Reading with the Raspberry Pi
Phys150 Special topics
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The “stretched pulse” should last for about 100 µs, which is plenty of time for the RPi to detect it.

We’ll go through how to do that today.

First I’ll discuss the homework and before that the schedule for picking up equipment.
Picking up equipment

You will each get one set to use throughout the quarter, but return after. I can ship to you if you aren’t local — email me.

A socially distanced pickup outside Broida, south side, on the following times:

- Friday 11:30 - 12:30
- Friday 4:30 - 5:00
- Monday 12:00 - 1:00
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Small things like adapters, jumpers, LEDs, resistors, SD cards, in drawer on Broida loading dock.
Homework

But first, let’s discuss the homework questions:

1). Why the shoulder at 120 mV and the filler in between peaks?

Some answers considered lower energy photons producing a different response.

Key idea of photons is that they are discrete quanta.

In photoelectric effect, there is a minimum wavelength; above that no electrons, and below that only one electron. Not 1.2 electrons. Often called “photo-electrons” to indicate their origin (cf beta, delta, auger).

In SiPM, it is similar although it is an electron-hole pair, rather than an ejected electron and remaining positive charge.

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So really, the discrete photons cause integer number of electrons. Suspect that the response to the electrons is varying somehow.
Let’s build some deeper understanding about SiPMs

They are just photodiodes operating in avalanche mode (aka geiger mode). So let’s review how diodes work. Silicon crystals can be doped with an excess of charge carriers, either n-type or p-type.

Pure silicon is an insulator, but doping with impurities adds “free charge carriers”. We can adjust n to control conductivity and hence resistivity.

\[ I = n A q v_d \]

Diagrams showing p-type and n-type silicon with extra electrons and holes.
A diode is made with a p-n junction

If I put a p-type piece in contact with an n-type piece, the opposite signed charge carriers can move to cancel either other.

As they do so, they will leave a region on either side of the junction that is *depleted* of charge carriers.

The bulk is charge neutral throughout, but the carriers are no longer *free charge carriers*. 
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If we put a resistor across this, no current would flow because the depletion region has high resistivity (\( n=0 \)).

Voltage, but no current, so no power. Unless we freed a charge carrier.

This is a photocell.
A diode is made with a p-n junction

This is a pn-diode, and its symbol matches that of a one-way valve.
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This is a pn-diode, and its symbol matches that of a one-way valve. We can see that one-way current behavior by applying an external voltage. That widens the depletion region but current still won’t flow through it.
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This is a pn-diode, and its symbol matches that of a one-way valve. We can see that one-way current behavior by applying an external voltage. Flip the battery’s polarity.
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We can see that one-way current behavior by applying an external voltage.

Flip the battery’s polarity. Once we overcome the 0.7 V internal voltage, current flows through continuous charge carriers.

(no depletion zone)
A diode is made with a p-n junction

If we go back to the reversed bias setup, we should get no current, so “off”.

But if a photon is absorbed in the depletion region, it can “ionize” an electron-hole pair. They are then free to move apart in the field and cause a (small) current. The photon just needs to have an energy $E = \frac{hc}{\lambda}$ high enough to ionize.

If so, 1 photon = 1 e-h pair.                        Current proportional to light intensity.
A diode is made with a p-n junction

But the “ionization energy” of the crystal (better called the band-gap) is only about 1 eV, so even IR photons can generate e-h pairs. We will see “dark counts”. Alternatively thermal fluctuations in the crystal itself will generate e-h pairs. This causes a “dark current”.

![Diagram of a diode with a p-n junction and labeled parts such as net charge, depletion zone, and net + charge. The diagram also shows the net E-field with arrows indicating the direction of the electric field between the p and n regions.]
Diode IV curve

This behavior is characterized in the IV curve.

- **Forward voltage to overcome depletion region.**
- **Large current when forward biased beyond intrinsic depletion voltage.**
- **Dark current when reverse biased.**
- **Then breakdown…**
Reverse breakdown

A large enough reverse voltage makes it go into breakdown, where any e-h pair (thermally or optically generated) is accelerated enough in the field to cause secondary “ionization” and hence an avalanche.

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At high enough reverse voltage, this avalanche just shorts across the diode. Quench with a resistor… measure output voltage across another resistor.
Reverse breakdown

This dumps the full charge from the capacitor through the resistor and makes a voltage pulse that is the same for any photon (as long as C and R are unchanged).

The bias voltage drops, reducing the reverse voltage so the diode recovers. Eventually the power supply reestablishes the bias to regain photon sensitivity.
Counting photons

To count more than one photon we need multiple diodes in parallel. A SiPM is just an array of reverse biased diodes. Each one gives a specific pulse if $\geq 1$ photon hits it. Multiple photons counted as multiple diodes breaking down. (MPPC). Quench resistors built into each $\sim 40 \times 40$ µm pixel.

![Diagram of SiPM circuit and pixel image]
But first, let’s discuss the homework questions:

1). Why the shoulder at 120 mV and the filler in between peaks?

1a). Why isn’t the distribution a series of delta functions?

Electronic noise, different capacitance for different pixels, different gain for different devices, different “pedestal offset”.

Maybe question 2 is just about 1a? Or at least, that may be part of it.
But first, let’s discuss the homework questions:

1). Why the shoulder at 120 mV and the filler in between peaks? OK, not a series of delta functions, but a series of gaussians. But, this doesn’t explain a shoulder or filler in between.
Homework

So let’s look at some waveforms…

Pulse 1 and 3 are consistent with gaussian fluctuations. More than the noise, so maybe pixel variation. Pulse 2 is really two pulses, ie 2 photons hitting two different cells causing two different capacitor dumps.
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Pulse 1 and 3 are consistent with gaussian fluctuations. More than the noise, so maybe pixel variation. Pulse 2 is really two pulses, ie 2 photons hitting two different cells causing two different capacitor dumps. If they were exactly coincident they would double the pulse height, if not they will have a max height somewhere between 100 and 200 mV.
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The filler is random overlap of two photons, but not exactly coincident.
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The shoulder is when they are just far enough apart in time to be resolved as a peak on a peak.
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2). If 1 photon = 100 mV, why doesn’t 2 photons = 200 mV? Maybe it is just the same thing, non-exact coincidence. But, then we do we get 2 photon peaks in the “dark times” when the thermal excitations are very rare? The odds of two thermal excitations exactly overlapping is too small!

Ah, but the diode becomes an LED during breakdown And illuminates the neighboring cells → “cross-talk”.

Homework

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2). If 1 photon = 100 mV, why doesn’t 2 photons = 200 mV?

If there is any delay in the cross-talk process, it will make the second photon pulse be slightly later and contribute to the falling edge of the first pulse so they add to less than twice the single photon pulse.
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But I prefer the lab!
Review: Electronics for the detector

SiPM → Amp → Comparator → AND → One-shot → Computer

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Use the RPi to read “Stretch” as an input digital signal and record the time when it is seen to go high.
Pi overview

Embedded Linux with GPIO pins
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Pi Zero W is smaller but fussy, with WiFi Micro-USB and Mini-HDMI. We will try to run it “headless”.

But first, let’s run it, see what it looks like, and learn a bit of Unix

Open terminal
ssh pi@phys150default.local
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Open terminal
ssh pi@phys150default.local
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Demo login…
Ramble about rsa keys…
The GPIO pins can be used for either INPUT or OUTPUT. But you have to specify it.

Python example flashing LED and reading input.

Python example reading input with time stamp.

Source code in ~/150/
Pi GPIO pins
Pi GPIO pins
Saving data

We will want to save the data in a format that allows later offline correlation. So, I will define an output file format as a text file with each line corresponding to one measurement or other data point.

**DataType  PiID  Date  Values**

**DataType=1** is for a hit detection. The value is the dead time required to record the entry.
**DataType=0** is used for a comment, e.g., change state or start run.
**DataType=2** is used for a pulse height measurement.
**DataType=3** is used for an altitude measurement.
**DataType=4** is used for a title angle measurement. (It has 3 values.)
**DataType=5** is used for a temperature measurement.
Other values are reserved for future use.

**PiID** is the ID# of the pi making the measurement. This will be used for correlation.
Saving data

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DataType  PiID  Date  Values

But, you are free to design your own, just document it.
Lab assignment this week

Use a raspberry pi to read the digital output of a detector (pick it up). Make some kind of interesting measurement with it, e.g.:

Is the rate different during the day and night?

Save the data on the pi and then copy it to your laptop using scp or the web server and analyze it offline.