# Exploring Solar Cell Technology

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The Spartan Solar Cell Project comprises a variety of activities for San José State University engineering students to learn about photovoltaic (solar cell) technology. Activities include process design, layout and fabrication of solar cells; and testing and design with solar cells. The ultimate goal of this project is to produce Spartan Solar City, a model city which will be powered by photovoltaic cells and will demonstrate various principles of energy conversion. The project has four phases of development:

1. Solar Cell Testing
2. Fabrication of Solar Cells
3. Optimization of Spartan Solar Cell design and process technology
4. Design and Construction of Spartan Solar City

Phase 1, Solar Cell Testing, is described here. This activity is provided to sections of the first-year engineering class (ENGR 10) as a one-week enrichment module. Phase 2, Fabrication of Solar Cells, has been pilot tested and will eventually be integrated into an upper division course on electronic materials as a one-week lab activity. Phase 3, Optimization of solar cell design, consists of a series of senior projects and masters theses focused on improving the electrical characteristics of our solar cells through improved process design. Finally, the last phase, Design and Construction of Spartan Solar City, is a long-range project to build a photovoltaic-powered miniature village for demonstration purposes.

The Solar Cell Testing module was developed as a way of enhancing the interest of first-year engineering students in semiconductors and microelectronics process engineering technology in general, and the Spartan Solar Cell project in particular. The project was piloted on several sections of the freshmen engineering class (Engr10) over one academic year, and has now been successfully offered to the entire freshmen engineering class (~500 students) in the Fall of 2002. The activity is robust and portable in terms of equipment, training, and academic benefit and should be easily adaptable by other institutions. Students have responded positively to the experience and recommended keeping it in the curriculum.

There are many lessons that engineering students can learn as they study photovoltaic power generation. In the phase of the project discussed here, students simply learn how solar cells function, how they are made, how to test and evaluate them, and how to design a simple solar array for a specified application. We currently use very inexpensive cells with relatively poor efficiencies (1-2%). Ultimately we plan to use our own higher efficiency, campus-manufactured solar cells for this project.

## Introduction to Photovoltaic Technology

Photovoltaic devices, or solar cells, are used to convert solar radiation to DC electrical energy. These devices are useful in locations or applications remote from conventional power grids. Increasingly, homeowners are installing photovoltaic systems on rooftops to reduce their utility bills, and some cities are installing photovoltaic arrays on city building rooftops. These systems are essentially localized power generation plants, as they can be tied into the utility grid where they run the electric meter backwards when using less power than is being generated[1]. The economic cost of installing photovoltaic power has to be offset with the social and environmental cost of continuing to use non-renewable natural resources. Photovoltaic technology uses semiconductor processing technology, and as such is not a completely "green" method of producing power, since it uses hazardous chemicals and generates hazardous chemical waste. Since a large PV power generation plant is simply a scale-up from a single PV cell, energy conversion calculations can be easily scaled from simple measurements in the lab.

Solar cells are essentially large area pn-junction diodes. Advanced solar cells (i.e. highly efficient cells, up to ~25% efficiency) are made from compound semiconductors, sometimes layered to provide a variety of light-absorbing regions, and may be textured to improve light gathering ability, provided with anti-reflection coatings, or packaged with solar concentrators to gather light from a wider area. Very inexpensive and wide area solar cells may use amorphous silicon thin films which are easily deposited over a large area but do not provide very high efficiency[2,3].

Solar cells are similar to batteries in that they provide a voltage to a load; but whereas a battery provides a constant voltage, a photovoltaic cell provides a voltage and current which varies with the load resistance itself[4]. Figure 1 shows the power curve for an inexpensive "hobby" solar cell used in this lab activity. The general equation which describes solar cell operation is given by:

$$I = I_s\left(e^{qV/kT} - 1\right) - I_L \qquad \text{(Equation 1)}$$

where $I_s$ is the reverse saturation current, $I_L$ is the *short-circuit current*, $V$ is the voltage drop over the load, which creates a forward bias on the diode, and is determined primarily by the product $I_L \times R_L$, the load resistance. In a real solar cell, other equivalent resistances such as *shunt resistance* and *series resistance* must be taken into account. The short circuit current ($I_{SC} = I_L$) is determined by the design of the cell and the materials used, and increases with the ambient light intensity. Not all of this current is available to the load: the voltage developed over the load is proportional to the photocurrent, which is then countered by the forward current produced by the forward biased diode. When the load resistance is small, only a small forward current is subtracted from the photocurrent. When the load resistance is large, the voltage increases but the current drops, producing less power. With an infinitely large load resistance, the cell is in open circuit condition, with maximum possible voltage (*open circuit voltage,* $V_{oc}$) but zero current. The ideal operating point of a photovoltaic cell is where the power output is a maximum, that is, the product of the load voltage and the net photocurrent at the maximum power point ( i.e. $P_{mp} = V_{mp} \times I_{mp}$).

The *efficiency* (η) of a solar cell is the power (electrical) output divided by the power (light) input. Equation 2 defines the *fill factor* which characterizes the squareness of the power curve. The fill factor can be used as a measure of efficiency when the light input is unknown. The fill factor of the cell shown in Figure 1 is 0.63. A commercially viable cell would need a fill factor greater than 0.80.

$$FF = \frac{I_{mp}V_{mp}}{V_{oc}I_{sc}} \quad \text{(Equation 2)}$$

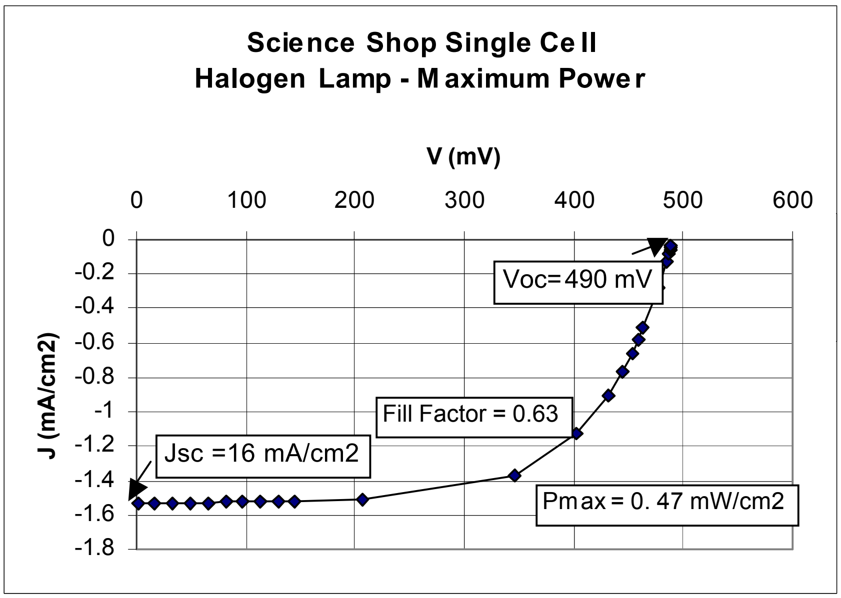



**Figure 1. Measured solar cell power curve.**

Engineering 10 Course (Introduction to Engineering)

This one-semester course consists of two hours of lecture and three hours of lab per week, and is required of all engineering majors in the College. It is also offered by community colleges. The lab component is weighted heavily towards providing students with computer skills such as using spreadsheets for computation and plotting, some design activities and introduction to engineering principles. Many of the course instructors are part-time lecturers with backgrounds in a variety of engineering disciplines, and the majority are working engineers in local industry. Enhancing the course are student projects selected by each instructor; in addition, every semester there is a required design contest. Examples of recent design contests are rubber band-powered airplanes, penny launchers, and edible mass balances. The solar cell project takes just one lecture period and one lab period for each class section. The guest lecture is delivered by a faculty member from the Microelectronics Process Engineering program; the lab sections are each staffed by two undergraduate or graduate student assistants who are provided with a modest stipend for their effort (a $25 gift certificate to the campus bookstore). Some of the E10 instructors are now able to teach the lab without any student assistants, an important improvement. We provide several hours of training to the student lab assistants. Each semester two experienced students are hired to maintain the test stations, design and run the training sessions and manage the staffing of the lab sections. In Fall 2002, 23 different lab sections were covered.

## The Solar Cell Testing Module

The goals of the E10 Solar Cell Module are expressed in a set of Learning Objectives, shown in Table 1. Each component of the module is specifically designed to meet different learning objectives. The course instructor assigns homework that the students are to complete before the guest lecturer arrives in class. The homework questions are designed to get the students to explore photovoltaic technology via the Internet. Thus they come to the lecture already prepared with questions and some answers about the technology.

**Table 1. E10 Solar Cell Activity Learning Objectives**

| After performing the homework assignment, the testing protocol, and the design problem and participating in class discussions, the E10 student should be able to: |
|---|
| 1. Identify when and where photovoltaic cells were invented. |
| 2. Explain the function of a solar cell. |
| 3. List some real applications of photovoltaic technology. |
| 4. Explain how a solar cell works. |
| 5. Read a circuit diagram. |
| 6. Build a circuit using digital multimeters, decade box or resistors, and solar cells. |
| 7. Measure current and voltage using a DMM. |
| 8. Record the data accurately and legibly. |
| 9. Plot the data appropriately in an Excel spreadsheet. |
| 10. Distinguish between current (I) and current density (J). |
| 11. Distinguish between power and power density. |
| 12. Describe how the illumination level influences power output |
| 13. Identify the fill factor of the solar cell and explain how it is related to efficiency. |
| 14. Build a circuit which includes two cells in series connection. |
| 15. Build a circuit which includes two cells in parallel connection. |
| 16. Compare the I-V curves of single cell, parallel connection and series connection. |
| 17. Evaluate the current, voltage, and power outputs of the different configurations. |
| 18. Design an array of solar cells for the desired power output. |
| 19. Evaluate the design solution in terms of cost and size |
| 20. Suggest and evaluate alternative design solutions. |

After the lecture period, the lab assistants take over and the students are divided into groups, ideally with 3 to 4 in each group. Each group receives a lab manual and is responsible for gathering the materials and equipment needed from the equipment depot in the front of the room. The lab manual is completely self-explanatory and student groups can begin to assemble their circuits and set up their spreadsheets for data collection. The test circuit is shown in Figure 2. The power curve is measured simply by varying the load resistance from 1Ω to 50kΩ, and recording the current and the voltage drop over the resistor at each resistance setting. The student assistants roam the class, answering and asking questions and trouble-shooting. It takes about 45 minutes for the testing protocol and graphing to be complete. Each solar cell may be slightly different, so the students must compare their plotted IV curve with an example in the manual. If the plotted data has the right shape, as shown in Figure 1, then they have successfully completed the testing protocol. They must also identify on their plot the short-circuit current and current density, open-circuit voltage, maximum power density, and fill factor.

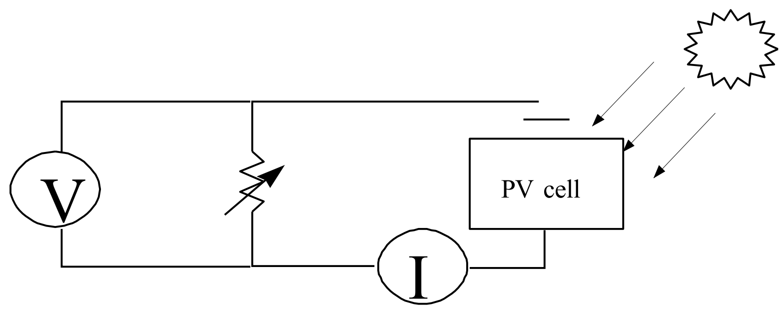



**Figure 2. Test circuit for solar cell.**

As each group completes the test protocol, they are given the design problem, which is shown in Figure 3. The problem is to design a solar cell array which will provide sufficient energy to charge the batteries of a vaccine storage refrigerator. The Design Guide (Figure 4) provides ample help in solving the problem. Because we use such inefficient cells, the students soon find that the storage refrigerator would need a vast array of cells to be powered. To answer the last few "evaluation" questions in the Design Guide, students have to consult their homework paper. This last step integrates the Internet research they've done with the concrete measurements they've taken.

Equipment

The equipment needed to perform this activity is shown in Table 2. The Lamp Station we use was designed and later modified by undergraduate students. Any halogen lamp (or even tungsten lamp) will work. We use halogen lamps because they are brighter than tungsten and more closely match the solar spectrum. Our stations also have a rheostat to control the light intensity, so that students can observe the effect of light intensity on the power curve. Other equipment includes two multimeters, to measure current and voltage, and an adjustable resistor (decade box) or a set of resistors.

Student Responses

Students have responded quite enthusiastically to this activity. We surveyed the students in Spring 2001 and again in Fall 2001 after some improvements were made. A common comment was the need to have more test stations so more students could have their hands on the equipment; we have built 10 new stations to keep the student ratio at 3 per group. The most often suggested improvement is that students would like to "make something work" with the cells, rather than doing a paper design. This will be incorporated into the next redesign of this activity. Students felt that their skills at using multimeters as well as their spreadsheet skills were improved by this lab activity. Our favorite comment was: "Cool lab. More fun than Matlab"!

**Table 2. Equipment List**

| Equipment List for One Solar Cell Test Station | | | |
|---|---|---|---|
| Item | Description | Vendor | Approximate Cost |
| Lamp Station | Any halogen lamp | Various; we built our own stands. | $35 |
| Two digital multimeters | We use hand-held, battery operated; any DMM is fine | Test Equity Thousand Oaks, CA | $130 |
| One decade box | Adjustable resistor; can use discrete resistors instead | IET Labs Westbury, NY | $160 |
| 2 solar cells | Cells must be tested; not all commercial cells have adequate performance | Science Shop San Jose, CA | $20 |
| Ruler | To measure cell area | Various | |
| 5 wires | 2 micro-clip to banana + 3 banana-banana | Various | $10 |
| Total Cost | | | $355 |

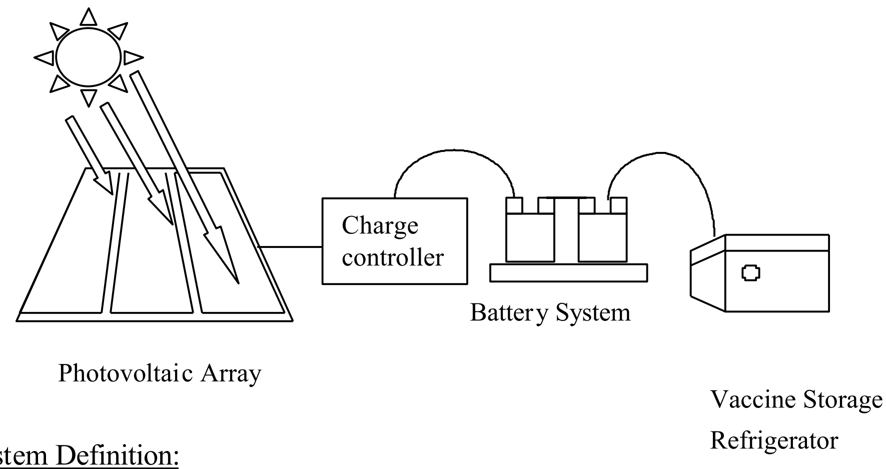
Future Plans

The project as it currently stands is fairly robust and a complete learning experience. The weakest part of the module is the design problem. Future plans are to provide students with electric motors or other devices and require them to design a solar array to make the electrical device work. This will provide a more concrete way of testing their design skills and also be more exciting than a paper exercise which cannot be tested. This will also motivate some students to participate in the Spartan Solar City project.

Once the Spartan Solar Cell fabrication process is stable, students will begin making solar cells in an upper division class. Some of these cells will then be used in the ENGR 10 module, and students will have the added excitement of using "home-made" solar cells.

Engineering 10 Solar Cell Activity: In-Class Design Problem

The figure below shows a photovoltaic system which powers a vaccine storage refrigerator, to be used at an off-grid location. The system provides a means of storing vaccines and medical supplies in a region where reliable power is not available. Your Team's job is to design a solar cell array (photovoltaic array) which will power this system to its required specifications.




System Definition:
The battery system is needed to ensure that the refrigerator works overnight or in bad weather. The refrigerator runs off DC power and uses 100 watts (W) delivered at 24 volts (V). The battery system consists of two 12V car batteries connected in series. The charge controller prevents overcharging of the batteries.

Performance Criteria:
Assume that the battery and charging system are 100% efficient, i.e. that 100% of the power output of the solar cells is delivered to the refrigerator. (A real charging system would probably only be about 50-70% efficient.) Assume that you need to be able to run the refrigerator for two days without any sunlight, for example in a rainstorm or dust-storm. Thus the battery system needs to store enough power for two days. This 2-day period is referred to as "days of autonomy". Also, assume that the batteries need to be re-chargeable over a one-day period. Assume that the photovoltaic cells in the system are the same as the ones you measured in the lab exercise. Assume that in sunlight the cells would produce the same amount of current as they do under the halogen light you used in the lab.

**Figure 3. Design Problem Statement.**

Engineering 10 Solar Cell Activity: In-Class Design Problem Guidelines

Calculations & Questions

1. Calculate the power requirement (in watt-hours) needed by the refrigerator.

2. Convert watt-hours to amp-hours (Ah) by dividing the power required by the delivery voltage (i.e. the voltage of the battery system).

3. Determine how many hours of sun are available per day, on average, in your location. Consult the map at your station to find the "solar insolation" (average hours per day of sunlight).

4. Size your PV array: Divide your amp-hour requirement by the number of sun-hours per day. This provides the total amperage needed from your PV array.

5. Calculate the number of cells needed in parallel. Cells in parallel produce current that can be summed. Divide the amperage needed by the current produced by one of your cells in its maximum power mode.

6. Calculate the number of cells needed in series. Cells in series produce voltage that can be summed. Divide the voltage needed by the voltage produced by one of your cells in its maximum power mode.

7. What is the total number of solar cells you need in your photovoltaic array?

8. Based on the cells that you measured in the lab, how big would this solar array need to be (in $m^2$)?

9. If the cells that you measured cost $2 apiece, what would be the cost of this photovoltaic array?

10. What do you think would be an affordable price for people to be willing to use this PV-powered refrigerator, in places where there is no other power source? What do you think is an appropriate size for the PV array to make the whole system most convenient?

11. Based on your homework research and your measurements, what are some possible ways we could reduce both the size and the cost of the PV array required for this refrigerator to make it both affordable and a convenient size?

**Figure 4. Design Problem Guide**

## References

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