Forecast:

More to an LED than meets the eye

The Relaxation Times

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VOL. IV No. 3 ***NEWSLETTER OF TEACHSPIN, INC.*** ***May 2013***

What's a SPAD ?

TeachSpin's Senior Scientist, George Herold is always curious. He is also almost addicted to his online electronic forum that has been of enormous help in solving various circuit "issues" that crop up from time-to-time in the course of designing new instruments.

A few months ago, a question came up on the forum about the reverse bias voltage of an LED (light emitting diode). It was listed as 5 volts. That number didn't sit well with George. Being a consummate physicist, he decided to set up some apparatus and actually measure this voltage on the LED that we use in many of our instruments. He found that it took about 25 volts before this LED exhibited avalanche breakdown. When he examined the wave form of the signal produced at breakdown, he noticed that the breakdown rate was sensitive to the light shining **on** the LED. Our curious George wanted to understand the phenomenon he had observed. As a result, TeachSpin has ended up with a new set of experiments!

A block diagram of the very simple circuit George used to observe the avalanche breakdown is shown in Figure 1.

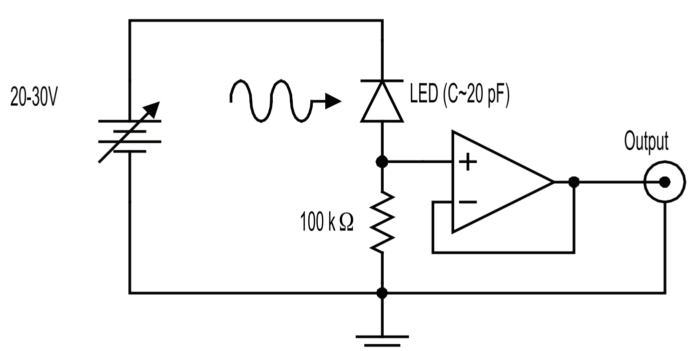

Figure 1: Block diagram of the circuit used to observe avalanche breakdown in our LED

For **one set** of parameters, Figure 2 shows the oscilloscope signals he observed when shining light on the LED.

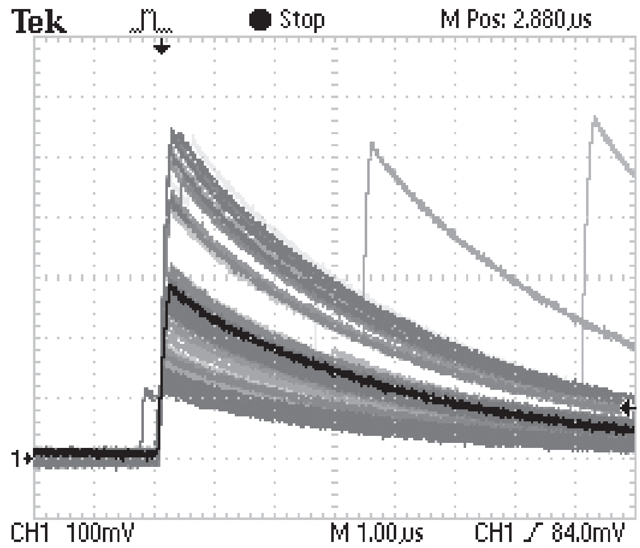

Figure 2: 'Scope signals of the avalanche breakdown in the LED with light shining on the LED

This device, it turns out, is well known in the literature and goes under the acronym **SPAD - Single Photon Avalanche Diode.** Essentially, SPADs are p-n junctions that operate under a bias voltage that is above the breakdown voltage of the junction. At this bias, the electric field in the junction is so large that a single charge carrier injected into the depletion region can trigger an avalanche. A voltage step is then created inside the junction. The size of the step is determined by how far the bias voltage is above the breakdown voltage. The avalanche lasts for as long as the voltage across the device is greater than the breakdown voltage. If a photon is responsible for injecting a charge carrier (an electron-hole pair), then the leading edge of the avalanche pulse marks the arrival time of the detected photon.

After the avalanche, the device is recharged through the 100 kΩ resistor (Figure 1) and is then ready to detect another photon. The recharge time is RC where R is the 100 kΩ so called 'quenching resistor' and C is the LED capacitance as well any stray capacitance in the circuit – about 20 pF. One might be tempted to decrease the recharging time by reducing the quench resistance. However, if too much current is allowed to flow, the avalanche becomes self-sustaining, thus lasting for a long time. In the finished TeachSpin (SPAD1-A) instrument, students will be able to vary the quenching resistance so they can see this behavior.

How can we verify that our LED is in fact responding to a single photon, even if it is obviously not responding to every photon that strikes the outer surface of the LED. It is “obviously” not responding to every photon because our diode was exposed to normal room lighting and produced an avalanche rate of the order of kilohertz. In other words, although we may have the world’s cheapest single photon detector, it is surely the world’s most inefficient.

We choose to support our ‘single photon detector’ conjecture with three separate experimental measurements, all made using TeachSpin’s new **Pulse Counter/Interval Timer, PCIT1-A.** The first measurements test the linearity of the relationship between the avalanche pulse counting rate and the incident light intensity. The second and third measurements test the randomness or Poissonian nature of the pulse counting statistics.

First we measure the avalanche count rate as a function of the light intensity on the LED. Here, we have selected an yellow LED as the light source. We change the light intensity by varying the LED current. In Figure 3, we show the plot of the avalanche count rate vs. the yellow LED current with fixed bias voltage and discriminator level on the PCIT. (A relative calibration curve for the yellow LED will be included with the unit.) This result strongly supports the single-photon conjecture.

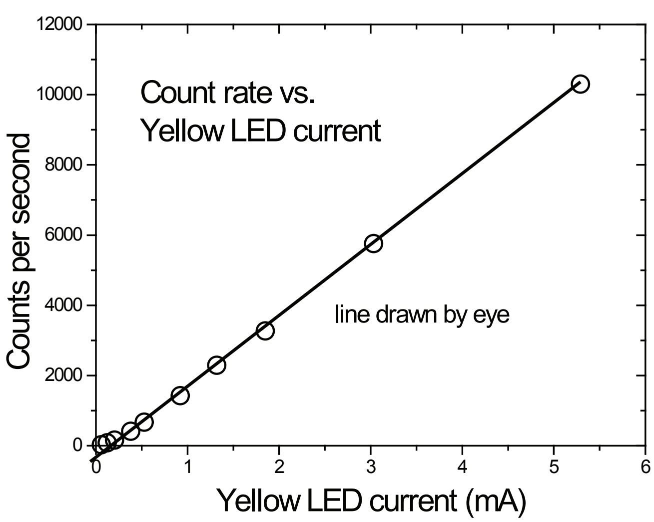

Figure 3: Avalanche count rate vs. yellow LED current.

Next we examine the *fluctuations* in the count rate for fixed external conditions of bias voltage, quenching resister, discriminator level, and light intensity. The data is shown in Figure 4.

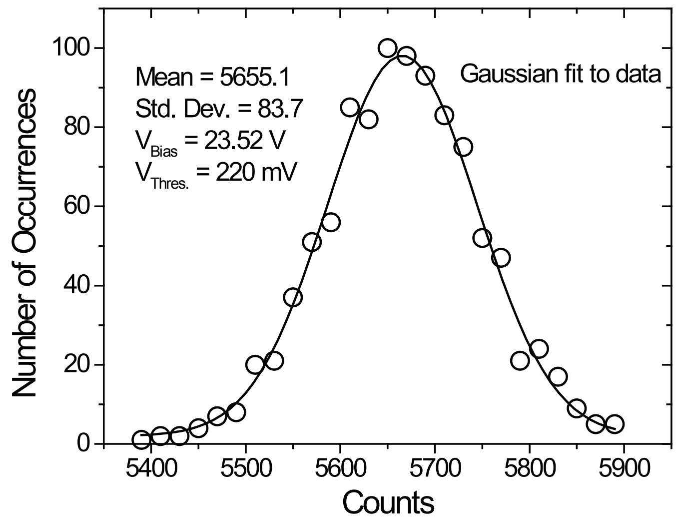

Figure 4: Histogram of count rate with fixed parameters

Although these data show a reasonable fit to a Gaussian distribution, the standard deviation deviates from the theoretical value of 75.2. This we attribute to long term drift in the light intensity.

However, there is a significantly more sensitive way to test the Poissonian statistics of these pulses. That is, we can examine the distribution of the ***time intervals between successive pulses.*** When one creates a histogram of the number of occurrences vs. the time between pulses, we obtain the data shown in Figure 5. Note that the data is plotted on a log/linear scale. This exponential relation between the number of occurrences and the time interval is a clear signature of Poissonian randomness. These data and their interpretation will surely surprise your students and many faculty, as it has several of us here at TeachSpin.

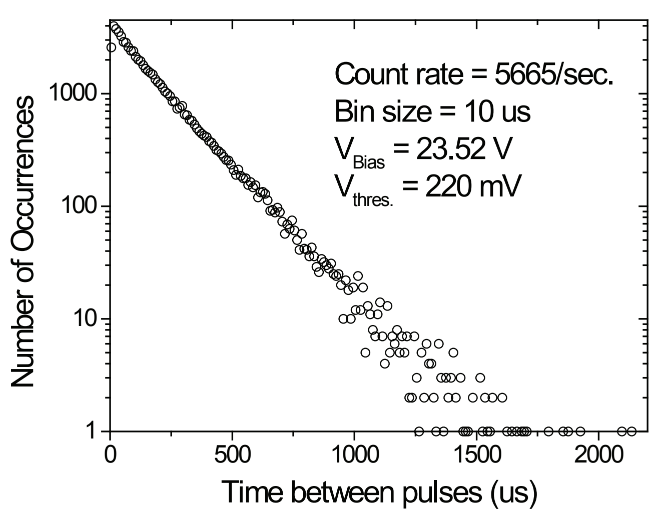

Figure 5: Pulses vs. Interval between arrivals

The observant student might notice a slight deficiency of counts at the shortest time interval. This deficiency we attribute to the finite reset time of our SPAD. With a few microsecond reset time, the counter cannot distinguish between two counts that happen on a time scale of 1μs or less.

But this reverse bias LED continues to yield interesting and unexpected data. We examine the same time interval data at low light levels. (Figure 6)

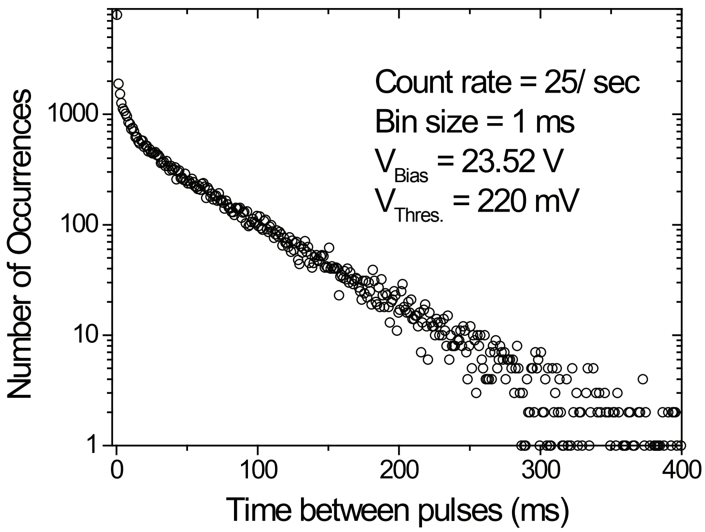

Figure 6: Pulses vs. Interval time for low light level

Note that the data cannot be represented by a simple exponential because there is clearly an excess count rate at short time intervals. In the literature, this phenomenon is known as *'after-pulsing'*. The avalanche breakdowns seem to come in bunches; that is, the probability of a second pulse occurring after the initial avalanche is apparently enhanced.

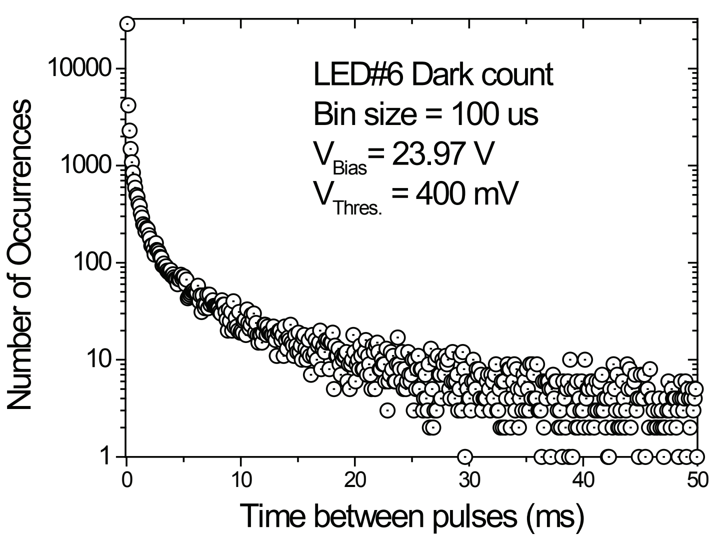

Figure 7: Pulses vs. Interval time with no light

This after-pulsing effect was also studied by examining the pulse count rate vs. time interval for the LED completely shielded from light. To obtain this data, the bias voltage had to be slightly raised in order to achieve a reasonable count rate. The data are shown in Fig. 7. It is quite clear these pulses do ***not*** obey Poissonian statistics.

We do not claim to understand everything we have observed in the behavior of this reversed bias LED in this simple self-quenched circuit. Nor do we expect your students to understand all the mechanisms at play. But that should not rule out studying this device in an electronics or advanced lab course. It offers an excellent opportunity for independent discovery because students can easily choose the experimental parameters. Making those choices gives students ownership – a very important aspect of an upper division lab. In addition, there is a particularly large parameter space to explore, which makes it a good candidate for a senior or capstone project. The list is impressive, including:

Bias voltage

Quenching resistance

Light intensity

Light wavelength

Temperature

Discriminator level

Other LEDs

So for all those reasons, TeachSpin has built the new 'box' we are calling SPAD1-A. We expect to have SPAD1-A available for you by late this summer. You will, however, need a counter/timer combination capable of measuring the ***time intervals*** between photon arrivals. Of course, we recommend the TeachSpin Pulse Counter/ Interval Timer, PCIT1-A, which many schools already own. It is an integral part of our "Two-Slit apparatus", TWS2-A, and is available as a 'retro-fit' for the TWS1 series.

One last comment, we may be witnessing the beginning of the end for photomultipliers. It is too early to tell, but could photomultipliers end up going the way of vacuum tubes? Let your students take a careful look at these new solid-state single-photon detectors. They will certainly be seeing more of them in **their** future.

TEACH SPIN

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INSIDE: **WHAT IS A SPAD???**

TeachSpin's newest addition will delight and intrigue your students, be the envy of your math department, and the plans are available if you want to build it yourself.

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Jonathan Reichert & Barbara Wolff-Reichert

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