PROCEEDINGS OF SCIENCE

PoS(GSSI14)027

Hands on Experiment- Silicon Photomultipliers: Dependence of Resistance and Breakdown Voltage on Temperature

---

Susan E. Walker[*][†]
Universita di Napoli Federico II
E-mail: susan.walker@unina.it

Marco D'Incecco
INFN- Laboratori Nazionali del Gran Sasso
E-mail: marco.dincecco@lngs.infn.it

Nicola D'Ambrosio
INFN- Laboratori Nazionali del Gran Sasso
E-mail: nicola.dambrosio@lngs.infn.it

The developing technology of Silicon Photomultipliers (SiPMs) may provide a low-cost, radio-pure alternative to PMT's for photon detection in noble liquid detectors for future particle physics experiments. Before these are suitable for use, the temperature dependence of the behavior of these devices must be thoroughly characterized. This paper discusses a study of the resistance of the quenching resistor and the breakdown voltage of five different SiPMs, over a range of temperatures from room temperature to 133 Kelvin. The resistance of the quenching resistors was shown to change as a function of temperature according to $R = k_1 \exp \frac{E_g(0) - \frac{\alpha T^2}{\beta + T} + \Delta E_g}{2 K_B T}$ where $E_g(0)$, α and β are constants of silicon. The temperature dependence of the SiPM breakdown voltage can be approximated linearly, but was demonstrated to follow more exactly the equation $V_{bd}(T) = V_{bd}(0) + k_2 T^2$, which relates the required change in voltage for a given temperature with the thermal energy density in the SiPM material.

Gran Sasso Summer Institute 2014 Hands-On Experimental Underground Physics at LNGS - GSSI14,
22 September - 03 October 2014
INFN - Laboratori Nazionali del Gran Sasso, Assergi, Italy

---

[*] Speaker.

[†] Special thanks to A. Razetto, G. Korga, D. Sablone, B. Rossi and G. Fiorillo

1. Introduction

Particle physics experiments frequently depend upon the production of scintillation light and efficient detection of that light. Photomultiplier tubes (PMTs) are typically used as light detectors because they have the required sensitivity and time resolution. However PMTs have a number of disadvantages. Some components are not radiopure, and they contribute significantly to the background radiation in low background experiments. They are also expensive and require high voltage. Modern silicon photomultipliers (SiPMs) operating in Geiger mode now have low light detection capabilities on par with PMTs and are a promising alternative for future experiments as the technology improves. SiPMs have high gain, low intrinsic background, small mass, lower operating voltage and power consumption, minimal nuclear counter effect, are insensitive to magnetic fields and have possibilities for mass production.

A number of difficulties must be addressed before SiPMs are truly suitable for low background particle physics experiments. Individual SiPMs have small surface area, and must be joined together as arrays, making electronic readout complicated. Parasitic capacitance increases the rise time of pulses, and negatively impacts pulse-shape discrimination. Dark rates are high in room temperature conditions, and after-pulsing and optical cross-talk must either be minimized or accounted for.

Several important parameters of SiPMs depend strongly upon temperature including gain, dark-rate, the resistance of the quenching resistor, and the breakdown voltage. Many particle physics experiments utilize noble liquid scintillators and require functionality and full characterization of photon detector performance in cryogenic temperatures. The work presented in this paper was performed to characterize the behavior of the resistance of the quenching resistor and the breakdown voltage of five SiPMs over a range of temperatures.

2. Method

The SiPM was placed in a light-tight box with a PT-100 sensor to monitor temperature. A Keithley 2450 SourceMeter was used to provide the Bias Voltage to the SiPM and readout the current. The box was flushed with cold nitrogen gas from a dewar to decrease the temperature through a range from room temperature to 133 Kelvin. The temperature was read out from an Agilent 34461A Multimeter connected to the PT-100. Table one summarizes the SiPM models tested from AdvanSid (FBK).

Figure 1 below, shows the electronic board used for testing. For testing the resistance, the SiPM was setup in forward bias and the SourceMeter was programmed to scan from 0 to 3.5 volts. For testing the breakdown voltage, the SiPM was set up in reverse bias with the SourceMeter scanning from approximately 20 to 27 volts. Limits were placed on the current drawn by the SiPM to assure that bias voltage always stopped before any damage could be done to the SiPM. These limits were 20mA for forward bias, and 5uA for reverse bias. For the VUV SiPM, the box was kept light tight, and thermal noise was sufficient to trigger breakdown for testing. However, with the RGB models, a very small hole normally dedicated to a laser fiber connection was uncapped to allow a small amount of room light to enter and trigger breakdown. The SourceMeter produced data files containing voltage and current for each run. This data was then processed and analyzed using Root.

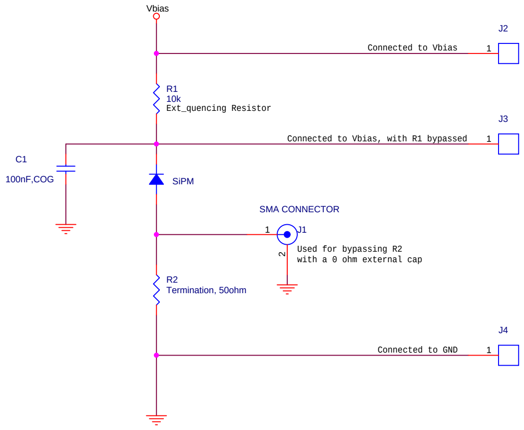

Figure 1: SiPM test board

3. Results

The plots of current versus voltage for the forward bias setup were fitted in the linear region with a 1st degree polynomial for each temperature tested. The reciprocal of the slope was then taken to be the total resistance of the SiPM. However, each microcell in the SiPM has its own quenching resistor. These resistors are acting in parallel, so the individual resistance can be calculated by multiplying by the total resistance by the number of microcells in the SiPM. The individual resistance of cells is the more informative figure for determining parameters of SiPM performance, particularly recovery time. These values were then plotted against temperature for each SiPM as shown in Figure 2.

The quenching resistors typically used in SiPMs are made from polysilicon. The resistivity of semiconductors increases non-linearly with decreasing temperature according to

$$\rho = A\exp(\frac{E_g}{2K_B}) \tag{3.1}$$

where A is a constant of the material, E_g is the energy gap between the valence and conduction bands of the material, K_B is the Boltzman constant, and T is the temperature in Kelvin. The energy gap of a semiconductor is dependent upon the temperature and can be calculated with equation 2.

$$E_g = E_g(0) - \frac{\alpha \cdot T^2}{(\beta + T)} \tag{3.2}$$

where α and β are constants of the material, $E_g(0)$ is the energy gap at 0 degrees Kelvin and T is the temperature.

However, when a semiconductor is doped, the bandgap will narrow. At lower levels of doping, ΔE_g will be temperature dependant, but at higher doping levels the material is considered degenerate, and has a constant value.

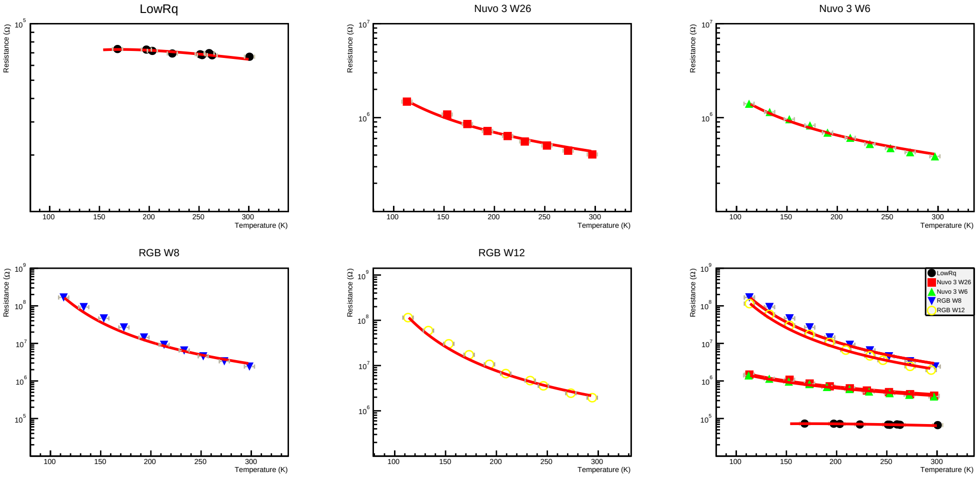

Figure 2: Resistance vs Temperature. The bottom right plot shows all the SiPMs together for comparison

Substituting equations 2 and 3 into equation 1 and including a factor for the dimensions of the resistor produces equation 4, which was used to fit the data. The first free parameter, k_1, represents the product of a material constant (A from equation 1) and a factor for the shape and size of the resistor. The second free parameter ΔE_g corresponds to the change in the energy gap with doping. Although this fit better describes the behavior than a simple exponential, the resulting ΔE_g values are unexpectedly high. This may be due to differences between polysilicon and silicon.

$$R = k_1 \exp \frac{E_g(0) - \frac{\alpha T^2}{\beta+T} + \Delta E_g}{2K_B T} \tag{3.3}$$

The breakdown voltage of a SiPM at a given temperature was taken to be the voltage at which the current suddenly increased from close to zero to the set safety limit. This was then plotted against temperature in figure 3 below.

Previous work by Lightfoot et al fit the temperature dependence of breakdown voltage linearly. While this provides a useful estimate and a reasonably good fit, the data appears to have a mild non-linearity. The breakdown voltage of a SiPM is the voltage at which electric field in the SiPM reaches the impact ionization threshold, thus allowing for internal gain. The threshold in silicon is $1.75 \cdot 10^5 \frac{V}{cm^2}$ for electrons and $2.5 \cdot 10^5 \frac{V}{cm^2}$ for holes. The voltage required to reach ionization threshold differs between SiPM models due to differences in doping and dimensions. Gain is temperature dependent due to the energy loss of electrons in interactions with phonons. The greater the temperature, the greater the number and energy of the phonons, and the greater the loss of electron energy. The loss in energy at a higher temperatures must be compensated with an increase in voltage. Breakdown voltage of a given temperature ($V_{BD}(T)$) should be equal to the breakdown voltage at 0 Kelvin ($V_{bd}(0)$), when there are no phonons present, plus an extra amount of voltage ($V_{tc}(T)$) to compensate for the energy lost to phonons at temperature T. Assuming that $V_{tc}(T)$ scales with the thermal energy density of the SiPM, it can be approximated as

$$V_{tc}(T) = k_{tc} c_p T \tag{3.4}$$

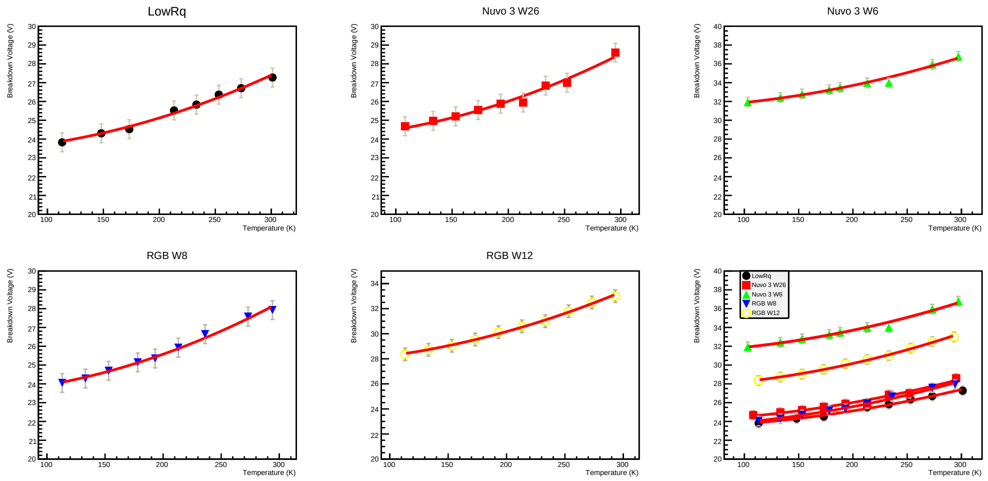

Figure 3: Breakdown voltage vs Temperature. The bottom right plot shows all the SiPMs together for comparison.

where k_{tc} is a constant describing the voltage required to compensate per unit of thermal energy, and c_p is the specific heat of silicon. However, c_p is not independent of temperature. In silicon c_p changes linearly with slope m from 0 Kelvin to room temperature where linearity begins to be lost. This leads to equation 6, which can be substituted into equation 5, resulting in equation 7 which was used to fit the data.

$$V_{tc}(T) = k_{tc} mTT = k_2 T^2 \tag{3.5}$$

$$V_{bd}(T) = V_{bd}(0) + k_2 T^2 \tag{3.6}$$

Table 1 below summarizes the parameters found for the SiPMs. Estimates for the doping concentration of the queching resistors from equation 3 are also included, along with fundamental SiPM information.

SiPM Name	Type	cell size (μm)	cell count	k_1 (10^5)	ΔE_g	$V_{bd}(0)$	k_2 (10^{-5})
LowRq	VUV	30	2560	2.013	-1.170	23.30	4.555
Nuvo 3 W 26	VUV	25	3600	6.490	-1.132	24.12	4.570
Nuvo 3 W 6	VUV	25	3600	6.058	-1.132	31.34	5.835
RGB W 8	RGB	25	3481	7.661	-1.043	23.33	5.835
RGB W 12	RGB	25	3481	5.479	-1.043	27.59	6.449

Table 1: Summary of parameter values found

4. Discussion

Both the ΔE_g and the k_1 values found for the two Nuv 3 SiPMs were quite similar, indicating that the doping concentration and dimensions of the quenching resistors are same, as would be expected for two SiPMs of the same model. Likewise, the ΔE_gs of the two RGB SiPMs match indicating consistent doping concentration, although the RGB W 8 has a higher k_1. This could be caused by small differences in resistor dimensions. SiPMs utilizing polysilicon resistors are ill-suited for cryogenic applications. The high resistance at low temperature will lead to poor timing performance. Starting with a low resistance quenching resistor that would have the correct resistance only at low temperatures could work in cryogenic systems, but would not be functional a room temperature. This would be a great difficulty in large scale projects where SiPMs would need to be tested repeatedly during the experiment's construction. A better choice would be a a resistor made out a metal alloy. These display linear behavior with temperature changes, and can have high resistivity and low temperature coefficients of resistivity.

The values for k_2 found are within a relatively small range around $5 \cdot 10^{-5}\ Vk^{-2}$. Differences could be attributed either to differences in the slope (m) or value of the specific heat or to differences in the constant k_{tc}. The values found for $V_{bd}(0)$ range from 23.3 V to 31.28 V, and do not appear to correlate strongly with the values of k_2. V_{bd} and k_{tc} would both be expected to vary primarily with the dopant concentrations and thickness of the n-type and p-type portions of the epitaxial layer, and should show some correlation. However, k_{tc} cannot be calculated without exact knowledge of m and c_p for different doping concentrations. Further studies on the doping dependence of specific heat and dielectric constant would be informative. Differences could also be attributed to experimental error, especially due to imperfect temperature regulation.

References

[1] D. Renker and E Lorenz, *Advances in Solid State Photon Detectors*, *Jinst* **4** (2009) 4004

[2] V. Chepel and H Aragujo, *Liquid Noble Gas Detectors for Low Energy Particle Physics*, [`arXiv:1207.2292v2`]

[3] H.P.D Lanyon and Richard A. Tuft, *Bandgap Narrowing in Moderately to Heavily Doped Silicon*, *IEEE Transactions on Electron Devices***Ed 26 No. 7**(1979) 1014

[4] Alfred Levitas, *Electrical Properties of Germanium-Silicon Alloys*, *Physical Review***Vol 99 No. 6**(1955) 1810

[5] J.W. Precker, M.A. da Silva, *Experimental estimation of the band gap in silicon and gemanium from the temperature-voltage curve of diode thermometers*, *Am. J. Phys.***Vol 70 No.11**(2002) 1150-1153

[6] P.K. Lightfoot, G.J. Barker, K. Mavrokoridis, Y.A. Ramachers, N.J.C. Spooner *Characterisation of a silicon photomultiplier device for applications in liquid argon based neutrino physics and dark matter searches*, *JINST***3**(2008) 10001