Silicon Photomultipliers: Characterization and Cosmic Ray Detection

by

Joshua Heller

Presented to the faculty of the
Department of Physics

Brandeis University

In partial fulfillment of the
requirement for the degree of the
Bachelor of Science

Jim Bensinger and Bjoern Penning, Advisors

Contents

Abstract

Silicon photomultipliers (SiPM) are smaller than many conventional photomultipliers, have a lower avalanche voltage, and are capable of single-photon detection, making them a viable candidate for experiments requiring sensitive light detection. We determine several properties of the ON Semiconductor C-Series SiPM, size 6mm x 6mm. The avalanche voltage, the voltage at which the SiPM gain begins to increase rapidly, is measured both in room light and near-darkness. We then use a lightproof box to measure the dark current for various bias voltages. Finally, we use a function generator to flash an LED against the image sensor, and measure the response pulse heights at several SiPM bias voltages. Based on these three characteristics, we suggest that the ideal working bias voltage range is between 26V and 27V. To further test the functionality of the SiPM, we seek to detect cosmic ray muons. We place scintillator plastic against the image sensor, with the expectation that muons passing through the scintillator will generate a shower of photons. Measuring in total darkness, we see pulses several orders of magnitude larger than the dark current pulses at a frequency consistent with muon flux rates. By arranging two SiPM-scintillator sets one above the other, we observe simultaneous pulses, indicating that a single muon has passed through both.

Introduction

Silicon photomultipliers (SiPM) are a type of photomultiplier employing an array of silicon photodiodes in series with quenching resistors. They are capable of single-photon detection and are much smaller than a typical photomultiplier tube, with area on the order of $10mm^2$ [1]. In our experiments we use the ON Semiconductor C-Series SiPM, size 6mm x 6mm. These are surface-mount chips and are capable of detection in the UV and visible light spectrums [2]. The avalanche voltage, the voltage at which the gain of the SiPM spikes due to displaced semiconductor electrons knocking other bound electrons free, begins around 25V. This is conveniently lower than many photomultipliers which require bias voltages orders of magnitude higher.

We begin this project with an investigation of several properties of the SiPM. The first of these is the aforementioned avalanche voltage, which we determine by comparing the bias voltage at which current levels increase rapidly in room light and a low-light environment. The second is the dark current, which is the background current generated within the SiPM as a result of spontaneously excited thermal electrons. This is measured in a lightproof enclosure, to be certain that no ambient light contributes to the measurement. The third property is the output pulse height of the SiPM an LED is shone upon the image sensor. To characterize this response, we vary the voltage applied to the LED as well as the SiPM bias voltage.

The second part of this experiment aims to detect cosmic rays using scintillator plastic and SiPMs. Cosmic rays are fast-moving, high-energy particles from space which, following collisions in the atmosphere, arrive at earth's surface as muons [3]. When the energetic muons enter the scintillator plastic, a shower of photons is produced. This burst is then observed as a SiPM pulse. By arranging two SiPM-scintillator pairs, one atop the other, we can observe coincidental SiPM pulses as a muon passes through both pieces of scintillator plastic on its earthbound trajectory. Analysis of the coincidence frequency and pulse height distribution would enable further study of muon frequencies and energies. Unfortunately, our project is forced to conclude before we can gather data.

Setup

Because the SiPM detects and responds to visible light, most controlled experiments require an environment of total darkness. Unless we state otherwise, all of our experiments are performed inside of a dark box – a box which, when sealed, allows no external light to penetrate to the interior. We use a plastic toolbox from McMaster-Carr as our box, but this alone does not sufficiently block all light. For this reason, when complete darkness is required, we also wrap the relevant devices inside in Thorlabs blackout fabric [4] and seal the fabric edges with tape. When, in later sections, we say that the dark box is 'sealed', we mean that the devices inside have been wrapped in the fabric and taped. The SiPM bias voltage is provided by a benchtop power supply.

Figure 1 – From left to right: SiPM chip mounted on breadboard in toolbox, breadboard wrapped in fabric, closed box.

Throughout our experiments we use two different circuit boards for mounting the SiPM chip. The first is a small breadboard with pins to connect wires to the bias voltage and output SiPM lines [Figure 2]. This board suffices for applications in which we are not reading out SiPM pulses but only taking measurements using an ammeter. We use this board for the sections on avalanche voltage and dark current. For reading out pulses on an oscilloscope, we use a different board [Figure 3]. On this board, the SiPM output leads to a BNC connector, which can plug directly into the oscilloscope. The circuit diagram for the latter board is presented in Appendix 2 [Figure 9]. We use this board for the sections on pulse height vs bias voltage and cosmic ray detection.

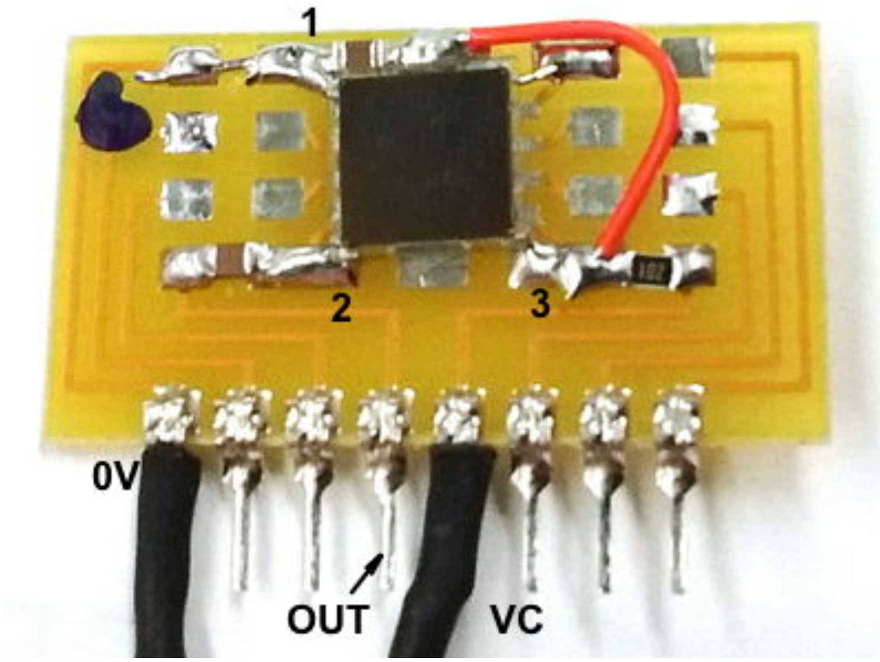

Figure 2 - SiPM chip mounted on breadboard. Bias voltage is applied through the wires labelled ‘0V’ and ‘VC’. Labels ‘1’, ‘2’, and ‘3’ refer respectively to the anode, fast output, and cathode pins of the SiPM chip. The SiPM fast output current flows through the pin labelled ‘OUT’.

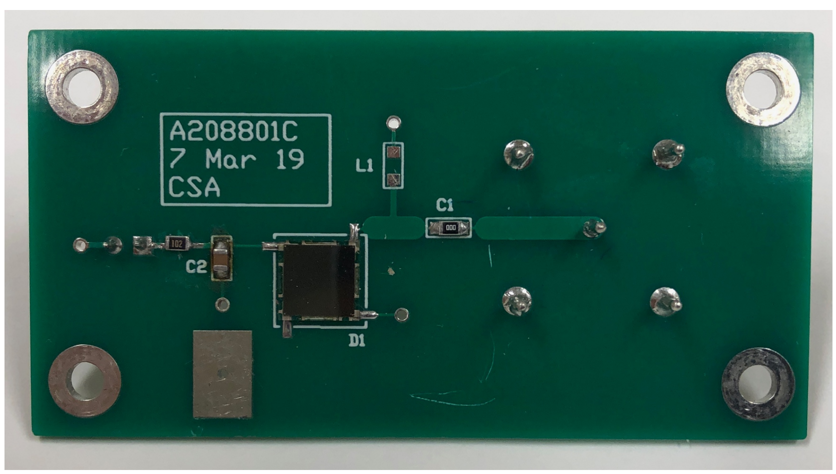

Figure 3 - SiPM chip mounted on printed circuit board. BNC and Molex (for bias voltage wires) connectors are on the back of the board.

Avalanche Voltage

When a photon strikes the photodiode, it is absorbed by the semiconductor material. If the absorbed photon is sufficiently energetic, it will ionize a molecule, producing an electron-hole pair in the semiconductor lattice. At a sufficiently high bias voltage, this displaced electron will accelerate, transfer kinetic energy to adjacent molecules, and displace more electrons. These in turn will accelerate in the field and continue the process [5]. The result is an exponential increase in electrons, an "avalanche", which is read out as a pulse. Therefore, the bias voltage at the point at which the displaced electrons begin to multiply is referred to as the "avalanche voltage". This is the voltage at which we can begin to observe light pulses from the SiPM.

We measure the avalanche voltage in two ways: in room light and in near-darkness. Room light may saturate the image sensor, so measuring also in near-darkness allows for a comparison. To achieve near-darkness conditions, we place the SiPM in a closed plastic toolbox but do not seal the box by wrapping the breadboard in lightproof fabric. We read out both room light and near-darkness measurements of the output current on an ammeter. We slowly increase the bias voltage until we see a spike in the output current, indicating a multiplication of the displaced electrons which produce an avalanche. Plots of both the room light and near-darkness cases are shown below.

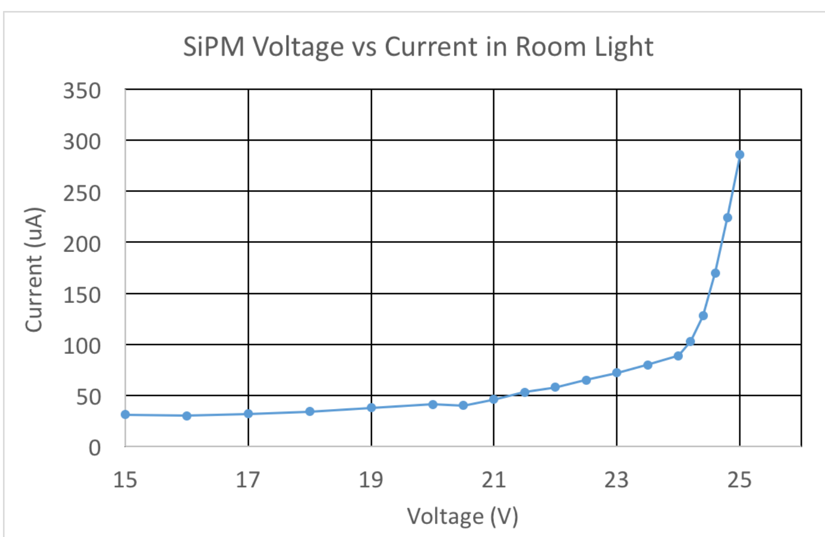

Figure 4 - Avalanche voltage in room light – bias voltage is increased with the SiPM exposed to room light, and the output current is measured.

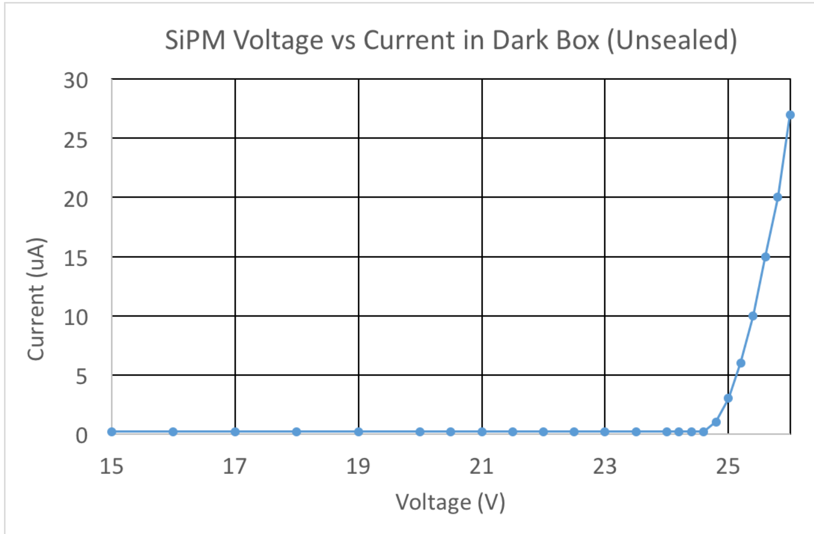

Figure 5 - Avalanche voltage in near-darkness - bias voltage is increased with the SiPM placed in the unsealed dark box, allowing some light in, and the output current is measured.

We find that, in room light, the current begins to increase around 21V. The spike in current does not occur until we reach 24.2V. In near-darkness, the current spike begins at 24.8V. The datasheet records the expected avalanche voltage as being between 24.2V and 24.7V (see Appendix 1, 'Breakdown Voltage'). Our value for room light then matches the lower bound of the datasheet's expectation, which can be explained by the relatively bright environment furnishing constant higher-energy photons. The value of 24.8V in near-darkness lands just over the upper bound of the datasheet. This is the value we reference during our remaining experiments, since they are all done in near or complete darkness.

Dark Current

Thermal noise leads to the production of electrons in the photodiode avalanche region. These electrons are not produced by the light source and are generated even in total darkness. The consequence is a small current flowing through the SiPM even when no light source is present. Therefore, when using the SiPM in low-light applications, the dark current is a source of background noise which must be taken into consideration. Dark current is dependent upon both temperature and the bias voltage applied to the SiPM. A higher temperature will result in a greater quantity of thermal electrons generated in the avalanche region, and an increased bias voltage will result in more of the thermally-generated electrons triggering an avalanche and thereby producing a pulse.

We investigate the relationship between the bias voltage and the dark current for our particular SiPM device. For this experiment the SiPM is put in the sealed and light-tight dark box. The output current (see 'OUT' in Figure 2) is the object of our measurement. Because the dark current is very small, on the order of 10nA, we were unable to measure it using an ammeter. Instead, we use a 1-megaohm resistor bridging the inverting input and output of a TL081 op-amp [6], connect the SiPM output to the inverting input, and ground the noninverting input. A photo of the setup [Figure 6] is shown below, and the circuit diagram for the SiPM and op-amp circuit is found in Appendix 2 [Figure 10].

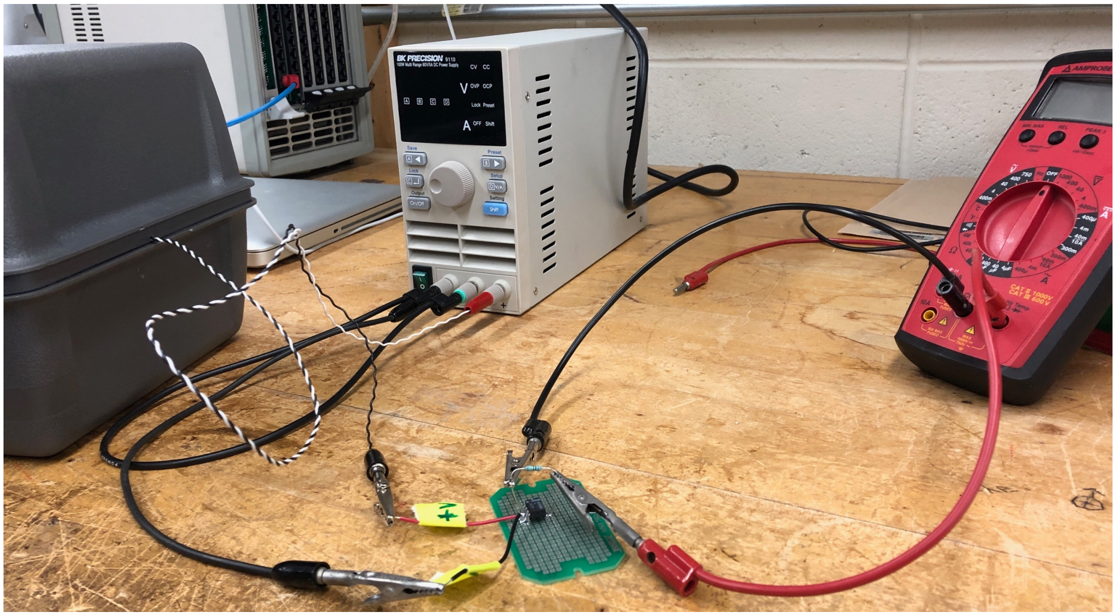

Figure 6 - Dark current measurement setup. The SiPM is sealed in lightproof fabric and the bias voltage is provided by the power supply. The SiPM output leads to the op-amp setup, normally powered by a second supply. Resistor voltage is read on the ammeter.

We then measure the voltage across the resistor and use Ohm's law to determine the current. This is repeated for several bias voltages; the results are plotted below [Figure 7].

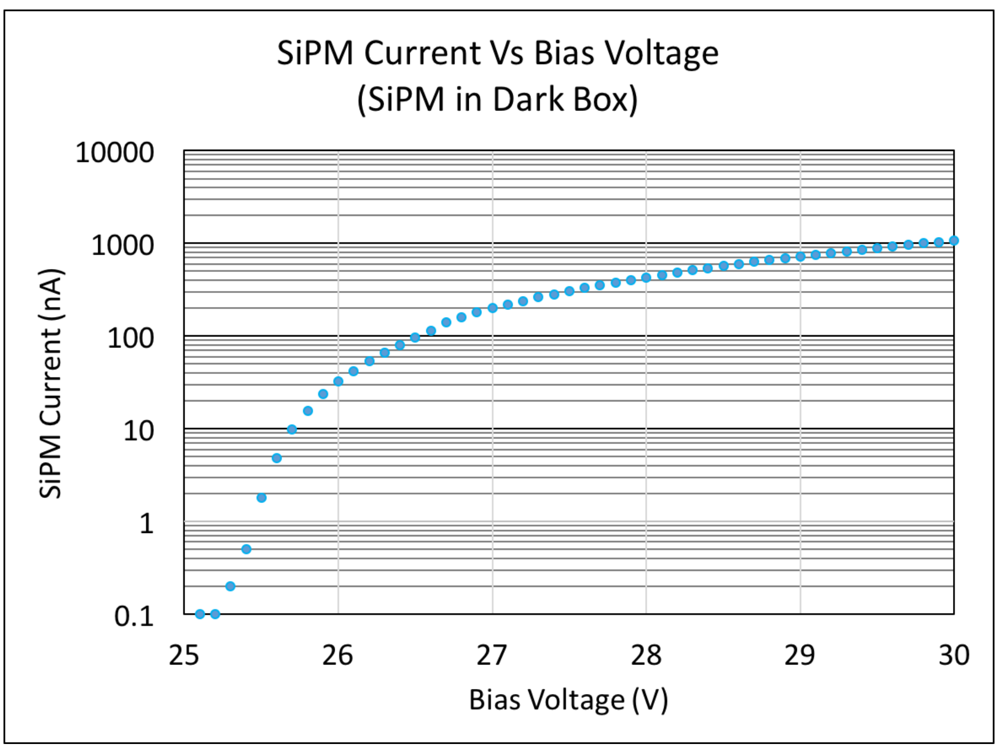

Figure 7 – Dark current vs SiPM bias voltage. Bias voltage is increased with the SiPM sealed in the dark box, and the output current is measured.

We observe, as expected, that the dark current begins to increase near the avalanche voltage. The datasheet records the typical dark current measured at 2.5V above avalanche voltage as being 618nA (see Appendix 1, 'Dark Current'). For our recorded avalanche voltage of 24.8V, an additional 2.5V brings us to 27.3V, where we measure a dark current of 260nA. While this is less than half the data sheet's expected dark current value, this does give the proper order of magnitude in an exponentially-increasing trend.

Pulse Height Vs Bias Voltage

Having established the dark current as our expected background in the dark box, we are ready to characterize the response of the SiPM to flashes of light. We place a blue-light through-hole LED against the SiPM image sensor and seal this setup in the dark box. The LED is powered by a function generator. When we flash the LED with the function generator, we can read out the SiPM pulses on an oscilloscope.

However, the SiPM pulses are very short and very sharp (600ps width [2]), making them difficult to observe on the oscilloscope. Because of this we connect the SiPM output to a shaper-amplifier designed at our lab. The amplifier provides a steady gain and the shaper extends the duration and decreases the amplitude of the pulse while preserving the area. The pulse is then wider and shorter on the oscilloscope readout. A full explanation of the shaper-amplifier's area-preserving property is given in citation [7], and the circuit diagram is presented in Appendix 2 [Figure 11].

With the SiPM and LED both in the sealed dark box, we use the function generator to produce short pulses of LED light against the image sensor. The pulses are 12ns and are emitted at a frequency of 10kHz. At this frequency the amplifier gain is 46. We find that the LED turns on at a bias voltage of roughly 2.1V, so we set our function generator pulse to operate with a 2.0V offset. With a bias voltage above the avalanche voltage applied to the SiPM, we increase the voltage across the LED (which brightens the light) until we can observe a shaped pulse rising above the dark current noise. The shaped pulses are about 100ns in duration and are easy to read out. We use the oscilloscope to record the height of five shaped output pulses at this LED voltage, taking the average of the five. Then, we increase the LED voltage by 0.01V, and record five more pulse heights, once again taking their average. We repeat this procedure for a total of ten LED voltages, and across a range of five SiPM bias voltages. The results are found below in Figure 8.

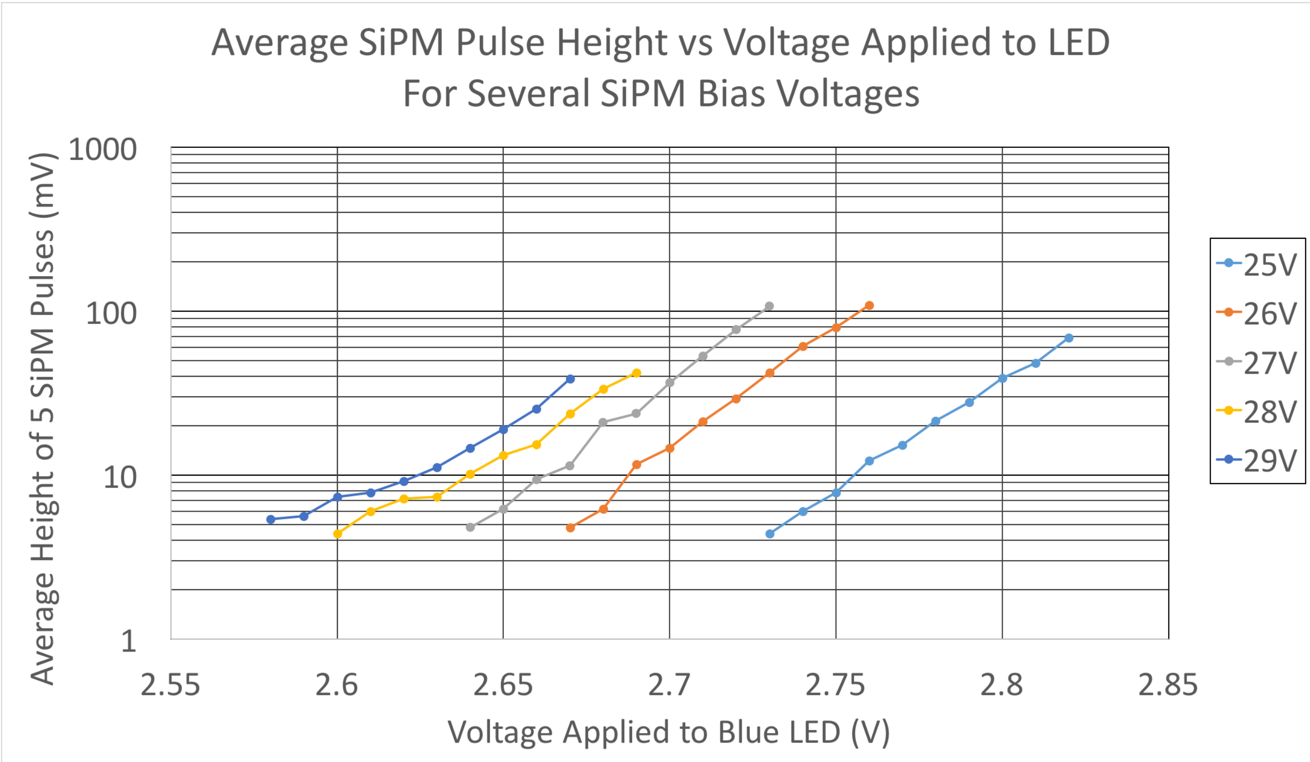

Figure 8 - Average SiPM pulse height vs voltage applied to LED for several SiPM bias voltages. Legend indicates color key for different bias voltages.

We find that the relationship between LED voltage and SiPM pulse height is nearly exponential for each of the SiPM bias voltages. By fitting the logarithmic curves to a linear approximation in Excel, we can determine how closely the SiPM pulse heights follow an exponential trend as LED voltage increases.

Bias Voltage (V)	R^2 value for linear fit
25	0.998
26	0.995
27	0.995
28	0.978
29	0.960

Based on our R^2 values, all of our curves display a very nearly exponential trend. However, the values consistently decrease with increasing bias voltage. Considering this result, our knowledge of the avalanche voltage, and our dark current measurements, we can suggest an ideal working range for the SiPM bias voltage. At 25V, though the trend shows the most nearly exponential behavior, we are too near the avalanche voltage, and the gain is too low to maximize SiPM sensitivity and detect flashes of only a few photons [Figure 5]. Upwards of 27V, the background dark current is higher [Figure 7] and the exponential behavior begins to break down. We conclude that the ideal working range for the bias voltage is from 26V-27V, where we strike a balance between dark current and exponential behavior.

Cosmic Ray Detection

Our final experiments in this project are aimed toward the detection of muons from cosmic rays. Cosmic rays are high-energy particles, mostly protons (89%) but occasionally helium (10%) and heavier nuclei (1%), arriving from outer space. Most of the lower-energy rays originate in the sun. The origin of the higher-energy rays is a source of speculation, though some likely come from supernovae remnants. Upon reaching earth's atmosphere, cosmic rays collide with atmospheric particles and create showers of pions, which quickly decay into muons 3]. The muons which arrive at the earth's surface mostly come from cosmic rays with energy of about 1GeV. The flux rate for these muons is about 10,000/m^2/s. For cosmic rays of 1,000GeV, the flux rate drops to 1/m^2/s [8].

To detect the cosmic ray muons, we make use of scintillator plastic. When a muon strikes the scintillator, a shower of photons is produced. A wavelength-shifting material in the plastic absorbs the photons and reemits them in the visible light spectrum, where they can be detected by the SiPM. We place the scintillator plastic, a 5cm x 5cm x 0.5cm piece, flat against the face of the SiPM chip. We then wrap the SiPM and scintillator in aluminum foil to reflect the maximum number of photons onto the image sensor. This object is then placed in the sealed dark box.

The scintillator plastic face is 25cm^2. Based on the flux rate, if every muon which struck the scintillator plastic was detected by the SiPM, we would expect 25 hits per second. However, the face of the SiPM image sensor is only 0.36cm^2. If only the muons which passed through the scintillator directly over the image sensor area were detected, we would expect 0.36 hits per second. On the oscilloscope, with a SiPM bias voltage of 28V, we observe shaped pulses with heights ranging from 20mV to 500mV roughly every 10 seconds. These pulses are far too large to be attributed to the dark current, and light leakage would not produce such irregular pulses. The frequency is lower than expected, but this may be attributed to our location in the building basement, beneath several layers of thick concrete floor.

To be certain that we have really observed muons, we take two foil-wrapped SiPM-scintillator devices and place one on top of the other in the dark box. We read them out separately on the oscilloscope. Our intention is to observe simultaneous pulses, which would indicate that a muon passed through both pieces of scintillator on its trajectory. We do observe several of these coincident pulses. Unfortunately, our ability to take data is halted at this time by unrelated circumstances (coronavirus). Given this lack of data, we must limit ourselves to stating that this setup showed promise for further detection and characterization of cosmic ray muons.

Our next steps would have been to collect data on the frequency vs pulse height of the pulses, and to attempt calculations of the energy deposited by the muons when passing through the scintillator plastic. We also planned to build a cosmic ray telescope: a stack of several SiPM-scintillator devices, rather than only two. With this, we might have been able to see muons decay within the stack, and to calculate angular distributions of their trajectories.

Appendix 1 – SiPM Datasheet

Sensor Size	Microcell Size	Parameter (Note 1)	Overvoltage	Min.	Typ.	Max.	Units
1 mm	10μ, 20μ, 35μ	Breakdown Voltage (Vbr) (Note 3)		24.2		24.7	V
3 mm	20μ, 35μ, 50μ						
6 mm	35μ						
1 mm	10μ	Dark Current (Note 6)	Vbr + 2.5 V		1	3	nA
	20μ				5	16	nA
	35μ				15	49	nA
3 mm	20μ				50	142	nA
	35μ				154	443	nA
	50μ				319	914	nA
6 mm	35μ				618	1750	nA
1 mm	10μ	Dark Count Rate	Vbr + 2.5 V		30	96	kHz
	20μ				30	96	kHz
	35μ				30	96	kHz
3 mm	20μ				300	860	kHz
	35μ				300	860	kHz
	50μ				300	860	kHz
6 mm	35μ				1200	3400	kHz
1 mm	10μ, 20μ, 35μ	Signal Pulse Width – Fast Output (FWHM)			0.6		ns
3 mm	20μ, 35μ, 50μ				1.5		ns
6 mm	35μ				3.2		ns
1 mm	10μ, 20μ, 35μ	Temperature dependence of Vbr			21.5		mV/°C
3 mm	20μ, 35μ, 50μ						
6 mm	35μ						
1 mm	10μ, 20μ, 35μ	Temperature dependence of Gain (Note 10)			–0.8		%/°C
3 mm	20μ, 35μ, 50μ						
6 mm	35μ						

All information taken from [2] on Works Cited list. We use the 6mm sensor size SiPM.

Appendix 2 – Circuit Diagrams

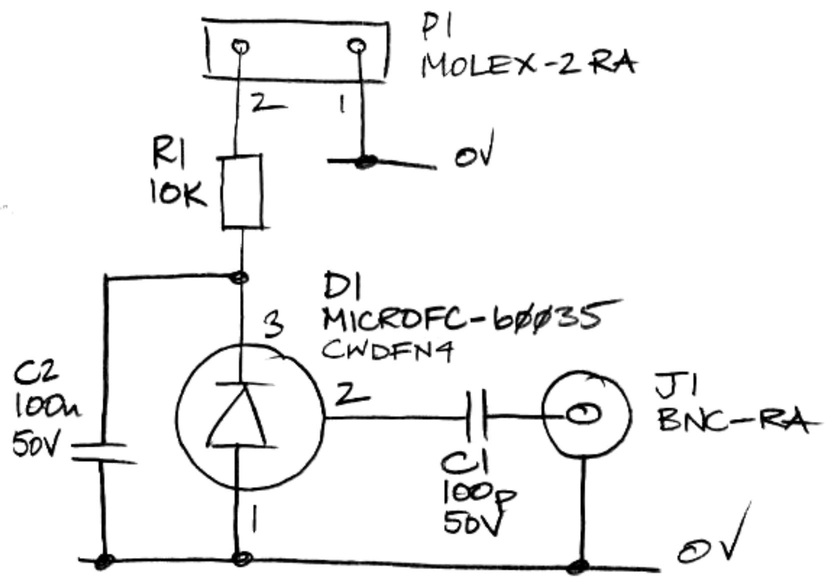

Figure 9 - Circuit diagram corresponding to SiPM board found in Figure 3. Drawing and design by Kevan Hashemi.

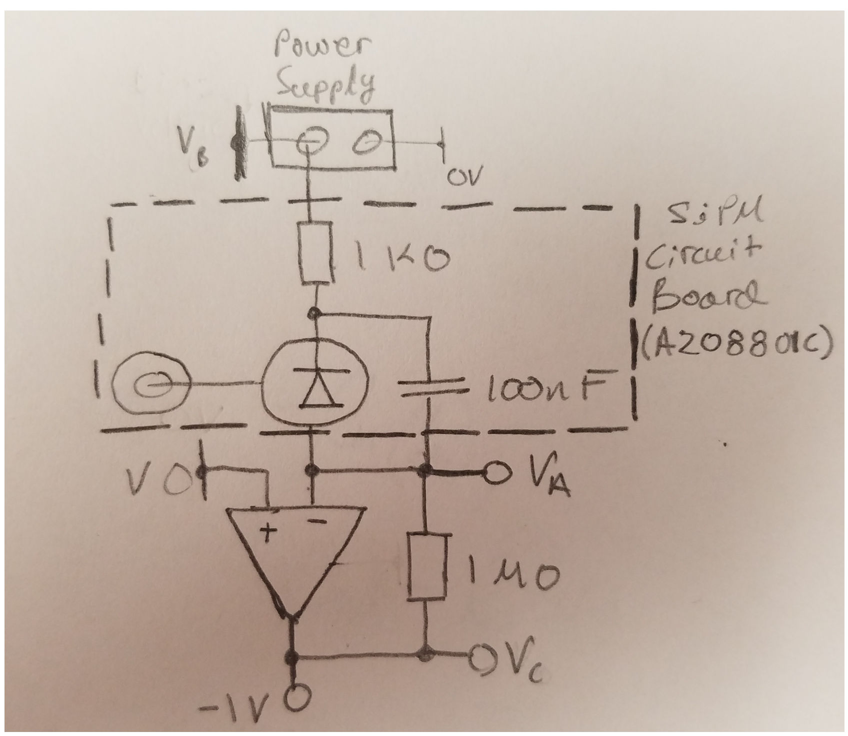

Figure 10 - Circuit diagram for SiPM board shown in Figure 2 and op-amp setup. Drawing by Chris Armstrong.

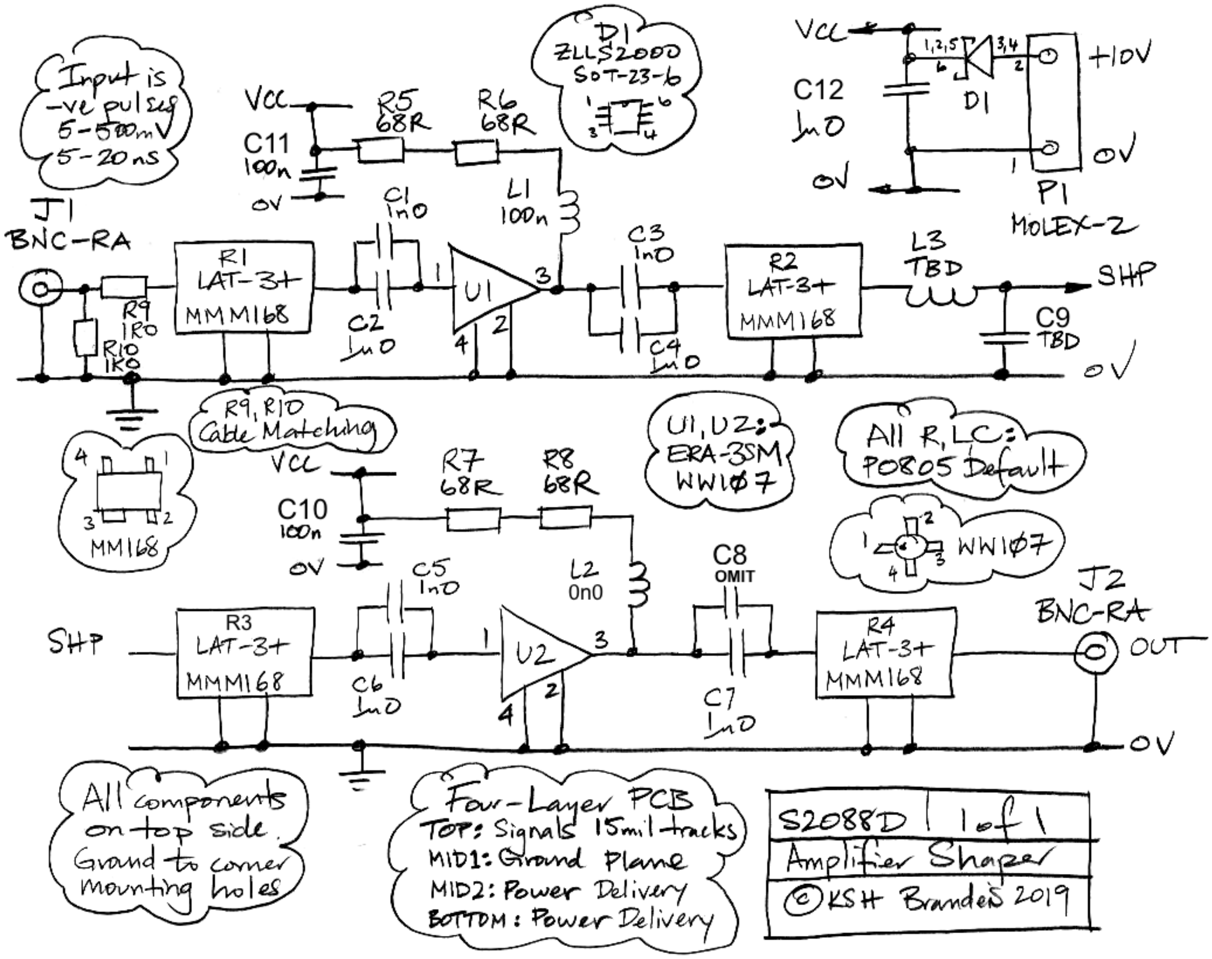

Figure 11 - Shaper-amplifier circuit diagram. Drawing and design by Kevan Hashemi.

Works Cited

1. "SiPM WORKING PRINCIPLE." *KETEK GmbH*, 25 Apr. 2017, www.ketek.net/sipm/technology/working-principle/.
2. Semiconductor Components Industries, LLC. "MICROC-SERIES - Silicon Photomultipliers (SiPM), Low-Noise, Blue-Sensitive." *ON Semiconductor*, Semiconductor Components Industries, LLC, Nov. 2018, www.onsemi.com/pub/Collateral/MICROC-SERIES-D.PDF.
3. "Cosmic Rays: Particles from Outer Space." *CERN*, home.cern/science/physics/cosmic-rays-particles-outer-space.
4. Thorlabs. "Blackout Fabric." *Blackout and Laser Safety Materials*, www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=190#2536.
5. Van Zeghbroeck, B. "Semiconductor Fundamentals." *Carrier Recombination and Generation*, University of Colorado Boulder, 2007, ecee.colorado.edu/~bart/book/book/chapter2/ch2_8.htm.
6. Texas Instruments. "TL081." *TL081 Data Sheet, Product Information and Support | TI.com*, www.ti.com/product/TL081.
7. Hashemi, Kevan. "Pulse Shapers." *Brandeis University High Energy Physics Electronics Shop*, alignment.hep.brandeis.edu/Lab/Filter/Filter.html#Pulse Shapers.
8. Pierre Auger Observatory. "Frequently Asked Questions About Cosmic Rays." *Pierre Auger Observatory*, June 2007, www.auger.org/cosmic_rays/faq.html.

Many thanks to both of my advisors, Kevan Hashemi, Richard Studley, Luke Korley, and all of my student colleagues in the HEP basement lab for their generous assistance and contributions.