Solar Cell Manufacturing

Hayden Bouley, Zachary Donaghue, Connor Geary, Max Goldman,
Dinor Nallbani, Noah Szymanski
Department of Mechanical and Industrial Engineering
MIE 375: Manufacturing Processes
Professor Yanfei Xu
December 2nd, 2024

Introduction

This project examines the manufacturing process of a perovskite solar cell for a commercial solar panel, focusing on enhancing thermal management using our material selection to optimize the panel design. A key challenge in solar cell performance is overheating, which reduces their efficiency and lifespan. Our project addresses this challenge by focusing on the glass layer covering the solar cell, specifically utilizing aluminum oxynitride (AlON) for its favorable thermal and optical properties. The AlON sheet is manufactured with a press, sinter, and polish process and can be bonded to the perovskite cell in place of glass. In order to assess the performance of the AlON layer, we will use a variety of tests. The project will measure thermal conductivity using a controlled experiment involving a 100W light source in a temperature-controlled environment, testing for power output compared to standard solar cells, testing the mechanical properties of the solar cell, and a test to see which wavelengths of light can pass effectively pass through the AlON. This investigation aims to contribute to the development of more efficient and durable solar cells by optimizing material selection and manufacturing processes for improved thermal management.

Solar Cell Materials

Solar cells come in a variety of types, each having benefits and drawbacks. Whether it's an organic, silicon-based, or thin-film cell, there's a certain type of solar cell that is most effective. Cost-effective strategies, environmental impacts, and future innovations must be deliberated upon this decision. With these factors in mind, the focus should be on one of the most promising technologies in solar energy: perovskite solar cells. A perovskite solar cell (PSC) is a type of photovoltaic device that uses perovskite, a unique crystalline structure semiconductor material to convert sunlight into electricity. Perovskite materials have demonstrated excellent light absorption properties and can generate electrical charges when exposed to sunlight. PSCs have rapidly gained attention due to their high efficiency, low production costs, and ease of fabrication. While their commercial use is still in the early stages, they hold significant potential for both residential and commercial solar installations with less unfavorable economic impacts, especially due to their ability to be produced with less energy-intensive processes than silicon-based cells.[1] Further research and testing of perovskite solar cells have been driven by several factors, particularly the need to improve efficiency, stability, and scalability. Ongoing advancements in perovskite photovoltaics are steadily enhancing their performance, with some devices reaching efficiencies comparable to or even exceeding traditional silicon-based cells. As of recent furtherance, perovskite solar cells have reached efficiencies exceeding 25%, which is comparable to the efficiency of traditional silicon solar cells (around 20-25%). In fact, perovskite solar cells have achieved 25.5% efficiency in laboratory settings, surpassing many commercial silicon cells in terms of potential.[2] As these technologies mature, perovskite solar cells are poised to play a major role in the future of renewable energy, offering a promising alternative to the aforementioned established solar technologies.

Choosing between different types of solar cells and what materials to use requires an understanding of how one functions. A perovskite solar cell uses a unique, light-absorbing perovskite material—often a compound made of a combination of lead or tin and halides like iodine or bromine. Unlike silicon-based solar cells, PSC's typically don't rely on p-type and n-type semiconductors. Instead, they use a single-layer perovskite material that absorbs sunlight and generates electron-hole pairs (excitons) when exposed to light. The layer of perovskite has n-doped and p-doped qualities in the material, allowing the electron-hole pairs to form.[3] In perovskite solar cells, the layer of perovskite material is sandwiched between two charge-collecting electrodes: a hole-transport layer and an electron-transport layer. When sunlight hits the perovskite layer, it excites electrons, causing them to move and leave behind holes. The electric field created at the interface of the perovskite material and the transport layers separates these electrons and holes, directing the electrons toward the electron-transport layer and the holes toward the hole-transport layer. A conductive wire connects the electron-transport and hole-transport layer, allowing the electrons to flow through an external circuit from the electron-collecting electrode to the hole-collecting electrode to create an electrical current. This flow of electrons through the external circuit is what generates electricity in the solar cell.

The main layers of a PSC include a back contact, a hole transfer material (HTM), a perovskite, mesoporous film, a blocking layer, a transparent conductive oxide layer, and a glass layer.[4] The back contact is typically made out of gold, due to its high conductivity, chemically inert, and favorable energy-level alignment. For the HTM, the current most used material is Spiro-OMeTAD, but many newer different types of HTMs are being researched. They facilitate the extraction and transport of photo-generated holes from the perovskite layer to the electrode while blocking electron flow to reduce recombination losses. The perovskite is the layer that absorbs the light and creates the electrical charge in the solar cell. Perovskite is an exceptional light absorber due to its high absorption coefficient, tunable bandgap, efficient charge transport, and compatibility with various fabrication methods. The mesoporous film is most important for its scaffolding of the deposition of the perovskite. It is typically made out of TiO_2. For the blocking layer, the typical material chosen is TiO_2 too.[4] This is because of its combination of high bandgap, electron selectivity, chemical stability, and easy fabrication. Its main function is to prevent charge recombination and ensure efficient charge extraction, both of which are critical for maximizing the performance and longevity of solar cells. The transparent conductive oxide layer acts as one of the two electrodes of the solar cell, and is, as its name suggests, transparent. This layer is also typically made out of TiO_2. Lastly, the glass layer is made of: you guessed it, glass. This is because glass is strong, transparent, durable, and weather-resistant. It is a great material for solar cells.

That being said, glass does have some downsides that lead to bottlenecks for solar cells. So how does this happen? It's because temperature has a drastic impact on the efficiency of solar cells. As temperature increases, the amount of energy in a solar cell required to produce a set voltage increases exponentially.[5] This drastically reduces the output of solar panels since the amount of energy in solar rays is about constant, so if the temperature rises, then the solar panels produce exponentially less electricity. Perovskite solar cells work best below 55°C, so we want to try and remove as much of the thermal energy caused by the light as possible in order to remain at peak efficiency.[5] That's where a chance to innovate comes into play. Glass, while it has so many things going for it, does not have an exceptional thermal conductivity. Glass has a thermal conductivity of 1 W/(m·°C), which isn't bad, but it pales in comparison to aluminum oxynitride (AlON), which has a thermal conductivity of 10.3 W/(m·°C).[6] In addition to over 10 times the thermal conductivity of glass, AlON also has a much higher strength. While glass has a strength of 45 MPa, AlON has a strength of 307 MPa, meaning AlON will be much stronger and more durable than glass would be.[6]

Solar Cell Manufacturing Process

This section details the manufacturing processes involved in our modified perovskite solar cell (PSC). At its most basic level, a solar cell is created by adding the necessary layers on top of each other until complete. These materials were discussed in the previous section. There are a lot of different methods for applying these layers, many of which are currently being studied due to PSC being such a new technology. Some of these include slot-die coating, spray coating, blade coating, and vacuum deposition.[7] However, one of the most promising production methods is screen printing, which could fabricate all the layers in a PSC, including the hole transfer material, perovskite, mesoporous film, blocking layer, and a transparent conductive oxide layer.[8] Screen printing involves taking what is essentially a squeegee and coating the material of the current layer over the substrate or previous layer. The screen-printing method is a common technique that can be applied to plenty of materials for film fabrication. The simplicity of using one manufacturing method is important because it allows for a fully screen-printed perovskite solar cell that is low-cost, low-energy consumption, easily designable, and highly compatible.[9] Screen printing offers a high degree of functional layer compatibility, pattern design flexibility, and large-scale ability, showing great promise.[8] That being said, the most difficult part of the process is the formation of a high-quality perovskite layer.[10] This is also the most important part of the process; the main factors adversely affecting device performance are heat due to high activity in the area and defects in the layers, particularly the perovskite one.[7] In order to be widely accepted by the industry, perovskite solar cells must become cheaper and more stable.[8] Screen printing helps solve the issue of price by offering a simple, effective method of producing layers. However, stability is a limiting factor because the process cannot be scaled up or expedited without improving this section. That being said, more durable and stable perovskite solar cells are being made possible by advances in encapsulation methods, stable perovskite compositions, interfacial engineering approaches, and a better comprehension of degradation mechanisms.[11]

In summary, the manufacturing process for this project will be screen printing. It will be used to apply the layers of the solar cell on top of the substrate in an efficient manner. Production is high due to the simplicity of the process. Screen printing has a low setup cost because the process is easily designed. However, potential defects involve instability in the formation of the layers. This can be fixed with research on the perovskite material composition and how it can be better spread. Thus, by this process, a solar cell has been created.

At this stage in the PSC manufacturing process, the cell would be bonded to a glass layer with a UV-cured resin.[12] As an innovative alternative, the glass can be substituted with a layer of processed Aluminum Oxynitride (AlON). As discussed earlier, AlON is a transparent polycrystalline ceramic with remarkable optical, mechanical, and thermal properties, making it an excellent candidate for solar panel applications as a durable and efficient alternative to glass. AlON sheets are manufactured using a standard press and sinter methodology followed by polishing and machining processes to achieve the desired optical properties for the final product.[13]

The press-and-sinter process for manufacturing AlON ceramics begins by mixing AlON powder with any additives. The AlON powder itself is synthesized using a simple reaction between Al_2O_3 and AlN.[14] To achieve more desirable optical properties, the powder is mixed with “various sintering additives … such as Y_2O_3, La_2O_3, MgO, SiO_2, and $CaCO_3$”.[15] These additives have been found to have high transparency to visible light and wavelengths that are critical for solar panel function.

The powder mixture is then compacted in a mold to extremely high pressures using isostatic pressing, which applies uniform pressure to form a dense "green body." This preform must then be subjected to temperatures above 1850°C in a nitrogen atmosphere[16], which will sinter the AlON to densify the material and reduce porosity. Optional steps like hot isostatic pressing can further enhance optical transparency or structural uniformity.[16]

After the sheet is sintered, the form must be ground and polished for the material to gain its characteristic transparency. This process can be difficult and time-consuming as AlON is a hard material and polishing often requires delicate detailing. However, this process can be improved by using rounds of automated bound abrasives, such as CNC grinding wheels. One study has shown that abrasives containing diamond and aluminum with large surface area sweeps are the most successful.[17]

Once the AlON sheet is polished, it will achieve the desired optical characteristics for use in a solar cell. With the perovskite cell finished and the AlON sheet ready, the cell is bonded to an AlON sheet using a high-strength, temperature-resistant adhesive such as an epoxy resin. Thus, the AlON-equipped PSC cell is complete.

Measurements & Quality Control

To evaluate the thermal performance and efficiency of the AlON solar cell compared to a standard solar cell, a controlled experiment will be conducted using the standard test conditions (STC) for solar cells. The experiment will adhere to the STC's AM1.5 requirements of solar radiation intensity of 1000 W/m^2 and cell temperature of 25°C +/- 2°C. The experiment includes an AlON solar cell and a standard solar cell and will attempt to isolate the cell efficiency from the effect of temperature variations on a solar cell. A 100W light bulb will provide a consistent radiation source within a temperature-controlled room.[18] The temperature of each of the cells will be meticulously monitored to ensure temperature is not a major factor. Electrical performance will be assessed using a variable bipolar operational power supply (BPS) measuring short-circuit current, open-circuit voltage, and maximum power point. A Fluke digital multimeter, along with a .01 ohm resistor for the current measurement, will provide additional validation of the BPS readings.[18] The difference in power output between the cell with the AlON protective layer and the standard solar cell will be calculated using the measurements. This methodology should provide a comprehensive dataset to quantify the efficiency gains of using a more thermally conductive material like AlON over traditional solar cell glass.

Mechanical robustness is another critical aspect of solar cell durability, especially concerning the protective layer that protects the sensitive electronics of the cell. To assess the mechanical properties of the AlON-enhanced solar cell, four-point bending tests will be conducted, a method known for its ability to apply uniform stress over a large area, encompassing both the surface and edges of the test sample.[19] This approach allows for a comprehensive evaluation of the material's strength and fracture resistance under stress conditions. This information is vital for understanding how the material will react to external factors such as inclement weather and unforeseen stresses. Samples from a batch of fabricated solar cells will be used to ensure consistency across the solar panels and minimize test variability.[20] Following established procedures, the tests will be performed using a universal testing machine (ZWICK 005) equipped with a 1kN load cell.[19] The fracture stress will be determined through analysis of the resulting data with a Weibull distribution, a statistical method well-suited for certain material properties. Electron microscopy and electroluminescence will be used to assess microscopic fracture behavior.[19,21] Furthermore, Ansys finite element analysis will be used to model the stress distribution during the tests and provide a deeper understanding of the stress states leading to fracture.

The optical properties of AlON are also crucial for its function. It must allow the correct wavelengths of light to pass through so that the solar cell can work at its maximum efficiency. To quantify these properties, absorption spectroscopy will be performed using a spectrophotometer across a range of wavelengths (200nm-1000nm).[22] This encompasses ultraviolet, visible, and infrared wavelengths and will ensure the ALON protective layer does not inhibit the absorption of light energy by the solar cell. This will provide a detailed profile of the desired wavelengths. The goal is to optimize the absorption of desired wavelengths (at around 850nm) while preventing the absorption of less desirable wavelengths which contribute to overheating without significantly enhancing energy production.[22] The absorbance measurements will be conducted at fine intervals of 5nm allowing the generation of a high-resolution dataset. The detailed analysis will provide precise insight into the wavelength-specific absorption behavior of AlON. This is a crucial piece of information to understand about the material because of the desire for selective absorption of wavelengths. If AlON can dissipate more heat into the surroundings, excessive temperature increases will be prevented and will therefore have a smaller effect on the more sensitive underlying photovoltaic layers. Targeting absorption will thus enhance the overall efficiency and longevity of the solar cell by maintaining the components closer to optimal operating temperatures.

Another important test is one that directly assesses the thermal management capabilities of the AlON-enhanced solar cell. A controlled experiment must be conducted in a dedicated solar room in which a halide lamp will be used to simulate solar irradiation.[23] Again, two solar cells, one AlON-enhanced, and one standard commercial cell, will be tested with temperature sensors to provide comprehensive temperature readings. A pyranometer will be employed to precisely measure and calibrate the solar irradiation levels within the solar room, ensuring that the testing conditions are consistent and controlled.[23] During the experiment, the surface temperature of each solar cell will be monitored, and recorded continuously, capturing the dynamic thermal response under the simulated solar irradiation. The real-time temperature data will be read in conjunction with the pyranometer data to determine the relationship between solar radiation and temperature rise in the solar cells.[23,24] By comparing the temperature profiles of the two cells, the more efficient thermal conductivity and heat dissipation of AlON can be directly compared to that of standard solar cell glass. A higher surface temperature would indicate a less efficient heat transfer and thus lower thermal conductivity. Prior experiments and simulations have indicated that the protective layer experienced the highest temperatures, making AlON’s higher thermal conductivity an important measurement for the solar cells' temperature regulation resulting in higher efficiency of the cell.

Conclusion

This paper investigated the benefits and manufacturing of aluminum oxynitride as a protective layer in perovskite solar cells to address the issue of overheating. By focusing on the advantages of perovskite, developing the AlON protective layer, and employing various well-suited manufacturing processes, we aim to create a more thermally efficient and durable solar cell. That, along with a comprehensive testing strategy, will ensure that our solar cell will contribute to the ongoing effort to develop advanced materials and manufacturing processes for more efficient and sustainable solar energy technologies.

References

1. Holzhey P, Prettl M, Collavini S, Chang NL, Saliba M. Toward commercialization with lightweight, flexible perovskite solar cells for residential photovoltaics. *Joule*. 2023;7(2):257-271. doi:10.1016/j.joule.2022.12.012
2. Zhang H, Ji X, Yao H, Fan Q, Yu B, Li J. Review on efficiency improvement effort of perovskite solar cell. *Sol Energy*. 2022;233:421-434. doi:10.1016/j.solener.2022.01.060
3. Mora-Seró I. How Do Perovskite Solar Cells Work? *Joule*. 2018;2(4):585-587. doi:10.1016/j.joule.2018.03.020
4. Mesquita I, Andrade L, Mendes A. Perovskite solar cells: Materials, configurations and stability. *Renew Sustain Energy Rev*. 2018;82:2471-2489. doi:10.1016/j.rser.2017.09.011
5. Halal A, Plesz B. A Comprehensive Study on the Thermal Behavior of Perovskite Solar Cell. *IEEE Trans Compon Packag Manuf Technol*. 2024;14(10):1753-1760. doi:10.1109/TCPMT.2024.3430220
6. Quinn G, Corbin N, McCauley J. Thermomechanical Properties of Aluminum Oxynitride Spinel. *Am Ceram Soc Bull*. 1984;63:723-725, 729.
7. Alanazi TI. Current spray-coating approaches to manufacture perovskite solar cells. *Results Phys*. 2023;44:106144. doi:10.1016/j.rinp.2022.106144
8. Chen C, Ran C, Yao Q, et al. Screen-Printing Technology for Scale Manufacturing of Perovskite Solar Cells. *Adv Sci*. 2023;10(28):2303992. doi:10.1002/advs.202303992
9. Chen C, Ran C, Guo C, et al. Fully Screen-Printed Perovskite Solar Cells with 17% Efficiency via Tailoring Confined Perovskite Crystallization within Mesoporous Layer. *Adv Energy Mater*. 2023;13(46):2302654. doi:10.1002/aenm.202302654
10. Kwon N, Lee J, Ko MJ, Kim YY, Seo J. Recent progress of eco-friendly manufacturing process of efficient perovskite solar cells. *Nano Converg*. 2023;10(1):28. doi:10.1186/s40580-023-00375-5
11. Mohammad A, Mahjabeen F. Promises and Challenges of Perovskite Solar Cells: A Comprehensive Review. *BULLET J Multidisiplin Ilmu*. 2023;2(5):1147-1157.
12. Vesce L, Stefanelli M, Rossi F, et al. Perovskite solar cell technology scaling-up: Eco-efficient and industrially compatible sub-module manufacturing by fully ambient air slot-die/blade meniscus coating. *Prog Photovolt Res Appl*. 2024;32(2):115-129. doi:10.1002/pip.3741
13. Crouch IG, Franks GV, Tallon C, Thomas S, Naebe M. 7 - Glasses and ceramics. In: Crouch IG, ed. *The Science of Armour Materials*. Woodhead Publishing in Materials. Woodhead Publishing; 2017:331-393. doi:10.1016/B978-0-08-100704-4.00007-4
14. Wang Y, Li Q, Huang S, et al. Preparation and properties of AlON powders. *Ceram Int*. 2018;44(1):471-476. doi:10.1016/j.ceramint.2017.09.200
15. Wu J, Wang Z jian, Hu Z chen, et al. Recent progress and challenges of transparent AlON ceramics. *Trans Nonferrous Met Soc China*. 2023;33(3):653-667. doi:10.1016/S1003-6326(22)66136-3
16. McCauley JW, Patel P, Chen M, et al. AlON: A brief history of its emergence and evolution. *J Eur Ceram Soc*. 2009;29(2):223-236. doi:10.1016/j.jeurceramsoc.2008.03.046
17. Marino AE. Grain decoration in aluminum oxynitride (ALON) from polishing on bound abrasive laps. In: *Optifab 2003: Technical Digest*. Vol 10314. SPIE; 2003:88-90. doi:10.1117/12.2284017
18. Malik AQ, Damit SJBH. Outdoor testing of single crystal silicon solar cells. *Renew Energy*.

2003;28(9):1433-1445. doi:10.1016/S0960-1481(02)00255-0
19. Kaule F, Wang W, Schoenfelder S. Modeling and testing the mechanical strength of solar cells. *Sol Energy Mater Sol Cells*. 2014;120:441-447. doi:10.1016/j.solmat.2013.06.048
20. Belis J, Louter C, Mocibob D. *COST Action TU0905 Mid-Term Conference on Structural Glass*. CRC Press; 2013.
21. Gabor AM, Janoch R, Anselmo A, Lincoln JL, Seigneur H, Honeker C. Mechanical load testing of solar panels — Beyond certification testing. In: *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)*. ; 2016:3574-3579. doi:10.1109/PVSC.2016.7750338
22. Absorbance Testing. Boston Bioproducts, Inc. February 7, 2024. Accessed December 2, 2024. https://www.bostonbioproducts.com/reagent-quality-control-testing/absorbance-testing/
23. Yang DJ, Yuan ZF, Lee PH, Yin HM. Simulation and experimental validation of heat transfer in a novel hybrid solar panel. *Int J Heat Mass Transf*. 2012;55(4):1076-1082. doi:10.1016/j.ijheatmasstransfer.2011.10.003
24. Cahill DG, Olson JR, Fischer HE, et al. Thermal conductivity and specific heat of glass ceramics. *Phys Rev B*. 1991;44(22):12226-12232. doi:10.1103/PhysRevB.44.12226