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SensL B-Series and C-Series silicon photomultipliers for time-of-flight positron emission tomography

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ABSTRACT

Silicon photomultipliers from SensL are designed for high performance, uniformity and low cost. They demonstrate peak photon detection efficiency of 41% at 420 nm, which is matched to the output spectrum of cerium doped lutetium orthosilicate. Coincidence resolving time of less than 220 ps is demonstrated. New process improvements have lead to the development of C-Series SiPM which reduces the dark noise by over an order of magnitude. In this paper we will show characterization test results which include photon detection efficiency, dark count rate, crosstalk probability, afterpulse probability and coincidence resolving time comparing B-Series to the newest pre-production C-Series. Additionally we will discuss the effect of silicon photomultiplier microcell size on coincidence resolving time allowing the optimal microcell size choice to be made for time of flight positron emission tomography systems.

1. B-Series and C-Series SiPM

SensL's Silicon Photomultipliers (SiPM) are single-photon sensitive detectors that can be used in a variety of low-light and timing-critical applications. Here we discuss B-Series and C-Series devices for Time-of-Flight Positron-Emission-Tomography (ToF-PET) applications, including basic characterization and functional test to determine ToF-PET level performance. Both products have high Photon Detection Efficiency (PDE), with a peak sensitivity corresponding to the spectral peak of Cerium-doped Lutetium-Orthosilicate (LYSO) at 420 nm. B-Series is a mature product and a complete characterization can be found in [1]. C-Series is a new ultra-low noise product which is pin for pin compatible with B-Series and improves on the high PDE of B-Series but with significantly reduced noise measured to be less than 100 kHz/mm^2 at 2.5 V overvoltage. C-Series SiPM were produced in a new foundry process which used process defect reduction techniques to reduce the dark count rate significantly. Both B-Series and C-Series devices had the high-speed, low output capacitance Fast output available in addition to the Standard anode–cathode output described elsewhere [2].

2. SiPM characterization

In the following sub-sections the basic characterization results are shown for PDE, dark count rate, crosstalk and afterpulse probability for B-Series and pre-production C-Series SiPM. Single device data is shown which is believed to be representative of the overall population. Devices were not selected or binned for the measurements performed.

2.1. Photon detection efficiency

Fig. 1 shows the PDE of B-Series and C-Series as a function of wavelength, at a bias of 5.0 V above the breakdown voltage (overvoltage). Devices tested were MicroFB-30035-SMT and MicroFC-30035-SMT, which are both 3 mm × 3 mm SiPM with 35 μm microcells. The plot shown is true PDE and does not contain the effects of afterpulsing and crosstalk. The wavelength varying data was collected using the responsivity method and was confirmed by a direct PDE measurement at a single wavelength to ensure that afterpulse and crosstalk were accounted for. A full description of this technique can be found in [1] which relies on the single electron gain measurement developed by Dolinsky [3] and the ability to directly measure the PDE at specific wavelengths developed by Otte [4] and Eckert [5]. The PDE peak was approximately 420 nm for both C-Series and B-Series. C-Series demonstrated significantly improved PDE at wavelengths below 400 nm. This increase in PDE at lower wavelengths was believed to be due

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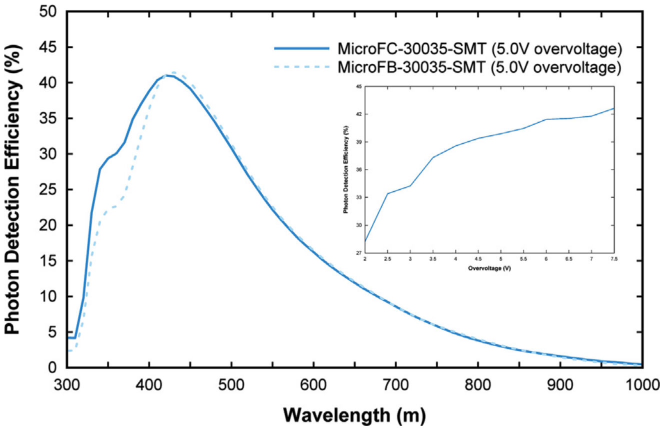

Fig. 1. Photon Detection Efficiency (PDE) of B-Series and C-Series SiPM. The inset shows PDE at 420 nm vs overvoltage.

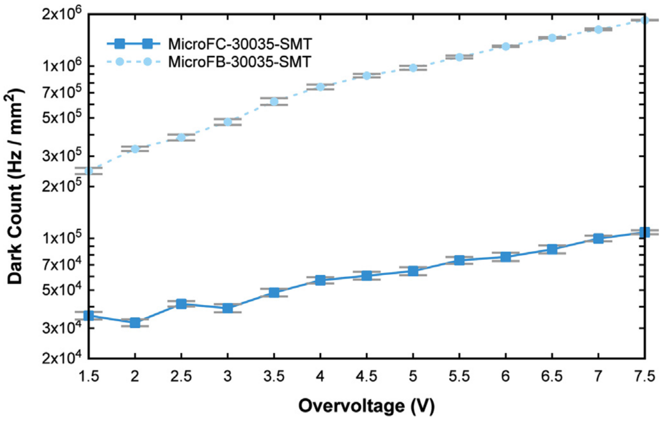

Fig. 2. Dark Count Rate (DCR) of B-Series and C-Series SiPM.

to changes in the material above the active area of the SiPM to reduce process defects.

2.2. Dark count rate

The Dark Count Rate (DCR) of MicroFB-30035-SMT and MicroFC-30035-SMT is compared in Fig. 2. For the measurement the DCR was defined as the rate at which SiPM electrical pulses with amplitude greater than one-half the single photoelectron level amplitude occur, in the absence of optical excitation. In this characterization, the Fast Output was used to determine the dark count pulse rate. A significant reduction of approximately an order of magnitude in the measured dark count rate was found between B-Series and C-Series. This reduction in dark count rate was believed to be due to reduced defect generation during silicon foundry processing.

2.3. Crosstalk probability

The crosstalk probability versus overvoltage is shown in Fig. 3. For the measurement crosstalk was defined as the rate at which electrical SiPM pulses at 1.5 times the single photoelectron level amplitude occur in the absence of optical excitation, normalized by the DCR. The Fast Output was used to determine this ratio.The data was determined by sweeping leading edge trigger and measuring the rate of dark counts at this trigger level. Cross talk was found to be similar for the SiPM measured and further testing on larger sample sizes is planned.

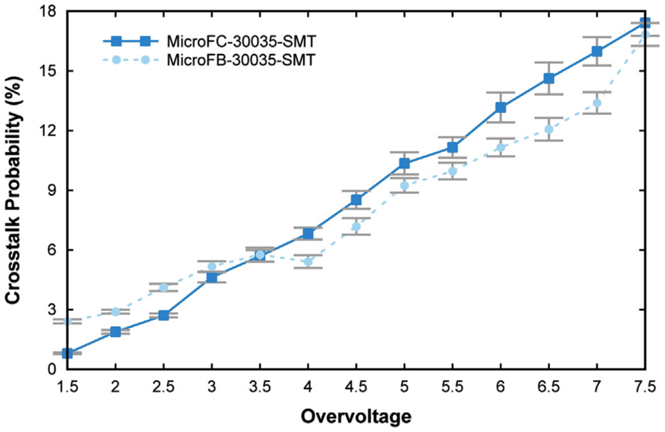

Fig. 3. Crosstalk of B-Series and C-Series SiPM.

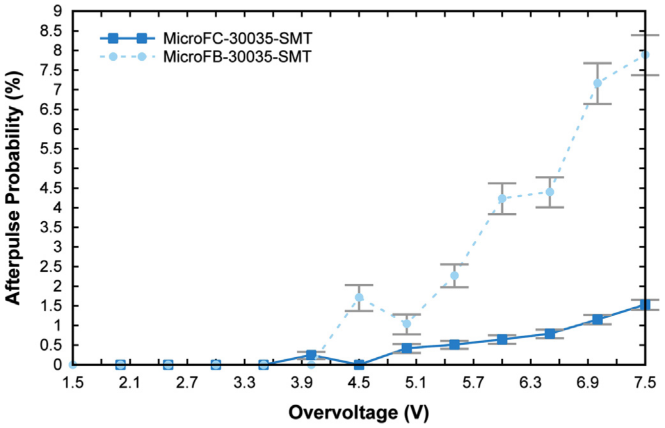

Fig. 4. Afterpulse probability of B-Series and C-Series SiPM.

2.4. Afterpulsing

Afterpulse probability is determined by measuring the statistical distribution of consecutive pairs of dark pulse events, triggered at one-half the single photoelectron amplitude. In this characterization, the Fast Output output was used. This procedure is described in detail in [5], and the results for B-Series and C-Series are shown in Fig. 4. In this sample set, afterpulse probability demonstrated an onset at 4 V and C-Series demonstrated a significantly lower afterpulse probability than B-Series. This is believed to be attributed to the same process defect reduction that reduces the DCR of C-Series SiPM.

3. Coincidence resolving time (CRT) with Ce:LYSO

Time-of-Flight Positron-Emission-Tomography (ToF-PET) imaging is enabled by the accurate determination of the position of a positron-emitting radio-nucleotide through triangulation of its 511 keV gamma decay pairs. The Coincidence Resolving Time (CRT) characterizes the timing response of two facing 511 keV photon detectors centred on a positron-emitting source, and is defined as the Full Width Half Maximum (FWHM) of a distribution of detection time intervals.

In our experiment, a facing pair of 3 mm SiPM in SMT packages each coupled to a 3 mm × 3 mm × 20 mm Ce:LYSO crystal from Proteus, Inc. are placed on either side of a ^{22}Na source. The crystals are wrapped in polytetrafluoroethylene (PTFE) tape on 5 sides, and the open side is optically coupled to the sensor surface using

BC630 silicone optical grease from Saint Gobain. The signal traces from the Fast Output output of each sensor was amplified using a Minicircuits ZX-60 voltage amplifier [6]. The pairs of traces was recorded with high speed dual channel digitizer [7], each pair being validated by leading edge trigger (typically between 10 × and 15 × single photoelectron amplitude). Each trace length was 320 ns, and the sample period was 312.5 ps with 50,000 trace pairs. The 511 keV peak selected from the integrated trace was selected for energy filter, with ± 50 keV around the peak. Interpolation was used to determine trace time-stamps for a range of leading edge thresholds. Typical energy resolutions of around 11% were achieved using the 35 μm devices. Time-walk correction was applied to remove the charge difference/time-stamp difference correlation; this is done by a straight-line fit of the charge difference and time-stamp difference for each trace pair, and by substracting the fit value at each charge difference value to eliminate the time-stamp difference correlation. CRT was computed by the FWHM of a Gaussian curve fit to the time-stamp difference histogram. Typically the lowest value CRT was reported for best leading edge threshold value.

CRT results depend on the threshold level and the type of numerical interpolation scheme used to perform time stamping of the crossing points in each detector output. Fig. 5 shows the effect of different numerical interpolation schemes and the effect of time-walk correction on B-Series SiPM (C-Series demonstrated an identical trend). For these SiPM, the CRT optimum (lowest) value was at a threshold voltage of 2 × the single photoelectron amplitude. At high threshold values, eliminating the correlation between time difference and energy (charge) difference, also known as time-walk, helped to reduce the CRT value. Linear, exponential and cubic spline interpolation schemes successively improve the value for the range of time-stamp voltages shown here. Here exponential is a linear interpolation of the logarithm of the trace voltage, effectively modeling the trace as an exponentially increasing. The greatest improvement was shown to be from linear to exponential, reducing the optimum CRT from 240 ps to 225 ps, and a further reduction to 222 ps can be achieved using cubic spline interpolation. At time-stamp values greater than 3 the exponential and cubic spline interpolated results converge. The CRT dependence on leading edge threshold for B-Series and C-Series is comparable within the experimental error reported here.

3.1. Microcell dimension

The CRT measurement was used as a guide to determine the optimal microcell structure for ToF-PET. Fig. 6 shows how the optimal CRT and operating current of two facing 3 mm B-Series SiPM changed with microcell size 20 μm, 35 μm and 50 μm, using exponential interpolation and time-walk reduction at 5.0 V overvoltage. The CRT initially decreased from 284 ps to 225 ps as the microcell size increased from 20 μm to 35 μm, however little additional benefit to CRT was achieved when increasing the microcell size further to 50 μm. The operating current, which includes contributions from both dark current and photo-current during the scintillating events, increased more than 3 times in each step. The improvement in CRT between the 20 μm and 35 μm microcell size was attributed to an increase in PDE between these designs, attributed to the fill factor, which increased from 48% to 64% respectively. The fill factor increased to 72% in the 50 μm design from 64% in the 35 μm design did not appear to benefit the CRT performance, likely due to the fact that with Ce:LYSO the performance limitation was believed to become dominated by rise time and single-photoelectron jitter. The increase in operating current with microcell size was due to the increased gain of the devices, resulting in an increase of both the dark current and photo-current of the devices. The authors believed that for lowest operating current and best CRT the 35 μm produced optimum results.

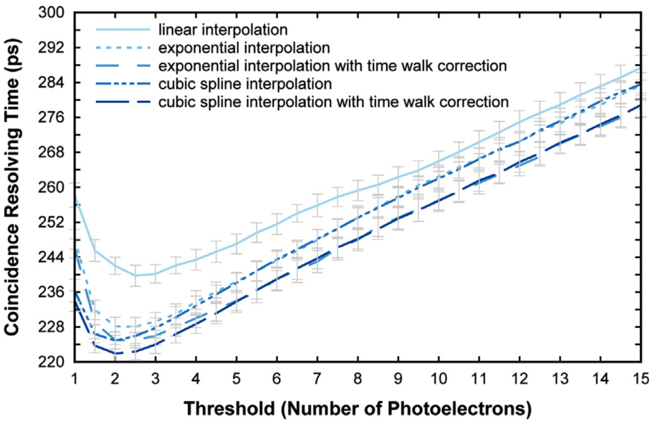

Fig. 5. CRT dependence on interpolation scheme.

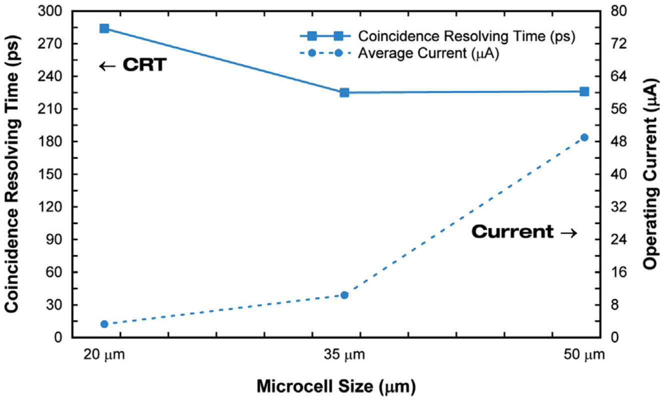

Fig. 6. CRT and operating current dependence on microcell dimension of B-Series SiPM.

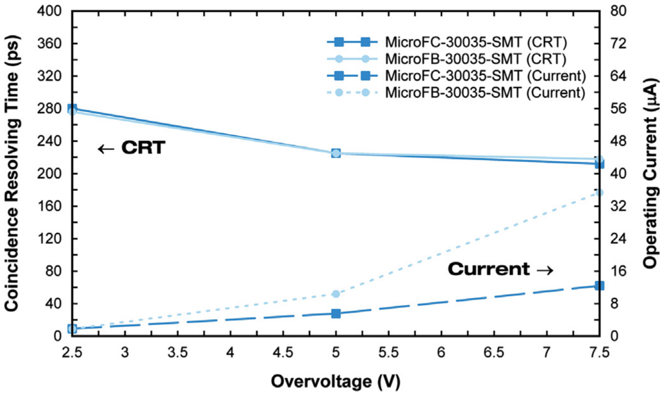

Fig. 7. CRT and operating current dependence on overvoltage of B-Series and C-Series SiPM.

3.2. Overvoltage dependence

CRT and operating current dependence on overvoltage for B-Series and C-Series devices is compared in Fig. 7. The optimal 35 μm microcell version was measured for each product type. Both B-Series and C-Series CRT demonstrated comparable CRT values which reduced as the overvoltage was increased. This reduction was attributed to the increase in PDE as the bias voltage was increased. The reduced operating current of the C-Series devices over the B-series devices was attributed to a reduction of dark-current contribution, as demonstrated in the dark count rate of C-Series in Fig. 2. The MicroFC-30035-SMT, C-Series SiPM, provided the ideal combination of low CRT and significantly lower operating current. For ToF-PET system designs which will use large arrays of SiPM which multiplex SiPM, this was a critical and dramatic improvement over the previous B-Series SiPM.

4. Conclusion

We have reviewed the main performance characteristics of pre-production C-Series SiPM and compared results to production B-Series SiPM. C-Series SiPM demonstrate significantly lower dark count rate and lower afterpulsing probability. Further improvements in PDE for UV light with similar crosstalk probability were also demonstrated for C-Series SiPM. The optimum design for ToF-PET was determined by CRT measurements and found to be the 35 μm type. Additionally the C-Series SiPM was shown to have similar CRT performance to B-Series with significantly improved operating current over B-Series. The improvements to C-Series are attributed to defect reduction techniques employed during manufacture.

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