Application Note

AFBR-S4XX

Working with Broadcom SiPMs

Silicon photomultipliers (SiPMs) are arrays of avalanche photo diodes (APDs) in a parallel circuit that are operated in Geiger-mode, which means above their breakdown voltage (V_{BD}). In this regime, the electric field within the diode's pn-junction is strong enough to allow primarily created charge carriers (for example, created by an incident photon) to gain sufficient kinetic energy to create further secondary charge carriers (electrons and holes). The secondary charge carriers can again create charge carriers by impact ionization, which leads to an avalanche of secondary charge carriers created from one initial electron-hole pair. The typical number of charge carriers created is in the order of 10^5 to 10^6. The number of secondary charge carriers (pairs) per initial electron-hole pair represents the SiPM's internal gain.

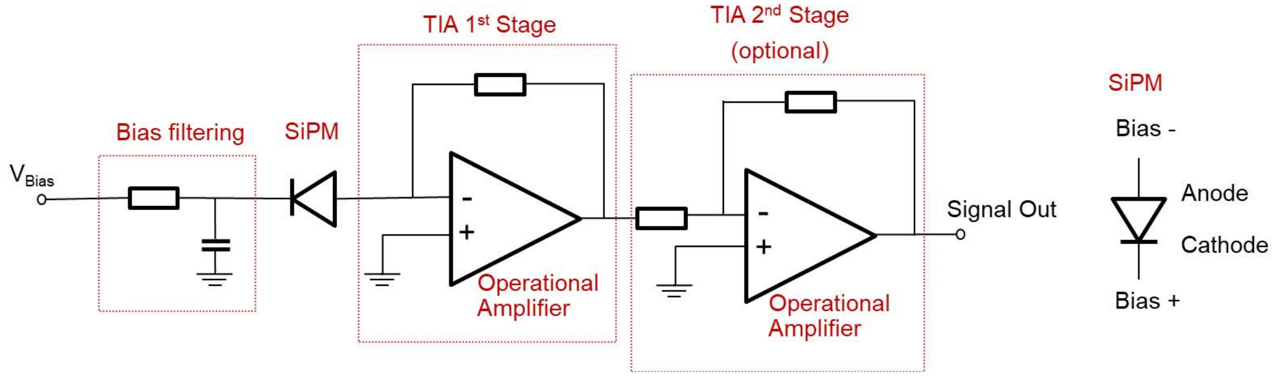
The avalanche breakdown is a self-sustainable process and must be quenched to allow the diode to return to an "active" state, which means to be able to detect a photon. Quenching is typically achieved by means of a quenching resistor (R_q) in series with the diode (passive quenching). The quenching resistor and the single Geiger-mode APD form a single-photon avalanche diode (SPAD), and many of these SPADs form a SiPM.

For further information on SiPMs and their characteristics, refer to the Broadcom *AFBR-S4XX: Brief Introduction to Silicon Photomultipliers* application note.

Connecting the SiPM

The typical SiPM design can be either a p-on-n design or an n-on-p design, depending on the target spectral sensitivity. Figure 1 shows the typical nomenclature and polarity for reverse biasing. The positive SiPM bias voltage is applied to the cathode; the SiPM signal is read out via the anode and fed in a transimpedance amplifier (TIA). The voltage signal can subsequently be further processed and digitized.

Figure 1: Polarity for Biasing P-on-N Devices (Such as the Broadcom NUV-MT SiPM) and a Possible Readout Circuit Schematic



Bias Voltage

SiPMs are operated as reversely biased diodes above the breakdown voltage (V_{BD}). Reverse bias means that the cathode is on the positive potential and the anode is on the negative one. Therefore, a SiPM can be biased with either polarity (positive or negative), as long as the potential difference between the anode and the cathode is obtained in the correct polarity.

The voltage range over the SiPM can typically be given by means of the overvoltage (V_{OV}), which is defined as the difference between the bias voltage and the breakdown voltage:

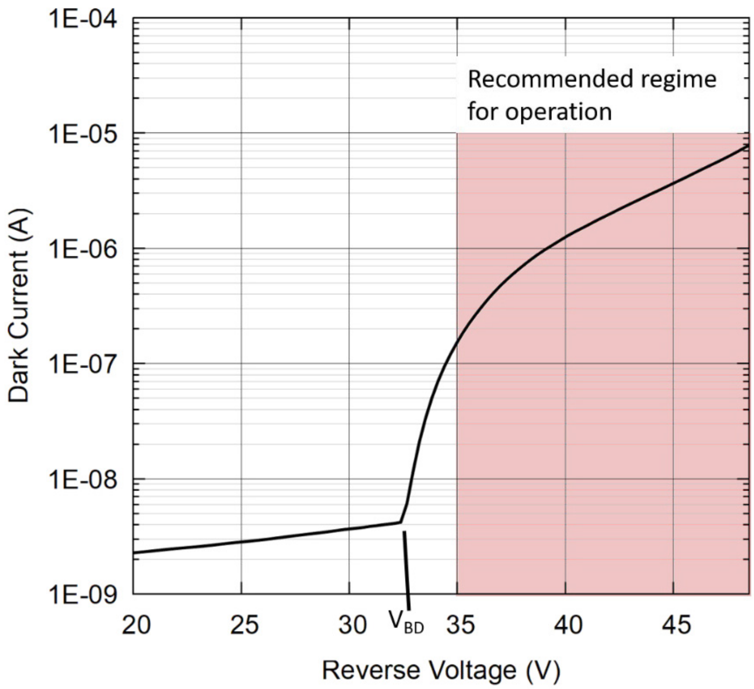
$$V_{OV} = V_{Bias} – V_{BD}$$

Many SiPM properties are a function of the applied overvoltage such as the gain, the dark count rate (DCR), and the photo-detection efficiency (PDE).

The lower limit for the applied voltage for a SiPM to be operated is the breakdown voltage. However, the ideally applied minimal overvoltage for stable operation is given when the dark current starts to flatten in the **I**-V curve of the SiPM (Figure 2).

The upper limit is determined by noise considerations (a steady increase of SiPM noise with increasing overvoltage) and potentially a second breakdown.

Figure 2: I-V Curve of a Broadcom AFBR-S4N44P164M (Single Channel) with Indicated Range for Recommended Operations Regime



How to Determine the Breakdown Voltage and the Correct Operation Voltage

The breakdown voltage of Broadcom SiPMs is stated in the corresponding data sheet. If the data sheet is not available or the customer wants to verify the breakdown voltage, there are various methods available. Typically, the breakdown voltage is retrieved from a voltage sweep measurement.

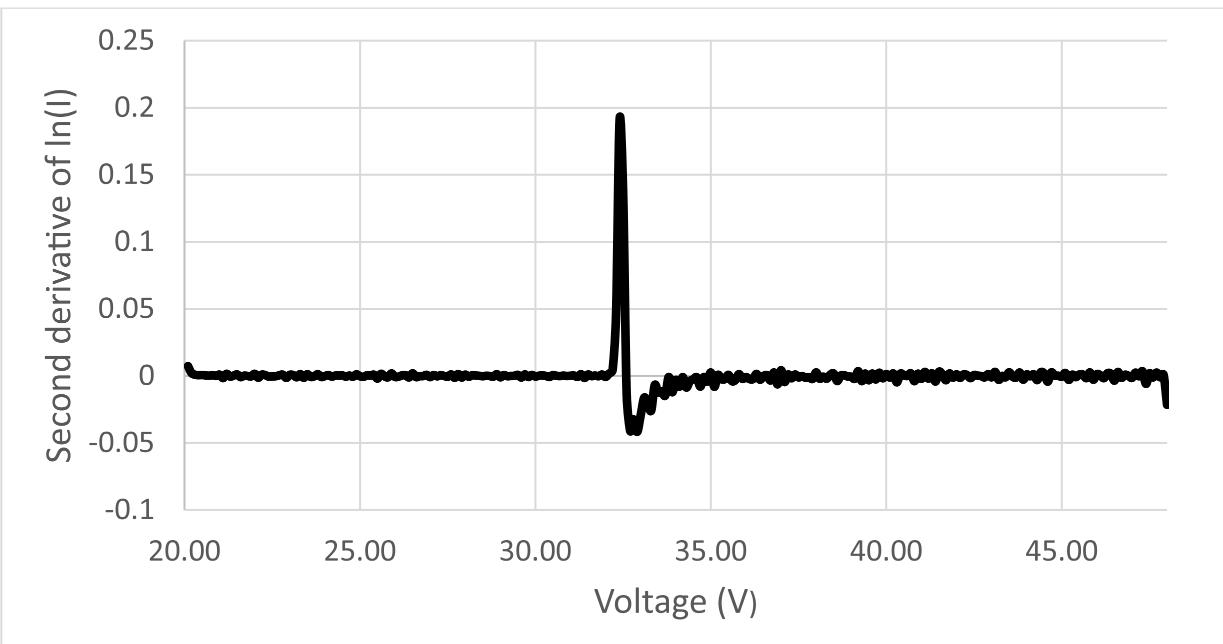
An easy, but low accurate method is using a gain versus voltage measurement. A linear fit to the amplitude/charge of the 1 p.e. pulse as a function of the bias voltage yields a good approximation of the breakdown voltage, which is represented by the x-intersect.

More accurate methods rely on I-V measurements. Among various methods, the V_{BD} calculation via the second derivative of the dark current ($\frac{d^2}{dV^2}\ln(I_{Dark})$) versus the bias voltage will be presented.

Determination of the Breakdown Voltage via the Second Derivative of ln($_{Idark}$)

This method is the one used by Broadcom to determine the breakdown voltage and is based on finding the maximum of the second derivative of ln($_{IDark}$). Figure 3 provides an example of $\frac{d^2}{dV^2}\ln(I_{Dark})$ versus the SiPM bias voltage and demonstrates the very sharp peak, which provided high accuracy in determining the breakdown voltage.

Figure 3: Second Derivative of ln($_{IDark}$) vs. Bias Voltage. The Maximum Corresponds to the Breakdown Voltage ($V_{Breakdown}$).



How to Determine the Bias Voltage Polarity

If there is doubt about which signal polarity is the correct one to apply in a given setup, the correct polarity can be determined as follows:

- Apply a current compliance limit of about 1 mA.
- Apply 1V to the device.
- If the current is driven into the current compliance limit, the SiPM is biased in the forward direction and the polarity must be inverted.

NOTE: Measurement must be conducted in dark conditions.

Signal Readout

Depending on the polarity of the SiPM bias, the signal can be obtained from the anode or the cathode. However, Broadcom recommends using the following convention for readout:

- Broadcom SiPMs with *AFBR-S4N* and *AFBR-S4K* serial numbers (p-on-n substrate), such as NUV-HD and NUV-MT, prefer the *anode* for signal extraction (positive bias via the cathode).
- Broadcom SiPMs with *AFBR-S4P* serial numbers (n-on-p substrate), that is NIR SiPMs, prefer the *cathode* for signal extraction (negative bias via the anode).

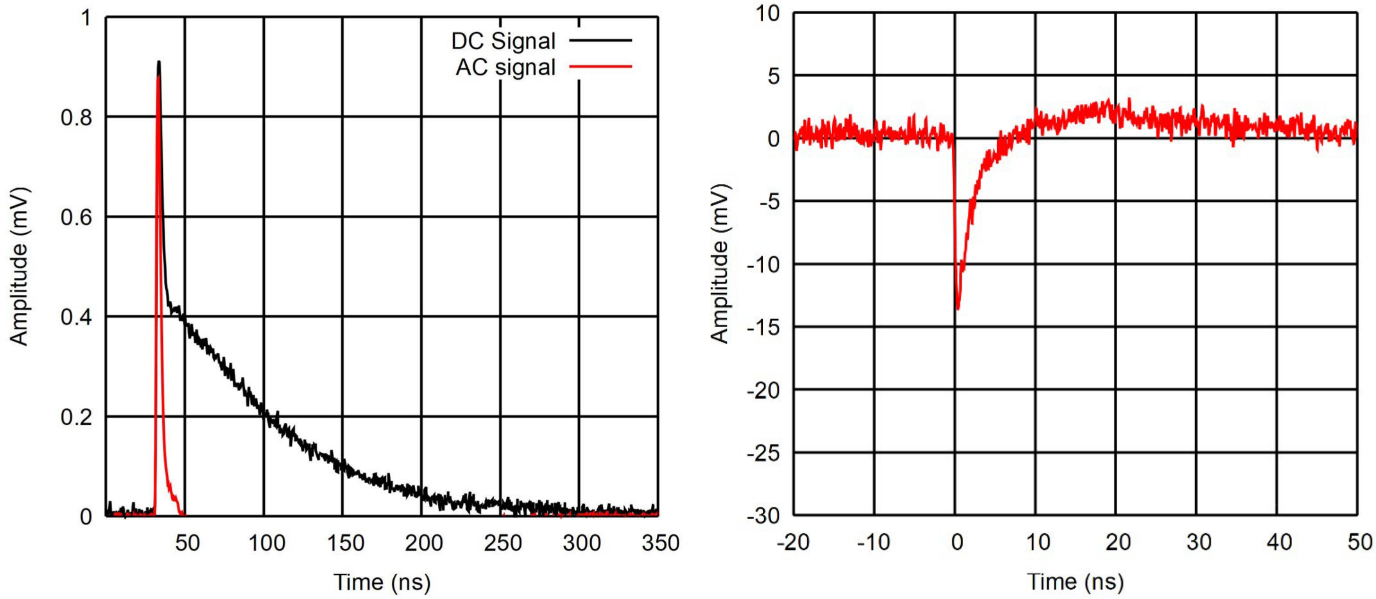
The SiPM signal must typically be amplified and shaped depending on the requirements of the intended application.

For adequate energy measurements, the recommended measurement method is charge integration. The integration time window must be set such that the full SiPM pulse is within the integration window, while the acquisition of baseline noise must be minimized. For short light pulses (< 1 ns), the time after which the signal has returned to baseline can be approximated by five times the SiPM's recovery time. Figure 4 (left) shows, in black, the pulse shape acquired from a single element on an AFBR-S4N44P164M readout over 25Ω after irradiation with a short (<70 ns) laser pulse. With a SiPM recharge time of 55 ns, the signal is back to baseline at approximately 275 ns.

AC Coupling: Fast Signal Frequencies

For applications with a focus on arrival time resolution and a sufficiently high photon flux on the SiPM, a high-pass filter can be used to retrieve only the fast frequency components of the signal. Figure 4 (left) displays, in black, the regular signal output (DC, over 25Ω) of one channel of a single element on an AFBR-S4N44P164M, and it displays the same signal filtered using a high-pass filter (BW > 200 MHz). Compared to the recharge time constant of 55 ns for this device, the fast signal (filtered, red) has a measured time constant of only 9 ns. Figure 4 (right) shows the signal of a AFBR-S4P11P011R filtered with a high-pass filter (> 400 MHz) and a time constant of 2 ns (versus 10 ns in DC readout, 25Ω).

Figure 4: Pulse Shape in DC (25Ω) and AC (200 MHz) Readout of a Single Element on an AFBR-S4N44P164M (Left) and an AC-Coupled Signal (400 MHz) of an AFBR-S4P11P011R (Right)



NOTE:

- Extracting an AC-coupled SiPM signal does not change the SiPM's intrinsic recharge time and may lead to a rate-dependent signal amplitude.
- The SiPM signal recharge time is proportional to the quenching resistance and the parasitic capacitances of the quenching resistor and the grid.
- The load resistor with the capacitances of the grid and inactive SPADs may act as a low-pass filter and prolong the observed signal decay time. This, however, does not change the intrinsic recharge time of the SiPM.

Large Area Readout

If larger areas (> approximately 36 mm^2), meaning larger than an area that can be covered with a single SiPM, need to be read out, SiPM arrays (for example, AFBR-S4N44P164M, AFBR-S4N66P024M) can be used or customized form factors can be built using singe-channel devices. However, some applications require a large area sensor with a single signal output to retrieve accurate energy information or trigger signals. In such a case, the direct parallel ganging of several SiPMs is not advisable, because this leads to an increase in the overall capacitances by summing the individual SiPM terminal capacitances and therefore to a slow signal with increased noise. One of the following two methods is therefore recommended:

1. **Signal summation via software:** If an accurate acquisition timestamp is available, the individual SiPM signals can be clustered by their timestamps and signal summing can be performed on the digitized signal.
2. **Analog signal summation via hybrid-ganging:** Multiple SiPMs are biased on a common electrode, for example, a cathode. In this case, a high-pass filter decouples the anode signal to the cathode of a neighboring channel. This allows extracting the signal of all firing SiPMs via a decoupling capacitor on the cathode side. The signal can subsequently be fed into a preamplification stage.

Figure 5 illustrates a basic schematic of the hybrid-ganging method.

Figure 5: Illustrative Sketch of the Hybrid-Ganging Method for the Summation of Analog SiPM Signals

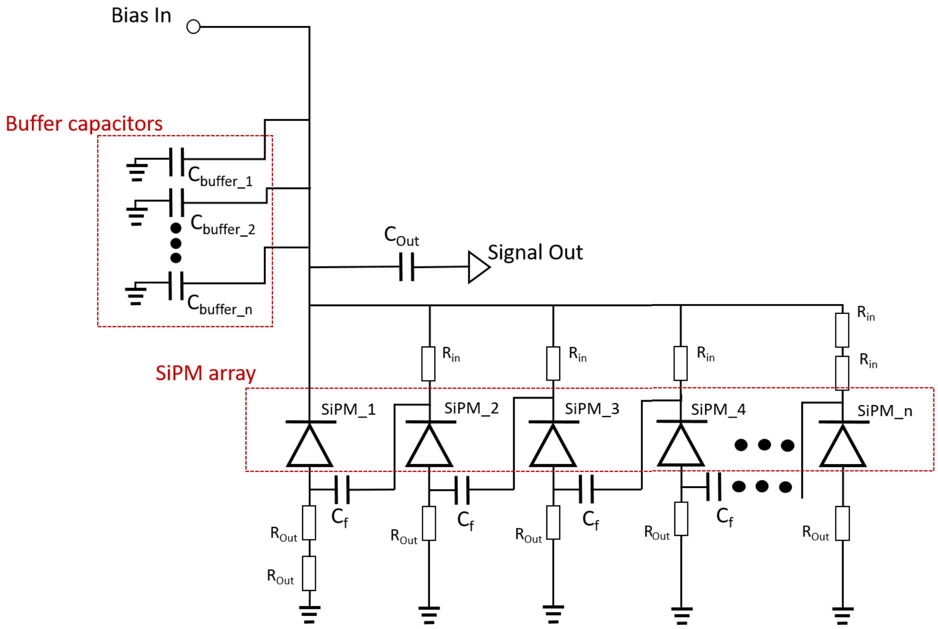
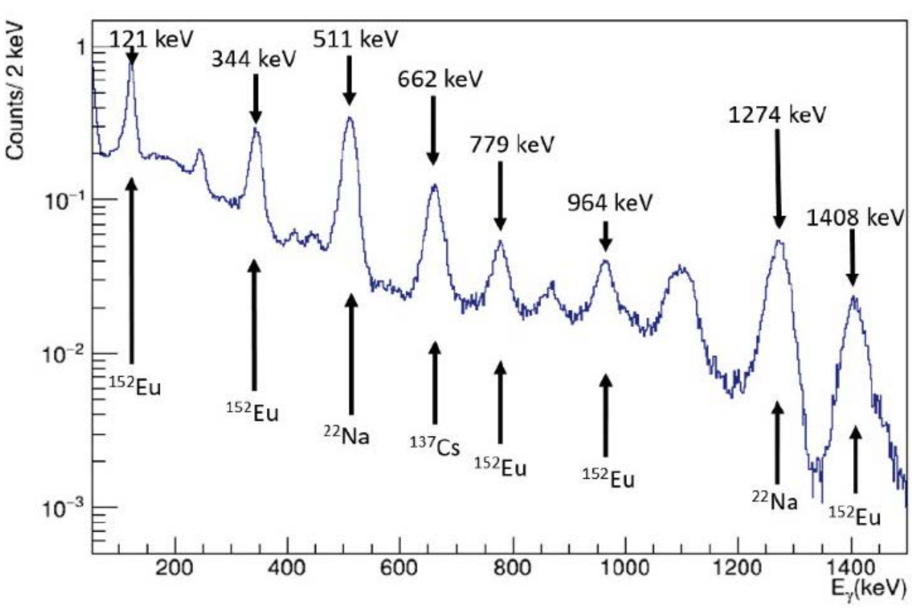


Figure 6 shows a γ-ray spectrum from a simultaneous irradiation with three radioactive point sources (^{152}Eu, ^{22}Na, and ^{137}Cs) acquired using a hybrid-ganging method to obtain one signal of four Broadcom AFBR-S4K33P6447L to read out a $LaBr_3$:Ce with a volume of 51 × 51 × 30 mm^3. The achieved energy resolution at 662 keV is 3.5%.[1]

Figure 6: Gamma-Ray Spectrum of Three Radioactive Point Sources[1]



1. T. Fitzpatrick, A Compton Camera Prototype with γ-PET Imaging Capability: From Component Evaluations to Online Tests Doctoral Thesis, LMU Munich, 2022.

Thermal Characteristics

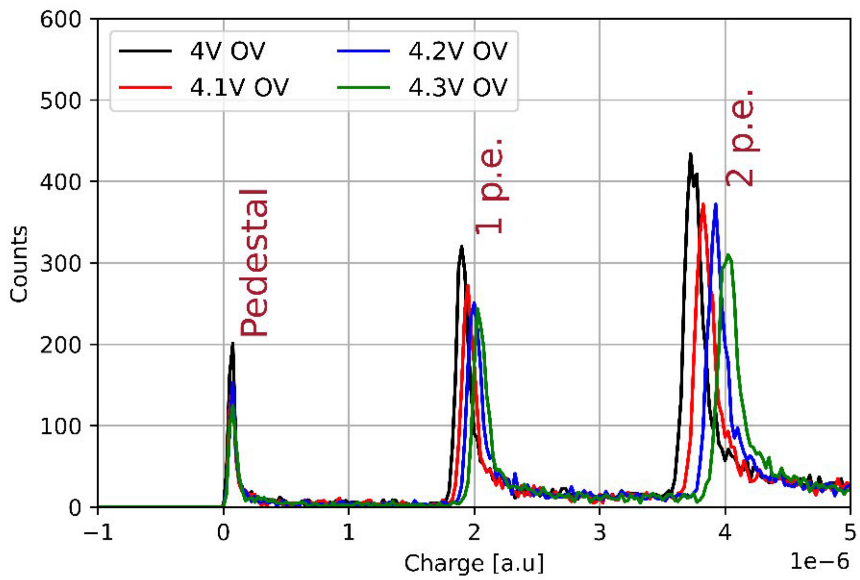
Changes in the SiPM temperature mainly cause tow effects:

1. **Change of V_{BD}:** With increasing SiPM temperature, the breakdown voltage shifts toward the higher voltage. From an I-V measurement over temperature, the V_{BD} shift can be seen (Figure 8). The exact value of the temperature coefficient depends on the exact device and can be found in the corresponding data sheet.

   Changes to the V_{BD} and, therefore, also a change to the applied SiPM OV can be critical in an application where count rates and light intensities are strongly varying. In such a case, a compensation circuit for the bias voltage is recommended.

   Example: The temperature coefficient for the Broadcom NUV-MT SiPM is 30 mV/°C. The effect of a varying overvoltage due to changes of the breakdown voltage is illustrated on the shift of the 1 p.e. and 2 p.e. peak in Figure 7. Here, the measured charge histogram is plotted for four different overvoltages (from 4.0V OV to 4.3V OV), which can be caused by a temperature variation of 10°C.

Figure 7: Pedestal, 1 P.E. and 2 P.E. Peak at Four Different Overvoltages

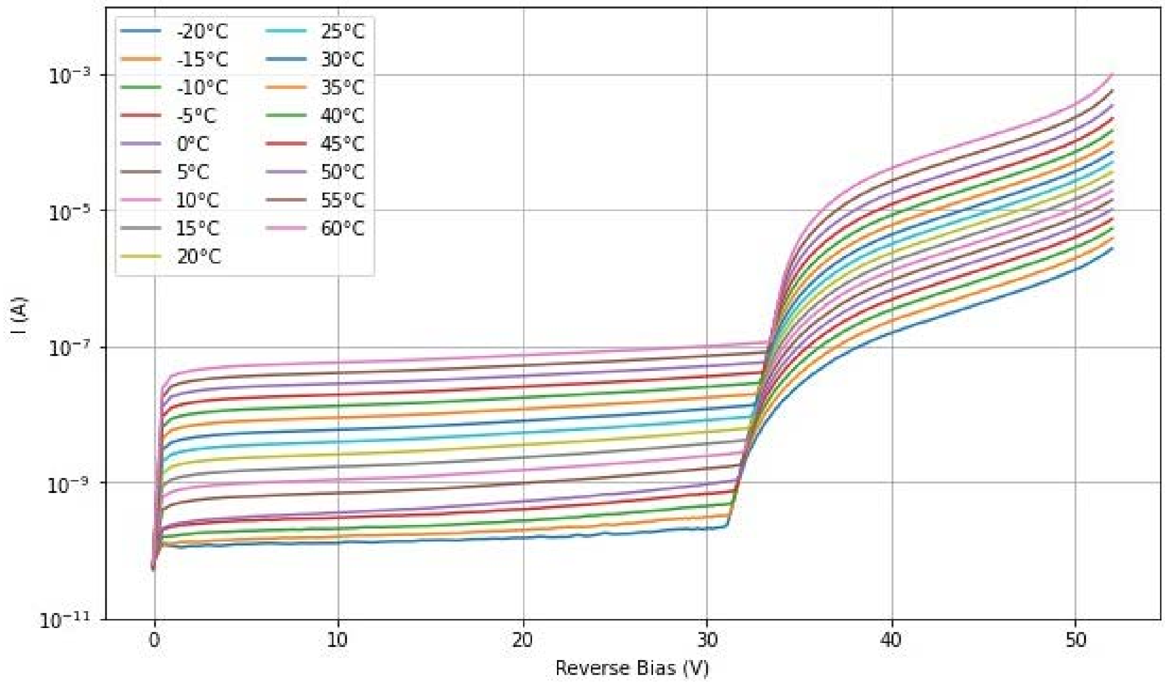


2. **Increasing DCR with increasing device temperature:** As dark counts originate from thermally generated charge carriers, the DCR increases with higher device temperature. Figure 8 shows I-V curves of an AFBR-S4N66P024M (single element) from –20°C to 60°C.

   If the SiPM is operated at a constant ambient temperature at rather constant count rates, typically no compensation for changes in V_{BD} is required.

NOTE: A cooling SiPM not only reduces the DCR, but also reduces the SiPM gain.

Figure 8: I-V Curves of an AFBR-S4N66P024M (Single Element) Measured over a Temperature Range from –20°C to 60°C



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