Wearable Flexible Solar Cell Charger

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Abstract — **In this paper, a design for a portable-charging T-shirt that utilizes flexible solar cells is proposed. The flexible solar cells are tested in various conditions to determine the best arrangement and design for the shirt. Different filters, circuit configurations, shade levels, angle degrees, and numbers of panels are experimented to collect data about the efficiency of the flexible panels being used. From the tests, the most efficient configuration is determined to be five 6 volts (V) panels connected in parallel, which enabled 5.56 +/- 0.10 V and 0.50 +/- 0.01 amps (A) of current. The design of the shirt contains a chest pocket for the placement of the portable device being charged. On the inside of the shirt is another pouch to hold the perfboard and wires necessary for the technology. Accounting for washability and aesthetic problems, Velcro strips are used to attach the solar cells, and the design is fashion forward. Finally, improvements to the cell's efficiency and practicality are discussed.**

I. Introduction

Flexible solar panels are increasing in popularity because they have a greater variety of applications and are more lightweight than the rigid solar cells that can commonly be found on buildings. A popular trend is to incorporate flexible solar cells onto clothing, known as *wearables*. Doing so would bring greater convenience to daily lives, especially in this digital age when people are nearly inseparable from their devices.

Because these flexible solar cells are significantly lighter and more pliable than conventional plated cells, they are more comfortable when attached to clothing. Currently flexible solar cells have been tested on backpacks, hats, and clothes, but there are still many issues with the products. In this work, a solar cell-powered shirt is prototyped to charge a cellular phone or any portable device that uses a Universal Serial Bus (USB) charger. This device will allow consumers to be able to charge their devices using solar energy.

The properties of the current solar cell technology that are being researched include the washability, durability, and aesthetics of the wearable technology. Other areas of consideration include the design and comfort of the shirt, the placement of wires connecting the solar cells to the device, the possibility of the cells or device overheating, and the low efficiency of the flexible solar cells in certain placements on the shirt.

The goal of this work is to successfully create a shirt that can charge a portable device, while solving the problems associated with the solar cells. The process entailed designing the product and circuitry, testing the flexible solar cells, and implementing the design onto the shirt, and using online materials for reference.

I. Background

A. How Photovoltaic Cells Work

Knowing the science behind solar cells is essential for applying the technology to the intended application. Also referred to as photovoltaic cells, solar cells convert sunlight into electricity. The semiconducting material of the solar cell, traditionally silicon, allows for the absorption of photons from the sun's electromagnetic radiation. The *photoelectric effect*, or photoemission, is the phenomenon that enables materials to absorb photons of light and eject electrons from a metal surface [1].

The choice of silicon as the material of the solar cell is based on the organization of silicon and the ability to create an electrical imbalance within the cell [2]. There are two types of silicon atoms, N-type and P-type; the former has spare electrons and the latter has missing electrons. When N-type and P-type are placed next to one another within the cell, spare electrons from the N-type fill in the spaces of the P-type. An electric field is created as the N-type becomes positively charged while the P-type becomes negatively charged. Thus, when the photons hit the silicon atoms, energy from the photons is transferred to these loose electrons and forces them off of the silicon atoms, as shown in Fig. 1. A flow of electricity can be generated by connecting the n-type and p-type layers with a wire that crosses the depletion zone through which electrons will travel.

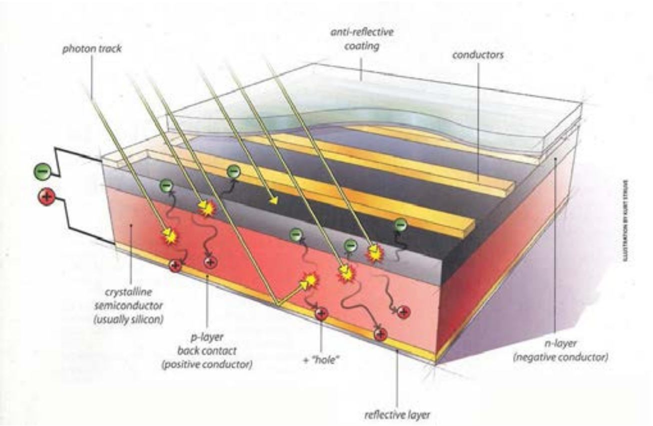

Fig. 1 Diagram of photovoltaic cell

B. Limitations of Flexible Solar Cells

Rigid cells are commonly preferred due to the many limitations associated with flexible solar cells. Because the flexible cells lack structure, they are prone to scratching and tearing from sharp or rough objects. Also, its power conversion efficiency is roughly 1.5-8.7%, whereas the power conversion efficiency of rigid solar panels is roughly 14-22% [6][7]. Therefore, although flexible cells have a lower cost, rigid panels cost less per watt of power. In addition, rigid panels have been developed more extensively, and therefore are more technologically reliable. However, flexible solar cells can provide many advantages, and if developed more, can become a strong source of low-cost, efficient electricity. The purpose of this research project is to overcome some of these limitations associated with flexible solar cells. The panel can be overheated when overworked and can also be uncomfortable when worn. Additionally, although they are waterproof, the cells are still prone to damage, especially during washing.

C. Experimental Materials

The type of solar cell used for this research project was thin-film amorphous silicon from PowerFilm. Thin-film amorphous silicon offers favorable product characteristics such as flexibility, durability, light sensitivity, and temperature resistance. Thin-film solar cells, which are a type of second generation solar cell, use extremely thin layers of semiconductor materials, such as amorphous silicon or non-silicon material, and are therefore flexible and versatile. It contrasts with first generation photovoltaic cells, which are usually made with either monocrystalline or polycrystalline silicon. Currently, third generation solar cells are aiming to improve the cost-effectiveness of photovoltaic systems through new non-silicon materials such as solar inks, dyes, and conductive plastics.

The panels purchased are the 3V and 6V cells pictured in Fig. 2. However, only the 6V ones are incorporated on the final shirt design while the 3V are used for experimental purposes. The 6V panels are 100 mA and the 3V panels are 50 mA. Both panels are printed on a plastic substrate [5] and are rated at around five percent efficiency.

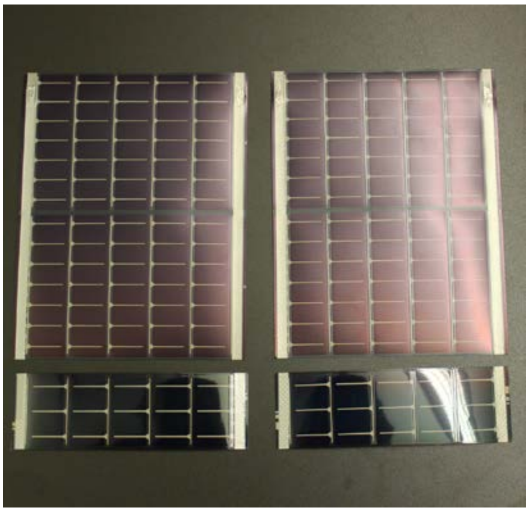

Fig. 2 6V (top) and 3V (bottom)

II. Methodology

A. Design Process

A T-shirt was decided to be the best garment for the purposes of this project because of the practicality and aesthetics. The shirt needs to comfortably house all the components necessary to charge a device while also addressing the issues of washability. To do so, two pockets were incorporated onto the shirt. The one on the outside of the shirt was added to make the shirt more fashionable and to give the wearer a possible place to put the device he or she is charging. The larger pocket on the inside was created to contain all of the hardware and wires. The panels were arranged in a rectangular pattern on the front, which were then wired together. The wire was placed under the shirt through a small hole in the center to contain all the components in the interior pocket.

To fix the issue of washability, the panels were designed to be attached with Velcro, instead of being directly sewn on, allowing them to be removable when the shirt needs to be washed. The electrical components and the wires can also be detached and removed. The initial design can be seen in Fig. 3.

Fig. 3 The original T-shirt design

While the initial design included a battery pack running parallel to a USB charging circuit and to the solar panels, the data on the final product showed that a battery would be unnecessary since the PV cells were able to generate sufficient voltage while in the sun. Due to problems that arose with the addition of the pre-made USB charging circuit in parallel with the circuit, modifications were made in order to achieve a sufficient voltage reading. This was done by removing the pre-made charging circuit and instead creating one through soldering a USB port with wires and resistors.

B. Efficiency Tests

A series of efficiency tests on the panels themselves were conducted to simulate different real-life conditions that the panels could have been put in and to discover the configuration with the maximum efficiency. This was done by altering one independent variable at a time and keeping all other variables constant. They were conducted under different light bulbs in a desk lamp and not the sun, as only relative values for each test were needed to see the general trends in the voltage and current in the designs.

In order to conduct the efficiency tests, a breadboard was used to connect the wires, solar cells, and basic electronic components without soldering. The breadboard configuration for the tests involved a IN5408 diode connected in series with a solar panel, as shown in Fig. 4, with exception to the last test which involved multiple panels connected in either series or parallel.

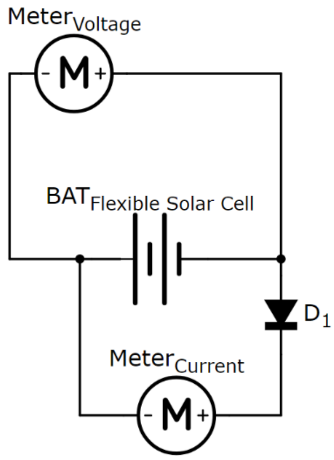

Fig. 4 Circuit configuration of solar cell in series with diode

First, a filter test was carried out to see how the panel's efficiency was affected by different colors of light. Research has shown that dyeing the cells with ruthenium bipyridyl dye allowed for the cells to absorb more wavelengths, such as infrared radiation and red light, which leads to an increase in efficiency [8]. Pink, blue, and clear transparent objects were used as filters and a control with no filter was tested. The control for this experiment involved the lamp at a forty-five-degree angle with a 60W incandescent light bulb and one unshaded 6V flexible solar cell.

Next, a test on how the panels worked in different levels of shade was conducted. The same control as in the filter test was used, as well as the same light bulb. The purpose of the shade tests was to discover how efficient the cells were, even with shade, which could be caused by someone wearing the shirt. Twenty-five, fifty, seventy-five, and one hundred percent shade were all tested, along with the zero percent shade control.

Then, the panels were tested in different angles of light, to simulate the different positions that a person could be in while wearing the shirt. This experiment, which also used only one panel, was conducted in sunlight. The angles tested were 0 degrees, as if a person were lying down, 45 degrees, as if a person were sitting down, and 90 degrees, as if a person were standing straight up.

The last and most crucial experiment was to test the optimal number of panels and how to wire them, either in series or parallel. All the panels were tested under a 19-watt fluorescent light bulb at zero degrees with no filter and no shade. Two to five panels were connected using alligator clips in both types of wirings. From this it was determined that five panels in a parallel configuration was the optimal setup, as it yielded the highest current.

C. Circuitry

A breadboard was first used so that soldering was not necessary. The design is shown in Fig. 5. The circuit was built using the five flexible solar cells in parallel as an energy source that output a voltage of 8V, a diode, a voltage regulator, a light-emitting diode (LED), resistors, and a USB port. The diode, next to the flexible solar cell, was used to keep the current running was one direction. The voltage regulator, next to the diode, converts a voltage greater than 7V to 5V. This part is essential to the circuit because voltages greater than 5 V will damage the phone. The USB port allows users to plug in their own charger. The LED, the first part connected to the output of the voltage regulator, will act as an indicator that will lights up when there is enough voltage. During our test it has been demonstrated that the LED stays lit up even when a phone is charging because this shows that the circuit is running in the right direction. When completed and exposed to the sun, the circuit output a voltage of 5V and .5A.

Afterward, the circuit was transferred onto a perfboard, which made the shirt less bulky. For this, soldering was required to attach the wires to the board. The circuit was the same but the way it was attached varied. This is due to the fact that in a breadboard everything in a row is connected and in a perfboard it is more complicated because different parts are connected to each other.

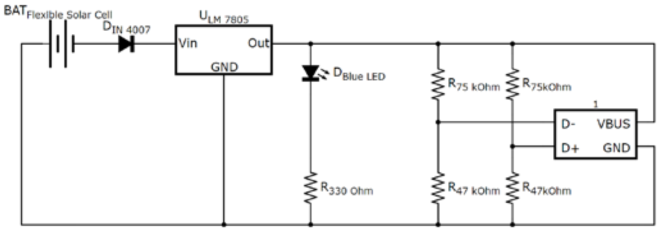

Fig. 5 Circuit diagram of our final circuit design

D. *Construction of the Shirt*

After designing the layout of the shirt, fabric was used to sew the necessary pockets and additions to the shirt. Once the circuit was finalized and tested, the solar panel design on the shirt was added. Considering the wire and perfboard placement, the inside pocket was created. To make the shirt washable, the wires, circuitry, and panels were made removable using Velcro rather than a permanent method of attachment. Alligator clips were also used to connect the wires from the solar panels to the perfboard rather than soldering them permanently. One side of the Velcro was sewn onto the shirt in the correct location, and the other side of the Velcro was attached to the solar panels and inside pocket. In order to make the shirt suitable for charging conveniently, the wires were organized and threaded through a hole to the inside of the shirt. The charging cable was connected and passed to the outside pocket so that the wearer can access the charger easily. Once the placement was confirmed, the circuitry was tested again to confirm that the attachments did not affect the circuit and charging capabilities.

Fig. 6 Final Shirt Design Outside

Fig. 7 Final Shirt Design Inside

III. Results and Discussion

A. *Efficiency Tests Results*

The results from the filter test were that the panel with no filter had the highest voltage and current, as seen in Table I, unlike what the article said. This information caused the conclusion that no dye would be used on the cells.

Filter Test

Filter	Voltage 1 (V)	Voltage 2 (V)	Voltage 3 (V)	Current (mA)
None	5.65	5.67	5.60	.80
Clear	5.18	5.25	5.20	.50
Pink	5.10	5.00	5.15	.50
Blue	4.50	4.49	4.50	.30

Table I Data table from the filter test

From the shade test it was determined that the panel worked in all different levels of shade to some extent, creating less voltage and current with each increasing percentage of shade, as seen in Table II. These results were expected, but it was confirmed that the charger would work even with the panels partially blocked.

Shade Test

% Shade	Voltage 1 (V)	Voltage 2 (V)	Voltage 3 (V)	Current (mA)
0	5.65	5.67	5.60	.80
25	5.00	5.08	4.90	.50
50	4.00	3.86	3.92	.20
75	3.69	3.66	3.68	.10
100	0.47	0.36	0.37	.004

Table II Data table from the shade test

The results of the angle test were that the panels worked almost equally as well at each angle, with slight variations between the three, as seen in Table III.

Angle Test

Angle of Elevation	Voltage 1 (V)	Voltage 2 (V)	Voltage 3 (V)	Current (mA)
0°	8.31	8.29	8.23	42
45°	8.18	8.18	8.23	36
90°	7.98	8.00	8.01	21

Table III Data table from the angle test

In the experiment that tested different numbers of panels and configurations adding the panels in series increased the voltage, but the current remained steady. Conversely, wiring them in parallel increased the current but did not significantly affect the voltage, as seen in Table IV and V.

Series Configuration

# of Panels	Voltage 1 (V)	Voltage 2 (V)	Voltage 3 (V)	Current (mA)
2	10.81	10.78	10.77	0.50
3	15.40	15.40	15.43	0.40
4	23.0	22.9	22.9	0.50
5	28.4	28.4	28.4	0.50

Parallel Configuration

# of Panels	Voltage 1 (V)	Voltage 2 (V)	Voltage 3 (V)	Current (mA)
2	6.05	6.05	6.05	1.1
3	5.68	5.68	5.68	1.7
4	5.88	5.88	5.88	2.3
5	5.56	5.56	5.56	2.8

Table IV and V Data tables from the number of panels tests in both series and parallel configurations

To effectively charge a phone there should be a maximum of 5V and around 1A to 2A of current. The current is important in the amount of time the phone takes to charge. Current is the rate at which charge flows, so the higher the current the faster the device will charge. It was known that no matter the configuration chosen, the voltage requirement would be met, as 6V solar panels were being used and only 5V were needed. Using the information from this test, it was determined that the optimal configuration for the charger would be five panels connected in parallel, as this wiring created the highest current. The voltage that was created by this was sufficient to charge a device and the increased current caused the device to charge in a reasonable amount of time, unlike if they were wired in series.

B. Performance of the Final Product

The first performance test was done on the breadboard using alligator clips to attach the five solar cells to the breadboard in parallel. The voltage coming from the cells was about 8V and the current was about .5A when the sun was out and 7V and .5A when the clouds were covering the sun. In both situations, the charger worked. An Apple phone was then put in to charge but it did not work. This is due to the fact that Apple phones are tailored specifically for Apple hardware.

Afterwards, the parts of the circuit were soldered to a perfboard and the wires were soldered onto the solar cells. To connect the perfboard to the flexible solar cells alligator clips were used to keep the cells removable. The voltage coming from the cells was about 7.8V and the current was about .5A. The drop in voltage was due to the fact that the panels were damaged while the wires were being soldered onto them. Table VI is a data table with the how fast the charger charges.

Number of Panels	Initial Battery Percentage	Time until full charge	Percent charge per hour
1	35%	~22h	~2.95%
4	35%	~4h	~16.25%
5	51%	~1h	~49%

Table VI Data table for time until full charge with Samsung Galaxy S8+

C. Shortcomings and Unexpected Results

The addition of the USB charging circuit (see Fig. 8) in parallel to the circuit configuration led to a significant voltage drop.

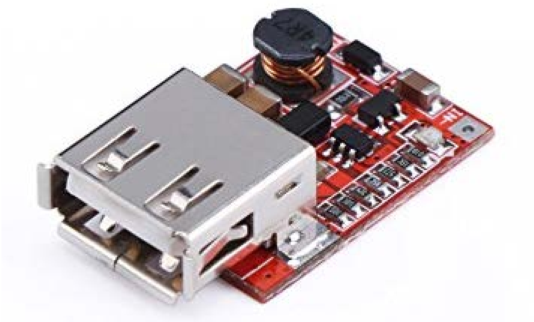

Fig. 8 USB charging circuit

It was assumed that the problem was a high resistance of the diode, so the diode was removed. As predicted, the voltage increased to a sufficient amount. However, when voltage was measured a second time, the voltage was measured to be zero once again. A likely explanation could have been that the voltage exceeded the maximum amount the USB charging circuit could withstand and thus was damaged during the first testing. A voltage regulator was used in the final model to prevent overvoltage from happening again.

After looking at the parts of the USB charging circuit, it was found that it contained a capacitor, which has a very high resistance. This caused the voltage to decrease by a significant amount so that it would not be able to charge a phone. Thus, the plan shifted to making a USB charging circuit without a pre-made chip attached.

One unexpected result was that all tests had been initially done using a portable cell phone power bank, and seeing that it was unable to be charged, it was assumed that the design of the circuit was at fault. However, later results revealed that that the specificity of the power bank was what had prevented the charger from working. This discovery was made upon switching the USB to microUSB cable from the power bank to an Android phone. The power bank was unable to be charged while the phone was successfully charging, with no alterations to the circuit configuration. Another unforeseen result was that the newly created charger worked only with Android phones; for the same reason as the power bank, Apple iPhones have very specific requirements for voltage and current when charging.

D. Comparisons to Existing Technologies

There are limited technologies out there that incorporate flexible solar cells. The cells are mostly used as tarps on RVs and sailboats to generate power while exposed to the sunlight [9]. Most RVs have separate non-solar energy sources, but some environmentally-conscious RVs owners may opt for the flexible cells. However, this is still a small fraction of the market.

Most of the other technologies utilizing these flexible cells in garments are novelty products that are not for sale to the public. Many of the wearables that include these cells are either backpacks or hats.

The design outlined in this paper is unique in that the panels are incorporated onto an actual piece of clothing, and not a removable accessory. There has been a line of garments made by Pauline van Dongen that includes these cells, but only one of each design was made and the product was not available to the consumer market [10]. There have been more of these experimental designs but none of them have been particularly feasible to become available to the public. The design in this paper is relatively cheap, as it is a basic T-shirt and not a designer garment, and works comparatively as well as other flexible solar cell wearables.

E. Further Studies

There are many experimental techniques that have been proven to increase the efficiency of solar cells in lab settings such as spray pyrolyzed aluminum oxide and solar-conducting fibers.

The effects of aluminum oxide deposited onto the panels through spray pyrolysis were explored. In this method, the aluminum oxide solution is sprayed onto the substrate that the panels are printed on, which is heated, causing a chemical reaction to happen between the substrate and the Al_2O_3. This reaction occurs with the iron in a steel substrate and is not tested on other types of backings, although it is assumed that the reaction would not work with other materials. The aim of this is to prevent outside molecules, such as sodium, from diffusing into the solar cells, decreasing their efficiency [11]. The diffused sodium decreases the band gap of the material, making it more conductive, which can disrupt the conduction-insulation balance of the semiconductor. This process would be effective in increasing the efficiency of the solar cells, as the concentration of outside particles would be three times less in the sprayed solar cells than in the unsprayed ones. However, this is not applicable to the specific cells that were used in the experiment described in this paper, as they had a plastic backing and not a steel one. It is possible that if the type of solar cells used in the experiment were changed to steel-backed ones that this technique could be applied to increase the efficiency of the cells.

A new technology that has also recently developed are solar-conducting fibers. These are similar to polyester thread. At the moment, they are very primitive and are only in labs instead of industry. A lab has created a fabric that weaves together these solar-conducting fibers along with piezoelectric fibers. In these fibers a polymer thread is surrounded by layers of copper, then manganese, zinc oxide, and copper iodide [12]. The zinc oxide is the photovoltaic material and the copper helps collect the charge. These shirts are still only in their initial phases of development and cannot produce much electricity, only about 2V/min. This is a promising innovation, if it is expanded on, as it can help fix many of the problems with aesthetics, washability, and bulkiness in the shirt detailed in this paper. In the future, shirts could be sewn with this material instead of having solar cells attached, which would make shirts more attractive and fashion forward.

IV. Conclusion

Flexible solar cells have properties that are appropriate for incorporating into wearables. Five amorphous silicon thin-film solar panels connected in parallel were incorporated onto a shirt, and the energy was used to charge various devices that use a USB charging cable. The shirt was customized to be a convenient charger for cell phones and other devices by adding features such as pockets and aesthetic additions. Various tests were performed to find the most energy-efficient configuration of the flexible solar cells. The circuit design consists of a perfboard that includes a USB port, a diode, a voltage regulator, an LED and resistors. The final shirt design can charge Android cell phones while it is worn.

After testing the final shirt, there were some improvements to the design that could have been implemented for comfort and convenience. Since charging devices can dissipate heat, there is a potential issue with the temperature of the outside pocket if the consumer stores their device in the pocket. To prevent this, a thin cooling pad could be added on the inside of the pocket to regulate the temperature. This problem can also arise on the solar panels themselves, so the cooling pad could be added behind the solar cells as well. Though the number of wires on the inside of the shirt was reduced, the wires still present can cause discomfort to the consumer, so an extra removable layer of fabric could be added between the wearer and the wires. The alligator clips used can be unreliable, so wire caps could be used to increase reliability while retaining the similar quality removability as the alligator clips.

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