Ultra-low noise and exceptional uniformity of SensL C-Series SiPM sensors

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ABSTRACT

SensL C-Series Silicon Photomultiplier (SiPM) sensors are fabricated in a high-volume CMOS foundry to a custom SensL process, and packaged as a reflow solderable surface mount device. Advances in SiPM production have resulted in significant improvement in PDE, dark current as well as tighter breakdown voltage uniformity for the C-Series SiPM sensors. The SiPM are fabricated with a shallow P-on-N junction optimized for the detection of shorter wavelength photons, with a peak PDE of 41% at 420nm and excellent sensitivity extending to wavelengths <300nm. The dark currents have been reduced through the reduction of damage during semiconductor processing and an order of magnitude reduction has been achieved. The breakdown voltage variation has been improved through process optimization to minimize variations. With these process improvements typical dark count rates of ~30kHz/mm^2 are achieved simultaneously with breakdown voltage uniformity of ±213mV demonstrated. In addition, application specific measurements of CRT (Coincidence Resolving Time) that are relevant to PET (positron emission tomography) will be shown to be 210ps at 7.5V overvoltage. In addition to device characterization work, this paper will address the wafer-level fabrication and testing, package level testing required by high volume SiPM sensor applications.

Keywords: Silicon photomultiplier, low dark count, SiPM uniformity, SiPM reliability, SiPM testing

1. INTRODUCTION

The Silicon Photomultiplier (SiPM) is a low-light sensor that provides a solid-state alternative to the vacuum-tube photomultiplier (PMT). The SensL SiPM to be discussed in this publication is a three-terminal sensor with anode, cathode and Fast Output. A schematic is shown in Figure 1 of the SiPM in which a small sub-section (a 3x4 microcell array) of the sensor is presented. The number of microcells in a given sensor can be varied depending on the size of both the microcell and sensor. For typical SiPM, the number of microcells is 576 (1mm^2 sensor), 4774 (9mm^2 sensor) and 18980 (36mm^2 sensor)[1]. These values are based on SiPM with the same 35µm microcell active areas. Each microcell consists of the photodiode, a quench resistor and a fast output capacitor. The fast output capacitor is a unique feature of SensL products and has been shown to provide excellent coincidence resolving times (CRT)[2].

SiPM sensors are now used in a variety of applications including Medical Imaging[3]-[7], Hazard and Threat Detection[8]-[10], 3D ranging or Light Detection and Ranging (LIDAR) and Biophotonics[11]-[13]. These applications require a device that designed for mass production, with high performance and reliability.

The latest family of SiPM sensors from SensL is the C-Series, which have been designed to provide optimized detection of Blue to Ultra Violet (UV) photons in conjunction with industry-leading dark count rates of 30kHz/mm^2. The C-Series sensors are fabricated on an 200mm wafer process in a CMOS foundry, with the entire supply chain, from wafers to packaging, geared to high-volume, high-reliability manufacturing. A high-performance custom MLP surface mount package is used which allows the creation of large area arrays. Previously, no standard reliability assessment program existed for SiPM. To deal with this issue, SensL developed a testing flow following rigorous industry standard tests designed for high-volume integrated circuits.

This paper will describe the wafer fabrication and testing as well as the MLP package and its testing and reliability program developed for it. Finally, we present in-house testing that SensL has performed to characterize the sensors.

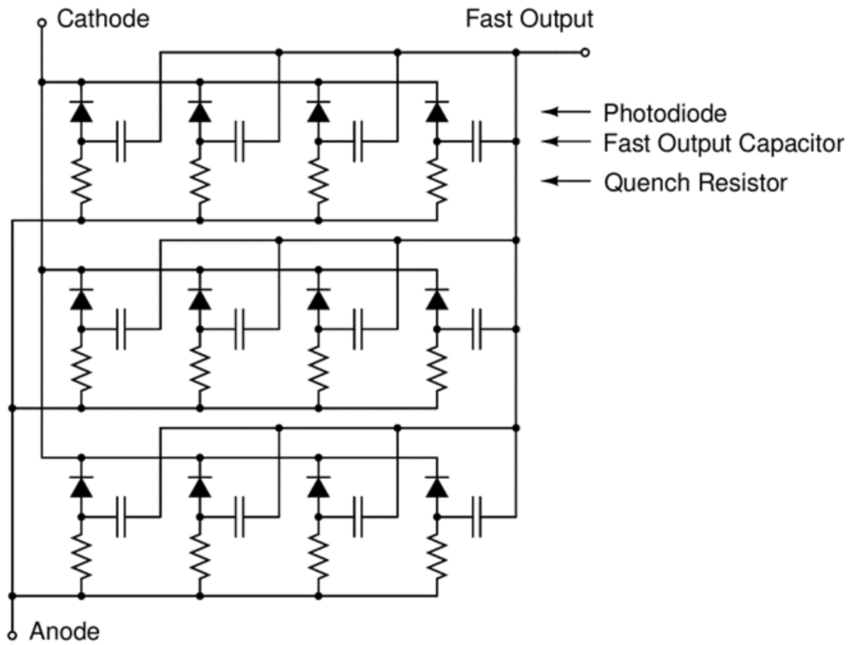

Figure 1: Standard SensL SiPM schematic architecture. The photodiode, Fast Output capacitor and quench resistor for one microcell is labeled.

2. WAFER FABRICATION AND TESTING

SensL's C-Series fabrication process was developed to produce a sensor optimized for the detection of blue to ultra violet (UV) photons. This is a requirement for positron emission tomography (PET) scanners that provide time of flight (ToF). ToF PET systems typically use Cerium doped Lutetium Yttrium Orthosilicate (LYSO) scintillation crystals with a peak emission of 420nm. The C-Series process has been tailored to produce a SiPM that has a typical breakdown voltage of 24.5V. A low breakdown voltage SiPM, has a low temperature coefficient of the breakdown voltage when compared with SiPM sensors that have a higher breakdown voltage. C-Sensors have industry-leading dark current, with order-of-magnitude reductions over SensL's previous products. These ultra-low dark currents have been achieved through the reduction of damage during semiconductor processing.

C-Series sensors also feature a fast output, which is a unique[14] feature of SensL products and is fabricated in the polysilicon, metal and oxide layers inherent in the SensL fabrication process. The fast output provides a low-capacitance output for direct interrogation of the switching behavior of the photodiode in each microcell and has been shown to provide low coincidence resolving times (CRT)[2]. The fast output is capacitively coupled with a capacitance value on the order of 2% to 4% of the total capacitance of the microcell and designed with minimal parasitic resistances.

2.1. Wafer Fabrication

SensL wafers are produced in a silicon foundry, using a CMOS compatible process. The sensors are manufactured on 200mm wafers in production lots of 25 wafers. The process is geared to high-volume production and leads to the best uniformity, consistency and reliability at a lower cost than the custom processes used by other manufacturers.

2.2. Wafer Testing

Following completion of the fabrication process, each wafer is comprehensively tested at Wafer Acceptance Test (WAT) using process control monitor (PCM) tests. WAT verifies that the wafer was processed correctly and that key technological parameters such as breakdown voltage, diffused and deposited film resistances are on target and within specified test limits. These test limits were established based on technology target values, material and process characteristics such as film thickness and resistivities, and from data collected during the technology development phase from skew or split lots. The measurement data from WAT is monitored wafer-to-wafer and lot-to-lot and trends are analyzed to verify process capability and stability. This process is a standard part of SensL's C-series process and is repeated for all production SiPM sensors produced.

Following PCM test all SiPM are tested at component probe (CP) using tester hardware that was developed for SiPM sensor testing. For C-Series SiPM sensors the breakdown voltage, dark current and optical response to short wavelength light are critical parameters measured on the SiPM product die. SensL has established a wafer probe flow that measures every die on the wafer under dark and illuminated conditions, with appropriate optical filters, so that response of the SiPM sensor under broadband and short wavelength conditions was measured. Die with failing characteristics are identified on electronic wafer maps, and only those die that pass all of the quality and performance screens are subsequently assembled as packaged sensors.

2.3. Wafer Testing Results

Breakdown Voltage: The breakdown voltage of a SensL SiPM is provided on the datasheet with maximum and minimum allowed values. For C-Series parts this is 24.2V to 24.7V and parts outside of this value are screened and not shipped to customers. The breakdown voltage is defined as the value of the voltage intercept of a parabolic line fit to the current versus voltage characteristic curve. Due to the tight uniformity achieved with the SensL SiPM manufacturing process this parameter was calculated from measurements of the dark current at several bias points surrounding the nominal breakdown voltage value for this work. Figure 2 shows the distribution of breakdown voltage values as measured from production lots obtained during the qualification of a single die size product. For the breakdown voltage variation plot shown in this work, a total sample size of 67,236 SiPM sensors of the 60035 (6mm) type were available. The 60035 sensor is ultimately packaged and sold as the MicroFC-60035-SMT product. A mean breakdown voltage of 24.5V was measured. The measured values were seen to be tightly distributed with all die having breakdown voltage values within ± 213mV (3σ) of the mean. This is an improvement over previous generations of SiPM from SensL and was obtained through process improvements. The improved uniformity of the breakdown voltage is due to the tight process control and design of the SensL SiPM. It should be noted that the breakdown voltage values shown in Figure 2 were taken at 25°C while the datasheet quotes the breakdown value of SensL SiPM at 21°C. Values in Figure 2 should therefore be shifted lower by 21.5mV/°C to correspond directly with the datasheet.

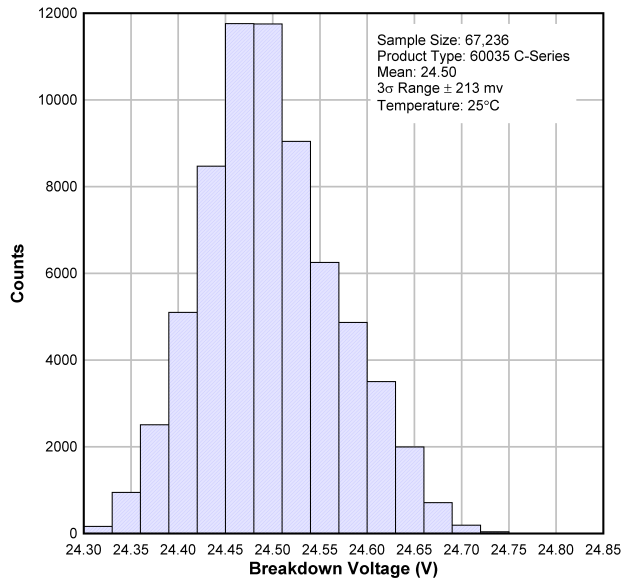

Figure 2: Distribution of breakdown voltage for a sample size of 67,236 SiPM sensors (60035 type). Data taken at a constant temperature of 25°C.

Dark Current: Dark current is a key parameter for the SiPM, and is measured in the component probe flow at several bias points above and below the breakdown voltage. Die with dark currents that are outside specification are screened out and inked electronically so that they are not assembled into packages. This ensures that the datasheet specifications are met.

Optical Uniformity: To ensure quality of the SiPM the output current from the sensor die is measured in the component probe flow under tightly controlled illumination conditions. For this measurement a uniform and calibrated blue light source with an output of 420nm to 520nm is used. This approximates intended use conditions in medical imaging PET and radiation detection applications. By measuring all die on the wafer it is possible to develop a full understanding of the optical uniformity of the SiPM. Two measurement conditions are particularly useful for customers working with a SiPM. The first measurement is at a constant overvoltage of 2.5V and the second method uses a fixed operating voltage of 29.5V. For the 2.5V overvoltage measurement; overvoltage is defined as:

$$Overvoltage\ (V) = V_{app} - V_{br}, \tag{1}$$

Where V_{app} is the applied voltage and V_{br} is the measured breakdown voltage. Assuming an accurate assessment of the breakdown voltage, measuring at a constant overvoltage should eliminate variation in gain due to variations in the V_{br}. An example of the optical uniformity taken at a constant overvoltage of 2.5V is shown in Figure 3. This demonstrates a 3 sigma optical uniformity of ± 7.45 %.

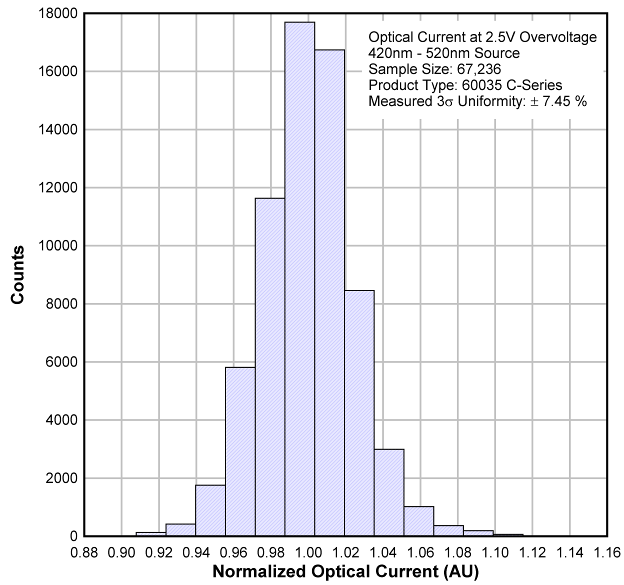

Figure 3: Distribution of the optical current at 2.5V overvoltage from 67,326 SiPM sensors (60035 type).

The second measurement is performed at a constant voltage of 29.5V. This voltage is independent of the breakdown voltage and therefore provides a good indication of the product uniformity at a constant bias condition. This is important for high volume application where it is desired to operate all SiPM at the same voltage. For the measurements shown in this work, all SiPM were measured at a constant voltage of 29.5V. Figure 4 shows the distribution of output current values as measured from multiple production lots, with a total sample size of 67,326 SiPM sensors of the 60035 (6mm) type. By measuring in this way, the effect of breakdown voltage variations from die-to-die, wafer-to-wafer and lot-to-lot was included and variations in parameters such as film thickness, doping level and gain are integrated into the final result in Figure 4. The measured distribution illustrates the tightly controlled uniformity characteristics of the C-Series SiPM manufacturing flow, with 3σ uniformity of ± 8.74 % for optical currents at these bias conditions. In production, die with illumination current values in excess of ± 10 % the established product mean are electronically marked and eliminated from the supply chain. This is done to ensure that all products adhere to the datasheet for volume production.

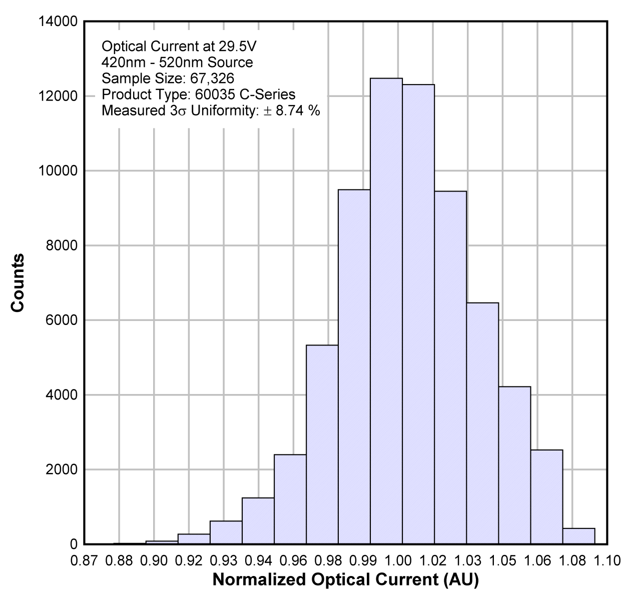

Figure 4: Distribution of the optical current at 29.5V from 67,326 SiPM sensors (60035 type).

3. PACKAGE TESTING AND RELIABILITY

The C-Series SiPM sensors are packaged in a custom clear MLP (Micro Lead Package) using a high-volume, mold assembly process. The package fabrication and testing, like the wafers, are geared for mass production and high reliability. The MLP itself has many benefits, being an SMT part that is compatible with reflow soldering, is able to withstand a wide range of temperatures and has high yield and low cost. In addition, the small form factor and minimal dead space at the perimeter mean they can be used to create arrays for imaging applications. An example of 4 types of large area arrays created from these SiPM is show in Figure 5.

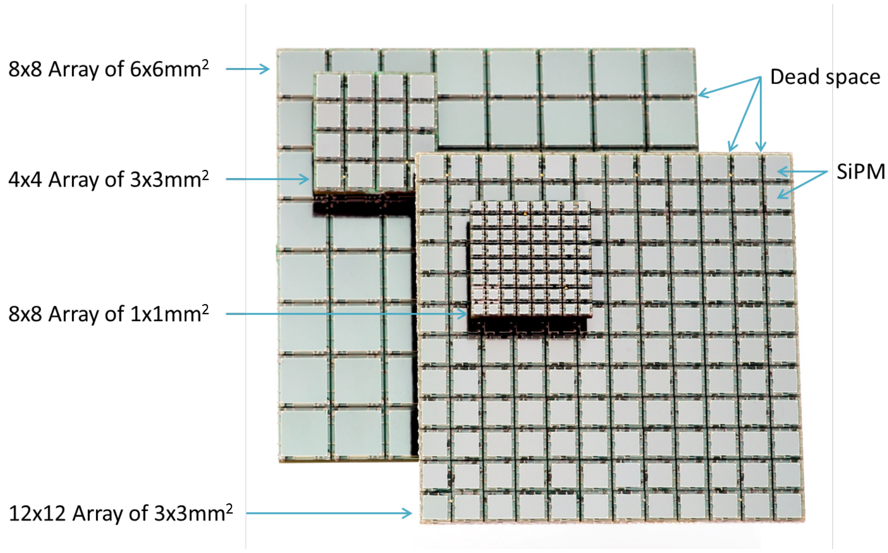

Figure 5: Example of 4 different types of large area arrays fabricated from smaller clear MLP surface mount sensors.

3.1. Package Testing

The packaging of the SiPM sensors into the MLP package is performed in volume on an entire wafer batch. After packaging is complete the parts are tested electrically and visual inspection of the die is performed. All failing parts are destroyed and all failed parts are removed from the supply chain. Parts which meet SensL's test criteria are placed on tape and reel. Tape and reel products are available in quantities of 3000 for the 1mm ($1mm^2$), 3mm ($9mm^2$) and 6mm ($36mm^2$) SiPM size.

3.2. Package Reliability

SensL has developed a reliability assessment flow based on the JEDEC[16] integrated circuit standard test conditions. The JEDEC standard for the main reliability test procedure can be obtained from JEDEC[17] and the full procedure carried out on SensL B-Series SiPM has been published previously[20]. For the C-Series SiPM, the package used is identical and it is not required to carry out a full package level reliability assessment, therefore data from the previous work on B-Series SiPM can be used to determine that the package is reliable. The silicon reliability assessment is underway and will be the subject of future work.

4. PERFORMANCE CHARACTERIZATION

SensL takes delivery of the reels of tape containing the MLP packaged SiPM sensors. Full performance characterization is then carried out on a sub-set of sensors in-house at SensL, using standardized testing. Some of the results of this testing are presented here. In all cases the measurements were performed on SiPM sensors packaged in the MLP (SMT) package at a temperature maintained at 21 ± 1°C.

4.1. Photon Detection Efficiency (PDE)

The PDE measurement technique is described by Eckert [16]. This technique produces the true SiPM PDE and does not contain the effects of crosstalk or afterpulsing. PDE of the packaged MLP sensor is tested at 2.5V and 5V overvoltage, and from 250nm to 1050nm. The resulting PDE plots for C-Series MicroFC-30035-SMT are shown in Figure 6 and have a peak PDE of 41%. The sensitivity in the blue/UV region has been enhanced over B-Series SiPM and provides an excellent spectral match to LYSO and LaBr3 scintillators[19].

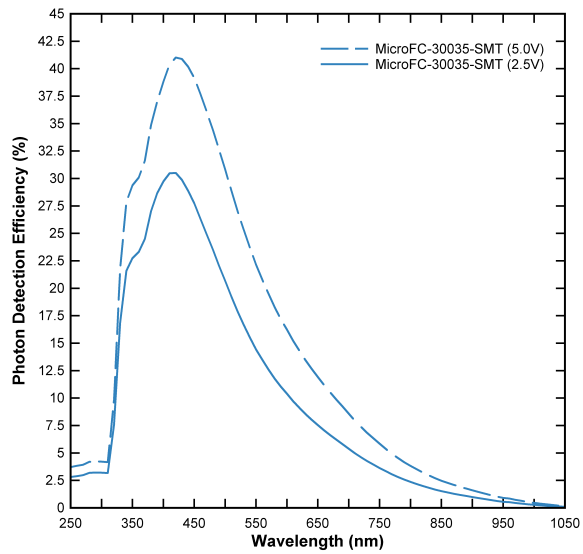

Figure 6: PDE of a MicroFC-30035-SMT (3mm) SiPM sensor at 2.5V and 5V overvoltage, showing a peak PDE at 420nm of 41%.

4.2. Dark Count Rate

Dark count rate is defined as the pulse rate measured in the dark with a leading edge trigger at 0.5 times the single photoelectron amplitude. The dark count rate was measured using an Agilent 53131A Universal Counter. The single photoelectron amplitude at each point was determined by observing when the rate first decreases as the leading edge threshold increased. By increasing the threshold until the dark rate changes it was possible to determine the maximum pulse height of the single photoelectron rate. A measurement of the dark count rate is not impacted by crosstalk but can be influenced by afterpulsing. In the case of these samples, afterpulsing is shown to be very low and not a significant factor in the measured dark count rate. The dark count rate per mm^2 for MicroFC-30020-SMT (20um microcells), MicroFC-30035-SMT (35um microcells) and MicroFC-30050-SMT (50um microcells) SiPM is shown versus overvoltage in Figure 7. The results in Figure 7 demonstrate a very well controlled dark count rate versus overvoltage suitable for mass production applications that require SiPM sensor output stability over a wide range of overvoltage conditions across a wide range of temperatures. A typical value of $30kHz/mm^2$ is seen for C-Series SiPM, at 2.5V overvoltage, and this represents an improvement of over an order of magnitude over previous generations of SiPM. Improvements to the dark count rate have been obtained through reduction in the damage to the silicon during fabrication.

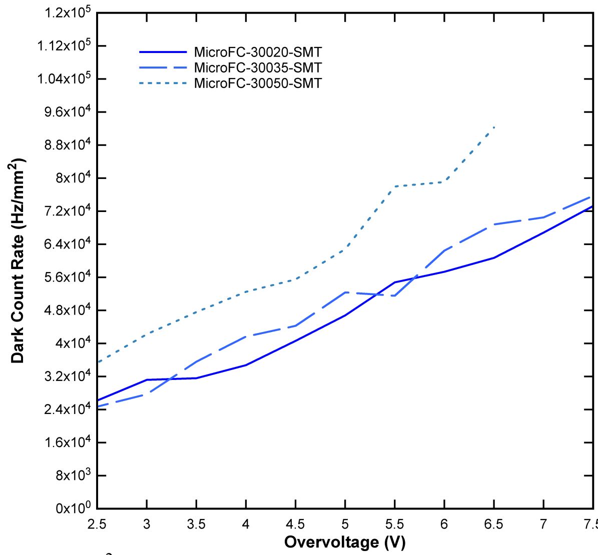

Figure 7: Dark count rates (per mm^2) for 3mm sensors with varying microcell sizes, as a function of overvoltage.

4.3. Crosstalk

Crosstalk is defined as the ratio of pulse rates from a SiPM measured at 1.5 times the single photoelectron amplitude to 0.5 times the single photoelectron amplitude. Crosstalk is an undesirable phenomenon, in that a single firing microcell fires a neighboring microcell almost instantaneously. Crosstalk pulses can therefore appear as multiple output signals in response to a single photon. This happens for a fixed fraction of events and is bias-voltage dependent. Increasing bias voltage increases crosstalk. Crosstalk can be caused by electrical charge leakage or optically generated due to the emission of light during the avalanche process in SiPM sensors.

To measure the crosstalk in SiPM sensors, the rate of events as a function of leading-edge threshold was measured as a function of bias voltage. This results in a staircase-like dependence of rate versus threshold, and progresses to lower rates as the threshold increases. The 1.5 and 0.5 photoelectron rates can then be measured and the ratio computed for each overvoltage and is shown in Figure 8. Very low crosstalk of ~9% is achieved even at 5V above the breakdown for the MicroFC-30035-SMT product. Crosstalk has been shown to be unchanged from previous versions of SensL SiPM.

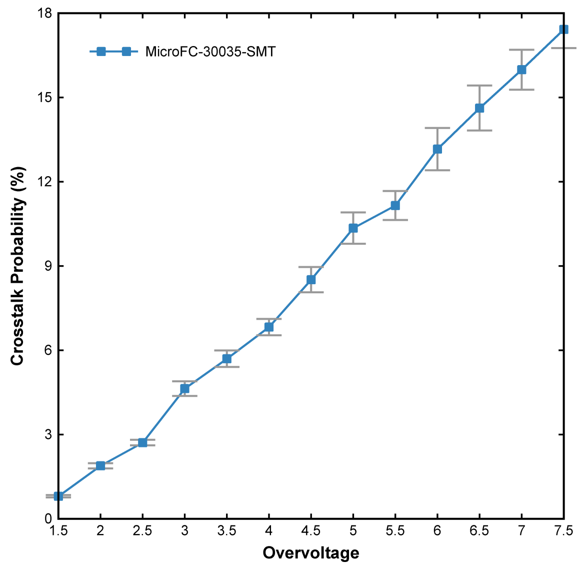

Figure 8: Crosstalk probability for a 3mm, 35um microcell SiPM as a function of overvoltage. At 5V over, the crosstalk is ~9%.

4.4. Afterpulsing

Afterpulsing is the phenomenon of a SiPM microcell randomly discharging with higher probability shortly after a previous discharge than with the expected thermal generation rate. Afterpulse events that occur after the recovery time cannot be distinguished from genuine, photon-induced events and therefore deteriorate the photon-counting resolution of a SiPM. Typical time scales for this phenomenon are tens of nanoseconds, comparable with the microcell recovery time. As a result, many afterpulse events are of partial discharge compared with the single photoelectron discharge of a microcell, due to partial recharge of the microcell. Afterpulsing is an undesirable effect because it increases the variance of the single cell charge, reduces dynamic range, and increases crosstalk in the SiPM. The degree of afterpulsing depends on the bias voltage, temperature, the design of the SiPM doping levels and the recovery time.

The afterpulsing was measured as a function of overvoltage and is shown in Figure 9 for a MicroFC-30035-SMT SiPM. This demonstrates the low level of afterpulsing present in the SiPM with afterpulse rates of ~0.5% at up to 5.0V overvoltage. The afterpulsing was in fact difficult to measure due to the low level and long measurement times of up to a day were required to provide sufficient statistics to achieve accurate results. This low level of afterpulsing has been shown to be lower than previous generations of SensL SiPM[19]. It is believed that process improvement to reduce damage during the SiPM fabrication improve the afterpulsing which can be achieved with SensL's C-Series SiPM.

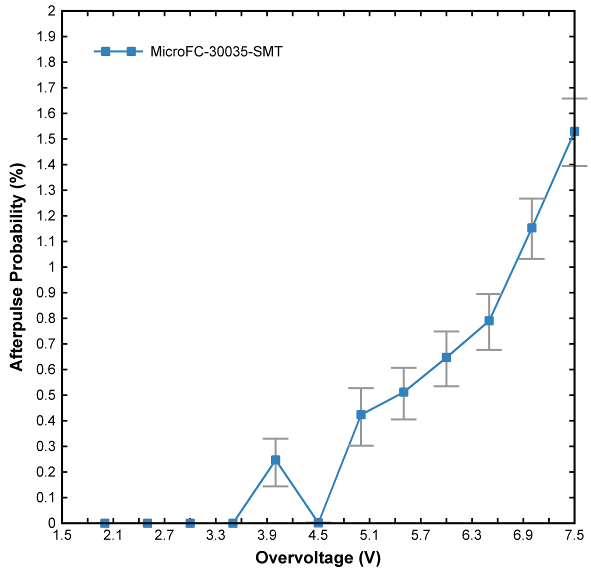

Figure 9: Afterpulse probability for a 3mm, 35um microcell SiPM as a function of overvoltage. At 5V overvoltage, the afterpulsing is ~0.5%.

5. APPLICATION SPECIFIC MEASUREMENT

To demonstrate the performance of SensL SiPM in an application environment the sensors were coupled to LYSO scintillation crystals. This is similar to the system configuration in a PET ToF system. When the SiPM sensor is combined with the scintillation crystal it forms a gamma-ray detector. It is desired to demonstrate a minimum coincidence resolving time (CRT) of coincident 511keV gamma-ray pairs that are produced in electron-positron annihilation. LYSO forms an optimal combination with SensL's C-Series SiPM, as the output peak, at 420nm, matches the photon detection peak of the sensor.

5.1. Coincidence Resolving Time (CRT)

Coincidence resolving time (CRT) is important to ToF-PET applications as it allows more accurate determination of the emission source position and better image quality. For this work, CRT was evaluated by determining the arrival time of coincident 511keV photon gamma pairs at a corresponding pair of scintillation-based detectors. A ^{22}Na positron source was placed between two facing $3{\times}3{\times}20mm^3$ LYSO crystals coupled to SiPM sensors, positioned head-on, and the resulting electrical signal from the detectors was amplified and recorded with a high-speed digitizer (USB Wavecatcher 12-bit, 3.2GS/s). Figure 10 shows the CRT of the Fast Output as a function of overvoltage, showing reduced CRT as the overvoltage was increased. A CRT of 210ps was achieved at 7.5V overvoltage making this sensor suitable for use in ToF-PET applications. The CRT measured was believed to be limited by the electronics setup. Work is underway at SensL to improve this test setup and it is believed that C-Series SiPM can demonstrate CRT of <200ps. This will be the subject of future work.

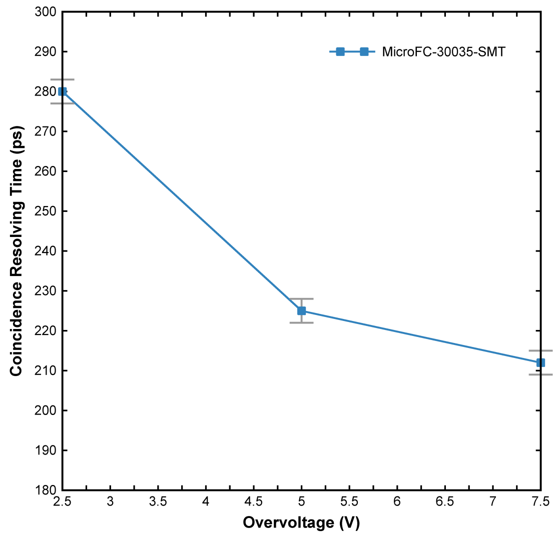

Figure 10: CRT for a MicroFC-30035-SMT (3mm) SiPM as a function of overvoltage. At 7.5V above the breakdown voltage, a CRT of 210ps is achieved.

6. CONCLUSION

In this paper we have demonstrated the main production flow for the SensL C-Series SiPM sensor including wafer production, wafer test, packaging, package test, reliability assessment and performance characterization. At wafer level the results of the 6mm 60035 type SiPM sensor were shown for 67,236 samples. The C-Series SiPM has been shown to have a low breakdown voltage of 24.5V and a distribution of 213mV (3σ) was demonstrated. The wafer level optical uniformity test was introduced and results shown for 2.5V overvoltage and also at 29.5V fixed single voltage. The fixed 29.5V uniformity is a key parameter for customers looking to use a single operating voltage for all sensors in use. It was shown that at 29.5V a distribution of 8.74% was obtained indicating excellent fixed single voltage optical uniformity. For the package characterization results the PDE, dark count rate, crosstalk and afterpulsing were shown. Crosstalk is unchanged from previous generations of SiPM while the afterpulsing is shown to have reduced. The PDE of C-Series SiPM is shown to have improved for blue to UV light and a maximum value of 41% was demonstrated at 420nm. The dark count rate is over an order of magnitude lower over previous generations of SiPM. The dark count rate was shown to be 30kHz/mm^2 for samples measured and it is believed that process improvements to preserve the high quality of the silicon during processing are responsible for the lower dark count and afterpulsing results shown. The authors believe that this represents the lowest dark count rate demonstrated for volume production SiPM to date. Finally CRT measurements were shown with values of 210ps demonstrated for measurements at 7.5V overvoltage. The C-Series SiPM has been shown to have leading edge performance and the uniformity demanded by high volume applications.

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