Evaluating the Next Generation of Solar Cells

Michael Crump - mcrump27@uw.edu
Malia Steward - maliaks1@uw.edu
Nicolas Wittstock - nwitts@uw.edu
Brandon Rotondo - brotondo@uw.edu
Kristine Parra - kpoparra@uw.edu
J. Devin MacKenzie - jdmacken@uw.edu
Brandi Cossairt – cossairt@uw.edu
David Ginger - dginger@uw.edu
Cody Schlenker - schlenk@uw.edu

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Abstract:

To facilitate the adoption of next-generation solar cells, future energy leaders, manufacturers, and technicians need to understand how solar cells operate and what the differences and tradeoffs are for conventional and emerging PV technologies.¹ This virtual curricular Module has been designed for community college and high school students and is focused on the fabrication and performance of hybrid perovskite solar cells. Hybrid perovskites are a rapidly improving class of materials for printable solar cells and nearly match the efficiencies found in conventional silicon solar cells. They can be printed like newspapers onto flexible materials.² Another critical element of clean energy is the supply chain for input materials used in technologies like PV Modules. Hence, this Module also invites students to analyze the current global supply chain for clean energy materials used in Washington state, consider what national and

international laws and regulations impact this chain, as well as what human and environmental factors should be considered.

**Key Words:** hybrid perovskite solar cells, supply chain, fabrication, current-voltage (J-V) measurements, UV-vis spectrophotometry

**Module Data**

- Type of Module: Experiment
- Intended grade level(s): Advanced High School, Community and Technical College
- Time required: approximately two 4-hour Modules
  - 90-minute prelab for each Module
  - 60- to 90-minute synchronous lab session for each Module
  - 120-minute post-lab
- Prerequisite knowledge (if any):
  - Basic Statistics (e.g., box plots, standard deviation, mean, etc.)
  - Ohm’s Law
- List of equipment and supplies needed:
  - Laptop/Computer
  - Internet: [https://www.youtube.com/playlist?list=PLiadNLX1inqK35QyUP1DEa6QtQFF](https://www.youtube.com/playlist?list=PLiadNLX1inqK35QyUP1DEa6QtQFF)

HMI1
Evaluating the Next Generation of Solar Cells

- Excel

Categories for Website Curriculum Listing

Semiconductors, Materials Properties
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Background

The Green Energy Transition

Energy powers your everyday lives and is instrumental for the prosperity of the average American. Historically, humans have relied on a variety of energy sources - from burning wood, to coal, oil and gas. Reliance on such fossil fuels for energy is associated with adverse effects on the environment. Fossil fuels are polluting air and water and creating toxic waste. Scientific consensus emerged in the 1970s over the role played by greenhouse gases in contributing to climate change. As displayed in the graph below\(^3\), Greenhouse gas emissions spiked because of the burning of fossil fuels, meaning these gases produced by human activity lead to global warming.

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The Intergovernmental Panel on Climate Change suggests that a complete energy transition towards renewables should proceed as fast as feasible. To keep the planet from warming more than 1.5 °C, global greenhouse gas emissions need to drop to 50% of their 2005 levels by 2030 and to reach net zero emissions by 2050 to keep the planet from warming more than 1.5 deg. C. This means that we need to engineer an energy transition away from fossil fuels, towards energy sources that are less environmentally damaging.

In principle, we could stop burning fossil fuels tomorrow. However, this would drastically change the way we live our lives since many demographics in our society currently have limited access to clean energy alternatives. Consequently, energy would become scarce, and prices would rise. This would imply that especially for the poorest Americans, access to energy would become more of a luxury. Without affordable access to energy, driving your car, freezing your food or medicine, or even toasting bread would become more expensive. Additionally, businesses that produce consumer goods would also face increasing costs, which forces them to raise prices. More costly energy effectively would lead to dramatic disparities in the standard of living in our society.

Given the importance of energy to the functioning of our everyday lives, progress on the energy transition has been slow. Initially, new ways of producing energy needed to be developed. Capturing energy from the sun is an old idea. The basic technology underlying the modern silicon-based solar cell was invented in the 1950s. However, initially this technology was much more expensive in generating energy compared to
fossil-fuel alternatives, so adoption was slow and limited to small markets, such as space.

Government agencies, politicians, researchers, engineers, businesses, and citizens must all work together to continue reducing the price of solar energy - to make this a feasible alternative energy source.

Solar energy is a key component of the renewable energy transition - both in WA and USA more widely. To make the switch to renewable energy resources feasible - the cost of solar energy relative to other energy sources must be competitive. Otherwise, higher costs will inhibit the uptake of renewables by businesses and households. Thus, improving the workings of solar technology, creating energy storage solutions, manufacturing more solar cells, and encouraging the installation of solar panels are all part of the process of phasing out fossil-fuel energy in exchange for renewable energy.

Washington is on its way to eliminating greenhouse gas emissions from electricity with the implementation of the Clean Energy Transformation Act (CETA). Governor Jay Inslee signed CETA into law in 2019, which commits Washington to an electricity supply free of greenhouse gas emissions by 2045. To achieve this goal - a lot of work is still needed. In its 2021 Washington State Energy Strategy, the state announced structural changes to ensure the capacity to provide electricity to replace fossil fuels in transportation, buildings and industry.

To be able to completely switch to renewable electricity - significant changes need to be made to how energy is produced. To that end, WA state is investing in new
transmission capacity and renewable generation to develop distributed energy resources with smart grid capabilities and in consumer equipment to ensure reliability and flexibility. As WA state seeks to switch entirely towards relying on renewables - the energy grid system needs to be updated. Several governmental bodies, research institutes, and private businesses are involved in this effort.

For consumers like you and me to gain access to cheap and reliable solar energy - several actors must work together. Researchers and scientists must create new technologies. Financial support from the government creates an avenue to accomplish this. Businesses are often hesitant to invest in such basic research - as the returns are uncertain and might only be realized far in the future. As a result, government investment is often necessary - especially because we seek to create alternative energy solutions as quickly as possible.

Then, researchers must communicate their technologies to different companies, which then manufacture different parts of new solar cells. Doing so, they must find ways to minimize their production costs to allow the final product to be as cheap as possible to the consumer. Finally, companies need to deploy these new cells. In all of these steps, it is crucial to minimize costs and generate as much energy as possible per dollar invested - to ensure that the final product is cheap enough for consumers.

The Washington State Department of Commerce manages the state’s Clean Energy Fund which provides grants to research organizations like the Clean Energy Institute at the University of Washington to advance renewable technologies. Among many,
companies like *Alpha Technologies* in Bellingham produce components for utility scale solar. *REC Silicon* in Moses Lake produces polysilicon for PV cells - and *Silfab Solar* in Bellingham manufactures solar panels, which are then installed on roofs by companies like Vancouver’s *SunModo*. These solar panels then end up on roofs all across the state.

In 2021, WA state has installed a total solar capacity of 250.3 MW - ranking 37th nationally. This is achieved through 23,788 solar installations in the state, generating enough capacity to power 25,154 homes. In 2021, WA state receives 0.25% of its electricity from solar energy. There are 3,781 people who directly work in the solar industry and WA state is home to 23 Manufacturers, 49 Installers/Developers, 46 other solar-related companies. As of 2021, $740 million have been invested in the solar industry of WA state.

The costs of solar energy have decreased significantly in recent years. In WA State, the average cost of a solar panel installation ranges from $11,348 to $15,352. On a cost per watt ($/W) basis, a solar panel installation in Washington ranges in price from $2.27 to $3.07. The average solar payback period is 13.19 years - meaning that the installation of a solar panel becomes amortized.

To make solar energy more affordable to the consumer, WA state is using policies like *net metering* to allow customers to send extra electricity generated by solar panels back to the electricity grid. So, on sunny days much of the electricity generated by a solar panel will not be used by the customer - but rather sold to the grid. In contrast, at night,
when the solar panels are not generating any energy - the user has access to the regular electricity grid and can cash in the generated credits for cheaper electricity. This reduction in cost is the joint result of public investment, ingenious research and engineering, business efforts to reduce costs, and subsidies provided by the government to those who install solar cells on their roofs.

Basic research related to materials plays a crucial role in making solar energy cheaper - and has been a driving force behind the recent cost declines. To make solar even cheaper, researchers also seek to find ways to generate solar energy more efficiently - reducing costs of materials, increasing yields, and optimizing processes.

Here, both the initiative taken by WA state through the Clean Energy Transformation Act as well as policy taken at the national level are crucial. In this vein, Perovskite materials are an exciting area of current solar cell research, as they would allow solar cells to become dramatically more energy-efficient. This would allow the creation of more solar energy at a constant price - or the same amount of energy at a lower price.

In 2020, the US Department of Energy announced that it would invest $20m in research to advance perovskite solar photovoltaic technologies. Then-U.S. Secretary of Energy Dan Brouillette announced: “We will continue to invest in early-stage research and development to improve the affordability, reliability, and value of solar technologies on the grid and position the United States as the world’s leading manufacturer of clean energy technologies.”
“Perovskites are a promising solar technology that could help us reach the next level of innovative and efficient solar power,” said then-Deputy Secretary of Energy Mark W. Menezes. “Our goal is to further advance this technology here in the United States. The research and development supported by this $20 million investment will help us better understand how perovskite solar cells, which can be manufactured quickly, can further this mission.”

In Washington state, the Joint Center for Development and Research in Earth Abundant Materials (JCDREAM) organizes research in earth-abundant materials and their application in the creation of clean energy.

Perovskites are especially attractive because they combine the benefits of earth-abundant elements (primarily lead, iodine, carbon, and nitrogen) with low-energy fabrication techniques. In the past, clean energy technologies have often relied on rare materials. This has raised concerns that solar energy or storage technologies may be economically infeasible. To make the entire US run on renewable energy would require massive upscaling of existing technologies - which might be impossible if they rely on rare materials. This has sparked a search for more abundant alternatives. A stronger reliance on earth-abundant materials in clean energy technologies ensures that the emerging energy grid is built on sustainable natural resources, sourced from environmentally and economically sustainable resources. While silicon is an earth-abundant element in the Earth’s upper crust, it typically is found as various forms of silicon oxide (e.g. sand) that must be melted at high temperatures (1,760 °C) to fabricate pure silicon wafers. Unlike silicon, perovskites are fabricated at much lower
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temperatures (<120 °C) yet still utilize earth-abundant materials. Perovskite solar cells hold much promise as an earth-abundant solar cell technology because they perform comparably to silicon while taking much less energy to make and much less financial investment to develop manufacturing.

How exactly can perovskites improve the energy-efficiency of photovoltaics to fasten the transition towards renewable energy?

**Photovoltaics and Perovskites - An Introduction**

**Photovoltaics** is the conversion of light energy directly to electrical energy. Solar photovoltaic cells directly convert incident radiation from the sun (~1000W/m² on the surface of the earth) to electricity using the photoelectric effect. Photovoltaic (PV) cells, arranged in Modules or panels, form the first stage of a solar energy system that includes the interconnection, DC/AC conversion and grid integration (Figure 1) [4].

*Figure 1*: Photovoltaic cells are assembled into sealed Modules or panels which are typically deployed on racks and fixtures in arrays for rooftop or ground placement, optimally angled toward the sun based on geographic location. The DC electrical power generated by the cells is locally converted to AC power by an inverter, which can be used to directly power household or commercial activities or feed power back into the grid [4].
To design and fabricate solar cells, it is important to understand how solar cells operate (Figure 2). Fundamentally, solar cells are composed of a light-absorbing semiconductor sandwiched between an anode and cathode that captures the electrical current generated by the absorbed sunlight. So, what is a semiconductor? Generally speaking, materials can be classified as insulators (glass, plastic), semiconductors (silicon, perovskites), or conductors (metals such as silver, gold, etc.) based on their ability to conduct electricity; their differences in electrical properties depend on the composition and crystal structure of each material. Why are semiconductors used to absorb sunlight? Insulators don’t allow electrical current to flow, while metals allow current to flow in two directions. Semiconductors allow current to flow in one direction, which is required to generate electrical power. When the semiconductor absorbs sunlight, positive and negative charges are produced. The
positive charges are harvested by the anode, and the negative charges are harvested by the cathode, resulting in a one-way flow of current.\(^4\)

\[\text{Voltage} \quad \text{Volts (V)}\]

\[\text{Current} \quad \text{Amps (A or I)}\]

**Figure 3:** The electricity generated by a solar cell can be compared to water passing through a hose. The voltage corresponds to the pressure in the hose, while the current corresponds to the size of the hose [5].

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\(^4\) A semiconductor contains electrons that cannot flow as free current without an energy source because these electrons are bonded covalently or ionically within the semiconductor. However, when sunlight is absorbed by a semiconductor, these electrons are liberated from their chemical bonds and promoted to a higher energy level. At this higher energy level, these electrons are free to flow as usable electrical current to the electrodes. Fundamentally, the voltage of a solar cell depends on the increase in energy of each electron when promoted to its high-energy level, and the current of a solar cell consists of the number of electrons freed by sunlight generated per second. The gap between the high-level and low-level energy states is defined as the **band gap** of the semiconductor and has units of energy (J or eV). This means that a semiconductor can only absorb light with an energy equal to or greater than its bandgap to liberate an electron; light with insufficient energy will pass through the semiconductor unabsorbed. The energy of light is defined as \(E = hc/\lambda\), where \(h\) is Planck’s constant (4.136 \times 10^{-15} \text{ eV-s}), \(c\) is the speed of light (2.998 \times 10^8 \text{ m/s}), and \(\lambda\) is the wavelength of light. For example, the bandgap of silicon is 1.1 eV, which corresponds to a wavelength of 1100 nm, which is infrared light. The range of visible light is 380 nm (3.26 eV) to 700 nm (1.77 eV), so all visible light is absorbed by a silicon solar cell, which explains why silicon solar cells are black. However, infrared light with a wavelength of 1200 nm (1.03 eV) does not have enough energy to liberate an electron in silicon, so this wavelength of light would pass through the semiconductor unabsorbed. After absorbing light, electrons will not remain at their high energy level forever; they eventually will fall back to their low energy level, meaning that its absorbed solar energy is lost. This physical event is called **recombination**. Cathodes and anodes are used to extract current from the solar cell before recombination occurs, and the materials used in the cathodes and anodes of solar cells are selected and designed to minimize recombination, which improves solar cell performance.
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This generation of electricity can be compared to water passing through a hose (Figure 3). Using this analogy, the pressure in the hose corresponds to the voltage, while the diameter of the hose corresponds to the current. A pipe with a small diameter could have high pressure (i.e. high voltage) and a small current.

Perovskites used in photovoltaics are primarily composed of lead, iodine, and the organic molecule methylammonium (‘MA’). The balanced chemical formula is MAPbI$_3$. These cations and anions form a cubic crystal lattice as depicted in Figure 4. The purple spheres represent iodide, the green spheres represent lead cations, and the molecule in the center is methylammonium, which has the chemical formula CH$_3$NH$_3^+$. 

Figure 4: A perovskite crystal structure of a new hybrid organic/inorganic semiconductor for PV cells. [6]

Figure 5: (left) the FOM Solar-X3 roll-to-roll printer located at UW’s Washington Clean Energy Testbeds (WCET) [7]. This printer can fabricate multi-layer solar cells and other flexible electronic devices. The labs at WCET also house a 3D printer, sheet coater, large-area solar simulator, and other fabrication and characterization tools for scalable manufacturing of clean energy technologies. (right) example of how large area flexible solar could provide a low cost, easy to integrate route to solar rooftop solar (Solopower).
In addition, perovskites are solution-processable, meaning they can be dissolved in a solution and then printed via a roll-to-roll (R2R) process (Figure 5). For example, the R2R printer located at the UW Clean Energy Testbeds (WCET) can fabricate large-area multilayer photovoltaic devices. This could lead to not only low cost, low carbon footprint solar PV Modules but also novel and lower- cost means of integration and installation compared to the fabrication of silicon solar cells.

**Measuring Light Absorption in a Perovskite Semiconductor**

The absorption and thickness of a perovskite semiconductor will be determined using **UV-visible light spectrophotometry** (UV-vis). UV-vis spectrophotometry measures the absorbance of light passing through a perovskite thin film as a function of wavelength. A **monochromator** is a tool used to isolate individual wavelengths of light from a lamp, and the beam from the monochromator is passed through the sample, where the detector will read the decrease in transmittance. The following equation defines the relationship between **absorbance** \(A\), scattering \(S\), and transmission \(T\):

\[
A + S + T = 1 \quad \text{(2a)}
\]

Assuming that no light is scattered \((S = 0)\), the fraction of light absorbed (absorbance, or \(A\)) is equal to \(1 - T\). Absorbance is defined as the common logarithm of the ratio of absorbed light intensity \((I)\) to total incident light intensity \((I_o)\):

\[
A = -\log \left( \frac{I}{I_o} \right) \quad \text{(2b)}
\]
In addition, the thickness of a semiconductor can be determined using the Beer-Lambert law:

\[ A = \alpha \times t \]  \hspace{1cm} (2c)

where \( \alpha \) is the absorption coefficient and \( t \) is the thickness of the semiconductor. The absorption coefficient measures the amount of light absorbed per unit length; a higher coefficient indicates the semiconductor is better at absorbing light.

**Figure 6** compares the absorption coefficient of silicon vs. perovskite. Note that perovskite is much better than silicon at absorbing light up to 800 nm, meaning much less material is required to absorb the same amount of light. For example, if a perovskite film were as thick as the height of the average human, a silicon wafer would need to be as thick as the tallest Sitka Spruce in WA state (191’) to absorb the same amount of light!

**Figure 6:** Absorption coefficients of silicon vs. perovskite as a function of wavelength [8].
Determining the Power Conversion Efficiency of Perovskite Solar Cells

Figure 7: schematic of experimental setup for J-V measurements [9]. Light from a solar simulator lamp passes through a filter simulating losses of light intensity due to the atmosphere and illuminates a solar cell with an area defined by a mask. A sourcemeter applies a voltage and measures current across a predefined voltage range. The upper-right figure shows the solar spectrum of the sun outside the atmosphere (am0) and inside the atmosphere (am1.5g) [10]. When the sun passes through the atmosphere, some sunlight is absorbed by ozone, water, and carbon dioxide. Note the units for the y-axis ‘Spectral Irradiance’ which is illumination power density per unit wavelength. A plot containing a J-V and P-V curve is shown on the bottom [11]. As voltage is varied, the maximum power point is identified, allowing for the calculation of power conversion efficiency.
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How do we characterize the performance of a perovskite solar cell? One key metric is the **power conversion efficiency**, which is defined as the ratio of solar cell output power to the input power of sunlight. The input power of sunlight is typically 1,000 W/m$^2$. The output power of the solar cell can vary based on the load resistance of the circuit it is connected to (light bulbs, electrical appliances, etc.), but power conversion efficiency is measured at the **maximum power point** of the solar cell. To find this maximum power point, a voltage is applied to an illuminated solar cell in increasing amounts while measuring the current. This curve is called a J-V curve (**Figure 7**, bottom). The letter ‘J’ is used in place of ‘I’ to represent the **current density** (units of A/m$^2$). Accounting for the area of the solar cells allows for direct comparison of solar cells with different geometries.

The solar cell **power density** (units: W/m$^2$) is defined as [9]:

$$P = JV$$  \hspace{1cm} (8)

Upon determining the maximum power point, the **power conversion efficiency** ($\eta$) is:

$$\eta = \frac{J_{mp} \times V_{mp}}{P_s} \times 100\%$$  \hspace{1cm} (9)

where $J_{mp}$ and $V_{mp}$ represent the current and voltage at the maximum power point and $P_s$ is the initial power density of sunlight (1,000 W/m$^2$).
In this lab, we will determine $V_{mp}$, $J_{mp}$, and the maximum power point to calculate photovoltaic conversion efficiency. In J-V characterization, light emitted from a solar simulator lamp passes through a filter that simulates the light scattering and absorption effects of the Earth’s atmosphere before it impinges on a sample with an area defined by a mask (Figure 7, upper right). While the photovoltaic cell is illuminated, **current-voltage sweeps** are taken using an electric sourcemeter to generate J-V plots. This sweep simulates the connection of a variable load resistor to a solar cell. Using the water hose analogy, the maximum possible voltage, $V_{oc}$, is equivalent to placing one’s thumb over the end of the hose. The maximum pressure (voltage) will be achieved, but no current will flow, meaning there is zero power generation at this point. The maximum current, $J_{sc}$, is equivalent to the largest hose diameter. The maximum possible flow could be achieved, but there is no pressure (voltage) to drive that flow, meaning there is also no power generation at this point. The sourcemeter will increase the voltage in a stepwise fashion and record the current; the speed and step size of the J-V sweep can affect the accuracy of the measurement.
Figure 8: a cross-sectional view of illuminated photovoltaic cells. On the left, the photovoltaic cells are not masked, and the area of these cells is assumed to be the area overlap of the cathode and anode (denoted by the red dashed lines). However, light scattered or waveguided by the anode can artificially increase the current density and efficiency of the photovoltaic cell. On the right, a mask defines a solar cell area within the cathode-anode cross section (denoted by the red dashed lines) and prevents additional light from entering from the defined area, resulting in an accurate measurement of power conversion efficiency.

To ensure an accurate measurement of the power conversion efficiency, we need to use a testing mask that precisely defines the area of a solar cell. If we assume that this area is only the overlap of the cathode and anode, then light passing through the anode can be scattered or waveguided laterally through the anode and enter the solar cell. This artificially increases the photogenerated current density by as much as a factor of 5 for some solar cells. So, a dark mask is introduced between the solar cell and the solar simulator to define the solar cell area precisely by eliminating extra contributions of light.
In this lab, we will fabricate perovskites using two lab techniques - spin coating and thermal evaporation. We need several materials to create PVs. The anode will be composed of the ceramic indium tin oxide and the polymer PTAA, and the cathode will be composed of buckyball (C\textsubscript{60}), the semiconducting molecule BCP, and silver (Ag). The perovskite layer will be spin-coated at different speeds to vary the thickness of the perovskite layer. Then, the perovskite layer thickness will be characterized with UV-vis spectrophotometry, and the power conversion efficiency will be measured via J-V characterization.

**Suggested Reading**

PVE Education (https://www.pveducation.org/) is a free online textbook describing the physics of silicon solar cells in greater detail. Calculators and animations are included to help convey these concepts.
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Pre-lab questions

A. What are the advantages of manufacturing perovskite solar cells instead of silicon solar cells?

B. At a wavelength of 750 nm, the absorption coefficient of a perovskite film is approximately $1 \times 10^7 \text{ m}^{-1}$, and the absorption coefficient of a silicon wafer is approximately $2 \times 10^5 \text{ m}^{-1}$. How much thicker than the perovskite film does the silicon wafer need to be to absorb the same amount of light at 750 nm?

C. Solar cell A has an output voltage of 12 V, an output current of 20 A, and an area of 2 m$^2$. Solar cell B has an output voltage of 12 V, an output current of 16 A, and an area of 1 m$^2$.

- What is the current density of each solar cell?
- What is the power density of each solar cell?
- What is the power conversion efficiency of each solar cell? Assume the input power of light is 1,000 W/m$^2$
- Which solar cell produces more total power?
- Which solar cell is more efficient per unit area?

D. What happens if solar cells are not masked for J-V testing? How are the maximum current and maximum power affected?
Methods:

https://www.youtube.com/playlist?app=desktop&list=PLiadNLX1inqK35QyUP1DEa6QtQFFHM1

We will fabricate perovskite solar cells with the following architecture (**Figure M1**):

ITO/PTAA/MAPbI3/C60/BCP/Ag, where ITO/PTAA is the semi-transparent **anode**, MAPbI3 is the perovskite semiconducting material, C60 is the fullerene **electron acceptor**, and BCP/Ag is the **cathode**. The fabrication process will be demonstrated via a recording of each layer up to completion of the solar cell, followed by its characterization.

![Perovskite solar cell architecture](image)

**Figure M1**: Perovskite solar cell architecture displaying: (a) cross-sectional view, and (b) top view with structure of ITO/PTAA/MAPbI3/C60/BCP/Ag. Dimensions are not drawn to scale. Image Source: Malia Steward | UW CEI

Two microfabrication equipment will be used: a **spin coater** and a **thermal evaporator**.

After completing the perovskite fabrication, light absorption and current-voltage measurements will be characterized via **UV-visible spectrophotometry** and a source meter with a **solar simulator**, respectively.

Each fabrication equipment and characterization tool will be discussed in this section.
In addition, the following materials are prepared:

Table 1: Solution preparation process

<table>
<thead>
<tr>
<th>Function</th>
<th>Material</th>
<th>Recipe</th>
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<tbody>
<tr>
<td>Hole Transport Layer</td>
<td>PTAA</td>
<td>2 mg/mL in toluene</td>
</tr>
<tr>
<td>Perovskite</td>
<td>MAPbI3</td>
<td>PBI2 = 0.691 g</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MAI = 0.238 g</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DMF = 0.9 mL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DMSO = 0.6 mL</td>
</tr>
<tr>
<td>Electron Transport</td>
<td>PCBM*</td>
<td>20 mg/mL in chlorobenzene (CB)</td>
</tr>
<tr>
<td>Layer</td>
<td>BCP</td>
<td>0.5 mg/mL in isopropyl alcohol (IPA)</td>
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</tbody>
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* If C60 is not available, PCBM can be used

**Glovebox**

The fabrication of perovskites (spin coating and thermal evaporation) will be performed inside a nitrogen-encased glovebox. Processing inside the glovebox aids in reducing oxidation and humidity effects on thin films. For more details regarding glovebox operation and maintenance, please refer to Appendix A.
Spin Coating

Spin coating is a microfabrication technique performed to produce a thin film of material. It involves dropping a small amount of solution onto a glass slide, or substrate, and rotating it at a high speed to spread the liquid on a film evenly, resulting in a thin film on a nanoscale or microscale.

The next step is to place the freshly coated sample on the hotplate to control the film morphology of the solution. This process is called thermal annealing, and this is done after any type of coating. The overall general operation is depicted in Figure M2.

![Figure M2: (a) A solution dropped on a glass slide, ready for spin coating. (b) Freshly coated glass slide on the hotplate for thermal annealing. Image Source: Malia Steward | UW CEI](image)

A brief procedure of the spin coating process is as follows:

**Preparation:**

a. Carefully place the sample face up in the center of the chuck inside the spin coater.

   An example of the chuck location is shown on Figure M3.

   ![Figure M3: Location of the chuck inside the spin coater](image)

b. Withdraw appropriate solution by using a 10-100uL micropipette.

**Procedure:**

1. Dispense the solution onto the slide, fully covering the whole slide.
2. Spin coat the appropriate material listed on Table 2 with the according spin speed parameter.

3. After spin coating, remove the sample, and place it on the hotplate to thermal anneal for the required amount of time, as listed on Table 2.

4. After thermal annealing for the required time, remove the sample from the hotplate, and place it at the “floor” of the glovebox to allow the sample to cool.

5. Repeat steps 1-4 for the remaining layers until completion.

Figure M3: Different models of spin coaters ((a) and (b)) showing location where the sample should be placed (on the chuck, highlighted in a red box).
<table>
<thead>
<tr>
<th>Layer #</th>
<th>Function</th>
<th>Material</th>
<th>Spin Coating Speed</th>
<th>Thermal Annealing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hole Transport Layer</td>
<td>PTAA</td>
<td>6000 rpm for 35 sec</td>
<td>100C for 15 min</td>
</tr>
<tr>
<td>2</td>
<td>Perovskite</td>
<td>MAPbI3</td>
<td>Condition 1: 4000 rpm for 25 sec, Condition 2: 8000 RPM for 25 seconds</td>
<td>100C for 15 min</td>
</tr>
<tr>
<td>3</td>
<td>Electron Transport Layer</td>
<td>PCBM</td>
<td>1000 rpm for 30 sec</td>
<td>100C for 10 min</td>
</tr>
<tr>
<td>4</td>
<td>BCP</td>
<td>BCP</td>
<td>4000 rpm for 30 sec</td>
<td>100C for 10 min</td>
</tr>
</tbody>
</table>

After spin coating all layers, we can proceed to operating the thermal evaporator.
Thermal Evaporation

An additional well-known microfabrication method to deposit thin films is thermal evaporation. In contrast to spin coating, the samples are suspended from the ceiling of the chamber, with the solar cells facing down (Figure M4). Thin film deposition takes place when the chamber is under vacuum. Therefore, the chamber is sealed and the pressure of the chamber is dropped to $\sim 5 \times 10^{-6}$ Torr to facilitate the vapor particles of the evaporated materials (i.e., metals, metal oxides, and organics) to move directly towards the substrate, where these vapors again change to a solid state. Once the pressure of the chamber is reached, heat is applied to a tungsten boat, or a crucible, that is holding the material to be evaporated (Figure M4). By controlling the boat heating process, thin films can be deposited controllably onto the samples at rates of 0.01-0.2 nm per second, achieving film thicknesses of 1 nm to $>100$ nm.

![Diagram of thermal evaporation](image)

**Figure M4:** (a) Thermal evaporation of a source material in a vacuum chamber where the sample is faced down (upside down). The boat, or crucible contains the source material (i.e., metal pellets) to be evaporated. (b) Completion of evaporation with the sample upright. Image Source: Malia Steward | UW CEI

A table describing the differences between thermal evaporation and spin coating is listed in Table 3.
## Table 3: Comparison between spin coating and thermal evaporation for thin film deposition

<table>
<thead>
<tr>
<th>Technique</th>
<th>Operation</th>
<th>Parameters</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin Coating</td>
<td>Spins solution at a high speed to create a thin film</td>
<td>Spin speed</td>
<td>Liquids</td>
</tr>
<tr>
<td>Thermal Evaporation</td>
<td>Use of heating (source) material to deposit by means of evaporation</td>
<td>Rate of deposition/evaporation</td>
<td>Metal solids, Metal oxides, Organics</td>
</tr>
</tbody>
</table>

In order for the thermal evaporator to operate, it consists of the following necessary hardware inside the chamber (Figure M5). A visual representation of each hardware piece inside the thermal evaporator chamber (Figures M6 - M9) corresponds to the overall setup in Figure M5.
Sample Holder and Sample Shutter

The samples are safely held while they are being suspended from the ceiling of the chamber.

In the initial stage of heating the tungsten boat, the source material will begin to heat and release vapor particles. During this process, the rate has not been stabilized. Therefore, this shutter will protect your samples while the rate stabilizes in preparation to deposit the material. The sample shutter should remain closed during the initial stage of the boat heating process.

Sensors

The sensors detect the rate of the vapor particles from the source material. In most thermal evaporator models, there are two sensors; each sensor corresponding to two sources (i.e., Sensor 1 is for Sources 1, 2. Sensor 2 is for Sources 3, 4)
Tungsten Boat

Boats are used for the vacuum evaporation of materials. They are designed to hold whatever material you want to evaporate (source material). Because the boat is the source of the heat for evaporation, the boat must operate at a much higher temperature than the source material. Tungsten (W) has the highest melting point of 3422 C (6192 F) and has the highest tensile strength. Therefore, using a tungsten boat is ideal for evaporation.

Sources

A (resistive) heat source where current is applied to the ends of the tungsten boat. As current increases, more heat is produced, melting the source material, eventually into vaporized particles to be deposited onto the sample.
Source Shield

This protects each source from making contact with each other to prevent an unintended path of current flow (also known as a “short circuit”). During deposition, only one source is operating. Two sources cannot operate at the same time since you only want to deposit one material at a time (therefore, one source at a time).

In this section, we will deposit thin films using thermal evaporation. This step is performed after completing spin coating.

A brief procedure of the thermal evaporation process is as follows:

**Preparation:**

a. Prepare the thermal evaporator by filling, or supplying, the chamber with nitrogen.

   By providing nitrogen, you “break” the vacuum, lowering the pressure in order to open the chamber lid. This process is called **purging** (i.e., the chamber is being purged with nitrogen). For most cases, this purging process takes about 10 min.

   *Note: While the evaporator is being purged, samples can be prepared for loading inside the chamber.*
b. With tweezers, carefully place each sample with the film faced down in the sample block (a platform to hold your samples facing down while suspended from the ceiling of the chamber), as shown in Figure M10.

![Figure M10: Movie screenshots of (a) sample film placed down in the sample block, and (b) block placed in the larger holder containing the samples](image)

**Note:** A patterned metal template, or stencil, called a **shadow-mask**, is often used for the top metal electrode deposition. It defines the active area, and allows the creation of multiple devices (or pixels) of a completed solar cell. A shadow-mask is used in this step if depositing a metal film. A general example is shown in Figure M11, which also corresponds to Figure M10.

![Figure M11: Image Source: Malia Steward | UW CEI](image)
(a) Thermal evaporation using a shadow-mask. The opening in the shadow-mask allows the patterning of the metal deposition. (b) After metal deposition using a shadow-mask.

c. If purging is complete, open the lid of the chamber to place the sample block (containing your samples) inside the chamber.

d. Load the sample block into the evaporation chamber (Figure M12).

e. Close the lid of the chamber.

f. Pump down the vacuum chamber to the pressure of ~ 5 x 10^-6 Torr.

**Procedure:**

1. Depending on the model of thermal evaporator used, thin film deposition can be performed **manually**, or **automatically**. Nevertheless, the concept of thermally evaporating a material remains the same.
2. The initial steps of the recipe involve slowly increasing the heat (i.e., **ramping power**) applied to the **tungsten boat** in order to melt the material from its solid state to liquid and finally, its vapor state (i.e., evaporated metal atoms). As the material begins to slowly evaporate, we begin to see how fast this evaporation process is at a given time (**rate power % per second**). At this point, the rate slowly increases in intervals until it reaches a constant rate. During this process, the shutters inside the thermal chamber remain closed to protect the samples while the material is being heated. An example of the recipe template used is described in more detail in Appendix B.

A typical recipe entails the following critical parameters for thermal deposition:

- **Source Material**

  The material chosen to be deposited (i.e., Ag for top electrode). The source material is placed on a **tungsten boat**, located in one of the **sources**, as previously shown in Figure M9.

- **Evaporation Rate**

  Rate of evaporation of the source material where heating is controlled by use of the ramp power. The evaporation of the source material is detected by the **sensor**, as previously shown in Figure M7.

- **Deposition Rate**

  Rate of deposition where heating is stabilized (ramp power is established). The **shutters** open, the thickness reading is calibrated to zero, and the
source material begins to deposit on the samples. The deposition of the source material is also detected by the sensor.

- **Targeted Film Thickness**

Desired film thickness that is to be deposited on the sample.

3. Choose the appropriate material listed on Table 4 and input the following parameters.

**Table 4: Thermal Evaporation Parameters**

<table>
<thead>
<tr>
<th>Layer #</th>
<th>Function</th>
<th>Material</th>
<th>Deposition Rate</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Cathode (Top Electrode)</td>
<td>Ag</td>
<td>0.40 angstrom/sec*</td>
<td>80 nm (= 8 x 10^-9 m)</td>
</tr>
</tbody>
</table>

*Angstrom = 10^-10

Once the rate is established, the deposition process begins, and the shutters will automatically open to allow deposition of the evaporated film at a constant rate. Although the deposition process is automated, it is important to monitor the deposition so that the target deposition rate and thickness are achieved.

After film deposition is complete, the evaporation chamber is vented with nitrogen. After venting, we can open the lid, remove the sample block, and retrieve our samples. This completes the fabrication process, and we can now proceed to characterizing our perovskite solar cells.

*Note: In this lab, the materials to be thermally evaporated is Ag with thickness of 80 nm. If PCBM was not used, C60 and BCP can be thermally evaporated in addition to Ag. If this is
the case, three recipes will be used. The recipes will be covered and discussed in a video recording. We will refer to the example recipe template in Appendix B.

Characterization #1: Current Density - Voltage (J-V) Characteristics

A solar simulator is used to test the performance of the completed solar cells and to characterize their electrical performance. *It simulates the illumination from sunlight by use of a high intensity lamp, and a power supply to apply a voltage sweep to the solar cell while under illumination* (Figure M13). With each voltage step, the output current is measured, resulting in the current density-voltage (J-V) curve with the solar cell active area taken into account. This type of setting provides a controllable indoor testing environment in a laboratory setting.

The setup includes connecting the terminals of the power source unit to the electrodes of the solar cell (ITO as the anode, and Ag as the cathode). Light emitted from the solar simulator lamp will transmit through the semi-transparent electrode (ITO).

*Figure M13:* Lamp (left) and lamp power supply (right)
A solar simulator is equipped with reflectors, lenses, shutters, power supplies, control electronics, and a high intensity light source that simulates the solar spectrum. If a solar simulator is an AAA-rated solar simulator, this means it has the highest grades in the following areas:

- **Spectral Mass Classification**
  
  How close its spectral output matches that of the sun

- **Temporal Instability Classification**
  
  How much the spectral output changes as a function of time

- **Uniformity Classification**
  
  How large of an area the solar simulator can illuminate with equal intensity

*Note: For this lab, Newport VERASOL-2 (AAA-rated) solar simulator was used.*

A brief procedure of J-V characterization is as follows.

**Preparation**

a. Turn ON the lamp. This is the source of our light intensity.

b. If provided, place a J-V testing mask in the sample holder. The mask should match the electrode positions of the solar cell.

c. Loading the samples onto the sample holder, carefully align the holes of the mask onto the electrodes of the solar cell. This ensures contact with the electrodes when measuring *(Figure M14).*
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Figure M14: PV sample holder with a J-V mask placed inside the sample holder. Note the orientation of the mask with respect to the sample holder.

   d. To ensure good contact with the electrodes, (if available), place a plate and adhere it with clips (Figure M15).

Figure M15: (a) PV cell placed on top of mask, and (b) PV sample holder assembly after clipping in the free plate with spring pins.

Note: The hardware setup used for this the Newport VERASOL-2 solar simulator is shown in Appendix C.
J-V Testing Procedure

(The procedure is performed after calibrating the light intensity**)

1. If testing is done inside a glovebox, ensure the glovebox light is turned OFF. The light from the glovebox will not interfere with the light intensity emitted from the solar simulator.

2. Select pixel 1 in the MaxSSD software.

3. Open the Labview program “Giles Solar Sim Program v17” from the Desktop. This program will be used to apply a series of voltages and measure the resulting current to calculate solar cell efficiency.

4. Run the program.

5. Create a folder to save all measured raw data.

6. Depending on the software used, input the following parameters (at a minimum):
   - Solar cell active area (cm2)
   - Sweeping voltage (V)
   - Step size (V)

   Note: The parameters used for this lab are listed in Appendix C.

7. Confirm that all pixels are turned ON (i.e., indicated by a green light).

8. Begin scanning (i.e., press “Scan”) to begin the J-V sweep.

9. Manually change pixels for each J-V sweep by using the MaxSSD software.

10. Retrieve all saved raw data under the folder that was created in Step 5.
It is important to note that prior to testing solar cells, it is recommended to calibrate the solar simulator by using a photodiode with a known integrated photocurrent and spectral responsivity. This information can be used to calculate the photocurrent equivalent to one-sun intensity. For more details regarding photodiode calibration, please refer to Appendix C.
Characterization #2: Ultraviolet-Visible (UV-vis) Light Spectroscopy

**UV-Vis Spectroscopy – adopted from the EMDS Nanoparticle lab (Dr. Michael Enright)**

Ultraviolet-visible (UV-vis) light spectroscopy is a technique used to measure light absorbance of a material across the ultraviolet and visible ranges of the electromagnetic spectrum. As light hits the surface of a material, the light can either be reflected, absorbed, or transmitted. A portion of light that is being absorbed in the UV-vis range will excite a charge from its low energy ground state to an excited state.

There are four basic components to a single beam UV-vis spectrophotometer:

- Light source
- Monochromator
- Detector
- Your sample

A general setup for UV-vis characterization is shown in Figure M16.

![Figure M16](image_url) Hardware setup of a single beam optical design for a UV-vis instrument
For this measurement, a sample with only the perovskite layer is used (i.e., no electrodes fabricated). This will allow us to characterize the absorption properties of the perovskite layer. Since UV-vis characterization is mainly controlled by use of software, this procedure will discuss the generic use of a software for accommodation (of choosing your preferred software). For this lab, the PerkinElmer UV WinLab software (Scan - Lambda 950) was used.

A brief procedure of UV-vis characterization is as follows:

**Preparation**

a. Power ON the UV-vis equipment and allow it to warm up for at least 30 min.

b. Open the appropriate software to perform the testing and collect data. An example of the program interface (*PerkinElmer UV WinLab software*) used for this lab is shown in Figure M17.

c. Input the necessary scanning parameters in the software for testing.

*Note: The scanning parameters can be customized. The recommended settings used in this lab are described in Appendix D.*
**UV-Vis Measurement Procedure**

Indicate the number of samples you want to run.

Begin scanning (i.e., click “Start”).

Note: When measuring each sample, also measure an ITO/PTAA-coated glass slide as a baseline to compare with the perovskite-coated sample.

Once all scans are complete, place a cursor at a desired wavelength (i.e., 550 nm) and record the absorbance of all samples and baseline films at this wavelength.

Take screenshots, and save all scans and open them in an appropriate program (i.e., Word) for record.
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Data Analysis

All post-lab analysis can be done in Excel, but you’re more than welcome to use other data processing and graphing software, such as Matlab, R, etc.

UV-vis - Thickness Estimation

A. You should have absorbance (A) vs. wavelength (λ) data for all three processing conditions. Plot all three spectra on the same graph and include this graph in your Lab Report.
B. Calculate the thickness of the perovskite thin films for each processing condition using the absorbance at 750 nm and equations. Show this calculation and include a table comparing film thicknesses in your Lab Report.

**J-V Results, Part I – Calculating the efficiency of a single pixel**

A. You should have current density – voltage results for a representative pixel from each solar cell.

B. Create a J-V plot for both devices by plotting J (y-axis) vs. V (x-axis).

C. Identify the short-circuit current density \( (J_{SC}) \) and open-circuit voltage \( (V_{OC}) \) of this pixel.

D. In a new column, multiply every value of J by its corresponding voltage V to calculate the power density \( (P) \) as a function of voltage.

E. Plot power density vs. voltage and identify the maximum power point \( (MPP) \) and \( V_{MP} \).

F. Use \( V_{MP} \) to identify \( J_{MP} \) on the J-V plot.

G. Calculate the PCE using \( V_{MP}, J_{MP} \), and the power density of the solar simulator (1,000 mW/cm).

**J-V Results Part II – Statistics**

A. You should have PCE, \( V_{MP} \), and \( J_{MP} \) for all pixels.

B. For each of these three solar cell metrics, prepare box and whisker diagrams for both solar cell processing conditions. This means you need to make four figures
C. In your lab report, include these box plots and use them to support your answers in the Discussion section.
Acknowledgements

This work was supported in part by the JCDREAM project, sponsored by the State of Washington, and by the MatEdU On-line Instructional Resources for Materials Science Technology Education project (NSF DUE #2000347).

References


[4] Figure 1


Lab Report

Introduction

Clearly describe the motivation for the experiment, connections to other fields, and broader impacts of photovoltaic technology on the green transition.

Methods

Summarize the major steps of the experimental method you read about. You can choose to summarize these methods with a one-paragraph summary or a process flow chart.

Data Analysis

Record all results and answers from the Data Analysis section here. Below is a checklist of results you must include:

- UV-vis
  - Absorption vs. wavelength plot (one graph with two traces)
  - Thickness calculation from absorption data
  - Summary table comparing thicknesses of both solar cells
- J-V
  - 1 J-V plot and 1 P-V plot of a pixel showing the calculation of \( V_{OC} \), \( J_{SC} \), the MPP (\( V_{MP} \) and \( J_{MP} \)), and PCE
  - 3 box plots per solar cell (one plot for each performance metric: PCE, \( V_{MP} \), and \( J_{MP} \)), meaning 6 total are needed.
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**Discussion**

A. Compare the UV-vis spectra of the two different solar cells. Which one absorbed more light at 750 nm?

B. Compare the PCE, $V_{MP}$, and $J_{MP}$ between the two solar cells. Identify the solar cell with a higher $J_{MP}$ and PCE and explain why (hint: how does light absorption affect the amount of current generated?).

**Conclusions**

Connect what you’ve learned to the larger picture of your own high school experience.
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Grading Rubric

Introduction: 20 points

Motivation for the experiment, broader impacts of PV on WA state energy policy / economics, and connections to other fields of study are discussed concisely and thoroughly - 2-3 long paragraphs is the expected length

Methods: 20 points

Students summarize and describe the methods in their own words - penalize or any direct copy/paste of language from the Methods section

Analysis: 45 points

**UV-vis: 15 points**

- Absorption vs. wavelength plot: 6 points
  - 3 points for plotting each curve
  - 3 points for correctly labeled axes and units

- Thickness calculation: 6 points
  - 3 points for using correct formula
  - 3 points for correct answer (i.e. deduct for math errors here)

- Thickness summary table: 3 points

**J-V Characterization: 30 points**

- J-V Plot: 8 points
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○ 3 points for plot with correct axes and units

○ 5 points for labeling each important feature (Voc, Jsc, MPP, Vmp, Jmp)

● **P-V Plot: 6 points**

  ○ 3 points for plot with correct axes and units

  ○ 3 points for labeling each important feature (MPP, Vmp, Jmp)

● **PCE Calculation: 4 points**

  ○ 2 points for using the correct equation

  ○ 2 points for calculating the correct value

● **Box plots: 12 points**

  ○ 2 points per box plot (6 total)

**Discussion and Conclusion: 15 points**

● Discussion Part A: 5 points

● Discussion Part B: 5 points

● Discussion Part C: 5 point
Appendix A

Glovebox Operation and Maintenance

Processing inside the glovebox aids in reducing oxidation and humidity effects on thin films. It is ideal to process perovskites in the glovebox, as the film morphology is highly sensitive to oxygen and the outside environment. In addition to using the spin coater and thermal evaporator, the process of operating the glovebox is critical when transferring in samples, as we want to monitor and maintain the quality and longevity of the glovebox equipment.

Glovebox Inspection

Prior to using the glovebox, confirm that the nitrogen pressure is above 200 psi and the H2O and O2 levels are <0.1 ppm (Figure A1).

Figure A1: Pictures of (a) the nitrogen pressure gauge and (b) the touchscreen for the glovebox. The Circulation Purifier is highlighted by the red box; the green light indicates it is active.
The circulation purifier flows glovebox atmosphere through the catalyst, which captures trace amounts of water and oxygen by forming various copper oxides and hydrates, whereas the LMF circulator contains molecular sieves to capture trace amounts of solvents. The “Circulation Purifier” and “LMF Circulator” are turned OFF, as shown in Figure A2 (both buttons will turn gray when off).

Figure A2: (a) Turning off Circulation Purifier - button should no longer be green

Transferring Samples Using Glovebox Antechamber

Figure A3: Pictures of the glovebox antechamber when (a) closed, (b) filling with nitrogen, and (c) evacuating
When loading the ITO substrates into the glovebox antechamber, perform the following:

a. If the antechamber is under vacuum (check the pressure gauge), then fill the antechamber with nitrogen by turning the valve such that the arrow is pointing to the left (Figure A3b).

b. Move the valve back to the closed position once the antechamber pressure returns to ambient pressure (Figure A3a)

c. Open the outside (air-side) door.

d. Load the substrates onto the tray.

e. Close the outside door.

We can now transfer substrates into the glovebox antechamber. While the substrates are inside the chamber, we perform the following to ensure we are transferring as little oxygen into the glovebox as possible:

a. Evacuate the chamber by turning the valve to the right (Figure A3c); upon reaching maximum vacuum, refill the chamber by turning the valve to the left – this completes one cycle

b. Repeat this cycle two more times to complete cycling.

c. After the third refill, leave the valve in the closed position.
d. Open the inner chamber door and transfer in the petri dishes.

e. Close the inner chamber door, evacuate the chamber, and then leave the valve in the **closed position**.

**Before Working Inside Glovebox**

As we are preparing to work inside the glovebox, wear disposable nitrile gloves over the butyl glovebox gloves while using solvents to protect the butyl gloves from contamination.

**Operating the Spin Coater Interface (example of Programming Spin Speeds)**

![Figure A4: Pictures of the (a) nitrogen gun used to blow off any dust from the substrate. (b, top) If the lid is opened too early after spin coating, a warning message will appear. (b, bottom) This can be cleared by pressing the checkmark.](image-url)
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Figure A5: Display of the spin coater showing (a) “Standby” screen and (b) Parameters screen - red boxes highlight the icons that must be pressed to edit spin coating parameters. (c) First segment, and (d) Second segment. Note that the times and speeds on the screen may not be correct.

Once the spin coater is turned ON, and is set in “Standby Mode”, we can change the spin coating parameters and program individual spin coating steps by pressing the DJ/soundboard icon (Figure A5a), followed by the train icon (Figure A5b). Segment 1 corresponds to the acceleration (Figure A5c), while Segment 2 corresponds to the spin speed (Figure A5d).
After working with solvents inside the glovebox, it is important to remove any solvent vapors that are present inside the glovebox. Therefore, purging of nitrogen is performed for about 10 minutes in order to remove solvent vapors that were evolved during spin coating and annealing. This is done by pressing the “Quick Purge” icon (Figure A6a). After the quick purge is complete, turn ON the Circulation Purifier and the solvent trap (“Circulation LMF Filter 1”).

Figure A6: Pictures of (a) Quick Purge button, and (b) Circulation LMF Filter 1
Appendix B

Thermal Evaporation Process

For thermal evaporation, the following recipe template is an example of choosing the appropriate parameters we can program in the software. The following template only displays the basic settings.

**Recipe Template for Material Deposition**

a. **Sources:** *(name of label)*
   i. Material: *(material name)*
   ii. Source: *(source name)*
      1. Max Power (%): *(user input)*
      2. Input Filter Size: *(user input)*
      3. Rate Control: *(user input)*
   iii. Tooling Factor: *(user input)*

b. **Startup**
   i. Step 1: Chamber Pump Down
   ii. Step 2: IO (Lower Substrate with a Timeout of ______ s)
   iii. Step 3: Substrate Rotation ( ______ RPM)

c. **Process – Layer 1**
   i. Precondition
      1. Substrate Shutter: Close
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2. Step 1 – Ramp Power
   a. Source: (name of label)
   b. Target Power (%): (user input)
   c. Ramp Rate (% Power / Second): (user input)
   d. Soak Time: (user input)
   e. Source Shutter and Sensor Shutter: Open

3. Step 2 - Ramp Power
   a. Source: (name of label)
   b. Target Power (%): (user input)
   c. Ramp Rate (% Power / Second): (user input)
   d. Soak Time: (user input)
   e. Source Shutter and Sensor Shutter: Open

ii. Stabilize
   1. Substrate Shutter: Close
   2. Source: (name of label)
   3. Target Rate: (input target)
   4. Accuracy Threshold % (+/-): (input threshold)
   5. Hold Time (s): (input time)
   6. Timeout (s): (input time)
iii. Deposit

1. Substrate Shutter: Open
2. Source: *(name of label)*
3. Target Rate: *(input target)*
4. Target Thickness (angstrom): *(input thickness)*
5. Timeout (s): *(user input)*
6. Zero Thickness at Start: Yes
7. Source Shutter and Sensor Shutter: Open

iv. Post Condition

1. Substrate Shutter: Close
2. Source: *(name of label)*
3. Target Power (%): 0
4. Ramp Rate: 1 % Power / Second
5. Soak Time (s): 0
6. Source Shutter and Sensor shutter: Open

v. Cleanup: no steps - should be blank

After film deposition is complete, the evaporation chamber is vented by clicking on the “System” box, as shown in Figure B1 (corresponds to Angstrom thermal evaporator).
Figure B1. Example of program to vent the evaporation chamber
Appendix C

JV Photodiode Calibration

Despite the high quality of the Newport VERASOL-2 solar simulator, its spectral output differs noticeably from the actual AM1.5G standard spectrum (Figure C1), so we must account for this spectral mismatch. Briefly, the script will integrate the product of the responsivity of a calibrated photodiode and the AM1.5G spectra from Eg to the upper wavelength limit (400 nm) to calculate the total photocurrent representative of 1-sun intensity (100 mW/cm²).

Figure C1: Comparing the spectra of the VERASOL-2 solar simulator to that of the AM1.5G standard spectrum.

Photodiode Calibration Setup

In this test, the photocurrent of the solar simulator is measured by using a calibrated diode. As a result, we will change the intensity of the incident
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illumination such that the measured photocurrent matches the one we calculated.

In setting up the equipment to perform calibration and measure our solar cells, confirm the lamp is ON, where we should see the light emitting from the lamp. As we identify the photodiode/holder assembly in the glovebox, plug in the BNC connector that connects to the cable going outside the glovebox to the Keithley sourcemeter.

Slide the photodiode assembly onto the optical rail and position the holder in the middle of the rail, locking in place with the set screw (Figure C1). At this point, the photodiode should be pointing down into the window.

**Figure C1**: (a) Photodiode assembly and optical rail before, and (b) after installation. The X-, Y-, and Z-micrometers are identified.

Once in place, ensure the photodiode is aligned approximately in the center of the square of light by holding a piece of lens paper between the lamp and the photodiode and using the x- and y- translation micrometers.
After setting up the hardware, turn OFF the glovebox light, and proceed to open the Labview program “Display Isc” from the desktop and confirm the following settings upon opening (Figure C2):

a. Keithley GPIB address: 24
b. Source: voltag
c. Measuring range: autorange
d. Number of Line Cycle Integrations: 1.00
e. Current compliance limit: $1 \times 10^{-3}$ A
f. Active terminals: Rear, 1
g. Autozeroing: you should see a green button

Press “Run” at the top of the toolbar and a live photocurrent value should be displayed (Figure C2). This is the value that will need to be matched when adjusting the height of the photodiode by turning the z-direction micrometer. Changes in the photocurrent should update live. It is important to note that this should be performed while the glovebox light is OFF.
Figure C2: “Display Isc” Labview screen

Once the photocurrent value is reached, stop the program by pressing the large “STOP” button highlighted in red, and record the value on the z-axis micrometer.

Software Setup (Example)

a. Open the pixel switching software, MaxSSD, on the desktop (Figure C3, left)
   
   i. This software will let us change pixels on the computer

b. Under the “Host PC configuration” tab, select:
   
   i. COM Port: COM 3 (or some other COM #)
   
   ii. Ensure Baud rate is “9600” and the Parity is “None”

c. Upon selecting the COM Port, a “Module Configuration” tab will appear (Figure C3, right)
Evaluating the Next Generation of Solar Cells

i. Check the following:

1. Slave ID: 247
2. Baud rate and Parity: same as before
3. Make sure “Broadcast to Multiple Modules” is unchecked

![Figure C3: MaxSSD program upon opening the program (left) and after selecting the COM Port number (right)](image)

ii. Click on “Get Module Settings,” which should create a new tab called “Digital IO” (Figure C4, left)

1. Check that “SeaDAC 8224” and “32 Reed Relay Outputs” appear under the Module Description

iii. Click on the “Digital IO” tab and ensure that:

1. The Bank selection is “1-2”
2. The Polarity is “Active High”

iv. Under the “Digital IO” tab, you should see a bunch of boxes with numbers; when a box is clicked, the circle inside turns
green, meaning that voltage will be applied to that pixel.

Select bit 10, not bit 1 (corresponds to pixel 1) to start (Figure C4, right).

**Figure C4:** MaxSSD program upon clicking “Get Module Settings” (left) and the “Digital IO” tab (right)

  d. Re-open the Labview program “display Isc” and run the program – a negative photocurrent should be observed for pixel 1 if the solar cell will work.

    i. If the photocurrent is positive, then switch the banana plugs connecting the pixel switcher to the BNC cable.

    ii. The device will not work if no photocurrent is observed above noise level (>10–11 A).

    iii. Unselect pixel 1 and select pixel 2 in the MaxSSD software to measure the photocurrent of pixel 2; repeat this for all 8 pixels and record which pixels have measurable photocurrent.

**J-V Testing Parameters**

The following parameters were used for this setting:
a. Mask area: 0.0454 cm²

b. Label: EMDS PV Track [number] (1A, 1B, 2A, etc.)

c. Experimental Variable: s

d. Value: the number on the substrate

e. Whole Pixel Area (for dark J-V): 0.0608 cm²

f. Scan direction: Jsc to Voc to Jsc

g. Stabilization time: 5 s

h. Minimum voltage: -0.2 V

i. Maximum voltage: 1.0 V

j. Step size: 0.02 V

k. Source delay: 0.001 s (default)
Appendix D

UV-vis Characterization

Scanning parameters recommended for UV-vis characterization for this lab:

a. *Method Settings:* From 900 nm to 360 nm
   i. Data Interval: 1 nm
   ii. Ordinate Mode: A (this is for absorbance)

b. *Lamp Change:* 319.20 nm (this is the default)

c. *Monochromator:* 900 nm (this is not default)

d. *Cycles:* 1

e. *CBM:* 100 %, Fixed

f. *Slits*
   i. *PMT:* Fixed at 2.00 nm
   ii. *PbS:* Servo

g. *Detector Settings*
   i. *PMT:* Auto with 0.20 s response
   ii. *PbS:* 1 with 0.20 s response

h. *Attenuators:* both 100%

i. *Detector Change:* 900 nm (this should automatically match the monochromator)
References
