, involve cell interconnections at overlapping edges, eliminating the dead-zones between cells as well as the need for busbars that cause shading losses. Shingled modules make cell-to-cell interconnects by contacting overlapping small fractions of the cell like the shingles on a roof without the high temperature and large mechanical stress involved in soldering of ribbons in standard modules. Thus, they are a key enabling technology for robust integration of thermally and mechanically sensitive perovskite cells. Shingled modules also boosted panel power by 10 percent relative simply by reducing inactive module areas (eliminating the gaps between cells) and reducing resistive losses by shortening metal finger lengths, reducing cell-to-module efficiency loss.

Using solution-processing methods, the project team conformally assembled the perovskite cell atop textured high-efficiency Si solar cells in a tandem format that boosted photocurrent using a tailored perovskite absorber chemistry. Critically, the rough, textured surface of the silicon cell enhances solar power conversion at oblique angles to better capture diffuse light throughout the day and harness the late afternoon sun — smoothing and extending the delivery of renewables to the grid. Reliability of the tandem modules was demonstrated via International Electrotechnical Commission (IEC)-standard accelerated environmental testing. By the project's end, the project team demonstrated durable PoSiT cells and Si modules and the knowledge generated in the project is well-positioned for integration into high-volume manufacturing.

The technical performance objectives of the project were as follows:

- Develop an innovative mechanically compliant conductive adhesive that meets the multi-faceted demands on a conductive adhesive in a PV module including mechanical compliance, conductivity, and adhesion across a range of operating temperatures and relative humidity. These performance demands arise due to the importance of minimizing electronic resistive losses (which play a significant role in the efficiency reduction in transitioning from cell to module level), as well as the fact that there are significant mismatches in the coefficient of thermal expansion of the various materials in the device stack, exacerbated by the mechanical fragility of perovskite materials. This means that the adhesive needs to be sufficiently compliant to accommodate as much of the strain as possible.
- Reduce the silver and precious metal content of PV modules to reduce environmental footprint and lower cost. This is of particular importance owing to the unsustainable rate at which photovoltaics are currently consuming the world supply of silver. Over the course of this project, the team transitioned adhesives with a reduced silver content to ones that replaced the silver altogether with low-cost multi-walled carbon nanotubes.
- Improve perovskite film chemistry and crystallization to enhance homogeneity, open-circuit voltage, efficiency, and stability of the perovskite cell. This was particularly challenging owing to the vast compositional space that perovskites exist in, which the project team approached through high-throughput synthetic and characterization route.
- Develop perovskite manufacturing approaches involving fewer toxic solvents and reduced lead concentration to reduce the environmental footprint.
- Examine mechanical and chemical perovskite cell recycling approaches to close the loop with lead-containing perovskite precursor preparation.
- Develop a perovskite-on-silicon tandem technology that achieves a power conversion efficiency higher or equal to 32 percent using deposition techniques that are scalable to m^2 products and demonstrated in this project at 100 centimeters squared (cm^2) areas or larger.
- Develop a novel shingled-cell tandem architecture that reduces cell-to-module efficiency losses and improves interface resilience in the perovskite sub cell. This architecture was demonstrated in shingled silicon cells, which were bonded together with a wide variety of the project team's MCCA compositions and subjected to a variety of electronic, thermal, and mechanical degradation conditions.
- Verify tandem module reliability by evaluating under the IEC damp heat and temperature cycling accelerated stress tests. Full PoSiT modules have not been tested but PoSiT cells have been subjected to these stress tests and have undergone micro-photoluminescent analysis to assess the degradation of the perovskite material.

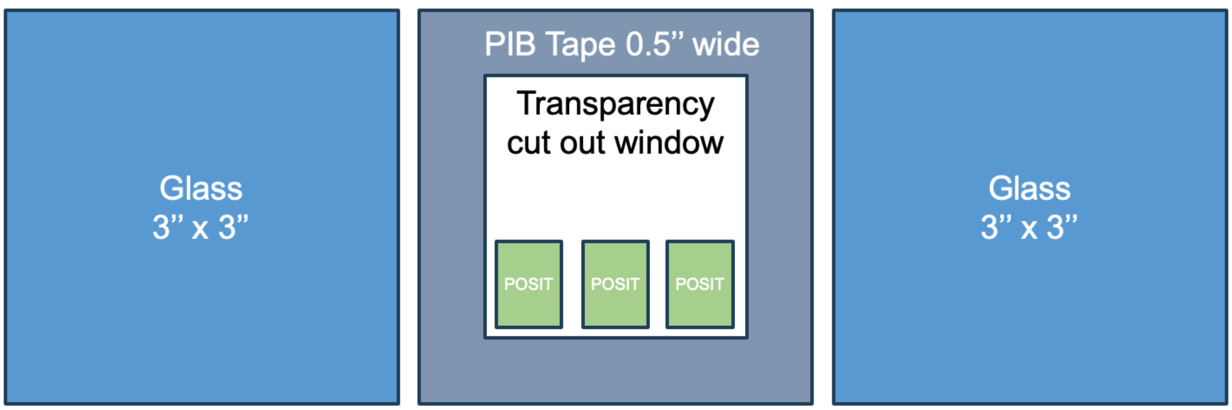
The project team, in partnership with subcontractor D2Solar who performed accelerated testing, accomplished the following technical tasks to meet the stated goals:

- Mechanically Compliant Conductive Adhesive Development: developed the MCCA to interconnect shingled modules and apply contacts to the perovskite.
- Perovskite-on-Silicon Tandem Solar Cells: addressed the engineering of the PoSiT.
- MCCA Incorporation atop Perovskite Solar Cells: integrated the MCCA onto standalone single-junction perovskite top cells.
- MCCA-Shingled PoSiT Modules Characterization: integrated MCCAs with PoSiT cells, encapsulated them into modules, and tested the power conversion efficiency.

Reliability Testing

To evaluate the reliability of the MCCA-shingled PoSiT modules, a series of tests were conducted, including damp heat testing, thermal cycle testing, and outdoor testing, supplemented by a state-of-the-art PoSiT encapsulation strategy using glass/polyisobutylene-desiccant-composite/glass packages (Figure 2).

Figure 2: Encapsulation Schematic of PoSiT Cells



Source: UC San Diego

Damp Heat Testing

The modules were exposed to 185°F (85°C) and 85 percent relative humidity for 168 hours to assess long-term reliability and stability. This test identifies potential weaknesses and failure mechanisms of the encapsulation. Comparing the photoluminescence (PL) signals of the cell before and after this exposure revealed changes in the module's performance due to high temperature and humidity.

Thermal Cycle Testing

The modules underwent thermal cycling under IEC 61215 standards to test durability and reliability under accelerated aging conditions. This test simulated the effects of temperature fluctuations on the modules' structural integrity and performance. Again, PL spectra comparisons before and after the test provided insights into any performance degradations.

Outdoor Testing

Modules were exposed to 168 hours of real-world rooftop (Figure 3) conditions to validate performance reliability, durability, and longevity. The benchmark for this test was the "t80" standard, where modules are tested to calculate the time at which their performance drops to 80 percent of their initial performance. By comparing PL spectra before and after outdoor exposure, the project team assessed whether the modules maintained performance above this threshold, thus indicating their effectiveness in real-world conditions and resilience against environmental factors. In summary, the PL spectra comparisons before and after each test type (damp heat, thermal cycling, and outdoor testing) provided a quantitative measure of the modules' performance degradation or resilience, guiding future design improvements.

Figure 3: Custom-Built Outdoor Cell Testing Platform

An electronic weatherproof enclosure (front left) contains measurement equipment with pass-through leads to modules (back right).

Source: UC San Diego

CHAPTER 3: Results

Development of MCCAs

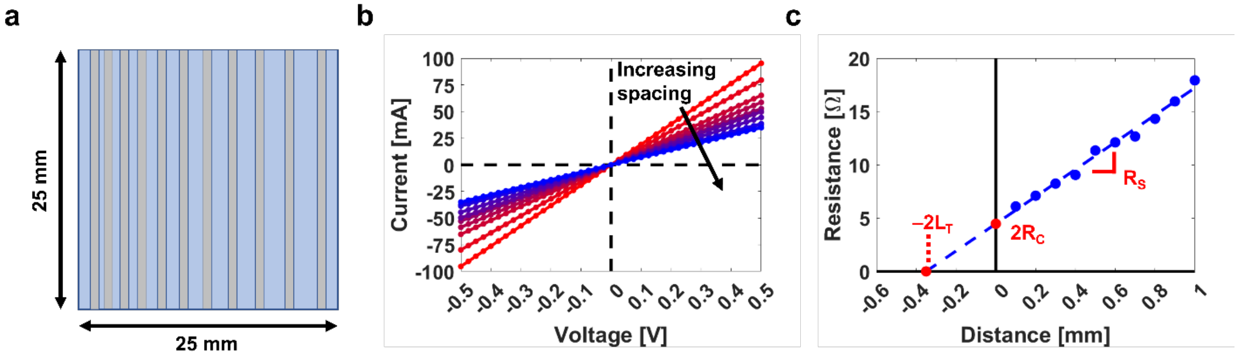
This section discusses the project team's efforts to develop silver-free (and metal-free), all-polymer conductive adhesives composed of a semiconducting polymer matrix for use as the adhesive interconnects between shingled solar cells. By replacing the insulating epoxy matrix with a conductive matrix, the amount of electronic filler needed to achieve resistivities comparable to silver-based electrically conductive adhesives (ECAs) can be significantly decreased. The mechanical properties of the semiconducting polymer matrix were tuned by rational modification of the chemical structure or by blending with a non-conductive polymer. Most importantly, the removal of metal in the ECA formulation significantly reduces the cost of the formulation, offering an avenue forward to low-cost conductive adhesives for shingled solar cells.

In the following sections, the transfer-length method (TLM) and various mechanical testing methods were used to investigate how incorporation of small-molecule secondary dopants, crosslinking molecules ([3-glycidyloxypropyl] trimethoxysilane [GOPS]), and multi-wall carbon nanotubes (MWCNT) affect the bulk and contact resistivity and the mechanical properties of (3,4-ethylenedioxythiophene) polystyrene sulfonate
(PEDOT:PSS) (Clevios PH1000).

Electrical and Interfacial Properties

The bulk and contact resistivity were compared, as measured by TLM (Figure 4), for PEDOT:PSS films blended with each additive (Figure 5). The addition of small polar molecules such as dimethyl sulfoxide (DMSO), ethylene glycol (EG), polyethylene glycol (PEG), and glycerol led to a decrease in bulk resistivity, indicating an increase in conductivity. The bulk resistivity decreased with increasing additive loading until saturation of the secondary dopant effect occurred. Glycerol, EG, and DMSO at specific concentrations resulted in similar bulk resistivities. However, further addition of DMSO showed a marginal decrease in resistivity, with the best conductivity at 8 volume percent. In contrast, blending with MWCNT as a conductive filler increased bulk resistivity. While small polar molecules outperformed MWCNT in bulk properties, a tradeoff between bulk and surface behaviors was observed. The contact resistivity was lowest at 0.5 weight percent MWCNT but increased with higher loadings. Crosslinking the PEDOT:PSS film with GOPS increased bulk and contact resistivity, which could be partially recovered with secondary dopants. Blends incorporating GOPS and secondary dopants exhibited similar bulk conductivities to films without crosslinker but contact resistivities were slightly increased. Glycerol and EG were more effective than DMSO in restoring contact conductance when the film was crosslinked.

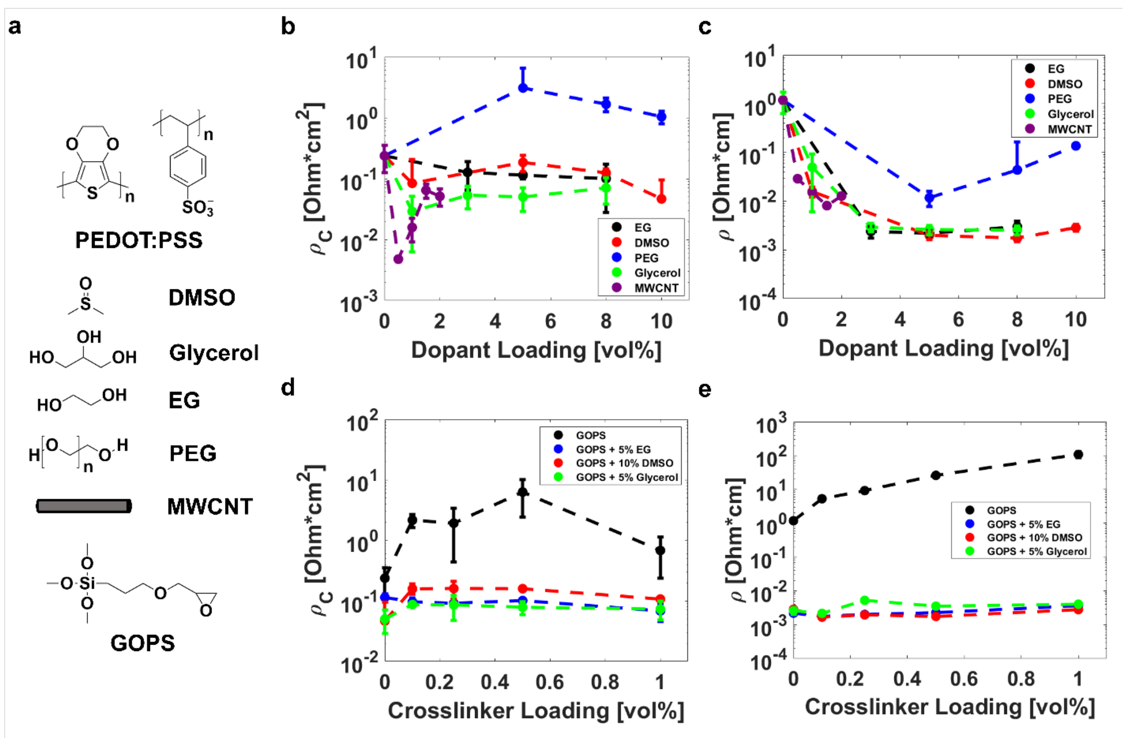
Figure 4: Comparison of the Bulk and Contact Resistivity, as Measured by Transfer Length Method



(a) Schematic of evaporated transfer length method (TLM) contacts (silver, 1.6 mm × 25 mm) on a PEDOT:PSS film. Eleven contacts were evaporated to measure 10 different spacings (0.1–1 mm, in increments of 0.1 mm). (b) Current-voltage (I-V) measurements were conducted at each of the 10 different spacings. (c) Resistance was calculated from Ohm's law and plotted relative to spacing. The data was fit using a linear regression, from which the sheet resistance (RS), contact resistance (RC), and transfer length (LT) could be extracted. Using the geometry of the metal contacts and film thickness, the bulk resistivity (ρ) and contact resistivity (ρC) were calculated.

Source: UC San Diego

Figure 5: Contact and Bulk Electronic Properties of PEDOT:PSS



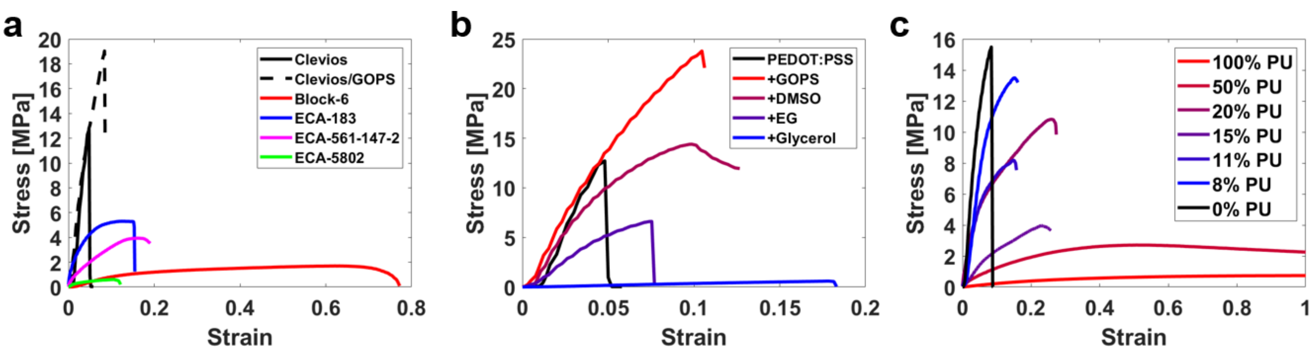
(a) Chemical structures of dopants (dimethyl sulfoxide [DMSO], glycerol, ethylene glycol [EG], and polyethylene glycol [PEG]) and of the crosslinker (3-glycidyloxypropyl)trimethoxysilane (GOPS). The (b) contact resistivity and (c) bulk resistivity relative to secondary dopant and dopant loading was determined from TLM. The effect of crosslinker loading, as well as crosslinker incorporated with EG, DMSO, and glycerol as secondary dopants, on the (d) contact resistivity and (e) bulk resistivity of PEDOT:PSS was determined using TLM.

Source: UC San Diego

Mechanical Properties

The study investigated the mechanical properties of polymer films, specifically focusing on PEDOT-based formulations for silver-free adhesives in comparison to conventional silver-based ECAs. Tensile tests (Figure 6) revealed that PEDOT:PSS (Clevios) exhibited high tensile strength and modulus but low fracture strain (5 percent), with the inclusion of GOPS leading to increased tensile strength and slightly greater fracture strain. In contrast, Block-6 displayed low modulus and tensile strength but high fracture strain (75 percent). Commercial ECAs, including ECA-183, ECA-561, and ECA-5802, demonstrated varying mechanical performances. The study explored the influence of additives on PEDOT:PSS, showing that GOPS enhanced tensile strength and fracture strain, while DMSO, EG, and glycerol increased fracture strain to different extents. Blending PEDOT:PSS/DMSO with polyurethane (PU) resulted in improved plasticity and toughness, with 20–25 percent PU representing an optimal balance between mechanical properties and resistivity. Shear tests on lap joint samples (Figure 7) indicated significant differences between PEDOT-based formulations and commercial ECAs, with the former exhibiting lower adhesive strength. The study highlighted the potential for enhancing conductive adhesive function by engineering interactions at the silver/polymer interface and suggested avenues for future improvements, such as optimizing the G/τ_{sh} ratio and intermolecular interactions for joint reliability, as discussed by Beaucarne (2016).

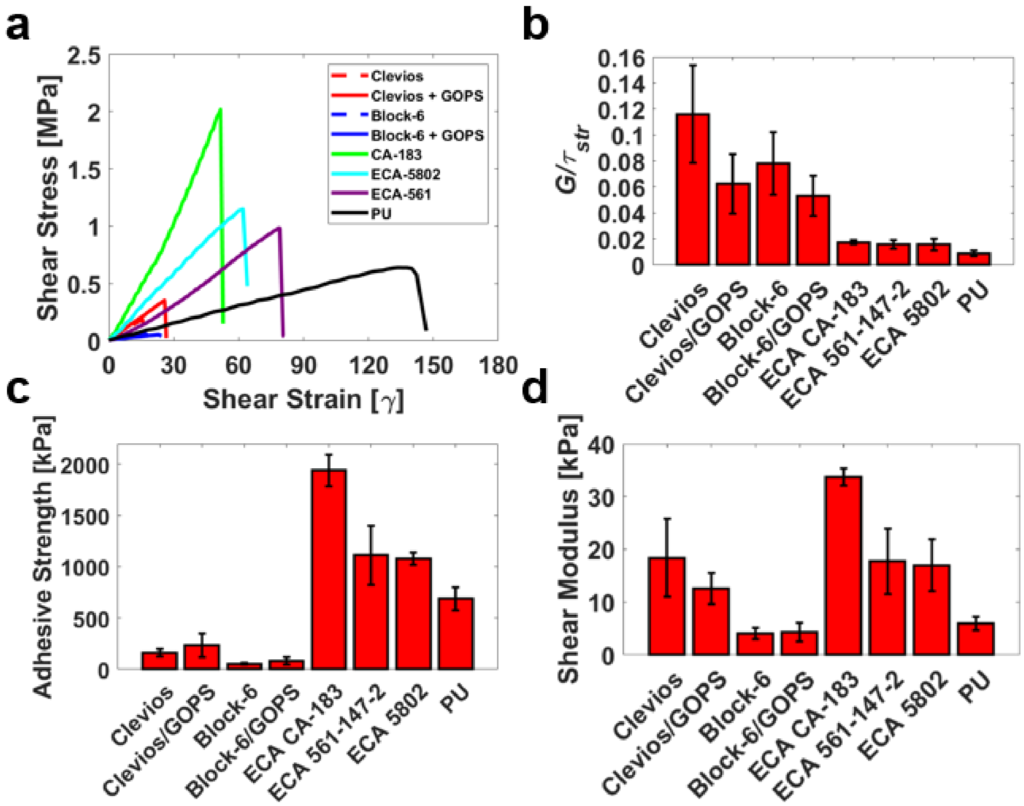
Figure 6: Tensile Tests of PEDOT:PSS



(a) Different polymer formulations used as conductive adhesives, (b) PEDOT:PSS blended with different secondary dopants (DMSO, EG, glycerol) or crosslinker (GOPS), and (c) PEDOT:PSS blended with different ratios of polyurethane (PU).

Source: UC San Diego

Figure 7: Shear Tests on Lap Joint Samples



(a) Representative shear stress-strain measurements for different adhesives tested in this work. (b) Comparison of the ratio of shear modulus and shear strength, which is an important figure of metric for understanding adhesive behavior. This ratio was calculated from the extracted (c) shear strength and (d) shear modulus.

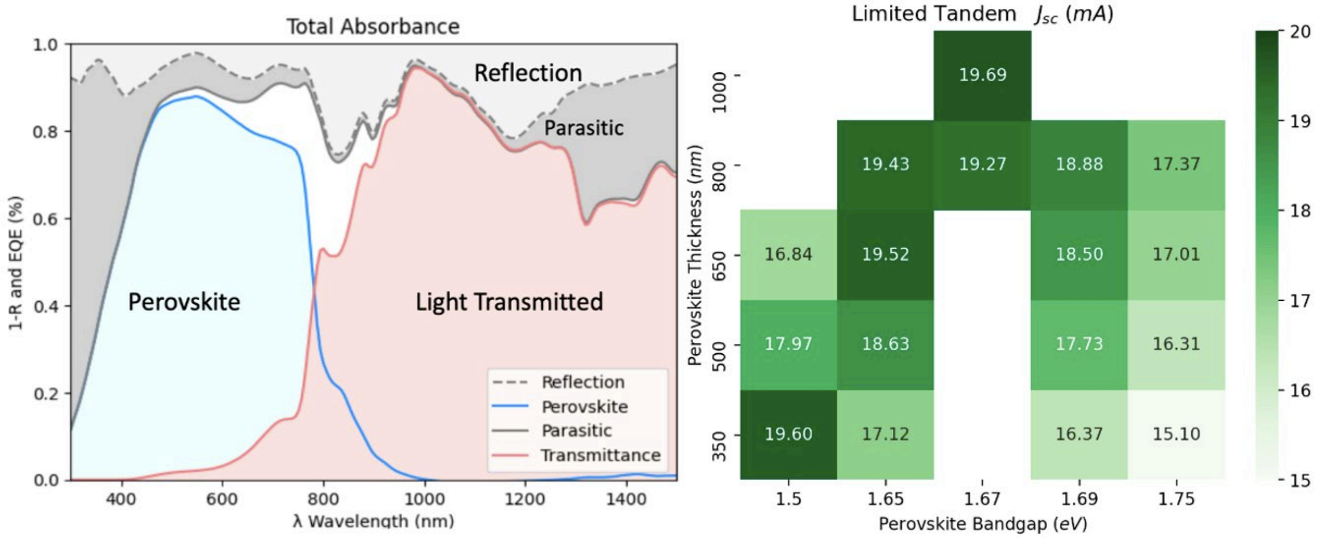
Source: UC San Diego

Perovskite-on-Silicon Tandem Solar Cells Results

PoSiT cells enable higher power conversion efficiency (PCE) than single-junction architectures by stacking a perovskite top sub-cell (bandgap 1.3–1.65 electronvolt [eV] or 750–950 nanometer [nm]) onto a silicon bottom sub-cell (bandgap 1.1 eV or 1130 nm).

To develop this technology, finite difference time domain simulations were conducted with Lumerical (Figure 8), calculating an optimal 1.67 eV bandgap and 1 micrometer (μm) thickness for PoSiT cell performance.

Figure 8: Finite Difference Time Domain Modeling of a PoSiT Cell



External Quantum Efficiency (left). The limiting current (right), obtained by conducting a parameter sweep over the absorber bandgap and the thickness of the top cell.

Source: UC San Diego

Perovskite halides and their alloys demand fine control over fabrication processing parameters to achieve high quality and phase purity. In this project, a custom-built perovskite solar cell assembly line (PASCAL) robot was leveraged to automate sample fabrication, demonstrating improved precision and repeatability with a focus on wider bandgap perovskites (FA, MA, Cs, I, Br, Cl) of interest for tandem photovoltaic applications.

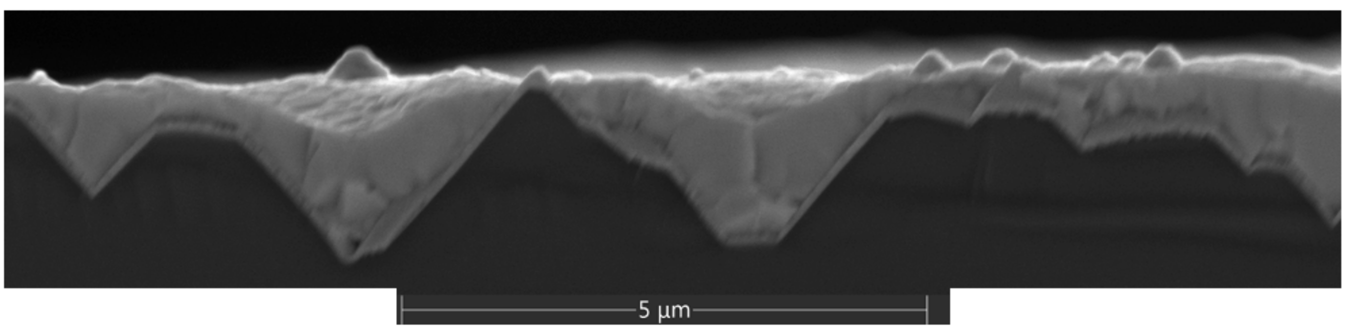
PASCAL integrates a liquid handler for solution precursor preparation and automated dispense, a custom spin-coater for multi-component and multi-step processing, and hot plates for crystallization annealing. The synthesis platform is automated via a gantry-mounted pick-and-place robot and a "maestro" control system. It can process more than 100 distinct recipes in approximately four hours. The PASCAL robot allows search over complex chemistries and processing space to probe temperature-time-transformations, solvent system effects, environmental impacts on processing, and more. The automation enhances compositional precision, removes operator effects, and boosts experimental learning rates relative to traditional manual experimentation. PASCAL integrates brightfield, darkfield, and photoluminescence imaging and ultraviolet–visible and photoluminescence spectroscopy to provide feedback on the thin film fabrication, coverage, and optoelectronic quality, including as a function of extended thermal or illumination stressing. The ability to rapidly prototype, and critically, characterize the resulting films in an automated fashion, accelerated the materials and prototype device development in this project.

Using PASCAL, the project team was able to remove operator variation and uncertainty in the timing of critical processes from the experiments, improving statistical power and efficiently using experimental and personnel resources. Several "hidden" variables were revealed, likely underlying operator-to-operator error in manual synthesis. These included the solvent environment, including some detrimental mixing of solvent vapors depending on process stage and the stability of the perovskite inks. The reduction in process variation enabled the Project team to reproducibly focus only on variations to durability arising from the composition.

PASCAL was used to investigate more than 100 distinct compositions of wide bandgap perovskites and probe early indicators of material stability under light and heat operational stresses. Screening across methylammonium and methylammonium-free compositions in the triple halide composition space, identified composition regions previously unidentified or understudied in the literature where the perovskite durability appears at least equal to if not superior to the state-of-the-art. This compositional search provides foundational understanding of the composition space of perovskite tandem design and highlights new areas for further investigation. A combination of objectives was used including bandgap, light stability, and thermal stability to down-select compositions for device development.

The team developed a conformal perovskite deposition technique using spin coating to use PASCAL, the automated experimentation platform. The team initially encountered coverage issues with 1.4 M perovskite solution on textured silicon/indium tin oxide (ITO) surfaces, resolved by increasing concentration to 1.7 M. At 1.7 M, pyramid-shaped protrusions (PSPs) were observed causing short-circuits in perovskite films (Figure 9).

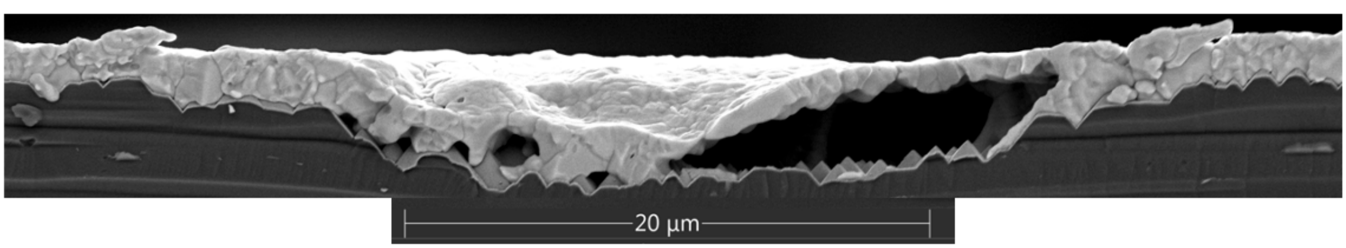
Figure 9: Scanning Electron Microscope Image of Perovskite on Textured Silicon (2 µm root mean square [RMS]) Showing the Formation of Pyramid-Shaped Protrusions



Source: UC San Diego

The PSPs were addressed by experimenting with antisolvent-free techniques, which led to void formation at the ITO/perovskite interface due to solvent trapping (Figure 10).

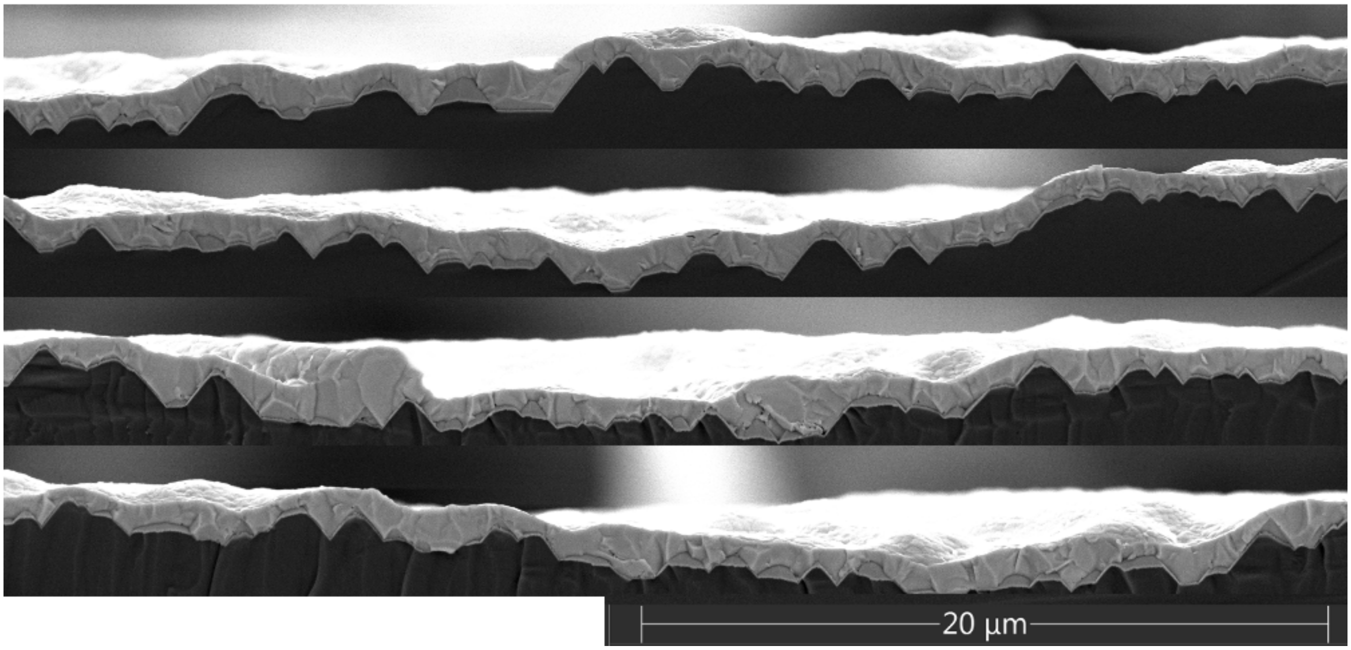
Figure 10: Scanning Electron Microscope Image of Perovskite on Textured Silicon (2 µm RMS) Showing Void Formation at the ITO/Perovskite Interface



Source: UC San Diego

Protrusion and void issues were overcome by refining spin coating process for the antisolvent process, involving a low rotations per minute (RPM) step at 500 RPM and a rapid thinning at 3,000 RPM (Figure 11).

Figure 11: Scanning Electron Microscope Images of Fully Conformal Perovskite Deposited on Textured Silicon (2 µm RMS)



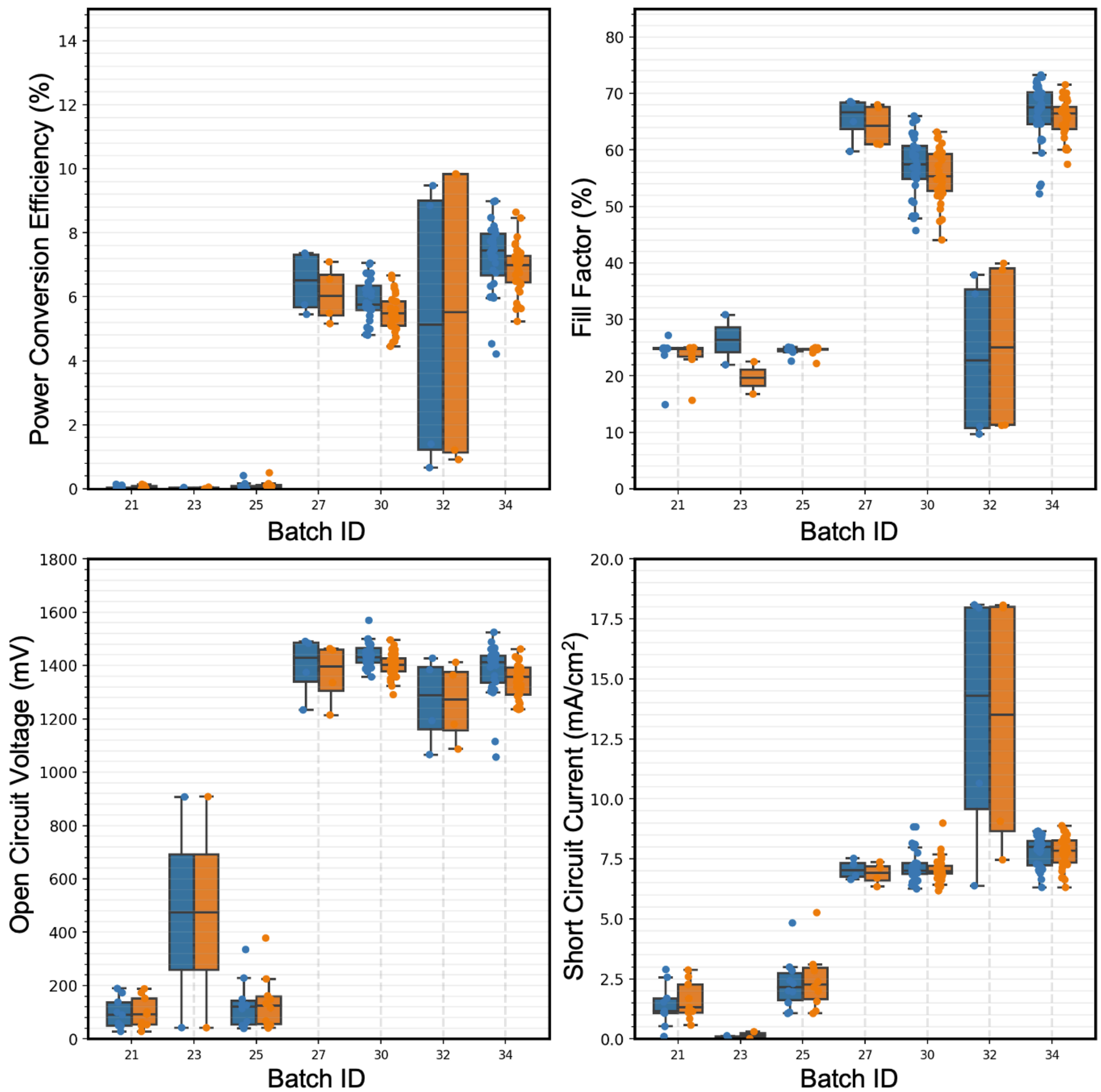
Perovskite thickness of 1.0µm±0.3µm, scale bar 20µm.

Source: UC San Diego

PoSiT Cell Results

Figure 12 shows the results of seven PoSiT batches (current-voltage [IV] characterization). Batches 21, 23, 25, contained early attempts at depositing a conformal layer on top of the textured silicon surfaces. Batch 27 was the first instance of achieving conformal coverage while maintaining tandem voltages. Batch 32 incorporated substitution of thin silver with transparent sputtered ITO to enable higher currents, and Batch 34 used a superior hole transport layer (HTL), which further enhanced fill factor.

Figure 12: Measured Device Performance Metrics Distribution of PoSiT Cells Across Seven Batches

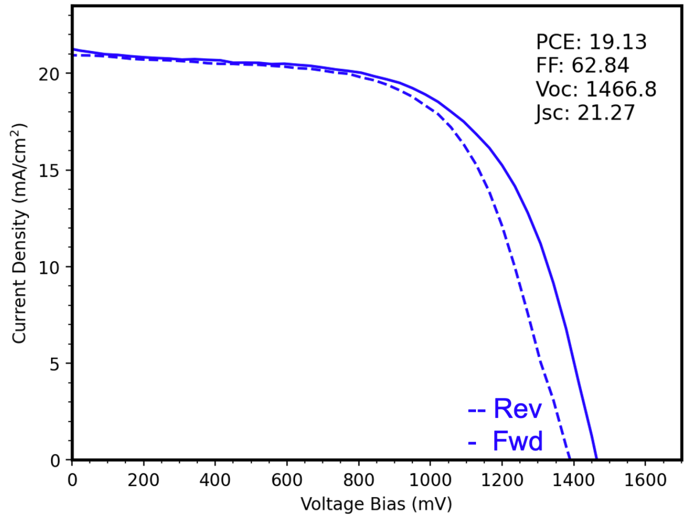


The standard cell architecture for these batches is ITO/Silicon/ITO/MeO-2PACz/Perovskite-Absorber/C60/BCP/Silver/Silver. However, there are exceptions: Batch 32 features an architecture of ITO/Silicon/ITO/MeO-2PACz/Perovskite-Absorber/C60/SnOx/ITO/Silver, and Batch 34 employs 4PACz instead of MeO-2PACz for the HTL, owing to its enhanced performance in PoSiT cells. The solar simulator used is a Class A AM1.5G device, with integrated irradiance calibrated to within ±5 percent of the specified range, as verified by a silicon reference cell.

Source: UC San Diego

The curve for a PoSiT cell is depicted in Figure 13. In this PoSiT cell, the baseline semitransparent electrode was replaced, which consisted of 10 nm of silver, with a transparent top electrode made of 100 nm ITO. The project team expected to achieve an 80 percent fill factor and an open-circuit voltage of 1,600 millivolt (mV) in future batches that employed this transparent electrode technology. The team believed that this batch suffered in fill factor due to the experienced tenfold increase in processing time due to unforeseen delays in developing a transparent electrode process.

Figure 13: Champion PoSiT Cell IV Curve



ITO/Silicon/ITO/MeO-2PACz/Perovskite Absorber/C60/SnOx/ITO/Silver architecture.

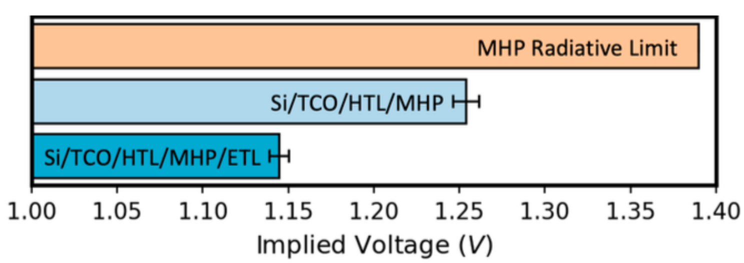
Source: UC San Diego

Developing tandem devices presented key challenges, particularly in achieving a conformal top cell. Initially, the project team attempted a two-step deposition, depositing lead (II) iodide and inorganic precursors onto textured silicon to create a porous layer, later converted to perovskite using organic halide salts like formamidinium iodide. While promising at first, the rough texture of the perovskite films complicated subsequent layer deposition. Techniques like atomic layer deposition were avoided due to scalability issues. Thermal evaporation, used for subsequent films, resulted in discontinuous films and significant cross-contamination, impacting other projects and leading to the abandonment of this approach.

While the tandem cells have shown notable improvements in recent iterations in the open-circuit voltage compared to standard silicon cells (about 0.6 V) and achieved short-circuit currents close to 80 percent of world-record devices, optimization challenges persist, particularly with the fill factor.

There is substantial room for cell optimization building from the compositional and process foundations developed in this project. A voltage-loss analysis for the perovskite top cell is shown in Figure 14.

Figure 14: Perovskite Top Cell Voltage Loss Analysis from Photoluminescence Quantum Yield Measurements



Source: UC San Diego

Approximately 130 mV was lost in going from what the metal halide perovskite absorber was capable of adding to the HTL, and another 115 mV was lost when adding the electron transfer layer (ETL) interface. Thus, interface passivation would be a critical next step. A critical need is to apply interface passivation without losing durability, as many reported approaches to passivation appear susceptible to degradation under 1-sun and 85°C testing conditions. A 185°F (85°C) test condition can be seen at the extremes in the field and the device must be capable of withstanding such conditions.

Furthermore, reducing losses at the interfaces was expected to improve fill factor, where rounding of the power curve could be attributed in part to interface recombination. Finally, enhancing cell performance involved addressing low shunt resistance at large scales and minimizing power loss from series resistance through engineering contacts. Overall, based on the foundational knowledge developed and disseminated in this project, it can be expected that applying established solar cell engineering strategies to optimize band alignments and passivate interfaces will substantially boost overall cell performance. Based on simulations and world-record reports, the original project target of greater than 32 percent PCE is feasible.

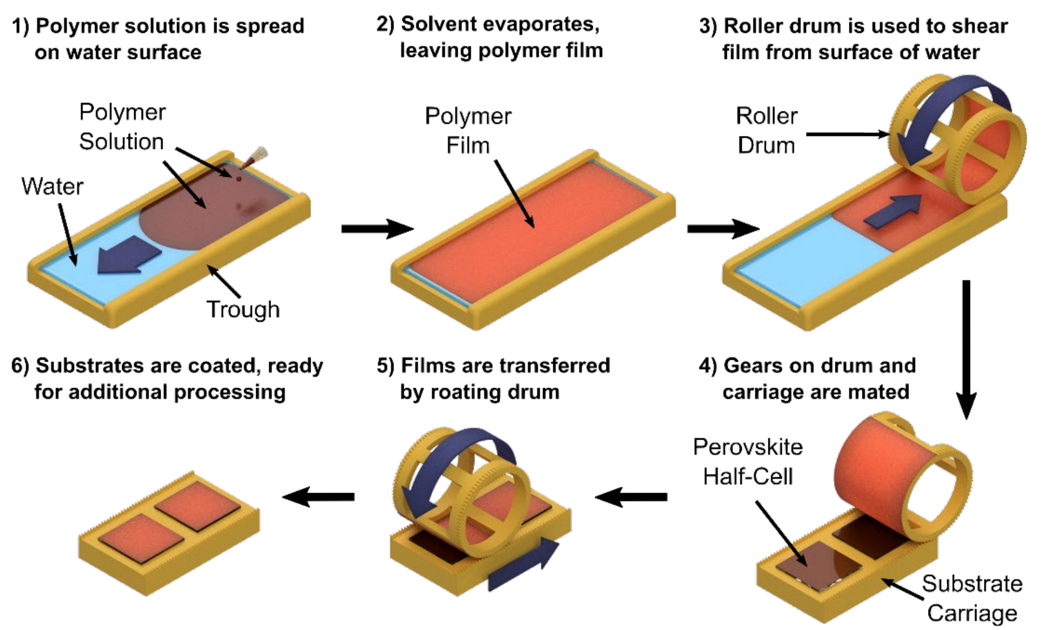
MCCA Incorporation Atop Perovskite Solar Cells

A crucial aspect of achieving robust and reliable shingled perovskite/silicon tandem modules was the interconnection between individual cells. The project team explored how MCCAs serve as a promising solution. The interface between an MCCA and the connecting cells plays a crucial role in the performance and overall efficiency of perovskite/silicon tandem cells. The solid-phase methods developed for the processing of MCCAs are discussed in the following section.

Transfer Approaches

Freestanding films to fully circumvent the concerns of solvent orthogonality, which are of particular importance to perovskites, were used by enabling deposition truly free of liquid solvents. The team named this process "solvent-free transfer" (SFT). A key step in SFT was to generate ultra-thin, freestanding films, for example using the technique of interfacial spreading described by others (Kim et al., 2017; Noh et al., 2016; Pandey et al., 2016; Runser et al., 2019). These films can be drawn up onto a planar or cylindrical frame, which supports the edges of the films by van der Waals forces, and then transferred directly onto a variety of substrates that are either bare or coated with other layers in a device stack in a manner that is compatible with roll-to-roll manufacturing (Figure 15). SFT was demonstrated to have significant potential in depositing over large areas by forming and transferring free-standing films which were up to 10 × 10 cm^2 in area, with thicknesses of approximately 20 nm (Figure 16). These films were characterized by various techniques and compared against spin-coated controls. These films could also be used, without initial removal from the water substrate, to form highly conformal coatings on textured surfaces such as found on typical mono-crystalline silicon solar cells (Figure 17).

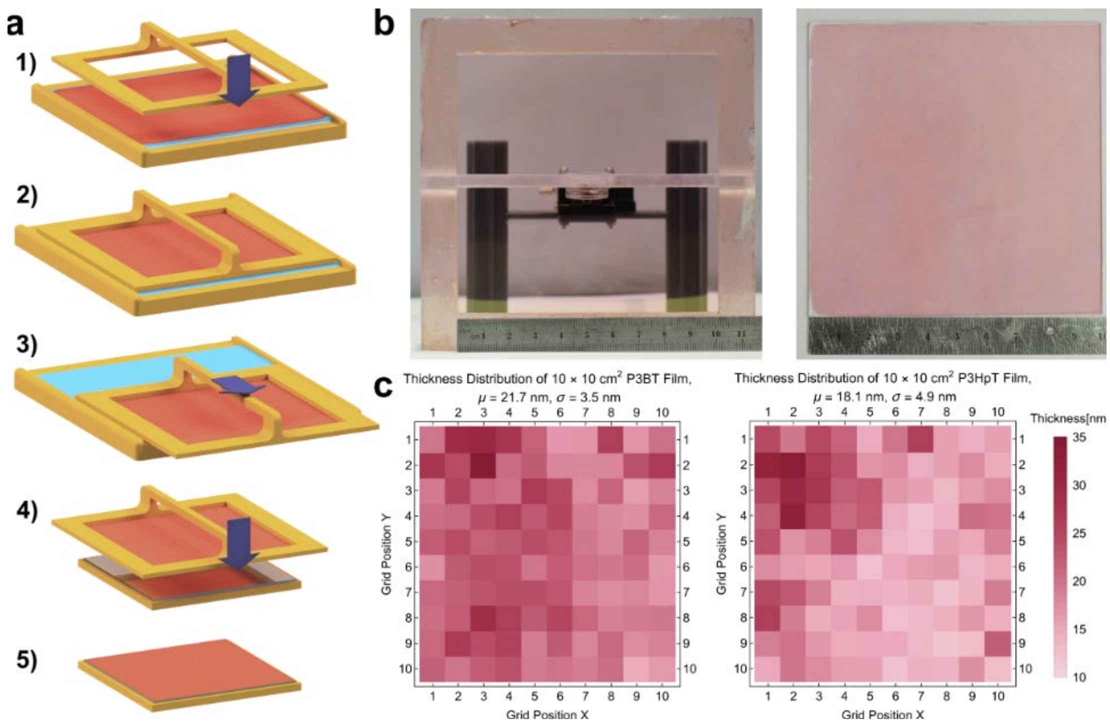
Figure 15: Summary of the Solvent-Free Transfer Process



A polymer film is formed on the surface of water before being sheared from the water surface using a cylindrical drum. The freestanding film can then be subsequently transferred to a solid substrate.

Source: UC San Diego

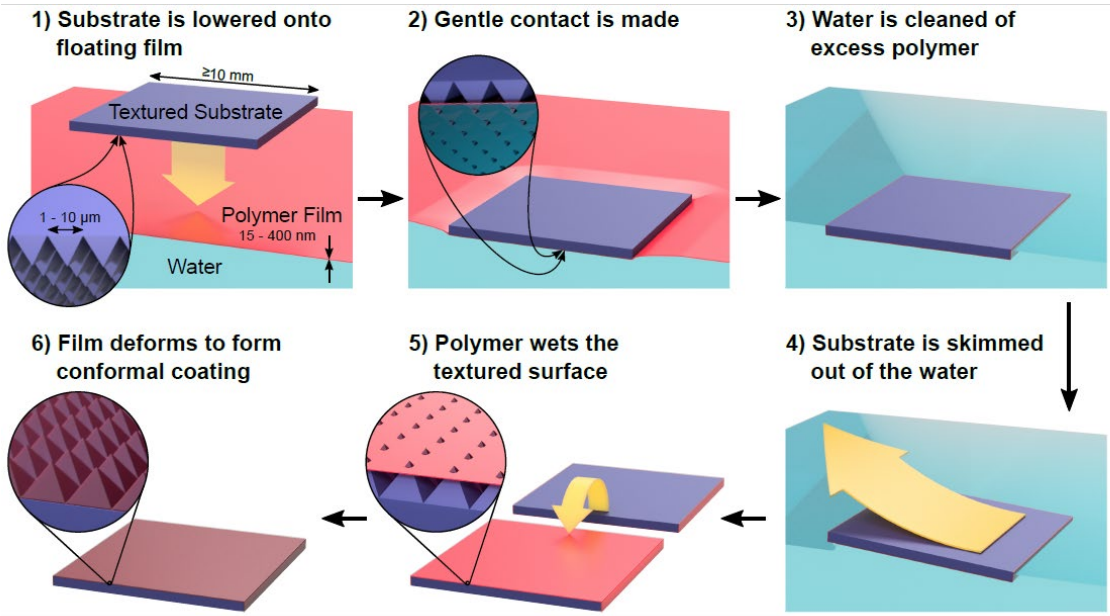
Figure 16: Solvent-Free Transfer Process



a) Summary of the large-area SFT variant, where the floating film is sheared off the water surface by a planar frame, which translates horizontally. This film can then be applied directly to a substrate. b) Photographs of a 10 × 10 cm^2 area film made of P3BT, mounted on the drawing frame (left) as well as after the same film was transferred onto a sheet of glass (right). c) Thickness measurements by profilometry of the same P3BT film (left) as well as a separate P3HpT film (right).

Source: UC San Diego

Figure 17: Summary of a Solid-Phase Deposition Process



Taking place in ambient conditions. A polymer film suspended on water is taken up by a textured substrate with high-energy surfaces, enabling the necessary deformation of the polymer as it conformally coats the substrate.

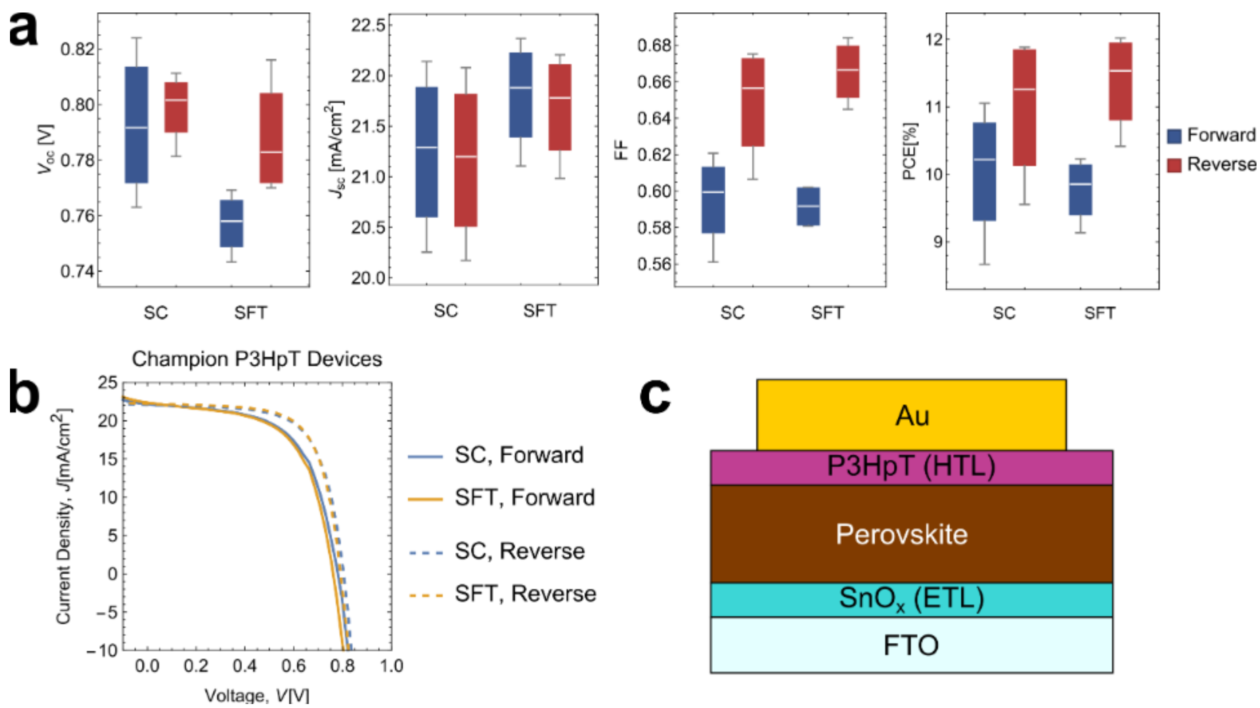
Source: UC San Diego

Cell Results

Ultimately, the project team was interested in how films deposited by SFT perform in devices in comparison to films produced by spin coating. In a typical perovskite solar cell (PSC), the absorber is sandwiched between two charge selective layers (the ETL and HTL). In general, the selective layers must exhibit high electronic conductivity for the desired charge carrier, have favorable band alignments with the absorber, be chemically compatible with the absorber, have a high degree of stability against operational stressors, be optically transparent, and form interfaces with low levels of carrier traps. The team reasoned that the HTL would serve as an adequate stand in for the MCCA, as SFT can be applied to form coatings of any polymer, in principle. Of course, SFT is highly appropriate for PSC given its sensitivity to solvents, and SFT enables the deposition of polymeric coatings in a solvent-free fashion. Findings are summarized in Figure 18.

In general, the performance of the SFT films was found to be comparable to the spin coating (SC) ones. The open-circuit voltage, V_{OC}, of SFT devices were somewhat lower, and showed greater hysteresis, when compared to those made with SC. However, the SFT devices displayed slightly increased short-circuit current density, J_{SC}, in both scan directions. The fill factor was comparable between the two types of devices, with SC slightly outperforming SFT in the forward scan, but the opposite in the reverse scan.

Figure 18: Summary of Results of Films Deposited by Solvent-Free Transfer Compared to Spin Coating



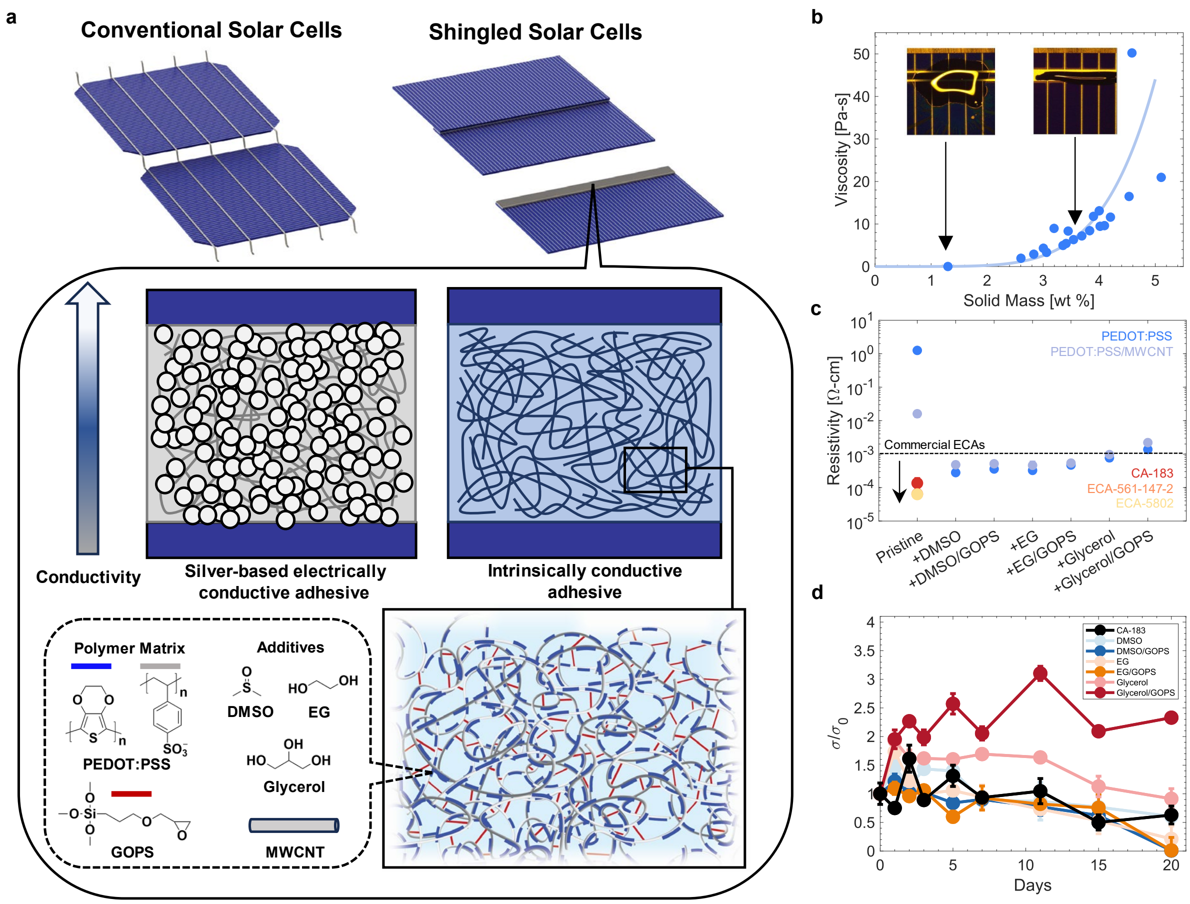
a) Photovoltaic metrics of perovskite solar cells using a P3HpT hole-transport layer deposited by solvent-free transfer (SFT) or spin coating (SC). b) JV curves of the champion devices made using the two different deposition methods. c) Architecture of the device stack.

Sources: UC San Diego

Shingled Modules Using MCCAs

The focus of this section shifts to repurposing poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), an π-conjugated polymer, as a silver-free MCCA for shingling solar cells. The fundamental hypothesis was that employing an intrinsically conductive polymer would eliminate the need for electronic fillers like silver, achieving comparable electronic performance. Various formulations, produced by incorporating a crosslinker (GOPS), polar small molecules, and MWCNT into PEDOT:PSS, demonstrated resistivities comparable to silver-based ECAs (Figure 19). The PEDOT:PSS-based MCCAs also exhibited promising performance and stability in shingled silicon modules, where they performed comparably to silver-based ECAs in various stability tests, and within an order of magnitude in three-point bending tests (Figure 20).

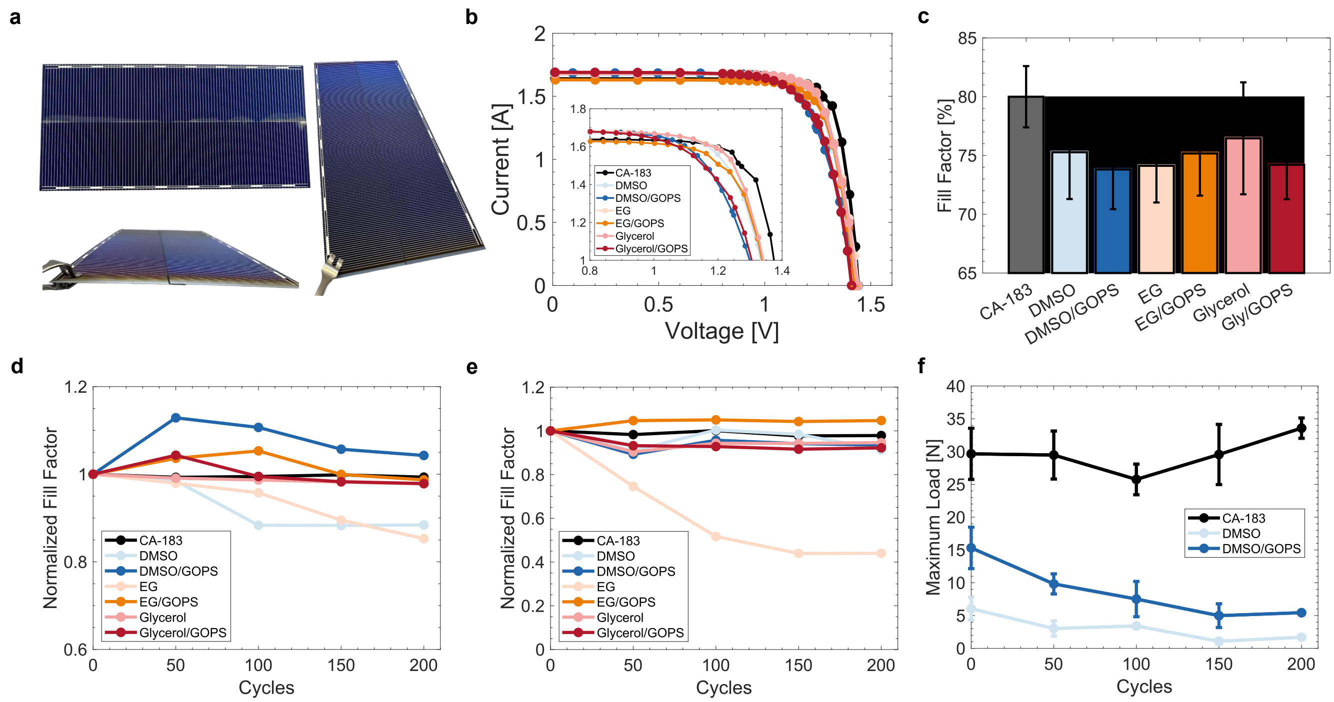
Figure 19: Design and Characterization of PEDOT:PSS-Based Conductive Adhesives



(a) Comparison of silver-based electrically conductive adhesives (ECAs) to intrinsically conductive adhesives (ICAs) for shingled solar modules. Chemical library and schematic morphology of PEDOT:PSS-based ICAs explored in this study. (b) Viscosity of PEDOT:PSS relative to solid mass in the dispersion. (c) Resistivity of PEDOT:PSS and PEDOT:PSS/multi-wall carbon nanotube (MWCNT) films with additives (8 vol percent DMSO, 8 vol percent EG, 5 vol percent glycerol, 1 vol percent GOPS, 1 wt percent MWCNT). Three silver-based ECAs (red, orange, yellow) are shown for comparison. (d) Normalized conductivity of PEDOT:PSS films under ISOS-D-3 (65 °C, 65 percent relative humidity) degradation conditions.

Source: UC San Diego

Figure 20: Characterization of Shingled Solar Cells



(a) Photographs of silicon solar cells shingled with CA-183 (top-left) and PEDOT:PSS-based (bottom-left and right) ICAs. (b) Representative I-V curves of pristine shingled solar cells. (c) Fill factor of pristine cells shingled with PEDOT:PSS-based ICAs (n = 6–10) in comparison to a silver-based ECA (CA-183) (n = 13). (d) Normalized fill factor of shingled cells after subjected to 200 thermal cycles (TC-200) from –40°F (–40 °C) to 185°F (85 °C). Three samples were individually tracked for each formulation throughout the TC-200 test, with champion samples shown here. (e) Normalized fill factor of shingled cells after subjected to a reverse current overload test at each 50-cycle time point. One sample was individually tracked for each formulation. (f) Maximum load before fracture as extracted from three-point bend tests (n = 2–4) relative to thermal cycling.

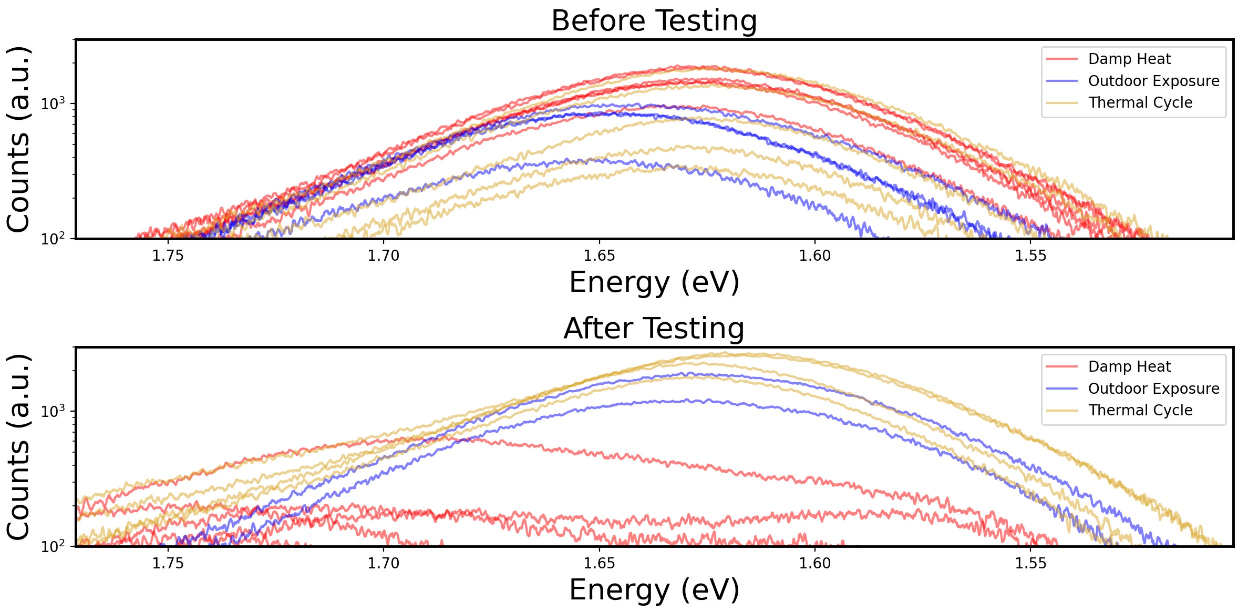
Source: UC San Diego

Reliability Testing Result

PoSiT cells were subjected to damp heat and thermal cycling accelerated stress tests and were tested outdoors. Outdoor tests were conducted at open circuit voltage, which is generally the most challenging load condition for perovskite devices. Figure 21 shows the variation in the performance of the perovskites overtime.

Before testing all encapsulated samples displayed peak PL emission energies at approximately 1.67 eV, as designed. After thermal cycling, the sample increased in PL intensity, and experienced peak broadening that is indicative of microscopic phase separation. Outdoor exposure of the sample resulted in a redshift of the PL emission energy and a slight increase in PL intensity, but otherwise limited changes. The initial round of damp heat testing resulted in full degradation of the PoSiT due to the encapsulant failing. Subsequent damp heat tests show little change in the perovskite performance.

Figure 21: Raman Microscope Micro-Photoluminescence Spectroscopy of Encapsulated PoSiTs



Before (above) and after (below) degradation testing.

Source: UC San Diego

CHAPTER 4: Conclusion

The research and development of perovskite-silicon tandem and shingled photovoltaic modules incorporating mechanically compliant conductive adhesives (MCCAs) represent a significant milestone in advancing clean energy and climate goals, not only for California but also for the broader clean energy sector. The implications of this project's outcomes extend to commercial markets, utilities, industry, consumers, and state policy, offering substantial benefits and lessons for future development opportunities. This chapter summarizes the key findings and their importance for California's clean energy and climate objectives, discusses market opportunities, and offers recommendations for future research and policy considerations.

California has long been a leader in clean energy initiatives and combating climate change. The development of tandem solar cells and shingled photovoltaic modules using MCCAs aligns with the state's ambitious goals of transitioning to a sustainable, low-carbon energy landscape. By enabling the production of more efficient, mechanically robust, and reliable solar modules, this technology contributes to reducing greenhouse gas emissions, meeting renewable energy targets, and promoting a cleaner environment.

The environmental benefits realized from this project are many-fold: First, MCCAs eliminate the need for silver-based ECAs, thus reducing the demand for this precious metal, which is globally driving up the cost of silver at an unsustainable rate. Second, the enhanced reliability and longevity of shingled modules will result in a longer operational life, decreasing the environmental footprint associated with the production and disposal of solar panels. Third, the deposition of perovskite layers atop textured silicon cells permits improved low-angle light collection. Finally, perovskite solar cells have potential to embody a low energy budget in their production, enabling tandem solar cells that convert substantially more solar energy with a small increase in embodied energy.

Moreover, the improved performance of textured and shingled photovoltaic modules translates into a more dependable and efficient renewable energy source. This increased efficiency not only helps California meet its clean energy goals but also ensures a stable and cost-effective energy supply, benefiting both ratepayers and the economy.

Implications for Commercial Markets, Utilities, and Industry

The implications of this project's outcomes extend to commercial markets, utilities, and the solar industry. Shingled photovoltaic modules using MCCAs offer a game-changing solution to existing challenges in PV and pave the way for broader adoption of solar technology, including the following:

1. Reduction of Silver Dependency: By replacing silver-based ECAs with MCCAs, the project significantly reduces the demand for silver, making the production of solar modules more sustainable and cost-effective. This change has positive ramifications

for the industry by mitigating the supply chain constraints and price volatility associated with silver.

2. Improved Reliability: The mechanically robust nature of shingled modules minimizes the risk of failures and cracks, ensuring longer operational lifespans. This enhances the reliability of solar installations, reducing maintenance costs and downtime for commercial operations and utilities.
3. Enhanced Efficiency: The improved performance of shingled modules means higher energy generation. This not only benefits consumers by reducing their electricity bills, but also makes solar energy more attractive for commercial and industrial applications, further accelerating the adoption of renewable energy.
4. New Development Opportunities: The introduction of MCCAs for shingled photovoltaic modules opens the door for further research and development opportunities. Researchers can explore new materials, manufacturing techniques, and optimizations to continuously improve solar technology.

Critically, these opportunities do not require a tandem architecture but could be applied to current and developing silicon cell technologies as well.

Perovskite-silicon tandems are on the commercial roadmaps of all major solar manufacturers. The project team has closely surveyed the composition space of wider bandgap perovskites suitable for deployment atop silicon. Project results show that the optoelectronic quality of perovskite materials that do not contain the canonical organic cation methylammonium can approach or even exceed that of methylammonium-containing layers. Significant concerns exist regarding whether incorporation of methylammonium is feasible for long term deployment, because of the acidity of the methylammonium cation and the subsequent tendency for degradation reaction.

The deposition atop etched saw damage has been identified as an often overlooked but critical component to commercial deployment of perovskite films on silicon. Through judicious modification of ink formulations, the project team achieved pinhole-free coverage atop both commercial pyramidal textures and the longer-range thickness variations introduced from the etching of saw damage. The on-ramp of tandem technology hinges on the minimization of additional processing steps to reduce the added cost. If additional surface preparation of the silicon can be avoided, while also enabling a textured substrate for low-angle light collection, it will have significant manufacturability advantages.

Consumer Benefits and State Policy Implications

For consumers, the technical development of shingled photovoltaic modules using MCCAs could have near-term benefits. These modules offer increased efficiency and reliability, leading to a higher return on investment for residential solar installations. By reducing energy costs and potentially enabling homeowners to sell excess energy back to the grid, this technology benefits the economy and individual ratepayers alike.

Perovskite-silicon tandem technology will require further investment in research, development and deployment in a closely coupled cycle. As more entities push to scale and deploy perovskite-silicon cells, the solar research and development community will gain new insights into limiting aspects. In addition, given the instability relative to an absorber such as silicon, early-stage research remains necessary to ensure that technological pruning does not happen too early for a technology that is 15 years old.

From a policy perspective, the successful development of shingled modules with MCCAs reinforces the importance of innovation and research in clean energy. It highlights the significance of supporting projects that not only push the boundaries of technology, but also have the potential to transform the energy landscape. Informed by the outcomes of this project, policymakers can consider the following recommendations:

1. Provide Incentives to Deploy Cutting Edge Technologies at Small Scales to Facilitate Adoption: Policy mechanisms that provide incentives for the deployment of novel solar (and more broadly, green energy) technologies necessarily entail higher risk. However, if a significant cost, sustainability, or consumer reward for adoption of such new solar technologies can be clearly identified, such as with the novel MCCAs in this project, mechanisms to accelerate time-to-market should be explored. Incentives such as tax credits, rebates, or low-interest loans can accelerate the transition to technologies with less proven track records that offer cleaner and more sustainable energy sources.
2. Research and Development: Continued investment in research and development, particularly in materials science and solar technology, is crucial to drive further innovation and enhance the performance of solar modules.
3. Standards and Regulations: Policy makers should collaborate with industry experts to develop standards and regulations that encourage the use of novel technologies in solar (and green energy technologies more broadly). This can help ensure quality and safety while promoting sustainability.
4. Education and Awareness: Raising awareness among consumers about the benefits of these advancements in solar technology is essential. This can be achieved through public awareness campaigns and educational initiatives.

Market Opportunities and Future Research

The market opportunities arising from this project are significant. The demand for cleaner energy sources continues to grow, and shingled photovoltaic modules using MCCAs are poised to capture a substantial market share. The solar industry can expect increased growth as consumer confidence in these modules grows and utilities see the advantages of investing in reliable and efficient solar installations.

Future research in this domain should focus on further improving MCCAs to enhance their electrical conductivity, mechanical flexibility, and longevity. Exploring new materials and innovative manufacturing techniques can lead to even more reliable and cost-effective solutions. Research institutions and industry collaborations should be encouraged to continue exploring the possibilities of MCCAs in various applications.

For perovskite-silicon tandem solar cells, the project team recommends investing in additional efforts with a focus on operational durability in accelerated cycles of learning across scales — from research-size lab cells to large area modules. Achieving high fill factors at large areas remains a challenge. The project team also recommends additional strategies such as surface passivation of the perovskite layer to further improve the carrier lifetimes toward effectively increasing the open circuit voltages of the device. Furthermore, engaging development of the selective contacts toward optimizing band alignments while achieving durable performance are recommended.

Recommendations

This project has shown the potential for transformative change in the solar industry. To build on these achievements and realize the full benefits of shingled tandem photovoltaic modules using MCCAs, the project team recommends the following:

1. Policy Support: Policy makers should provide continued support for clean energy research and development, with a focus on innovations that enhance the efficiency, reliability, and sustainability of solar technology.
2. Industry Collaboration: Encourage collaboration between the solar industry, research institutions, and policy makers to expedite the adoption of novel technologies into solar and green energy manufacturing.
3. Public Engagement: Promote public awareness and engagement to ensure that consumers understand the benefits of these advancements in solar technology.
4. Ongoing Research: Support ongoing research and development efforts to refine perovskite and silver-free conducting adhesive technology and explore their applicability in various clean energy technologies.

Closing Remarks

In conclusion, the development of perovskite-silicon tandem cells and shingled photovoltaic modules using mechanically compliant conductive adhesives is a significant step forward, fully enabled by taxpayer dollars funding research at institutions of higher learning. Such advancements in achieving clean energy have the potential to leave a lasting positive impact and reverberate throughout the solar industry and the broader energy landscape. As California continues to lead in climate action within the United States, this project is a testament to the power of research and innovation in advancing a sustainable and environmentally responsible future.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
cm^2	centimeters squared
DMSO	dimethyl sulfoxide
ECA	electrically conductive adhesive
EG	ethylene glycol
ETL	electron transport layer
EV	electronvolt
GOPS	(3-glycidyloxypropyl)trimethoxysilane
HTL	hole transport layer
ICA	intrinsically conductive adhesives
IEC	International Electrotechnical Commission
ITO	indium tin oxide
IV	current voltage
kWh	kilowatt-hour
LCOE	levelized cost of electricity
LT	transfer length
m^2	meters squared
MCCA	mechanically compliant conductive adhesive
MV	millivolt
MWCNT	multi-wall carbon nanotubes
nm	nanometer
ρ	bulk resistivity
ρC	contact resistivity
PASCAL	perovskite solar cell assembly line
PCE	power conversion efficiency
PEDOT:PSS	Poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate)
PEG	polyethylene glycol
PL	photoluminescence
PoSiT	perovskite-on-silicon tandem
PSC	perovskite solar cell
PSP	pyramid-shaped protrusions
PU	polyurethane
PV	photovoltaic
RC	contact resistance

Term	Definition
RMS	root mean square
RPM	rotations per minute
RS	sheet resistance
SC	spin coating
SFT	solvent-free transfer
Si	silicon
TLM	transfer-length method
μm	micrometer

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Project Deliverables

The Project Deliverables included:

- Polymeric Contact Layers for Robust Conductivity, Compliance, and Adhesion Analysis Report
- Perovskite-Silicon Tandem Cell Efficiency Distribution and External Verification of Efficiency Report
- Methods for Robust, Large-Area Perovskite Contacts Report
- Stability under Outdoor and Accelerated Testing of Perovskite-Silicon Tandem Modules with Resilient Interfaces Report

Project deliverables are available upon request by submitting an email to pubs@energy.ca.gov.