Design of New Material Solar Cell and Analysis of Efficiency, Cost and Resource Availability

DESIGN DOCUMENT

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Executive Summary

Project Brief

The goal of this project is to further research on cadmium selenide solar cells by writing reports on fabrication and testing processes used, economic viability, and material feasibility studies. Solar cells produced during this project have a goal of 1% efficiency.

Development Standards & Practices Used

Software used:

- MATLAB - Simulation
- Band Eng - Simulation
- Google Sheets - Simulation
- LabView - Testing

Hardware:

- Thermal Evaporation Chamber
- Sputtering Machine
- Scanning Electron Microscope
- Annealing Furnace
- Quantum Efficiency Measurement Device
- Current-Voltage Measurement Device
- Reflectance Measurement Device
- Spin coater
- Chemical Cleaning

Standards:

- IEEE 1547: "Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces"
- IEEE 1562-2021: "Recommended Practice for Sizing Stand-Alone Photovoltaic Systems"
- IEEE P2778: "Guide for Solar Power Plant Grounding for Personnel Protection"
- IEEE 1526-2020: "Recommended Practice for Testing the Performance of Stand-Alone Photovoltaic Systems"
- OSHA 1910.1027: "Toxic and Hazardous Substances: Cadmium"
- OSHA 1926.55: "Safety and Health Regulations for Construction"

Summary of Requirements

- Solar cell design must use cadmium selenide (CdSe) as the main generation layer.
    - Supporting layers must be transparent because this technology is intended to be used as a tandem cell with silicon beneath it.
    - Solar cells produced will have a cross-sectional area of 1 sq. cm.
- End of project deliverables will include:
    - Feasibility study of CdSe material.

  - Economic models of CdSe's potential impact on the solar cell market and consumers.
  - The final design of fabricated solar cells must achieve a minimum of 1% efficiency.
  - Thorough documentation of fabrication and testing processes, including initial methods and revisions made throughout the semester to the final product.

Applicable Courses from Iowa State University Curriculum

- EE 201 - Electric Circuits
- EE 230 - Electronic Circuits and Systems
- EE 232 - Professional and Ethical Issues in Electrical Engineering
- EE 332 - Semiconductor Materials and Devices
- EE 351 - Analysis of Energy Systems
- EE 452 - Electric Machines and Power Electronic Drives
- EE 538/438 - Optoelectronic Devices and Applications
- EE 535 - Physics of Semiconductors

New Skills/Knowledge acquired that was not taught in courses

- Design principles of heterojunctions
- Fabrication of solar cells:
  - Thermal evaporation
  - Cadmium chloride ($CdCl_2$) treatment
  - Sputtering
  - Annealing

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Symbols

- SQL — Shockley - Queisser Limit
- E_g — Band Gap Energy
- CdSe — Cadmium Selenide
- CdTe — Cadmium Telluride
- a-Si — Amorphous Silicon
- a-(Si,C) — Amorphous Silicon Carbide
- ETL — Electron Transport Layer
- HTL — Hole Transport Layer
- MRC — Microelectronics Research Center
- FTO — Fluorine Doped Tin Oxide
- ITO — Indium Doped Tin Oxide
- PV — Photovoltaic
- QE — Quantum Efficiency
- IV — Current vs Voltage

- PPE Personal Protection Equipment
- NREL National Renewable Energy Laboratory
- CSVT Close Space Vapor Transport
- TE Thermal Evaporation
- ZnTe Zinc Telluride
- P3HT Poly (3-hexylthiophene)
- PTAA Poly [bis (4-phenyl) (2,4,6-trimethylphenyl)amine
- EHP Electron-Hole Pair
- V_{OC} Open Circuit Voltage
- I_{SC} Short Circuit Current
- FF Fill Factor
- EQE External Quantum Efficiency
- IQE Internal Quantum Efficiency
- IEEE Institute of Electrical and Electronics Engineers
- NSPE National Society of Professional Engineers

1. Introduction

1.1 Problem Statement

The dominant material in the solar cell market is, by far, crystalline silicon. Silicon is considered an optimal material for single-junction solar cells due to its unique properties, sufficient research and development, and affordable manufacturing process. Despite its ideal characteristics, years of development are taking silicon's efficiency to the limit, and if solar energy cost and efficiency are to keep improving, a solution must be found. Finding a way to produce renewable energy at a lower cost means implementing a higher volume of renewables and decreasing dependency on fossil fuels. Additionally, more efficient sources of energy can provide users with energy at lower cost. For this reason, it is imperative that engineers work to push solar cell technology as far as they can, and a promising solution is multi-material cells.

Multi-junction solar cells (also known as tandem junction solar cells) can absorb light with less energy loss than a single-material cell. Each tandem cell has an optimal material pairing to maximize total efficiency. The foundation for this idea was explained in detail in 1960 by Shockley and Queisser when they published their paper *"Detailed Balance Limit of Efficiency of p-n Junction Solar Cells,"* which derived the theoretical maximum efficiency of single material solar cells. This became known as the famous Shockley Queisser limit (SQL).

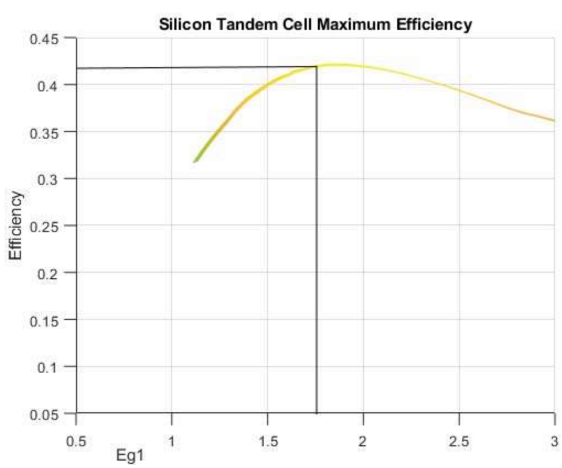

Figure 1: Tandem Cell E_g vs SQL for Silicon

A semiconductor property known as the bandgap energy (Eg) determines the portion of the spectrum of light that can be absorbed and which and how efficiently different wavelengths are absorbed. The ideal material pair for silicon, one of the most common solar cell materials, is one with a bandgap of 1.7eV. Cadmium selenide (CdSe) has a bandgap of 1.74 eV, which is very close to this optimal pairing. With two junctions, silicon, and CdSe, solar cells reach a hypothetical maximum efficiency of 45%, which is 13% higher than a single-junction silicon cell. However, the challenge of reaching efficiencies close to this number is substantial.

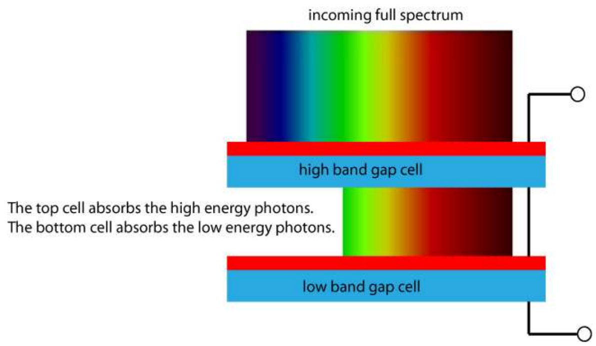

Figure 2: Tandem Cell Configuration

Solar cell fabrication is a delicate process that takes years of research to develop. CdSe has very little data published, and for it to progress, engineers need to start laying the groundwork for this material. Our advisor has given us a goal to fabricate at least a 1% efficient CdSe solar cell. This will be a realistic goal for our team to achieve, and it is feasible to surpass this performance within the time we have. Additionally, we are to study and complete an economic analysis of CdSe solar cells and how their implementation would impact the cost of solar energy. Our priority and most important task as a team is to report accurate and well-documented data and conclusions so that other engineers can utilize our work to keep progressing with CdSe solar cells. Our second goal, after this, is to produce successful cells that progress towards efficient CdSe solar cells.

1.2 Intended Users

The end goal of our project is a product that everyone can use. Everybody on the planet needs energy, and our goal is to create a product that improves how we generate energy. Our immediate users are fellow engineers who can utilize the data and reports from our project to make improvements to CdSe. We have come up with 3 personas that are examples of users of our product.

Solar Cell Engineer

The first is a solar cell engineer who works at First Solar, an American solar cell manufacturer who specializes in cadmium telluride (CdTe) solar panels. CdTe is a unique contender in the solar cell market, as it has been the only major material to challenge silicon in the last few decades. First Solar has made great strides in the manufacturing process of CdTe, and it can now be produced quicker than silicon (but at a lower efficiency). As a material, CdTe is closely related to CdSe, so it is suspected that a similar manufacturing process could be used to produce CdTe solar cells. For this reason, First Solar, and their engineers are very interested in the development of this material. For our project to benefit them, we would need it to be well documented. This includes a technical description of the processes we are using to fabricate the solar cell and the reasoning behind those decisions.

Energy Consumer

The second is an energy consumer who is interested in green energy. They are active in government policies and are well-educated in the types of green energy. One of their favorites is solar; they want to see more solar power plants constructed. Because of this, they are interested in innovations being made in solar cell materials. They also want the new green energy to be low-cost, similar to the current electricity rates. This benefits the energy consumer because it is in line with their ethical needs. For our project to be beneficial to them, our product must be considered “green.” This means we must have strict environmental considerations for hazardous materials and land usage of utility-scale solar farms. They would benefit from decreased carbon emissions due to the development of solar cell technology.

Industry Specialist

The third is an industry specialist who works in the power generation industry. They run a successful company installing gas and coal power plants, and don’t see much use in green energy yet due to its high cost. They are interested in new technologies, but not at the expense of money. The concept of solar is interesting to the industry specialist, because it is a completely new technology that may be able to become more economical than gas and coal in the future if it can become cheaper and more efficient. If that happens, they will switch the power plants they make to solar. This would be a benefit to them because they would be able to obtain a larger profit from building a power plant.

2. Requirements, Constraints, And Standards

2.1 Requirements & Constraints

Functional requirements

We must get 1% or greater efficiency to consider our product on par with current CdSe technology**.** Due to its bandgap energy, we must also use Cadmium Selenide (CdSe) as our absorbing layer.

The supporting materials must also be transparent so that the light can pass through them to the CdSe junction. However, we must also ensure the bottom materials of our stack are transparent so that the light that isn’t absorbed by the CdSe can pass through to be absorbed by the Si junction. These materials must also be able to serve their purpose in the stack. We need transparent materials for both of our junction contacts, the electron transport layer (ETL) and the hole transport layer (HTL). For these, the contacts to the ETL and HTL need to have a conduction band similar to the respective transport layer it is connected to.

Resource requirements

We will require access to the testing and fabrication facilities at the ISU Microelectronics Research Center (MRC). Part of our project is to design a process that can be used to fabricate CdSe cells. We have and will continue to conduct research on this process. The resources at the MRC will be necessary to test the manufacturing process we construct from our research. Specifically, we will need access to a thermal evaporation chamber, a furnace, a plasma-enhanced sputtering machine, hot plates, respirators, and glass slides with pre-deposited FTO. The fabrication itself will clearly require access to the materials out of which we have designed our solar cell. The MRC has supplies of these materials, which our advisor has granted us access to. These include CdSe, amorphous silicon, CdS, indium tin oxide (ITO), and fluorine tin oxide (FTO).

Physical requirements

Mathematically, the efficiency of a cell is constant throughout an arbitrary cross-sectional area, meaning the power output of a cell is proportional to that area. However, we are constrained for thickness to be within one diffusion length of the materials we use. This is because any thickness past this length will result in additional losses in the efficiency of our fabricated solar cells as a result of recombination. For the purposes of our project, the cross-sectional area of our solar cell will be 1 cm^2, which is determined by the dimensions of the substrate provided to us at the MRC, and the thickness of our CdSe layer specifically will be varying but constrained to be within one diffusion-length. The results we present will be based on these dimensions and will be consistent with a cell of any size.

Economic requirements

We will create a viability analysis of CdSe as an alternative and/or addition to current silicon-based solar cells. As we have described, a CdSe cell is poised to boost the efficiency of solar power. In theory, this would create an economic opportunity for solar companies in that more power may be produced at the same cost. The only potential caveat is the case wherein our CdSe cells are marginally more expensive to manufacture and implement, meaning that the potential cost advantage of our cell is lost due to overhead. Our analysis will involve a statistical analysis of current solar energy data, which will be extrapolated to our CdSe cell parameters to create a projection of efficiency vs. cost for our proposed CdSe cell.

For our Viability analysis, we want to make CdSe as viable an option as possible. So, we need to choose a manufacturing process to analyze that will be the most cost-efficient possible. This means finding a balance between cell efficiency and manufacturing costs. As described in the paragraph directly above, high manufacturing costs could outweigh the economic benefit of implementing CdSe cells in current solar farms. If it ends up being the case that our proposed cell's manufacturing process is too costly to justify its efficiency, this viability analysis will suggest alternatives that tradeoff efficiency for lowered manufacturing cost.

Environmental requirements

The solar cell we make will have to be resistant to degradation, as the material CdSe consists of heavy metals that are harmful to the environment. Where we get our CdSe and other supporting materials is a big consideration since mining is generally very environmentally harmful. Fortunately, cadmium and selenium are common byproducts of other material production. Cadmium is produced as a zinc byproduct, and selenium is produced as a byproduct of copper, nickel, and lead. This allows us to use materials that may not be used and could potentially become waste and turn them into something useful, indirectly protecting the environment. Another environmental requirement is about what to do with the materials after the solar cell's lifetime is over. Our plan is to develop a recycling process for the solar cells, which prevents the need to dispose of large amounts of cadmium and selenium. It also decreases the need for new materials sourced from mining. This is already a commercially implemented process by First Solar, where they recycle their CdTe cells. They are able to recover 90 percent of the semiconductor material from a cell and reuse it in future fabrications.

2.2 Engineering Standards

Due to the nature of the project, there are many standards that must be considered and met as the design process continues. However, cadmium selenide solar cell technology is relatively undeveloped and does not have a fully fleshed-out set of standards and specifications for the tandem technology. Because of this, we believe that it is wise to better relate this to the current standards applying to silicon solar cells. When broken down, we believe silicon solar cell standards to have six main categories: Material, Performance, Quality Management, Testing, Module Installation, and Safety. Where each category has multiple standards which have specific requirements to meet them. Each of these categories can be surmised as follows:

- **Material -** Standards relating to material-specific properties. For example, average grain size, solar-weighted spectral absorption coefficient, etc.
- **Performance -** For industrial applications, it is necessary to ensure that solar cells have a minimum level of performance and reproducibility.
- **Quality Management -** Sets requirements for implementing, maintaining, and improving quality management systems and reducing and/or minimizing environmental footprints.
- **Testing -** Standards relating to necessary physical properties of the solar cell. It may include durability, surge resistance, cell performance, other electrical properties, etc.
- **Module Installation -** Concerns how solar panels are connected to the rest of the circuitry and how it interfaces with the power grid.
- **Safety -** Standards set in place to reduce the risk of potential hazards such as electrical, fire, mechanical, environmental, grid interface, etc.

The following existing standards are believed to be within the project's scope.

- IEEE 1547: "Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces"
  Distributed energy resources are any energy resource that generates electricity close to the site of its consumption. This standard ensures that DERs such as solar panels correctly integrate with other power systems. Testing a CdSe cell integrated with a larger power grid would be necessary to ensure its safety and performance.
- IEEE 1562-2021: "Recommended Practice for Sizing Stand-Alone Photovoltaic Systems"
  This standard applies to solar systems operating as stand-alone entities. In this case, a PV panel needs a battery to store the energy produced from the panel. The panel is the only thing capable of charging the battery and needs to be sized to reflect the energy generation capabilities of the cell. The standard provides guidance for how these sizings should be made and details control systems that can be used to protect the battery from overcharging.
- IEEE P2778: "Guide for Solar Power Plant Grounding for Personnel Protection"
  The standard for the safety grounding systems of utility-scale solar plants. Although not applicable to our activities in this project, when a full-scale solar cell is made, we will have to think of the safety of people operating the machines. Grounding is a significant part of those safety considerations.
- IEEE 1526-2020: "Recommended Practice for Testing the Performance of Stand-Alone Photovoltaic Systems"
  Standards for testing photovoltaic systems and verifying their design. There are many aspects to these tests, including testing outdoors and under simulated conditions. We will likely have to test our solar cells, and although likely not to the extent described in this standard, it will have to happen.
- OSHA 1910.1027: "Toxic and Hazardous Substances: Cadmium"
  Standards for exposure and handling of cadmium in all forms. This describes the exposure limit, health monitoring of individuals using cadmium, PPE requirements, and employer requirements. Safety is essential for our project as we will be handling potentially dangerous chemicals and materials when fabricating the solar cell.
- OSHA 1926.55: "Safety and Health Regulations for Construction"
  Standards for exposure and handling of selenium in all forms. This describes the exposure limit, health monitoring of individuals using selenium, PPE requirements, and employer requirements. Safety is essential for our project as we will be handling potentially dangerous chemicals and materials when fabricating the solar cell.

3 Project Plan

3.1 Project Management/Tracking Procedures

We are using the AGILE project management style because the flexibility and iterative style will work well for our group and the nature of the research our project demands. We have never done a project like this before, and AGILE will allow us to be flexible so we can adapt and make changes as we go through our project.

To track our progress, we have a shared Google Drive for all completed work, discuss current and impending issues at our weekly meetings, and report our work on weekly reports. Between the three of these, we are able to track everyone's progress.

3.2 Task Decomposition

This project is split up into three main categories. These are theory and simulation, fabrication, and economic outlook and analysis. Theory and simulation will concern gaining the necessary knowledge of device physics and any tests or simulations necessary to understand how well the solar cells we produce perform. Additionally, it will cover how to redesign the cell to fix inconsistencies and underperforming factors. Next, fabrication is a large portion of research as it is an involved process that requires understanding every step of the fabrication process, what can go wrong, and what changes can be made to potentially increase the efficiency of the cell produced. Finally, economic outlook and analysis are important as one of the main factors of this project is to understand the economic and environmental feasibility of cadmium selenide given how it is intended to be used. This is necessary information for the project as the technology scales upward to more industrial needs. Our goals are as follows:

Theory and Simulation

- Background - understanding of device physics taught in EE 332
- Understand the design principles of heterojunctions
- Learn how temperature, impurities, doping, and grain size affect material properties
- Learn how to conduct and interpret quantum efficiency and IV characteristics
- Use the BandEng simulator to design heterojunctions efficiently

Fabrication

- Understand the safety procedures of using deposition and fabrication equipment.
- Understand the fabrication process and how all of the steps of the fabrication process work.
- Fabricate a complete CdSe with all of our supporting materials deposited onto it.
- Test our solar cell after fabrication and change fabrication settings to be able to improve and optimize efficiency by up to 1%.

Economic Outlook and Analysis

- Devising a way to quantize the per-cell output of existing solar installations.
- Using a model, we can accurately estimate how the production of a solar farm may change with an increase in cell efficiency.
- Given this, we can run a cost analysis to determine how long until a farm is profitable after a total replacement of the old cells with the increased efficiency cell.
    - We can take into consideration the current degradation of cells in the field and help use this information in the analysis.
- Overall, the goal is to see when replacing current infrastructure with new infrastructure at a much higher efficiency would be cost effective.

3.3 Project Proposed Milestones, Metrics, and Evaluation Criteria

Milestones

For a project designed around a specific semiconductor material, it is necessary to determine the key factors of the project. First, we must prove that CdSe is theoretically able to improve current technology. Then, we must be able to discern whether it is available and an economically viable option. After these have been determined, we can then set out to learn methods of creating and testing the solar cells, getting proper training and PPE, followed by going through an iterative design process to perfect our design. Finally, we must be able to report our findings concerning to what extent our fabrication and testing were successful and if CdSe is an environmentally safe and economically viable material.

- Milestone 1 - Develop a model for efficiency prediction of CdSe and Si
- Milestone 2 - Determine CdSe availability and environmental impacts within the US
- Milestone 3 - Establish a solar cell device structure
- Milestone 4 - Develop a fabrication process
- Milestone 5 - Create a testing process
- Milestone 6 - Complete lab safety training
- Milestone 7 - Simulate the predicted performance of the cell device structure
- Milestone 8 - Fabricate solar cells
- Milestone 9 - Report on fabrication process results
- Milestone 10 - Report on economic viability

Metrics and Evaluation Criteria

Our end goal for our project is to develop a CdSe cell with >1% efficiency and explain the benefits of implementing high-efficiency CdSe into the market. A >1% efficiency CdSe cell will likely not be obtained in our time on this project, and this is more of a long-term research goal. Our attainable objective for senior design is to fabricate a functional CdSe cell, and to make continuous improvements until the end of the course. If we saw efficiency increase at all, and were able to report on how we made improvements, both us and our advisor will be satisfied with the outcome of the project. An efficiency we would be very happy with is 2%. Regarding economics, we would like to understand the cost of implementing efficient CdSe cells and how much development is needed to be economically viable.

3.4 Project Timeline/Schedule

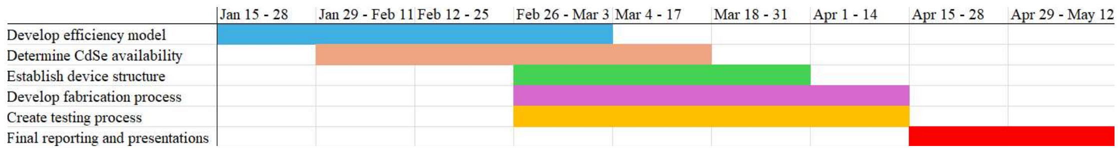

Figure 3: Semester 1 Gantt Chart

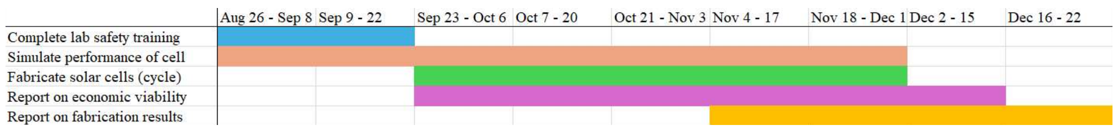

Figure 4: Semester 2 Gantt Chart

The fabrication "Cycle" consists of the following: Creating a cell → Testing the Cell → Adjusting The Process

3.5 Risks And Risk Management/Mitigation

The risk factor, R, is the variable we will use to guess how many risk tasks have been guessed to have based on the timeline seen in the Gantt chart above.

Tasks:

- Development of Device
  - Rudimentary research on CdSe cell stacks (R ~ 30%)
  - Design basic for CdSe cell structure and propose to Dr. Dalal (R ~ 60%)
  - Come up with or find fabrication procedures for materials used in cell structure (R ~ 30%)
  - Write a report on our process and findings (R ~ 10%)
- Economic Analysis and Simulation
  - Gather generation data from 10 different solar farms (R ~ 50%)
  - Create a model for a "typical" solar farm's generation (R ~ 20%)
  - Make predictions about how the implementation of CdSe will benefit utility-scale operations (R ~ 20%)
  - Write a report on our process and findings (R ~ 10%)

Throughout the development of the device, research on cell stacks and material fabrication pose some risks, although small. While many research studies have been done, and there are examples of solar cell designs and fabrication processes, CdSe is a very underdeveloped material. Therefore, much of the research that will be conducted and the information used may be based on what has been conducted by research groups at Iowa State. In order to diversify resource material, we will need to make an effort to look at the strategies other groups have taken in the design process of cell stacks and fabrication, as opposed to the exact steps and materials that were used.

The biggest challenge in this project for this portion of the deliverables will be getting a rough design of the solar cell structure approved by Dr. Dalal. This is due to the need for many sources to be read, and many of our group members have not done anything such as this. Hence, we will have to acquire a deep fundamental knowledge of device physics throughout the project to be successful. To ensure we meet our timeline goals, we have increased the number of weekly meetings. We believe we will increase our team's accountability and efficiency by adding meetings specifically designated for working on research and design of the solar cell structure.

In addition to the development of device risks, the economic analysis has its own host of risks involved. In order to make an accurate model and prediction of how the implementation of CdSe solar cells will affect the market, we need reliable and plentiful data. However, as we continued this project, we found that many companies do not openly share the generation data that we will need. If the target data can not be achieved, we may have to create a model based on other factors such as yearly solar irradiance, electricity price history at select locations in the US that have seen large implementations of solar farms, yearly temperature data, and other chosen variables deemed important.

3.6 Personnel Effort Requirements

There are several steps that will need to be completed for our project to be successful. One of the first steps will be determining the materials we will use to make our device. This includes which types of contacts we will use, which types of electron and hole transport layers we will use, etc. Once we have an idea of what structure we want to do, we will need to learn the fabrication techniques and how to operate the associated equipment. This will have to be done by each person so that we all understand the process. After a device is made, we will need to do testing on it. These tests may include IV measurements, Quantum Efficiency measurements, etc. We have also included a large amount of time in redesigning our initial design. The purpose of this is that our initial design will by no means be perfect. One of the goals of this project is to make advances in this material, which will involve a lot of redesign and testing

Another major task in this project is the economic viability study of a CdSe solar farm. We intend to analyze current solar farm technologies with an emphasis on their current abilities to generate electricity. With CdSe being more efficient compared to the industry standard, we suspect farms equipped with CdSe cells would outperform current industry leaders. However, for solar companies to begin producing CdSe cells, they must feel certain there is a market for them. Our investigation into the economic viability will aim to show why a typical solar farm would see an economic benefit to switching to CdSe cells, thereby implicating a market for these cells should a company decide to begin fabricating them. We intend to accomplish this by analyzing current solar farm data and then extrapolating using metrics from our CdSe design. Looking ahead, this will also involve an analysis of material prices and fabrication costs as we try to create a detailed study of the economic viability of a CdSe solar farm.

Table 1: Task Breakdown and Time Commitment

Task Description	Estimated Hours
Training on How to Operate the Fabrication Equipment	90 (15-20 per person)
Design and Redesign of Fabrication Process and Device Structure	100
Testing of Samples	50
Economic Research and Reporting	100
General Group Discussion and Meetings	200
Total	540

4 Design

4.1 Design Context

4.1.1 Broader Context

Public Health, Safety, and Welfare

The direct user base of our project would be the utility company purchasing the complete solar cell, but the tertiary user base would be those receiving the electricity. However, due to the material properties of the cells, the land they are placed on is susceptible to contamination of cadmium and selenium during and after installation. The average person should not come into direct contact with CdSe, but side-channel exposure is possible.

When individuals become exposed to cadmium and selenium via a respiratory or oral passageway, the cadmium, and selenium can be absorbed into the body. They can bind to a handful of molecules within the body, mimicking biological processes, and remain there for many years, causing cancer. Exposure could occur most often during manufacturing and installation, so those creating and installing the panels are most likely to be exposed. Generally, though, even if the panels were damaged during installation, proper PPE could mitigate most issues present.

Global, Cultural, and Social

As the global impact of climate change becomes more and more apparent, more people are realizing the importance of moving toward renewable energy sources. Energy has become a basic need in our society and, as such, affects all groups that use electricity. Our project strongly reflects the values of those wary of climate change's effects and continue to use electricity. This group includes countless subgroups, including various nations, professions, workplaces, and ethnic cultures. It is likely that most of these subgroups agree with the need for more reliable renewables. However, the results of our project may not meet their reliability aims in case our solar cells are not efficient enough and/or are too expensive to fabricate.

In some countries, air quality is extremely poor due to manufacturing and energy generation emissions. Not only does this contribute to climate change due to the heat-trapping nature of the emissions, the air quality is extremely toxic. Renewable energy sources are very useful in remedying this problem. They would not help with manufacturing emissions, though replacing traditional electricity generation with solar would improve air quality, thus improving public health and softening the effects of climate change.

Environmental

Ideally, our project would have a strongly positive environmental impact. Carbon emissions have a negative impact on the environment due to their effect on global warming. The carbon emissions generated from fabricating a solar cell are much less than that of fossil fuels. Furthermore, the energy produced using solar energy does not produce any emissions. Increasing the efficiency of solar cells will allow them to further replace fossil fuels which have a negative impact on the environment.

Subsequently, water contamination is a possibility. If a cell is damaged in any way, this leaves the possibility for the cadmium and selenium to leach out into the environment and find their way into waterways. This can lead to bioaccumulation within plants and wildlife. The contamination of waterways may also directly affect people and wildlife.

Economic

This project would be an economic benefit to the energy industry and to those who consume solar on a residential scale. The increase in efficiency would allow solar companies to produce more energy at the same panel area and cost, thereby increasing their own profits and, as a result, allowing them to expand their businesses. Residentially, increased panel efficiency would allow users to generate more of their energy independent of the grid, increasing the monetary return they see for excess energy returned to the grid. There is also a government incentive for users of solar in the form of tax credits and rebates.

Farmers would benefit greatly from the ability to produce energy independent of the grid due to the increased cost of infrastructure in remote locations. This cost is even further increased due to the power demands of their tools and machinery. The cost of solar includes installation and infrastructure and afterwards is extremely low cost as electricity is produced from sunlight, which is free. The economic benefit is brought to the farmer through electricity savings, allowing them to live more comfortably and making them more productive in their work.

4.1.2 Prior Work/Solutions

1. Bagheri Thesis

CdSe solar cells have been a research interest for our advisor, Dr. Dalal for many years now. In 2020, while working under Dr. Dalal, Dr. Behrang Bagheri published his PhD thesis on CdSe solar cells. Dr. Bagheri has accomplished significant development on CdSe solar cells, specifically in his fabrication process. Portions of our fabrication process will be based on the research that Dr. Bagheri accomplished, specifically using $CdCl_2$ to passivate grain boundaries and grain enhancement. Dr. Bagheri noticed a significant improvement in charge mobility by adding these steps to his process. The difference between our project and this thesis is that we will be focusing primarily on using amorphous silicon as the p-layer. In contrast, the thesis compares a variety of p-layers.

2. PVEducation

PVEducation is a free-to-use website created by Arizona State University Faculty Christiana Honsberg and Stuart Bowden. Dr. Honsberg and Dr. Bowden are faculty at the Arizona State University School of Electrical, Computer, and Energy Engineering, where they research photovoltaics. PVEducation is a website they created, which originally started as a CD called PVCDROM, which is intended to be an introductory photovoltaic course. It includes information about the basics of light, basic semiconductor physics, basic solar cell parameterization, manufacturing techniques, solar arrays, and even battery technology. It has been a vital resource for inexperienced members of our team to learn the basics of Solar Cells.

3. Detailed Balance Limit of Efficiency of p-n Junction Solar Cells

In 1960, William Shockley and Hans J. Queisser published their paper “Detailed Balance Limit of Efficiency of p-n Junction Solar Cells,” in which they derived the Shockley-Queisser (SQ) limit. This paper was very influential because it defined the limits of solar cells. It gave researchers a benchmark for solar cell performance. We realized the need for tandem solar cells because Shockley and Quessier defined the limits of single-material cells, and thus, our project exists because this paper was published.

Shockley and Quessier assume an ideal semiconductor with no reflection or defects and consider factors such as the spectrum of the sun, the distance between the sun and the solar panel, the angle of incidence, generation and recombination properties, and transport properties of a semiconductor to derive the maximum efficiency of a semiconductor as a function of band gap energy E_g.

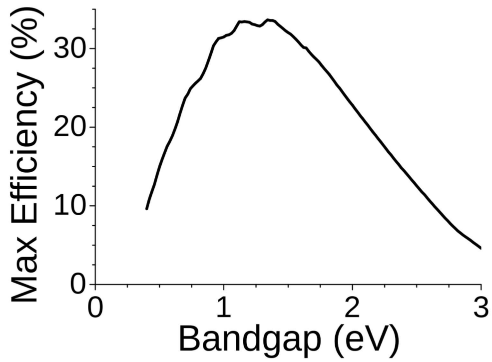

Figure 5: SQ Limit of a Single Junction Solar Cell

4. Physics of solar cells Jenny Nelson

Physics of Solar Cells by Jenny Nelson is a semiconductor textbook specifically about solar cell physics. It goes into much more detail about solar cell physics than basic semiconductor textbooks. Our advisor, Dr. Dalal suggested it to us, and it is one of the textbooks for Dr. Dalal's EE 590. It has been a good resource for us to read about thin film solar cells, defects in thin film solar cells (specifically grain boundaries), passivation, annealing, and general device physics. It has been and will continue to be a great resource for the duration of our project.

5. Perovskites - perovskite material paper, perovskite solar cell paper, NREL chart

Perovskite is any material whose crystal structure contains a lattice of BX_6 octahedra. It has an overall stoichiometry following ABX3 (ACS energy) formula, where A and B are positive cations and X is an anion. This group of materials is confusingly named after Perovskite, a mineral that also has the Perovskite crystal structure.

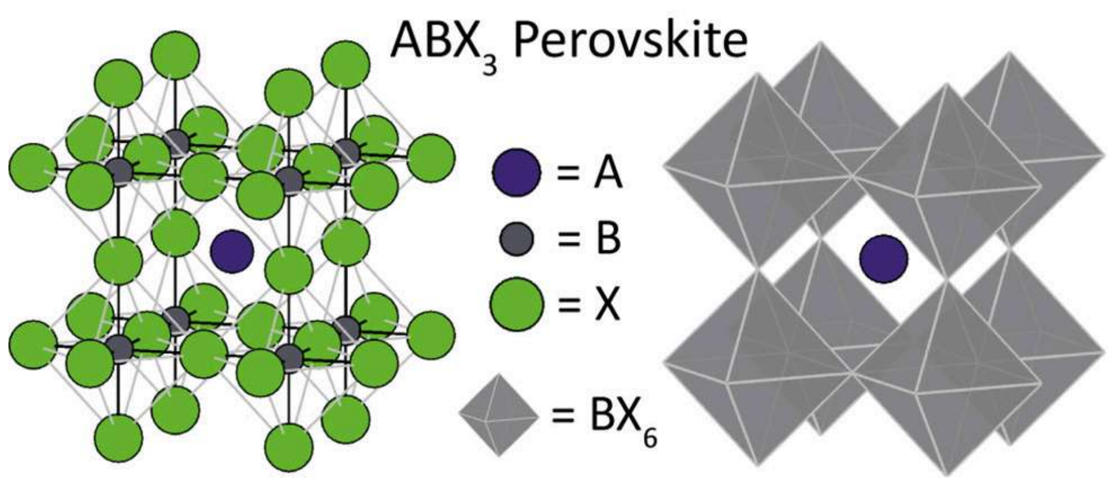

Figure 6: Structure of Perovskite Crystal

Perovskites, are semiconductors, have received a lot of attention in the photovoltaics industry due to their superior electrical properties and tunable band gap. Perovskites are commonly used in tandem with silicon, specifically monolithically (in series), and have already achieved high efficiencies. They have already been used in tandem with crystalline silicon (c-Si) solar cells to achieve the highest tandem junction efficiency ever, 33.9%, which passes the single junction S-Q limit (NREL solar cell highest efficiency chart). While perovskites may seem to be winning the tandem cell race, two major drawbacks hold them back. Perovskites break down in the presence of water and oxygen, and the Perovskites with the best electrical properties are made with lead. This is catastrophic because the implementation of Perovskite cells means putting a material that leaches lead into the environment in the presence of two very common substances. This is a major health concern, and while it may be possible to seal the solar cells so they do not come in contact with oxygen or water, it cannot be guaranteed that waterproof seals will not break and prevent lead from being leached into the environment. Even if it could be guaranteed, it would be hard to curb the skepticism of the public and officials. Nevertheless, Perovskites still draw much interest. It may be possible to increase their safety with durable waterproofing solutions or to switch to lead-free Perovskites altogether. Significant research is going into both.

6. First solar products

First Solar is a company that aims to provide an alternative solar energy technology to crystalline Silicon (a-Si) through thin film cadmium telluride (CdTe). Currently, CdTe technology is well-researched and has seen efficiencies up to 22.1%. Additionally, First Solar has nearly perfected the fabrication process of this material and uses it commercially around the world, with ~25GW of energy produced annually. While CdTe is a more developed technology, its main drawback compared to CdSe is its theoretical limit is ~30%, while CdSe + Si solar cells can theoretically reach ~45% efficiency. Furthermore, it is suspected that CdSe may do well with a similar fabrication process to CdTe, making research in this material much more likely to gain traction.

7. Close-spaced Vapor Transport:

An important distinction between our project and others is that we are utilizing thermal evaporation for our manufacturing process. Thermal evaporation is not a likely industry solution for manufacturing CdSe. Companies like First Solar, which are currently manufacturing a similar solar panel technology using CdTe, are using close space vapor transport (CSVT). First Solar can manufacture a CdTe solar Panel from start to finish in 4.5 hours. CSVT is a crucial step in First Solar's manufacturing process, and CdSe would likely be manufactured in this way since it is very efficient.

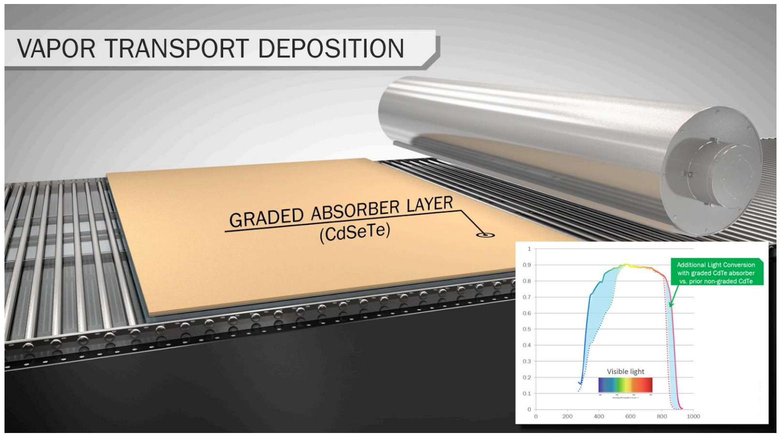

Figure 7: First Solar CSVT Process (Solar F, 2017)

4.1.3 Technical Complexity

Our design has a significant level of technical complexity, extending from the semiconductor device physics level to the power system level. Our project utilizes the understanding of microelectronics fabrication and the connection between process and physics. One example is the understanding of trap states, which increase the recombination rate and decrease the efficiency of solar cells. This understanding affects how we approach the development of our fabrication process because we will be using additional steps such as post-deposition annealing and $CdCl_2$ treatment.

On a large scale, we are planning an economic viability study to determine the cost-benefit of a solar farm with Si and CdSe tandem cells. This shows technical complexity in the way it proposes a solution to a current engineering problem: reducing carbon emissions. Solar farms are currently very expensive due to the large area they require per energy generation. Because of this, solar farms don't perform as well as coal or natural gas. The land area can be decreased by increasing the efficiency of a solar farm, which is the problem we are addressing.

4.2 Design Exploration

4.2.1 Design Decisions

Primary Material

Because of its bandgap, CdSe was chosen to make a tandem junction solar cell with silicon. The theoretical maximum efficiency of a two-junction solar cell with the bottom cell as Si peaks at 1.7 eV, the band gap of CdSe. The theoretical maximum for a multijunction cell is significantly higher than that of a single junction, making silicon-CdSe cell development an attractive innovation to the solar cell market. It will be able to utilize a fuller portion of the sunlight's wavelength and energy. Theoretically, we could get a multijunction CdSe-Si cell with up to 44% efficiency as opposed to silicon's theoretical single junction cell efficiency of 33%.

Contacts

We have chosen to make our contacts out of ITO and FTO. We have chosen these materials because they are transparent and conductive. This is a necessary decision because CdSe will be the top cell in our design. If the contacts weren't transparent, the bottom cell would essentially become useless as all the light would be reflected off the top cell, and no light would reach the Si bottom cell.

Electron and Hole Transport Layers

The choices of material for the electron transport layer and hole transport layer are CdS and amorphous silicon carbide (a-Si,C). Both of these materials have band gaps larger than CdSe, which means they won't be absorbing the light that we want to be absorbed by the lower Si cell. Additionally, electron transport layers are most efficient when they have a conduction band energy that matches the conduction band energy of the adjacent materials. The same is true for the valence band energy level of the hole transport layer.

CdSe Growth

To deposit material onto our silicon wafer, we use thermal evaporation. This technology is available to us at ISU through the microelectronics research center. It happens to be very effective for our specific fabrication needs. There are also many researchers at ISU who are well-versed in this process and are willing to help us learn how to use this process for ourselves.

Grain Boundaries, Post Deposition $CdCl_2$ treatment and Annealing

We are using CdSe as our absorbing layer in our solar cell, but there are several forms CdSe can take. Ideally CdSe will form a perfect crystalline structure, meaning that it is an infinite representing pattern of atoms arranged in a lattice. In reality it is very hard to produce a perfect crystal, and not necessarily reasonable to exhaust the time and effort to produce perfect crystals. It is much easier to produce what is called a poly-crystalline structure, which instead contains "grains" or locally perfect crystals surrounded by other locally perfect crystals with a different orientation.

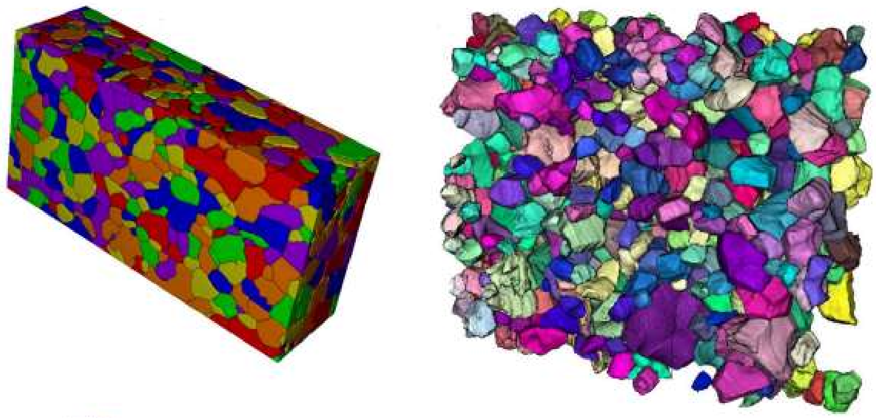

Figure 8: Diagram of Grain Boundaries in a Polycrystalline Material

The boundaries between these grains are detrimental to the overall efficiency of CdSe. Former ISU researchers heavily invested time into decreasing the number of defects at grain boundaries. They used spin coating the device with $CdCl_2$ after depositing CdSe and then heating the device. Heating causes two things to happen. First, $CdCl_2$ will passivate the material, and chlorine will form covalent bonds with the unbonded defects. This works because chlorine is a halogen and needs 1 additional electron to form a stable covalent bond. For this reason, chlorine can easily bond with each individual defect. Heat also anneals the crystal, allowing the material to reform into larger grains. Larger grains mean fewer grain boundaries and, therefore, reduce the number of grain boundary defects.

4.2.2 Ideation

One of the big decisions was the material we are using for the hole transport layer. There are several possible options that can be used, but we have decided to use a-(Si,C). The other materials we considered besides this are a-Si, ZnTe, PTAA, and P3HT. To determine the best material to use, we made a list of the pros and cons of each material. The things we were looking for from a material are a wide band gap, low degradation over time, and a valence band energy which is similar to the valence band energy of CdSe.

4.2.3 Decision-Making and Trade-Off

After identifying the major pros and cons of each of the materials listed above, we decided to use the material a-(Si,C). One of the main driving factors of not using PTAA or P3HT was that they are all organic materials, which degrade easily under high-energy light. While these materials have been studied extensively, they would not be practical to use in utility-scale projects that would be expected to last 20-30 years. Another material that was considered was ZnTe. The downside of this material is that there would be a large decrease in the possible open circuit voltage due to the material's valence band energy being significantly higher than CdSe. This leaves a-Si and a-(Si,C):H as the other two options. Ultimately a-(Si,C):H was chosen due to its higher bandgap energy.

Table 2: P-layer Pros and Cons

P-layer Material	Pros	Cons
PTAA	Largely researched and used Valence band matches Cdse	Organic and degrades under light
P3HT	Largely researched and used Valence band matches CdSe	Organic and degrades under light
a-Si:H	Inorganic and doesn't degrade	More complicated process Valence band doesn't match CdSe
a-(Si, C):H	Adjustable bandgap Valence band matches CdSe Inorganic and doesn't degrade	More complicated process
ZnTe	Inorganic and doesn't degrade	Valence band doesn't match CdSe

4.3 Proposed Design

4.3.1 Overview

There is a fundamental efficiency limit to solar cells called the Shockley-Queisser limit. For solar cells made out of a single material, this limit is about 33%. This theoretical limit can be exceeded by using multiple solar cells, each with a different material. Every material absorbs different energy ranges of sunlight most efficiently. The goal of using multiple materials is to have each material designated to a specific energy range. This will cause each material to utilize the energy range that it absorbs most efficiently. By using two materials, each absorbing its own energy range of sunlight most efficiently, that 33% limit can be exceeded to 45% if the right combination of materials is used.

The most widely used solar cell material is silicon, a very mature technology that has been developed for a very long time. It has a complementary partner that would maximize efficiency that hasn't been researched or developed much yet: CdSe. This project aims to develop a fabrication process for a CdSe solar cell, a physical sample of a CdSe cell, a simulation of the cell, and a cost forecast of a solar farm that uses these materials.

4.3.2 Detailed Design and Visuals

Device Structure

Our design will consist of a top layer contact, ITO, followed by P-type amorphous silicon, N-type CdSe, N-type CdS, and a bottom layer contact FTO. The top and bottom contacts, ITO and FTO, are clear conductors. ITO will be deposited using sputtering, and we will receive glass substrates with FTO already deposited on them. Below the ITO layer, P+ a-(Si,C) will be used, because it can be made so the valence band is close to that of the valence band of CdSe, allowing the transportation of holes from CdSe to a-(Si,C) with minimal energy loss. This is known as the hole transport layer (HTL).

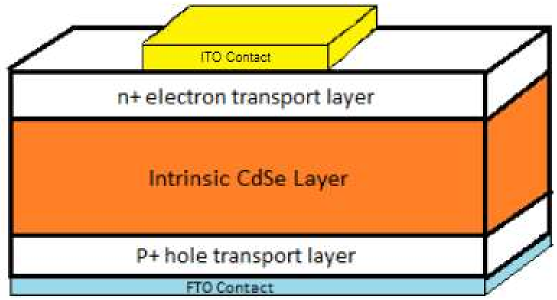

Figure 9: 3D Layering of the Designed CdSe Device Structure

Next, the layer of CdSe will be used. CdSe is the generation layer. It is much thicker than the other layer in hopes that more photons will be absorbed in this layer. It will be deposited using thermal evaporation. Finally, we will have a layer of CdS, which will be used as the electron transport layer (ETL) due to how its bandgap matches CdSe. The ETL and HTL layers' purpose is to reduce the recombination rate of the generated EHP's. This means our solar cell will have a higher likelihood of being able to utilize the excess charge carriers for power consumption. The configuration for our solar cell is also known as a P-i-N double heterojunction.

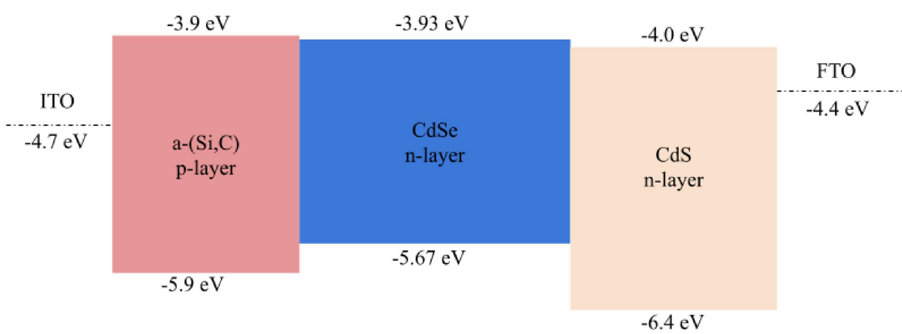

Figure 10: Energy Band Diagram of the Designed CdSe Solar Cell

Fabrication

The first step in our fabrication process involves the glass substrate and FTO contact layer. This is something that can simply be purchased from a supplier, then cleaned and prepped for us to use. The cleaning process includes two steps: wet cleaning and dry plasma cleaning. The wet cleaning step involves rinsing the substrates in deionized water, methanol, and acetone. These steps aim to remove any impurities that may have stuck to the FTO during its storage and transportation. After the samples are rinsed, they will be stored in fresh methanol to keep them clean. Once a sample is ready to have the CdS deposited, it is removed from the methanol and dry-cleaned in a plasma chamber. This is the final step in the cleaning process and removes any final particles left on the FTO. After this cleaning step, the substrates are placed in plastic cases where they are stored until CdS is deposited.

The CdS and CdSe layers will be the next two layers deposited on the sample. Both will be done in a thermal evaporation chamber equipped with a crystal monitor and thermocouple to measure deposition thickness and temperature. Inside the chamber there are also two boats, one with CdS and CdSe. Above each boat is a shutter, which can be opened and closed depending on which material we want to evaporate. Thermal evaporation is done at a pressure close to a vacuum, which decreases the temperature required to create a vapor from the source material. The CdS layer will be deposited first, and the CdSe layer will be deposited second.

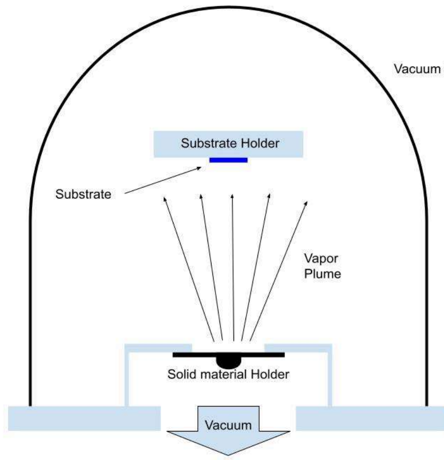

Figure 11: Simplified Sketch of a Thermal Evaporation Chamber

One thing that is a major limiting factor in all solar cells is interface defects, which increase the recombination rate and limit the short circuit current. These defects arise at the boundaries of two crystals due to broken bonds. After the CdSe layer, we will perform the first of the CdSe grain enhancement steps, which is post-deposition annealing. This will be done at 400°C, increasing grain sizes and decreasing the total surface area between grains. The second grain enhancement step is $CdCl_2$ surface passivation. Chlorine is a halogen that bonds with unbonded CdSe surface crystals and removes a significant number of surface defects. $CdCl_2$ is a liquid that can be placed onto the sample with a pipette, then is then spin coated to create an even layer on top. After the spin coating, it is placed into a furnace to heat up the layer of $CdCl_2$ and break the bonds. This allows the chlorine to separate from the $CdCl_2$ molecule and bond with the broken CdSe lattice.

The final fabrication steps are depositing the amorphous silicon layer and ITO contacts. Due to the safety hazards that come with depositing amorphous silicon, we will not be depositing this layer ourselves. The danger comes from the chemical used in this process called silane. Silane is a pyrophoric gas that ignites even when diluted to a one percent mixture. Because of this, it will be done by our advisor. After the amorphous silicon, the ITO contacts will be deposited on the top using plasma-enhanced RF sputtering. After the fabrication, we will perform the testing described in section 5 and adjust our process accordingly.

4.3.3 Functionality

Ultimately, the end goal of our small CdSe test samples will be expanded to a solar module containing multiple cells. The user would care about how to install the solar module on a farm. This means the considerations we would have to make while designing the product for the user involve ease of installation. Things that would affect are the degradation of the cells over time, how brittle this material is and how likely it is to crack, how heavy the cells are, and whether it would require extensive machinery to install them.

Another way the user would experience this product is through the environmental side. Cadmium and selenium can both be toxic to the environment and animals, and these cells may be placed in a variety of locations. Rooftop solar is becoming increasingly popular, so design considerations would have to be made to make the solar modules safe to be placed on rooftops in the event of a house fire.

4.3.4 Areas of Concern and Development

Our primary concern is maximizing the efficiency of the cell. A higher efficiency directly translates to economic benefits for producers and consumers of silicon-based solar cells. In the case of a solar farm, our CdSe cells can be fixed to existing solar cells to improve their efficiency. This is a huge benefit for solar farm companies in that new infrastructure does not have to be constructed for the CdSe cells. The price of materials such as concrete and metal is a large component of the cost of constructing a solar farm. So if this cell is not of sufficient efficiency, there is no benefit for solar companies to integrate our cells with their farms. This is why the efficiency of our cells is most important. To address these concerns, we are staying in contact with our faculty advisor for consistent feedback and help. The common questions are about our design decisions, such as which materials to use for the ETL and HTL.

4.4 Technology Considerations

The major different technologies that will be used in our design involve the fabrication process of the solar cell. There are a wide variety of methods to deposit one material on top of another, but not every method is possible for each material.

One technology is sputtering, which is a method of depositing a material by bombarding it with ions. The ions smash into a target, which consists of the material that will be deposited. This high kinetic energy ejects the target material into the surrounding area and is attracted to the desired location. We must take into consideration that this is a high-energy process and may lead to defects when the particles from the target hit the sample. The main material in our process that will use this technique is ITO. While there are other methods of depositing this material, sputtering is the primary method used at our available lab.

Another technology consideration is the deposition of CdSe. At the lab we will be fabricating in, we will be using thermal evaporation (TE). There is another method that is widely used for CdTe by First Solar called close space vapor transport (CSVT), but it is not available at our lab due to its cost. This is something that will be considered in the economic study section of the project because a large company will have the capability to use CSVT and will not be limited to TE.

4.5 Design Analysis

This semester, we have worked to understand our advisor's suggested CdSe structure. We have built several programs to calculate various parameters for solar cells, such as optimum band gap, optimum band pairings, and optimal band gap in single material cells, and made progress towards macros to calculate solar farm efficiency changes with the addition of CdSe-based on historical data and theoretical efficiencies. We are also working to understand the cost of potentially upgrading existing silicon solar cells to tandem cells with CdSe.

As we finish up our research we are moving to simulation. Our plan is to spend the rest of the semester simulating. Simulation for semiconductors is something that is traditionally taught in semiconductor courses at Iowa State. It is very new to us, and we expect it to take several weeks to figure out. We have done research to find simulators but are limited by cost and a lack of CdSe-specific simulators. Building our own is not very probable because the physics involved goes beyond the scope of an electrical engineering senior. For this reason, we are limited to just a few options. For the remainder of the semester, our device team will be working solely on simulation and coming up with our first fabrication process.

We cannot begin fabricating until next semester because we are road-blocked by respirator training. Unfortunately, we cannot move forward until we are trained, and the process of applying for training and getting trained takes a long time. Our best option at this point is to develop a simulation and have a fabrication process ready for the beginning of next semester.

One thing to note is that semiconductor fabrication is challenging, and developing a process takes time. Our first try at fabricating may not work well, or even at all. If it does produce power, it will likely not be efficient. We will not just be making a single cell however, we will do iterations throughout the semester. Graduate students are producing several cells per week. It is hard to gauge how many we will produce, as we've never done it before and do not have as much time as the graduate students, but we expect to produce several over the course of the semester. Over these iterations, we do not expect to make an increase in efficiency over what other engineers have achieved with CdSe, however, we do expect to make an increase in our own efficiency. Our end goal is to produce a working cell, make improvements to that cell, and report what we learned in hopes other engineers can use our data.

5 Testing

5.1 Important Parameters

In the scope of our project, we are interested in a few important solar cell parameters. First and foremost is efficiency. Solar cell efficiency is defined as the ratio of incident power to electrical power output, typically denoted as $\boldsymbol{\eta}$. It can be calculated by three important measured parameters. These parameters are open-circuit voltage (V_{OC}), short-circuit current (I_{SC}), and fill factor (FF). Isc is the current produced by a solar cell exposed to light when the device terminals are shorted. Open-circuit voltage is the voltage produced by the cell when it is exposed to light and connected to an infinite impedance. Fill factor is the ratio of the maximum power produced by the cell to the product of Voc and Isc.

Other parameters we are interested in involve how effective the solar cell is at ejecting electron-hole pairs from the semiconductor before they recombine. What tells us this is the quantum efficiency, the diffusion length L, and the mobility-lifetime ($\mu\tau$) product. Quantum efficiency is a plot of photon-to-electron hole pair efficiency vs wavelength. The diffusion length is the average distance a charge carrier travels before it recombines. The $\mu\tau$ product is also an extremely important parameter, as it represents a larger picture of how well the material acts as a solar cell. Mobility determines how easily charge carriers can move throughout the semiconductor, and lifetime represents how probable the charge carriers are to recombine.

5.2 Measurement Methods

Quantum Efficiency

Quantum efficiency (QE) measures the ratio of electron-hole pairs that contribute to current to the total number of incident photons of a specific wavelength. This metric is measured over a spectrum of wavelengths, specifically the range of wavelengths that make up the relevant portion of the solar spectrum, roughly 400-1100 nm. There are two types of quantum efficiency: internal (IQE) and external (EQE). IQE measures the ratio of generated current to absorbed photons, factoring in both transmittance and reflectance, while EQE measures the ratio of current to all incoming photons. IQE shows how well absorbed photons are contributing to current, and tells information about the internal parameters of the device, while EQE gives a broader measurement of quantum efficiency. QE is an extremely powerful measurement as it can reveal many solar cell characteristics, such as mobility-lifetime product, diffusion length, band gap, and defect energy levels. It can also be used to intuitively understand the cause of limiting factors in the cell.

Setup

The QE setup consists of three major components: the light source, monochromator, and measurement devices. The light source provides a wide spectrum of light in the similar range of the solar spectrum. This light then enters the monochromator, which has an adjustable diffraction grating to separate the input light by wavelength. This diffraction grating has an adjustable angle, meaning that it can be rotated to emit a specific wavelength of light through the monochromator's output slit, allowing for measurements at specific wavelengths. After the monochromator, the light goes through a series of lenses, optical filters, and mirrors to increase accuracy. Finally it arrives at the solar cell, which is connected to the measurement apparatus which measures the current. This piece of equipment measures the EQE, so additional reflectance measurements are needed to determine the IQE.

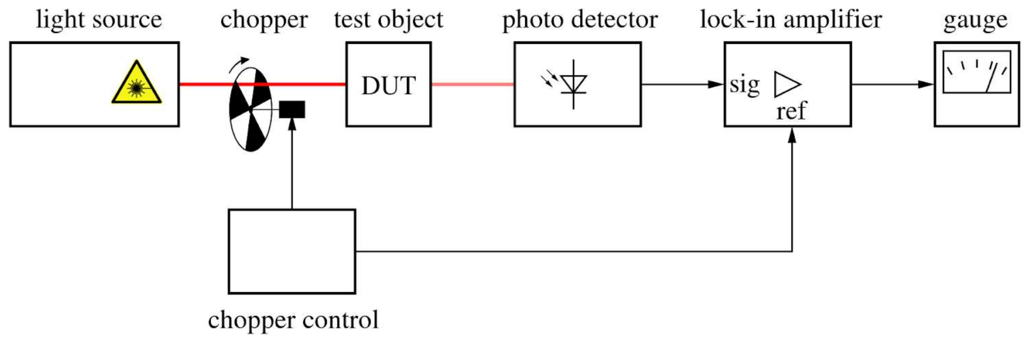

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Figure 12: Block Diagram of a Quantum Efficiency Measurement System

Measurement Results

The diffusion length can be obtained through the IQE and absorption coefficient, α. The relationship is shown in Equation 1. The plot of IQE^{-1} vs α^{-1} will result in a linear relationship with the slope being L^{-1}.

$$\frac{1}{IQE} = 1 + \frac{1}{\alpha} \cdot \frac{1}{L} \quad (1)$$

The diffusion length and its relationship with carrier lifetime can also be used to obtain the mobility-lifetime product, which is shown in Equation X.

$$\mu\tau = \frac{L^2 q}{kT} \quad (2)$$

Reflectance

Another valuable metric we will use to measure the properties of our product is reflectance. This is simply a measurement of the ratio between the intensity of reflected light to incident light. The reason why we care about this is because of power loss. In a solar cell, light reflection off the surface is one of the big causes of lowering efficiency. Ideally, all the power incident to the device will enter the material and be absorbed, but this is usually never the case due to differing refractive indices. This is the reason why most commercial solar cells have anti-reflective coatings. Even though anti-reflective coatings aren't something that we will explore in this project, reflectance is necessary to know when performing QE measurements. As described in the section above, the quantum efficiency setup measures EQE, not IQE. However, IQE can be calculated by measuring EQE and reflectance. The relationship between these variables is shown in Equation 3 below.

$$IQE = EQE(1 - R) \quad (3)$$

Current vs Voltage (I-V)

The I-V curve tells imperative information about the performance of a solar cell device. As mentioned, Open circuit voltage is the voltage produced by a solar cell exposed to light and attached to an infinite impedance. Isc is the current produced by the device when exposed to light, and the terminals are shorted. Efficiency is a percentage of incident optical power converted into electrical energy, and fill factor is a parameter best understood by examining the I-V curve:

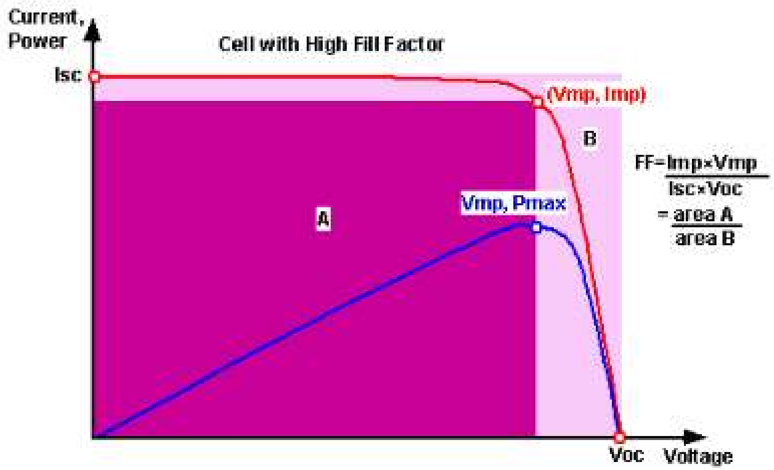

Figure 13: Example Graph of a Solar Cell's I-V Curve

Fill factor is the ratio of the maximum power produced by the cell divided by the power produced if the cell operated with current and voltage equal to Isc and Voc, respectively. The maximum power produced by the cell is equivalent to the largest area that can be shaded by using a coordinate pair on the I-V curve as the height and width. This is because power is simply the product of current and voltage, and the largest shaded area represents the largest product. The current and voltage pair that results in the largest area are denoted Imp and Vmp. The product of these parameters is the maximum power produced by the cell.

$$P_{max} = I_{mp} V_{mp} \tag{3}$$

$$FF = \frac{P_{max}}{I_{sc} V_{oc}} \tag{4}$$

$$\eta = \frac{I_{sc} V_{oc} FF}{P_{in}} \tag{5}$$

Mathematically, it may appear that you don't need a fill factor to calculate efficiency, as to find efficiency, we convert the fill factor to Pmax by multiplying by Isc and Voc. This is true; however, it is imperative to measure fill factor. Fill factor tells you key information about the quality of the solar cell. It is a percentage of how close to ideal the I-V curve is and is a parameter that can be improved on its own. It therefore gives key insight into what is causing inefficiency in the cell. A typical Fill Factor standard is above 70%.

Setup

The I-V measurement setup available to us consists of a light source made to closely mimic the solar spectrum. The light is directed through a light pipe from this source to the placeholder for the solar cell samples. The cell holder contains two contacts, one grounding contact, and a metal spherical contact controlled with a dial. The grounding contact is used to hold the cell in place and can simply be lifted and dropped onto the FTO connection point. The ballpoint contact must be slowly lowered onto the ITO contacts until the measurement instrument reads a voltage. The contacts are both connected to a power supply and digital multimeter. These devices are controlled remotely by a computer and used to "sweep" the device (take measurement of current at all voltages within a range). The measurer simply has to touch the contacts to the cell, press the "Sweep" button and save the data. The measurement device takes care of the rest of the setup and calculations.

Scanning Electron Microscopy (SEM)

An SEM uses the wave property of particles to perform microscopy the same way an optical microscope does. It utilizes high energy electron beams to create extremely focused images that are capable of showing detail on the nanometer scale. This tool is widely used to look at material's grain boundaries and patterns and will tell us how post-deposition annealing affects grain sizes.

6 Implementation

A large portion of next semester's implementation plan involves the fabrication of our solar cells. We have developed a fabrication process that we plan to follow and adjust as the semester progresses. Below are the major milestones we must achieve in the following semester.

- Milestone 6 - Complete Lab Safety Training
- Milestone 7 - Simulate the Predicted Performance of the cell device structure
- Milestone 8 - Fabricate Solar Cells
- Milestone 9 - Report on Fabrication Process Results
- Milestone 10 - Report on Economic Viability

7 Professional Responsibility

One of the major components of engineering design is professional responsibility. It is the foundation of engineering ethics and integrity, and ensures that engineers meet the technical demands of the profession but also serve as holders of public trust. As a result, engineering professional societies have developed their own ethics standards. Here, we discuss the IEEE code of ethics and how our project upholds these standards.

7.1 Areas of Responsibility

We are referencing the paper "Contextualizing Professionalism in Capstone Projects Using the IDEALS Professional Responsibility Assessment" and how the IEEE Code of Ethics addresses the seven responsibilities listed in this paper. An additional column has been added to Table 3 of this paper to consider the similarities in the IEEE code of ethics.

Table 3: Ethical Responsibilities and their NSPE and IEEE Cannons

Area of Responsibility	Definition	NSPE Cannon	IEEE Cannon
Work Competence	Perform work of high quality, integrity, timeliness, and professional competence	Perform services only in areas of their competence; Avoid deceptive acts	To undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations
Financial Responsibility	Deliver products and services of realizable value and at reasonable costs	Act for each employer or client as faithful agents or trustees	To be honest and realistic in stating claims or estimates based on available data
Communication Honesty	Report work truthfully, without deception, and understandable to stakeholders	Issue public statements only in an objective and truthful manner; Avoid deceptive acts	To improve the understanding by individuals and society of the capabilities and societal implications of conventional and emerging technologies, including intelligent systems
Health, Safety, Well-Being	Minimize risks to safety, health, and well-being of stakeholders	Hold paramount the safety, health, and welfare of the public	To hold paramount the safety, health, and welfare of the public To disclose promptly factors that might endanger the public or the environment
Property Ownership	Respect property, ideas, and information of clients and others	Act for each employer or client as faithful agents or trustees	To protect the privacy of others
Sustainability	Protect environment and natural resources locally and globally		To strive to comply with ethical design and sustainable development practices
Social Responsibility	Produce products and services that benefit society and communities	Conduct themselves honorably, responsibly, ethically, and lawfully so as to enhance the honor, reputation, and usefulness of the profession	To seek, accept, and offer honest criticism of technical work

The IEEE standard is very similar to the NSPE standard for work competence. The IEEE standard states that someone may only work on tasks they are qualified to perform. One difference between the NSPE and IEEE standards is that the IEEE standard mentions that the engineer must disclose any limitations they may have when completing a task. The financial responsibility section of the IEEE standard states that an engineer must be honest to the best of their ability when discussing cost estimates and claims. This is also quite similar to the NSPE standard since there is no explicit reference to cost. However, the IEEE standard directly mentions decision-making and estimates based on data, while the NSPE standard does not.

The standard for communication honesty from NSPE is much less specific than the IEEE standard. While they both discuss similar topics, such as informing the public, the IEEE code specifically discusses informing the public about new technologies and how they will affect the public. The IEEE code is also more detailed about its health and safety portion. Not only does it speak on ensuring the safety and health of the public, but it also makes the point that the public should be informed on how engineering decisions will affect them. Sustainability is similar to health and safety, but rather than protecting the health and safety of the public, it is about protecting the health and safety of the environment. This is a section that is in the IEEE code of ethics but not the NSPE code.

Another important ethical standard is property ownership, which is about respecting what others own. IEEE states this in a different way than the NSPE because it mentions protecting the privacy of others. This is important because rather than just respecting it, the IEEE code ensures that engineers should strive to protect the privacy and information of others. The final area of responsibility for engineers is social responsibility, which is about engineers providing a benefit to society rather than a detriment. While this isn’t specifically mentioned in the IEEE Code of Ethics as it is in the NSPE code, it is heavily implied throughout.

7.2 Project Specific Professional Responsibility Areas

Due to the complexity of our project and our limited experience, we encountered work competence, financial responsibility, and communication honesty early in the project. While we have learned about the topic of solar cells before, this project is a large extension of what we have learned. Honesty about our knowledge, experiences, and possibilities for error have been quite apparent. Because of this, we have been in constant contact with our faculty advisor about our knowledge and their expectations. It has been made clear that due to our limited knowledge, there is a cost required to learn some of the fabrication techniques. This cost is mostly in the materials and time needed to practice certain portions of the fabrication process before making our own solar cell. Due to this, we would rate our team in the medium to high range for these responsibilities.

We have also experienced heavy responsibility in the health, safety, and well-being responsibilities and sustainability. Our solar cell design depends on the use of cadmium and selenium, both of which are toxic metals. Therefore, a part of our design will include steps to mitigate these environmental and health hazards. Despite the fact that we are only making small square-inch cells, we are designing them with the idea that they will be scaled in the future. Our design takes into account the risks associated with using the materials in solar cells. These risks come from mining the material, recycling, and disposal of the device after its lifecycle, fabrication using toxic chemicals, and accidental release of the material into the environment from disasters such as wildfires. After all of these considerations, we would rate our team high in these two responsibilities.

The final is social responsibility. We have been in contact with teaching assistants and professors for advice on our work, and we have received very constructive feedback. However, this is one aspect that we believe has been lacking and that we should be asking for feedback more often. Because of this, we would rate ourselves as a medium for social responsibility.

7.3 Most Applicable Professional Responsibility Area

Sustainability is the most important professional responsibility for our entire project since the initiative to use solar panels for energy generation entirely stems from achieving greater sustainability, both from a renewable and not finite energy perspective as well as from an environmentally friendly perspective. Building a solar cell that is just as damaging to the environment as mining and burning coal, gas, and oil defeats the purpose of creating the solar cell. The scale at which we will be operating will likely not have a significant impact on the environment, but on a larger scale it will certainly be a consideration. These materials must be mined which obviously incurs a significant environmental impact, although both cadmium and selenium are byproducts from mining other materials, zinc for cadmium and copper for selenium. However, These materials could go to waste if not used in something like our solar cells. Cadmium selenide is a carcinogen and can be problematic if swallowed, inhaled, or contacted with your eye. Once deposited, the CdSe solar cell will be layered on top of silicon cells, which will quickly degrade if exposed to water, so we require a waterproof casing on the cell regardless. So the CdSe shouldn’t ever get into the environment during its usage life. Ultimately, by working with this material to add to the preexisting and well-developed silicon solar cell technology, we will greatly increase the economic viability of solar cell technology and allow us to produce significantly more energy from the same land area and number of solar cells, which will increase the amount of money made from any given plot of land for similar infrastructure costs, which will help us move away from dirty nonrenewable energies.

8 Closing Material

8.1 Discussion

Our goal is a one percent efficient solar cell. We will be measuring the I-V characteristics of the solar cell to determine the efficiency and quantum efficiency to aid in tweaking the design process. The main hypothesis we are testing is that a solar cell can be made with CdSe and amorphous silicon as a hole transport layer. The success of the project will largely depend on the efficiency of the solar cell we achieve.

8.2 Conclusion

Over the course of the Spring 2024 semester, our team has spent the vast majority of time focusing on researching similar and current technologies, learning more about the necessary device physics for the design of the solar cell, fabrication techniques available to us, simulation software for economic and band diagram models, and economic data of current solar cell technology. These areas of research are a reflection of our end-of-project goals as we intend to provide well-documented reports on the fabrication and testing process, economic viability, and material feasibility, as well as have physical specimens of our fabricated solar cells. While our team would have liked to get started on device fabrication in the current semester, we are currently constrained to next semester as in order to fabricate CdSe solar cells, and we must have proper training in respirators, which is not accessible until next semester.

With the timeline of fabrication being constrained to next semester, we intend to use this extra time to further our knowledge of the fabrication and testing processes to create a more well-developed iterative design process. This will allow us to get a head start on the fabrication process with clear goals and timelines implemented at the start of the fall semester.

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8.4 Appendices

Appendix A

Thermal Evaporation Background Information

Thermal evaporation is a chemical deposition technique. It is primarily used for thin film deposition of materials, in uses such as protective films on toys, and depositing semiconductor materials into a substrate, which can be used in solar cells and other semiconductor devices, as well as depositing thin film metallic contacts that are needed for many electronics. The thin film capability is the desired behavior for solar cells from this deposition technique. The reason for this is that the thin film creates a smaller and lighter-weight solar cell that is easier and cheaper to transport as well as set up. It creates a slightly less efficient solar cell as opposed to crystalline solar cells. Still, lots of research into these thin film materials and the deposition techniques has greatly increased their efficiency, and the efficiency difference between crystalline and thin film has greatly decreased. In our project we will be using thermal evaporation for all of the layers of our solar cell.

Thermal evaporation utilizes a vacuum chamber, created using a vacuum pump at the bottom of the chamber apparatus, with a heating element with a boat for solid material. Above the solid material boat is a substrate holder and substrate. The substrate is kept at a lower temperature than the heating element that heats the solid material. The thermal evaporation process begins by heating a solid material in the boat until it eventually evaporates. When it evaporates, it creates a vapor pressure, and due to the low pressure inside the vacuum chamber, the vapor rises and creates a vapor cloud. As this vapor cloud continues to rise, it turns into a vapor stream and rises toward the substrate. When the vapor stream hits the substrate, it deposits as a solid again as a thin film on the substrate.

Appendix B

Effect of Grain Boundaries on Material Properties

A poly-crystalline structure contains small 3 dimensional volumes called grains. Poly-crystalline materials are made of many grains, and within each grain the material's crystalline structure exists but at a different orientation than neighboring grains. Within each colored 3D volume exists the same crystalline order but at a different orientation. These individual grains make up the entirety of the polycrystalline material. An important term to know is “Grain Boundary.” The grain boundary is the intersection between two grains on a 2D “slice” of the material. The grain boundary is important because the intersection between grains can be a massive problem for semiconductor materials.

The intersection of two grains causes defect states. Defect states are states that are created by the presence of defects in the material. These states typically do not exist and, therefore, allow electric charges to go places it is not expected to be. These defect states, commonly referred to as traps, aid in recombination, a process in which the semiconductor dissipates energy.

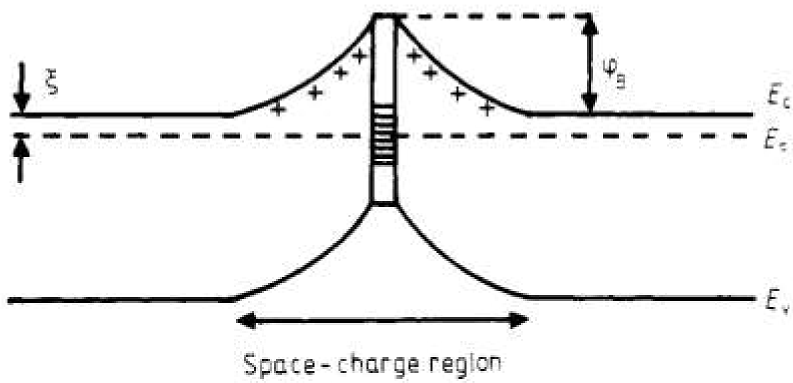

Figure 14: Energy Band Diagram of Grain Boundary in a Polycrystalline Material

In addition to creating trap states, the grain boundary creates a potential barrier for charges. Figure 14 above depicts the energy band diagram of a semiconductor at a grain boundary. In the center of the photo, between the conduction and valence band, are the traps, depicted on dashed lines. The potential barrier is labeled φ_B. The potential barrier can be summed up as making it more difficult for an electric charge to move through the material. Electrons or holes overcoming a potential barrier is a probabilistic process and, therefore, causes the loss of some carriers.

9 Team

9.1 Team Members

- Payton Bills - Electrical Engineering
- Drew Jensen - Electrical Engineering
- Anders Peterson - Electrical Engineering
- Michael Thomas - Electrical Engineering

- Jacob Steffens - Electrical Engineering
- Jonathan Timm - Computer Engineering

9.2 Required Skill Sets for Your Project

Table 4: Skill Sets Necessary for this Project

Skill Set	Reasoning
Semiconductor Physics	This project is centered around semiconductor physics and understanding how electrons move through a material, and how to design a device around that.
Simulation Experience	Simulations of our cell will be made to predict how changing certain parameters affects the performance of the cell.
Power Systems Experience	One of our deliverables will be an economics report about the viability of CdSe solar cells, which requires knowledge of power systems.
Device Fabrication Experience	Fabrication is another core part of our project because one of our deliverables is to make a CdSe solar cell, which requires fabrication.
Device Parameterization Experience	In order to determine if our solar cell works as expected and what needs to be improved, we will need to perform tests and data analysis.

9.3 Skill Sets covered by the Team

Table 5: Skill Sets Fulfilled by Team Members

Skill Set	Team's Experience
Semiconductor Physics	Each team member has some experience in semiconductors.
Simulation Experience	Jonathan, Jacob, and Michael have some experience working with simulation software
Power Systems Experience	Payton, Anders, Michael, and Jacob all have internship and coursework experience in power systems
Device Fabrication Experience	Payton and Anders have brief experience in device fabrication
Device Parameterization Experience	Payton and Anders have experience in device parameterization from coursework taken

9.4 Project Management Style Adopted by the team

Our team is implementing the agile project management style.

9.5 Initial Project Management Roles

Table 6: Project Management Role Breakdown for Each Team Member

Team Member	**Project Management Role**
Payton Bills	Team lead and Device Fabrication
Anders Peterson	Device Fabrication and Testing
Drew Jensen	Economic Viability and Testing
Jonathan Timm	Statistical Analysis and Simulation
Jacob Steffens	Economic Viability and Simulation
Michael Thomas	Simulation and Testing

9.6 Team Contract

Team Members

1) Payton Bills 2) Anders Peterson
3) Drew Jensen 4) Jonathan Timm
5) Jacob Steffens 6) Michael Thomas

Team Procedures

1. Day, time, and location (face-to-face or virtual) for regular team meetings:
    a. 4-8 PM Friday/11 AM Saturday
    b. TLA - Coover Hall
2. Preferred method of communication updates, reminders, issues, and scheduling (e.g., e-mail, phone, app, face-to-face):
    a. Text and Email
3. Decision-making policy (e.g., consensus, majority vote):
    a. General Consensus
4. Procedures for record keeping (i.e., who will keep meeting minutes, how will minutes be shared/archived):
    a. Personal notes are taken and are shared after each meeting.
    b. Google Drive folders are used to keep track of work week-to-week.

Participation Expectations

1. Expected individual attendance, punctuality, and participation at all team meetings:
    a. Attendance at all weekly meetings is expected of all team members
    b. After five missed meetings, action will be taken depending on the circumstances:
        i. Majority excused absences: The team will meet with the member and discuss if a new time needs to be chosen or what needs to happen to make sure they can meet weekly.
        ii. Majority unexcused absences: The team will meet with the member and find the reasons for the absences. If the team determines that the unexcused absences are justified, the team member will be put on watch and earn a strike. Otherwise, the team will approach the professors about removal from the team. While on watch, we will use the same process but with two missed meetings instead of 5. After three strikes, the group will approach the professors about removal.

2. Expected level of responsibility for fulfilling team assignments, timelines, and deadlines:
    a. Attend all meetings
    b. Dedication of time each week will vary depending on weekly goals.
    c. Taking some level of thoughtful notes on the material you are covering when necessary.

3. Expected level of communication with other team members:
    a. Communicate often and update the group as unforeseen circumstances arise. If a member finds a topic or part of the project to be far more difficult than expected, reach out to other group members for assistance.

4. Expected level of commitment to team decisions and tasks:
    a. The expected level of commitment and time dedication will vary from week to week, depending on the short-term goals set at the previous weekly meeting.

Leadership

Table 7: Team Member Responsibilities

Member	Responsibilities
Payton Bills	Team lead | Client interaction
Anders Peterson	Client interaction | Component design
Drew Jensen	Individual component design | Testing
Jacob Steffens	Simulation research | Research aid discovery and distribution
Jonathan Timm	Simulation research | Simulation testing
Michael Thomas	Individual component design | Testing

1. Leadership roles for each team member (e.g., team organization, client interaction, individual component design, testing, etc.) shown above.
2. Strategies for supporting and guiding the work of all team members:
    a. Providing resources for learning relevant topics and concepts
    b. Opportunities to ask questions of more experienced team members
    c. Foster an environment in which questions can be asked freely.

3. Strategies for recognizing the contributions of all team members:

In the weekly reports, each member will have an opportunity to showcase their work and progress towards their individual goals.

Collaboration and Inclusion

1. Describe the skills, expertise, and unique perspectives each team member brings to the team.

Table 8: Description of Each Team Member's Previous Experience

Member	Skills and Experience
Payton Bills	I have taken several courses on the physics of semiconductors and devices and have general knowledge of the power industry through both my club and internships. Additionally, I have simultaneously led three separate large projects for a national collegiate level competition through my role as the president of the Wind Energy Student Org.
Anders Peterson	I have taken several courses in physics, semiconductors, and power systems. I have also had internships in power systems and feel I have a decent understanding of the advantages and disadvantages that solar energy can have on the environment.
Drew Jensen	I have taken 332, a course about semiconductors and semiconductor devices, which includes solar cells. I have worked on papers discussing solar cells and on professional engineering teams.
Jacob Steffens	Most of my experience relates to the application of silicon devices. I also have experience with how power companies operate with regard to solar installations.
Jonathan Timm	Significant programming experience including Java, C, Matlab, Python, and SQL. Experience with Git. Co-op in integrated circuit simulation/verification. Experience with integrated circuit design.
Michael Thomas	I have done four internships in high-power reliability testing for products and individual components. My expertise lies in locating long-term weaknesses in the designs of products and addressing them. Additionally, I am currently taking EE 332, semiconductors materials & devices.

2. Strategies for encouraging and supporting contributions and ideas from all team members:

Table 9: Contributed Individual Team Working Strategies

Member	Strategies
Payton Bills	We need to hold each other accountable to ensure everyone has a chance to speak and that no individual owns the conversation. It will also be imperative that our communication is a positive environment so that no one's ideas are discouraged by the fear of being criticized.
Anders Peterson	Before meetings, I think it would be good to form a list of topics we want to discuss; this way, it would help prevent ideas from being skipped over during the meeting.
Drew Jensen	I think having plenty of time before and after the meeting to give team members time to present ideas and generally having an environment where we don't talk over others and make sure everyone feels free to share.
Jacob Steffens	At the start of each meeting, we should give a five-minute window to each member where they can freely voice questions, comments, ideas, or concerns.
Jonathan Timm	When ideas are shared, provide constructive criticism after the speaker has finished sharing their idea. If able, offer to help implement changes to an idea when finished providing feed.
Michael Thomas	I think that having a document ahead of time with a list of topics we want to cover will help us stay on track, and help us be more efficient with our meeting times. Additionally, we need to fully hear out contributions or ideas before discussing and addressing feasibility or offering constructive criticism. We should try to allow ourselves extra time at the end of our scheduled meetings in case some topics need to be more thoroughly discussed. Finally, we should try to keep track of what team members are contributing so that if someone seems to fall behind, we can help push them in the right direction or motivate them.

3. Procedures for identifying and resolving collaboration or inclusion issues (e.g., how will a team member inform the team that the team environment is obstructing their opportunity or ability to contribute?)

The conflict should be brought up and identified at the weekly team meeting. If a solution cannot be reached via team discussion, then the issue should be escalated to the team advisor.

If the conflict is between individuals, the rest of the team will help decide what is best to do by majority consensus/vote. In the event of an evenly split decision, the conflict will be escalated to the Team Advisor.

Goal-Setting, Planning, and Execution

1. Team goals for this semester:
    - Research and understand the current technology of traditional solar cells.
    - Break down the design aspect of our solar cell into smaller components to divide the workload.
    - By the end of the semester, have an initial design.

2. Strategies for planning and assigning individual and teamwork: Having a shared EXCEL or Word document where we can plan tasks, assign work, and have goal dates for completing things

3. Strategies for keeping on task: Touch base with each person during meetings to see if anyone needs help or encouragement to continue working on tasks

Consequences for Not Adhering to Team Contract

1. How will you handle infractions of any of the obligations of this team contract?
    a. Infractions of the team contract will result in the offending party meeting with the Team Lead, where they can discuss the infraction and appropriate steps towards improvement.
        i. In the event a member refuses to meet, the issue will be escalated to the Team Advisor.
        ii. In the event that infractions are committed by the Team Lead, the issue will immediately escalate to the Team Advisor.

2. What will your team do if the infractions continue?
    a. If the infractions continue, a meeting with the Team Lead and Team Advisor will be necessary. In this, they may decide what appropriate action is needed.
        i. In the event the continued infractions are committed by the Team Lead, the remaining team members and Team Advisor will vote on whether to impeach the Team Lead.
            1. If the team lead is impeached, all members, including the impeached Team Lead and Team Advisor, will vote for a new Team Lead immediately following the impeachment.
            2. In the event that the Team Lead remains, all members and the Team Advisor will discuss possible solutions to ongoing issues.

****

a) *I participated in formulating the standards, roles, and procedures as stated in this contract.*
b) *I understand that I am obligated to abide by these terms and conditions.*
c) *I understand that if I do not abide by these terms and conditions, I will suffer the consequences as stated in this contract.*

1) Michael Thomas DATE 1-30-24
2) Jonathan Timm DATE 1-30-24
3) Payton Bills DATE 1-30-24
4) Anders Peterson DATE 1-30-24
5) Jacob Steffens DATE 1-30-24
6) Drew Jensen DATE 1-30-24