An Investigation of Diode Failure

A Senior Project

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May, 2020

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1. INTRODUCTION

With the decreasing cost of solar energy per watt (Kavlak et al., 2018)[i], DC solar electric cooking is becoming increasingly accessible globally. This technology is not dependent on expensive electrical grids, making it available to the most rural and poorest regions. Furthermore, by replacing biomass cooking with DC solar electric cooking, we can reduce greenhouse gas emission (MacCarty et al., 2008)[ii], deforestation, and the 3.8 million annual deaths caused by indoor air pollution (WHO, 2020)[iii].

The cost of DC solar cooking can be reduced in several ways. First, we can eliminate the need for an expensive solar charge controller and power storage system by using the power from a solar panel as it is generated (Grimm and Peters, 2016)[iv]. We can also insulate our cooking apparatus, greatly increasing the thermal efficiency of the system and thereby reducing the number watts of solar electricity required. These steps can reduce the cost of the cooking system to less than 50 USD. We refer to this technology as Insulated Solar Electric Cooking (ISEC) (Watkins et al.,2017)[v].

Solar panels inherently have a fixed maximum voltage (V_{mp}) which is mostly independent of incident sunlight. However, the amount of current a solar panel can supply is dependent on the intensity of the incident sunlight. If a device tries to draw more current than the panel can provide, the voltage of the solar panel will drop to nearly zero. While a resistive heating element is the cheapest option as a heating element, it is only capable of reaching V_{mp} at a single current, meaning that the maximum power will only be extracted from the solar panel at a single solar intensity. An alternative solution is the use of diodes as a heating element, as the voltage drop across a diode is mostly independent of current and temperature. A chain of diodes can be designed to have a single combined voltage drop that will be able to maintain V_{mp} across any given solar intensity, greatly increasing efficiency (Gius et al., 2019)[vi].

Additionally, we can increase the functionality and appeal of the cookers by utilizing the diodes' intrinsic fixed voltage drop to charge small electronic devices. Access to charging cell phones is important to those who live outside of electrical grid coverage (Rao and Shonali, 2017)[vii], as cell service often reaches to places that power lines do not. By adding an integrated cell phone charger to our cookers, we are greatly incentivizing their use. In addition, our design includes a basic rechargeable battery powered lighting system, as it will also encourage cooker usage while helping to reduce pollution from disposable alkaline batteries.

The main drawback of using diodes as a heating element is that affordable diodes are not specifically made for high temperature applications. Diodes are generally rated for a maximum current and temperature, but what happens when those limits are exceeded? Can the limits be stretched? The answers to these questions are key to this project.

2. EXPERIMENT AND BATTERY CHARGER DESIGN

2.1 EXPERIMENT DESIGN

We tested whether diode failure is caused due to excessive current. The diodes (IN5408 rectifier diodes) were submerged in distilled water and subjected to currents far beyond their rating (Figure 1). The distilled water acts as an effective heat sink for the diodes and keeps them at an operating temperature within their original specifications (<100°C) even at currents many times greater than the specs. This eliminates excessive temperature as a potential cause of diode failure. Note that it is necessary to record the amount of current passing through the water itself and subtract it from our readings, in order to obtain accurate data. This was accomplished by measuring the current passing through the water with the power supply leads placed at a fixed distance apart. This same lead separation was used when testing the diodes in the water. In addition, we attached a thermocouple to the diode body to measure the temperature of the diodes when they fail. The diode was then tested by applying an increasing current until failure while recording the temperature and current. Results from this experiment indicated that diode failure is almost totally dependent on temperature.

Next, we needed to determine the critical temperature at which our diodes failed. This was accomplished by attaching a diode to the leads of a power supply and applying a gradually increasing current until the diode failed, as described earlier. Throughout this experiment, the diode body was buried in a jar of sand as a safety precaution in case the diode “popped” and propelled fragments outward (Figure 2). The diode was subjected to a gradually increasing current until it failed, and the current and thermocouple temperature were recorded. This test was repeated until we found a statistically significant “failure temperature”.

The positioning of the thermocouple on the diode was a point of interest over the course of these experiments, as different points on the diode reached different temperatures. Initially, we attached the thermocouples to the junction between the metal diode lead and the plastic diode body - this is the hottest point on the diode. Issues began to arise from this setup, as moving the thermocouple a very small distance (<1mm) from this junction significantly affected the temperature and keeping the thermocouple in this exact location was challenging. In order to make temperature data between different trials more consistent, we attached thermocouples to the center of the diode body (as shown in Figure 1 and 2) using JB Weld (a high temperature epoxy), as the temperature is more uniform in this area.

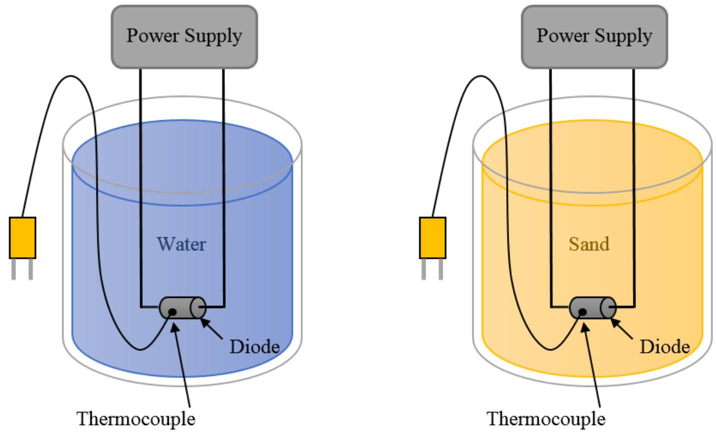

Figure 1 (left) and Figure 2 (right): The testing setup used in the previously described experiments. Both setups had a diode directly connected to a high current power supply and a thermocouple directly attached to diode body to record temperature. Figure 1 shows a diode submerged in distilled water while Figure 2 shows a diode buried in sand.

2.2 BATTERY CHARGER DESIGN

At the most basic level, all that is required to charge a cell phone is a 5V DC power source that can supply at least half an amp. In principle this should be easy to source from the ISEC's diode chain, as placing leads across 6 diodes should yield just over 5V. However, in practice it is not this simple. The voltage drop across a diode varies with temperature and is slightly less when the diode is hot. While this change in voltage is small in individual diodes (about 0.1V), it quickly compounds in a long diode chain. This isn't a major issue for cooking, as we can design our diode chains to run at maximum efficiency when hot, but it is an issue for cell phone charging. If we design our diode charger to provide 5V when cold, then it will provide only 4.5V when hot, which is too low for some phones to charge. If we design our diode charge to provide 5V when hot, then it will provide 5.5-5.7V when cold, which can destroy some cell phones (older phones seem to have less overvoltage protection). This variation in voltage drop over the range of the operating temperature renders the use of the diode as a voltage regulator impractical. We set out to find an alternative means of regulating the voltage externally.

We tried to design our own voltage regulator using transistors and Zener diodes. While this circuit did help regulate voltage, its output was still proportional to the input voltage to a degree that was too great for our purposes. After further research, we decided the best way to create a stable output voltage was to use a voltage regulator chip, also known as a low-dropout regulator (LDO). These regulators are small and cheap when purchased in bulk. They are also capable of supplying a stable output voltage over a wide range of input voltages. Any 5V LDO can be used to create an ISEC phone charger; however not all 5V LDO's are created equal. The ones that can supply higher currents are preferable for charging phones. I chose to use a "STMicroelectronics L7805ACV-DG" as it can provide up to 1.5A at 5V and cost only 0.25 USD when purchased in bulk. A note of caution on using LDO's: it is important to pay attention to the range of input voltages specified for the LDO. The input range for our LDO's was 7-20V. At input voltages below 7V, the output from the LDO began to decrease below 5V and at inputs above 20V the output began to increase above 5V. For this reason, as well as to minimize the amount of energy the LDO must dissipate as heat, it is recommended to supply the LDO with a 7-10V input.

In order to use a stable source of voltage to charge a cell phone, we must connect the LDO's output to a cell phone's charging port. While modern cell phones use different, sometimes proprietary ports (micro-USB, USB-C, Lightning, etc.), all phones can connect to and charge from a standard female USB port via some type of cable. Hence, it is advantageous to connect our LDO's stable 5V output to a female USB port (Figure 3).

A standard USB-A port has four pins: the positive and ground power pins (referred to as "V+" and "V-") and two data pins ("D+" and "D-"). The first step is to connect the LDO's output to the V+ pin and the LDO's ground to the V- pin, which will supply the USB port with its standard 5V. The data pins are responsible for "telling" the cell phone that the USB port is meant for charging or data transfer. Under USB protocols, a Standard Downstream Port (SDP) can supply 0.5A to any connected device. An SDP is usually found as part of a computer system and is primarily used for data transfer. A device will recognize a port as an SDP if the D+ and D- pins are separately grounded through 15kΩ resistors. We want the device to recognize the USB port as a Dedicated Charging Port (DCP), which will allow the device to draw up to 1.5A. USB protocols dictate that DCP's are recognized by a short between the D+ and D- pins, however, upon examination of multiple real world DCP's, we have found that there is a very small (<50Ω) resistor between the D+ and D- pins.

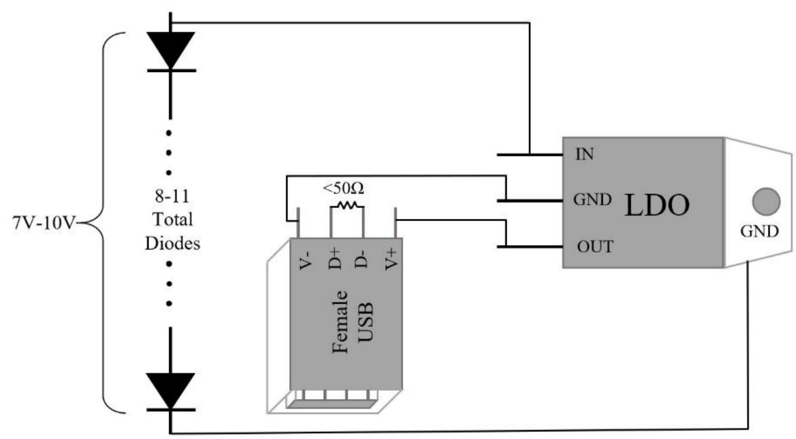

Figure 3: A circuit diagram of the ISEC phone charging circuit connected to the ISEC's diode chain.

A word of caution on using USB ports. When soldering the LDO outputs to the female USB's power pins, it is important to check for continuity within the female USB itself. To elaborate, some female USB have their V+ and V- pins crossed over inside the port, so that the rightmost pin on the back of the USB is connected to the leftmost pin inside the USB. If this is the case and you do not correct for this issue when soldering, the charger will not work.

Additionally, some phone manufacturers (like Apple), have a proprietary method of using the data pins to initiate faster charging or to control the amount of current a charging phone will draw. Although manufacturers often do not publish their proprietary charging protocols, analysis done by enthusiasts has shed some light on the matter: Apple uses a series of voltage dividers to set each of the data pins to a different, specific voltage, which correspond to the amount of current the device will draw. Designing a charger that will work with proprietary charging standards would be too costly, and realistically we may not want to enable fast charging in modern cell phones, as many of them use a significant enough amount of current that it may impact the cooker's performance.

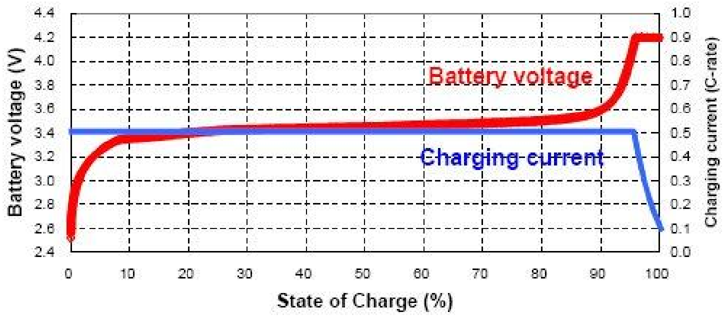

Figure 4: Charging Diagram of a single cell LiFe battery

Upon further research, we found that a potential cheap alternative to using the LDO charging circuit are pre-made phone chargers designed to stabilize a higher DC voltage, specifically car chargers. While not as cheap as purchasing LDO's in bulk, car chargers are designed to take roughly 12V DC and convert it to 5V DC. Car cell phone chargers must also be able to work given a range of voltages, as car batteries are nominally 12.6V and regularly reach nearly 15V when the car is running. Many car phone chargers regulate voltages using an LDO or similar technology.

2.3 RECHARGABLE LIGHTING SYSTEM DESIGN

The rechargeable lighting system is built around a Lithium Iron Phosphate ($LiFePO_4$ or more simply LiFe) battery. This type of battery was chosen based on its ease of charging, low cost, and overall resilience. A single LiFe battery cell maintains a nominal voltage of 3.3V. This means that a LiFe battery will output anywhere from 2.5-3.6V. A LiFe battery can also be force charged by applying an overvoltage until it reaches 4.2V (Figure 4). We can charge a single cell LiFe battery using a 5V USB port by placing it in series with a single rectifier diode, as the diode will act as a simple charge controller by cutting off current when the battery reaches 4.2V. Creating a lighting system using a LiFe battery has other benefits. Many LED's, particularly white LED's designed for lighting applications, have a voltage drop of about 3.3V. This is ideal for our system, as a single LED can be directly connected to the battery without risk of burnout while also preventing the battery from being drained below the 2.5V minimum. This allows us to connect many (10-20) LED's in parallel, which creates an adequate lighting system similar in function to a lantern.

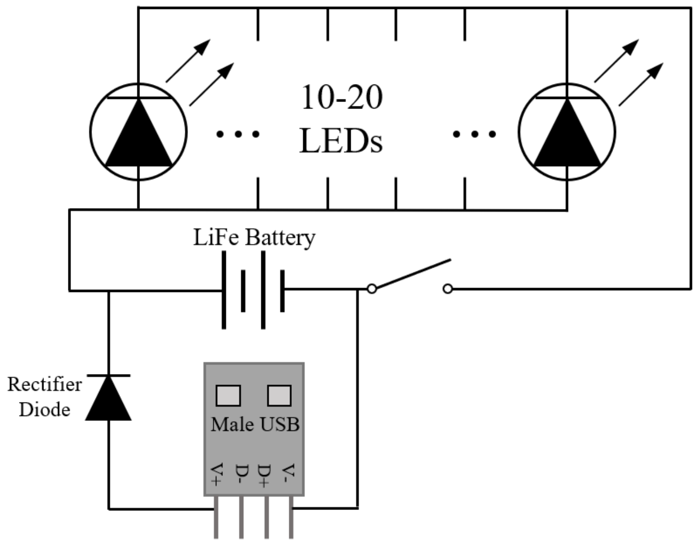

Figure 5: Circuit diagram of LED lighting system, including the LiFe battery and recharging system.

3. DATA ANALYSIS AND RESULTS

We found that diode failure is dependent entirely on temperature, as diodes that were cooled using distilled water were able to withstand close to 50A despite its 3A rating. The data from one of these tests can be seen in Figure 6. The data indicates that the current and temperature of the

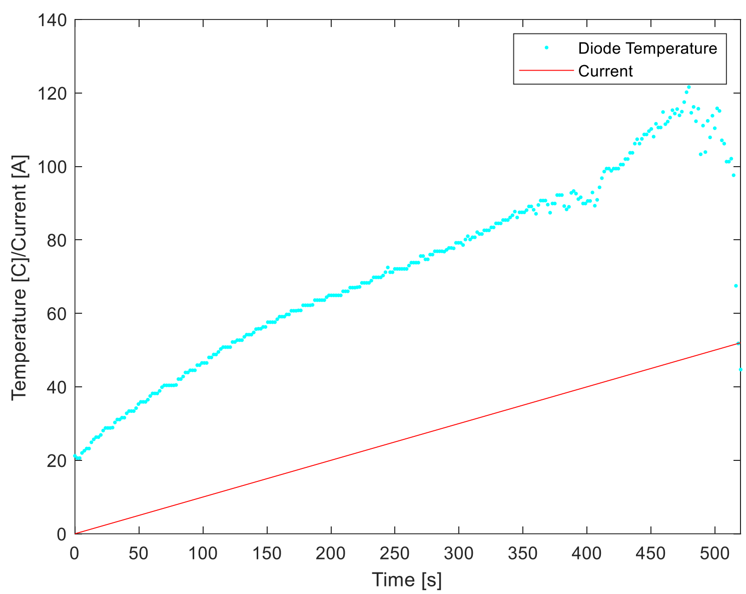

Figure 6: A graph of diode temperature and current vs time from a water-diode test. Data collection ended with diode failure.

diode are nearly proportional. This specific diode was able to withstand almost 45A. The temperature of the diode began to fluctuate and drop once it passed 100°C, while the current was still increasing. This was caused by the diode beginning to fail and subsequently die, as the last few temperature data points fell to 30°C (Figure 6). The reason for this temperature fluctuation must be a change in the voltage drop across the diode, as the increasing current cannot be responsible for a decrease in dissipated heat. The behavior of the voltage drop across a diode can be seen in Figure 7. As the diode was heated, the voltage across it decreased due to internal

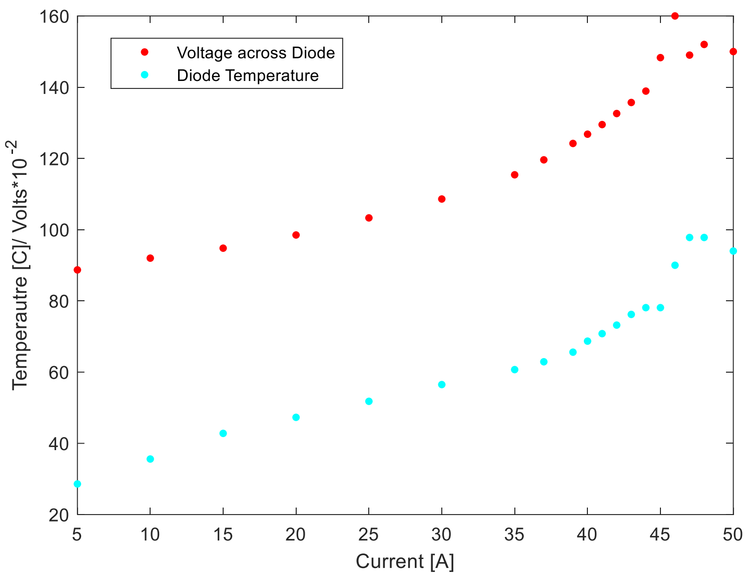

Figure 7: A graph of diode temperature and voltage drop vs current from a water-diode test. Data collection ended with diode failure. Note the changing rates in the increasing voltage drop across the diodes.

effects. At the same time, the voltage across the diode slowly increased with the greatly increasing current. These phenomena combined with the linearly increasing voltage drop due to the resistance of the power supply cables leads to a linear voltage increase between 5 and 30 amps. Once the diode reaches roughly 35 amps, the voltage begins to increase more rapidly, indicating that the voltage drop across the diode must be increasing at a greater rate. This anomalous behavior is the very first sign of diode damage, as higher current and temperatures lead to an even greater spike in the voltage drop across the diode. After this spike, we can see the voltage drop and temperature begin to fluctuate and fall, indicating diode failure.

Our second test yielded the failure temperature of our diodes. We buried the diodes in sand giving us a definitive failure temperature. Sand does not have the thermal conductivity of water. This allowed the diodes to heat up and “cook” until they reached a temperature at which they began to fail. Due to the failure properties of diodes (discussed later), care was taken to determine the exact failure point of the diodes. This was accomplished by letting the diodes heat up, remain at a fixed temperature for several minutes, then cool down. The diodes were then slowly reheated to an even higher temperature, while observing the current vs voltage relationship. This process was repeated until the diode visibly failed or did not retain its original current vs voltage relationship. This process was repeated many times in order to find an average failure temperature for our diodes (Figure 8). We found that diodes failed at an average

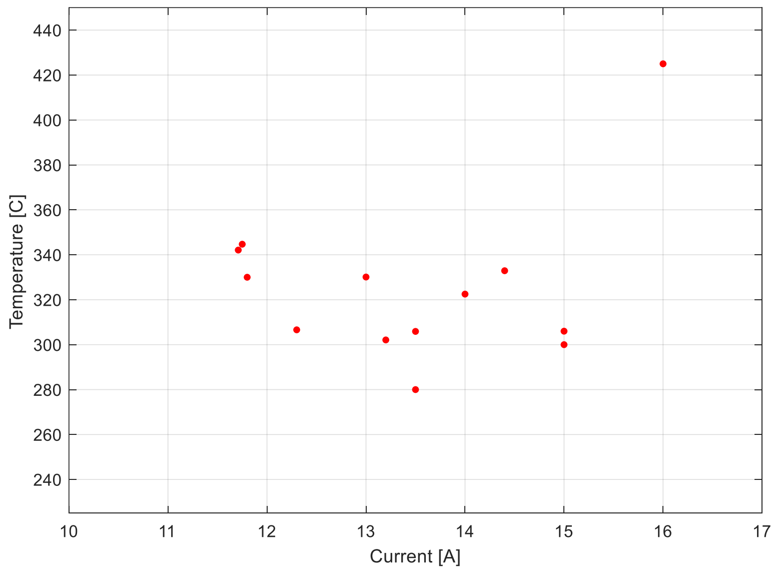

Figure 8: Failure point from multiple diode failure tests. Each point represents the failure of a diode at a given current and corresponding temperature. This data was taken in collaboration with Andre Li.

temperature of about 275°C, which led us to classify any running temperature below 250°C as safe, ensuring that failure is unlikely even with repeated uses.

There appears to be a discrepancy between this data and that of our water tests where the diodes failed around 100°C. While in the water tests the external temperature of the diode remained below 100°C, the internal temperature was far greater. The diode was dissipating almost 80W of heat while being cooled effectively by the water. This testing also revealed some interesting properties of diodes and the way they fail. Diodes would usually begin to show physical signs of failure around 250°C, starting by smoking and developing small cracks in the body. Higher temperatures caused more drastic failures, including increased smoking, diode bodies breaking in half, and diodes oozing a clear liquid. The electrical properties of damaged diodes are also of interest. Exposure to high temperatures (above 250°C) begins to affect the way a diode responds to voltages. The diodes in our test were biased so that they started to allow current to flow around 0.8V. Many “failed” diodes continued to operate, but would experience a change in bias level, allowing current to start flowing at much lower voltages (in some examples even 0.1V).

The amount that the biasing changed varied diode to diode but was only noticeable at low voltages; at higher voltages the voltage drop stabilized between 1V and 1.5V. In the case of extreme damage (being subjected to over 350°C), diodes lost all biasing and acted like simple resistors, with the current flowing through them being proportional to the voltage applied across them.

4. CONCLUSION

Diodes provide a promising solution for ISEC; the combination of their low price and high efficiency is ideal. Through this experiment, we were able to show that diodes fail from high temperatures rather than from exceeding their specified maximum current. We determined that maximum safe operating temperature of our diodes is below 250°C, making them suitable for our cooking applications. Diode cooking chains can also be used to charge USB compatible devices using an LDO (low-dropout regulator). This provides the necessary voltage stabilization to safely charge electronic devices while maintaining affordability. Additionally, $LiFePO_4$ batteries synergize well with LED lights, providing a safe, cheap, and reusable source of lighting using the ISEC USB charger.

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