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Readout Methods for Arrays of Silicon Photomultipliers

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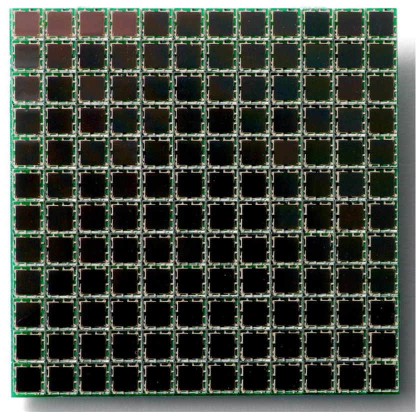
APPLICATION NOTE



Silicon Photomultiplier (SiPM) technology is rapidly becoming the primary choice of photosensor in a wide range of applications, such as medical imaging and hazard and threat detection. These sensors have many advantages over other types of photodetector, such as low bias, uniformity, compactness, ruggedness and insensitivity to magnetic fields. SiPMs also have the benefit of allowing a great deal of flexibility in the creation of 2D arrays of the sensors for imaging applications.

ON Semiconductor produces a range of SiPM sensors in compact surface mount packages that are suitable for reflow soldering. Creating large arrays with minimal deadspace on PCB is now a well developed process that makes custom arrays easily available to a wide range of users. There is an Application Note available that describes how to use these packages to create large area arrays.

The challenge in many imaging applications is how to readout and process the data from arrays that may contain a large number of pixels. This document describes a number of the ways in which the readout of a large number of pixels can be achieved and presents some case studies where users have employed these techniques.

1:1 (INDEPENDENT) CHANNEL READOUT

The most obvious way to readout a multichannel sensor is to read each channel out independently, with one amplification and data acquisition channel per sensor, hence 1:1 readout. This results in a total of $N \times M$ readout channels, where N is the number of array pixels in the X direction and M is the number of array pixels in the Y direction.

The benefits of such an arrangement are the ability to distinguish multiple interactions or scatter in the sensor array, correct for non-uniformities in the image and have greater bias control if required. Since each signal is acquired independently, the signal-to-noise is maximized. Independent channel readout also allows for the highest count rates without system pile up.

Such a 1:1 readout scheme is practical for low channel count systems with discrete electronics, or for high channel count systems when using an ASIC. Either way, 1:1 readout will provide the highest levels of sensor performance, and has been successfully implemented in commercial applications.

MULTIPLEXING METHODS

There are many practical reasons why it may not be possible to implement 1:1 readout, and in those cases, some multiplexing is employed to reduce the channel count. There are a number of different readout architectures that can be used to achieve the desired multiplexing, depending on the application.

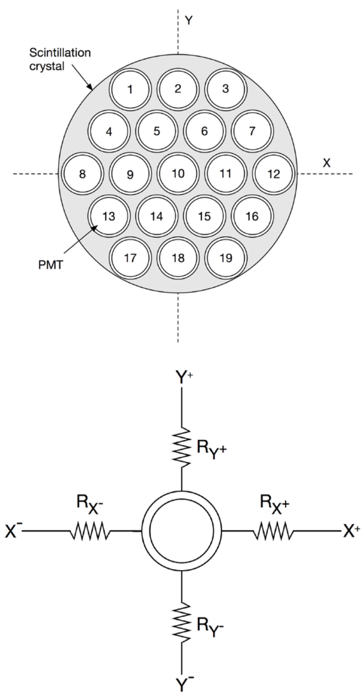


Figure 1. Anger Camera (Top) and the Multiplexing Principle (Bottom)

The benefits of multiplexing are the reduction in complexity and cost due to the use of fewer electronic and data acquisition channels. A potential draw-back is that multiplexing may reduce the ability to recognize multiple events or scatter interactions, or correct for anode/pixel non-uniformities. In addition, the multiplexing of multiple SiPM sensors via resistor networks can lead to a degradation of the timing performance of the detector due to the high capacitance of SiPM sensors.

Some common multiplexing schemes are discussed below.

Anger

In 1957 Hal Anger first described the gamma camera [1], or Anger camera (Figure 1), which still forms the basis of the majority of nuclear medicine examinations performed today. The Anger camera is formed of an hexagonal array of Photomultiplier Tubes (PMT), coupled to a continuous scintillator and collimator.

To provide position information from the analogue outputs of the PMTs, multiplexing via a resistive network is used. The output from each PMT is shared between four outputs (X+, X−, Y+, Y−) using resistors (Figure 1). The fraction of the signal going to each output is determined by the value of the resistors used, being proportional to 1/R. The value of the resistors are chosen such that the calculated X and Y positions vary linearly with the position of the interaction. The X and Y positions are determined by combining the four signal values using Equation 1.

$$X = \frac{X^+ - X^-}{X^+ + X^-} \qquad Y = \frac{Y^+ - Y^-}{Y^+ + Y^-} \qquad \text{(eq. 1)}$$

This ‘Anger logic’ is used for reconstructing event locations in a number of multiplexing schemes, even if the position encoding circuits are in a different form.

DPC

The DPC (Discretized Positioning Circuit) is based upon an idea first used in single wire, position sensitive proportional counters and later applied to MAPMTs (Multi-Anode Photomultipler Tubes) as proposed by Siegel [2]. Each pixel in the array is connected to a node in a row of discrete resistors, with a column of resistors at either end connecting the rows together such as the arrangement shown in Figure 2. In this way, the signal location is given by the proportional current attenuation from the resistive chain, that results in an M × N array being readout out by just 4 channels. Using these four position-encoded output signals (in this case denoted A, B, C and D) the interaction position is calculated using Equation 2.

$$X = \frac{A + B}{A + B + C + D} \qquad Y = \frac{A + D}{A + B + C + D} \qquad \text{(eq. 2)}$$

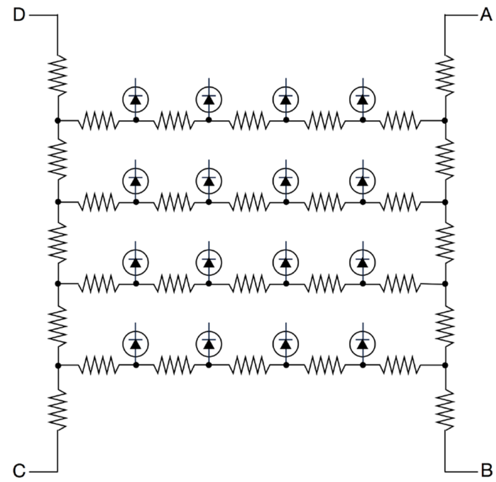


Figure 2. An Example of a DPC Circuit for a 4 × 4 Array of Pixels

Like Anger’s method, the benefits of this method of multiplexing are the low complexity and its passive nature. Although the DPC method uses fewer resistors per node, it has the drawback of asymmetric charge division in the X and Y directions which tends to distort the image and can result in poorer pixel definition in one direction.

It should be noted that the best results are obtained with smaller numbers of pixels, and as the pixel count increases, the image quality and other performance parameters typically degrade.

Recently, the DPC has been applied to the readout of SiPM arrays by a number of groups including Zhang [3], Goertzen [4], Kolb [5], and Song [6].

Row/Column Readout

Row/column readout (also known as crosswire readout) is based on summing the signals from all nodes in a given row or column, resulting in an output channel per row and column of the array. Therefore, an N × M array will require N + M readout channels. This technique was originally developed for use with MAPMTs (Multi-Anode Photomultipler Tubes) [7] where the signal from each anode is split by a symmetric resistive divider, dividing the current equally in two as shown in Figure 3. Half of the current flows to the X output line, and the other half to the Y output line.

When this technique is applied to an array of SiPM sensors, the resistive divider at each node can be omitted and the sensors wired in such a way that:

- All cathodes of pixels in the same column are summed to form a set of column “X” outputs.
- All anodes of pixels in the same row are summed to form a set of row “Y” outputs.

An example of a row/column scheme for a 4 × 4 SiPM array is shown in Figure 4.

If a sensor responds to incident light, it will generate a current pulse in one or more of the corresponding X and Y outputs. The X and Y signals can be combined using Anger Logic to determine the original interaction point of the gamma-ray photon.

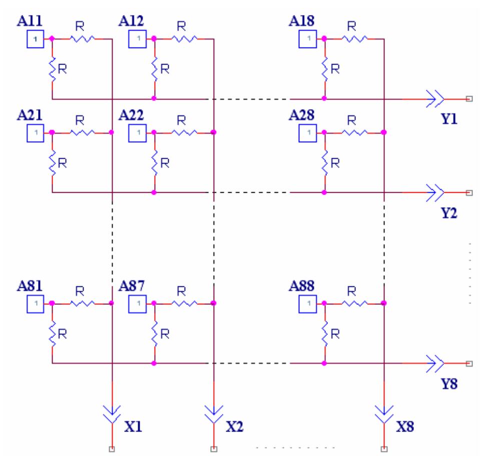


Figure 3. Row/Column Readout with Resistive Dividers using Only Anode Connections [7].

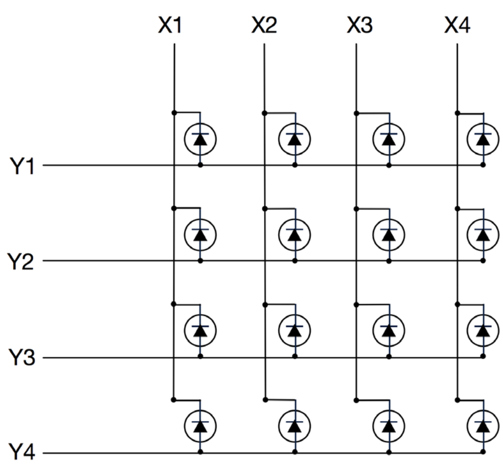


Figure 4. Row/Column Readout for a 4 × 4 Array of SiPM Sensors

Row/column techniques can limit the performance of the sensors, particularly energy resolution and timing. When multiple sensors are connected to the same output it results in higher capacitance and noise levels. The amount of performance degradation depends on system level parameters and should be considered.

Recent applications of the row/column technique to the readout of arrays of SiPM typically go a step further and use the SCD (Symmetric Charge Division) technique to reduce the number of readout channels to four.

SCD

The SCD (Symmetric Charge Division) multiplexing scheme takes the row/column method described above and further reduces the number of readout channels to just 4 (two X and two Y). This is achieved by placing a resistive chain between the row (or column) outputs, as shown in Figure 5. Anger logic can be used with the signals from either end of the chain to decode the position of the original signal.

In a further adaptation proposed by Popov [8], amplifiers can be added to each X or Y signal before the resistive chain. Doing so improves the signal-to-noise ratio and reduces the effect of sensor output capacitance and crosstalk between inputs, at the expense of additional cost, power and complexity.

In one study by David [9] it was found that the SCD achieved a higher peak-to-valley ratio in the image, as compared to the DPC.

In addition to [9], SCD has also been applied to the readout of ON Semiconductor SiPM arrays by Wang [10].

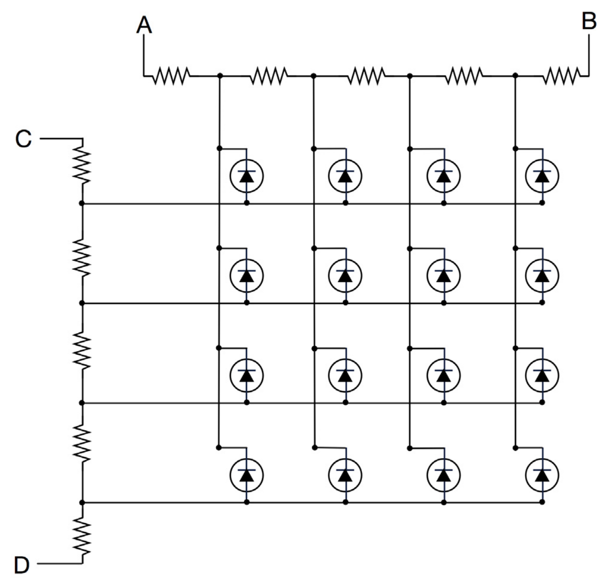


Figure 5. An Example SCD Circuit for a 4 × 4 Array of Pixels

SiPM MULTIPLEXED READOUT CASE STUDIES

The suitability of the various multiplexing schemes depends upon the application. A number of case studies that use multiplexing in the readout of SiPM arrays are described on the following pages. The case studies can be grouped into those applications trying to achieve high spatial resolution and those aiming for optimal timing. Where possible, the case studies references the publicly available source information.

Readout for High Resolution

High resolution imaging is achieved by increasing the granularity of the imaging elements, resulting in an increased number of sensor pixels. Therefore, spatial resolution is often increased at the expense of a rise in the number of readout channels. Multiplexing schemes are then often necessary, but the challenge is to find the correct arrangement that minimizes the number of readout channels, and preserves the ability to correctly identify all of the pixels in the imaging plane and retaining a certain level of other performance parameters (e.g. energy resolution, timing resolution).

A. Multiplexed Readout with 12 x 12 Arrays by West Virginia University and AiT

Goal:	**Minimize channel count**
	Achieve similar operation to the H9500
Multiplexing:	**16:4, 144:4 and 144:24**
Crystal pitch:	**1.5 mm (LYSO)**

The group at West Virginia have done a great deal of work using SiPM arrays with multiplexed readout for nuclear medicine applications [11], [12]. Work with the first generation of SensL® arrays (the SPMArray4 and SPMArray4p9) investigated the potential for inclusion in a MRI-compatible small-animal PET imager. The goal was to achieve a performance similar to that of the H8500/H9500 MAPMTs, which have good imaging performance, but are not candidates for use with MRI. In this early work, the group was aiming to achieve the highest channel reduction factor, with acceptable compromise in the detector energy and spatial resolution at room temperature. Channel reduction was desired to avoid the high complexity and cost associated with the direct readout. The degree of reduction was limited by the fact that SiPM sensors have higher noise levels than PMT detectors. This noise increases with the number of multiplexed pixels and with increasing temperature.

Both the SPMArray4 and the SPMArray4p9 were equipped with a multiplexing circuit from AiT [11] that reduced the number of channels to four. It was found that the SPMArray4 with 16:4 multiplexing, could distinguish an array of $1 \times 1 \times 10$ mm^3 LYSO pixels at 511 keV and room temperature (Figure 6) with an energy resolution of 14−15%. The SPMArray4p9, with 144:4 multiplexing, was able to resolve 1.5 mm LYSO pixels at room temperature at 511 keV (Figure 7), with an energy resolution of around 16%.

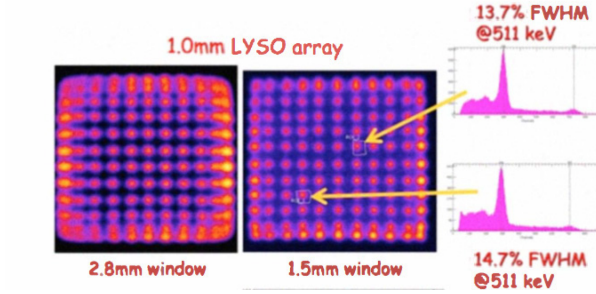


Figure 6. Imaging Results Using 16:4 Multiplexing from [11]

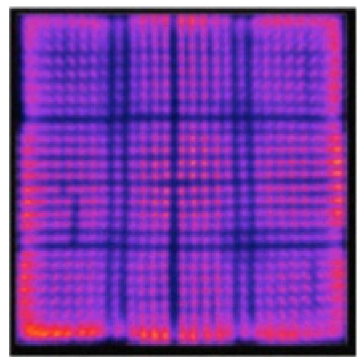


Figure 7. 144:4 Multiplexing of the SPMArray4p9 with 1.5 mm LYSO and Illuminated with 511 keV at Room Temperature [11]

The group has made more recent measurements using the SensL B-Series arrays. The design is intended for a PET−MRI pre-clinical insert that is based on SiPM and LYSO modules that are 4.4 cm × 9.2 cm in size [12]. Each is composed of two 12 × 12, 3 mm-pixel SiPM sensor modules (ArrayB−30035−144P−PCB) coupled to an LYSO array of 1.57 mm × 1.57 mm pixels via a tapered light guide and light spreader. The light spreader is used to ensure that the light from the small scintillation pixels is distributed across multiple SiPM sensors for accurate centroiding.

For this work the 144:4 multiplexing scheme was used. Using the higher sensitivity B-Series sensors it was found that at room temperature, the 144:4 multiplexing was able to resolve down to 1.5 mm LYSO pixels (using 511 keV photons). However, some of the edge pixels are not properly resolved (Figure 8).

By repeating this set-up at 10°C, the pixel resolution increases substantially, as seen in Figure 8, due to the reduced noise as a result of cooling.

At both temperatures, energy resolution was 11%−12% @ 511 keV. Timing performance was not reported.

In order to avoid the complications associated with the use of cooling, it was decided to try a less severe multiplexing scheme, so a 12X + 12Y row/column scheme was tested, giving 144:24 multiplexing. In this set-up, energy resolutions were between 10−11% and all 1.57 mm pixels were clearly resolved all the way to the edges at room temperature (Figure 9).

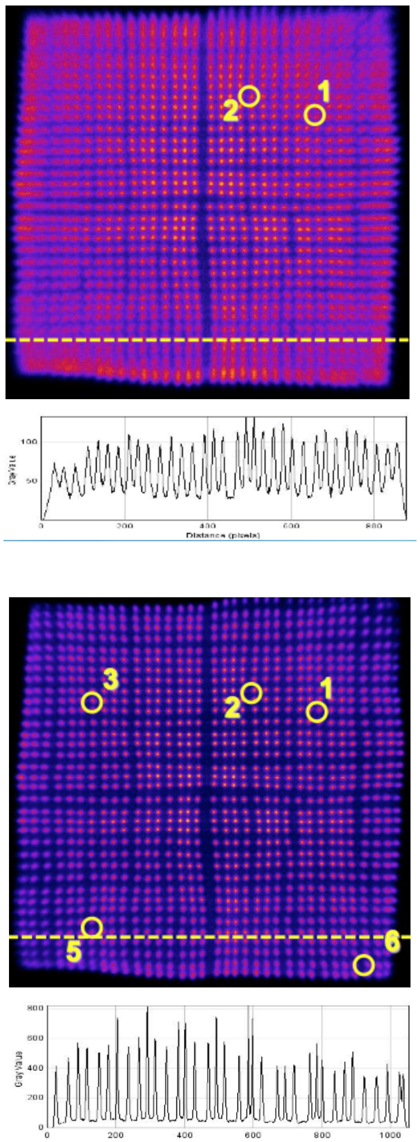


Figure 8. 144:4 Multiplexing, (Left) Flood Map and Pixel Profile at 22°C and (Right) at 10°C. The Numbered Pixels Correspond to Energy Spectra that are Shown in the Referenced Paper [12]

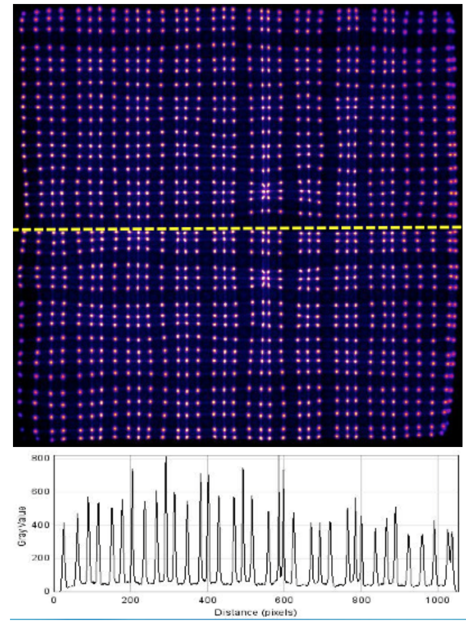


Figure 9. 24-channel Row/Column Readout (12X + 12Y) of an Array of 1.57 mm Pitch Pixels of LYSO, at 29.5 V [12]

B. Charge Division Circuit for the Array4 by the University of Manitoba

Goal:	**Dual layer scintillator readout with 4 output channels**
Multiplexing:	**16:4 and 48:4**
Crystal pitch:	**1.67 mm and 3 mm (LYSO)**

A team from the University of Manitoba is developing a PET sensor based upon 3 mm pixel SiPM arrays from SensL with LYSO scintillation pixels and multiplexed readout to reduce channel number [4]. The group had previously used an adapted row/column system that reduced the number of channels to three, that worked well but used a lot of op-amps. As an alternative, the DPC multiplexing scheme shown in Figure 10 was used, that minimizes both ADCs and op-amps. Based on the original design by Siegel [2], it has resistors connecting the pixels of each row of the array and a column of resistors at each end of the rows connecting the rows together. At each of the four outputs (i.e., the corners of the device), the signals are amplified using an op-amp. The use of just four op-amps for the entire array minimizes power consumption and reduces the number of active components on the sensor readout circuit. This reduces the 16 pixels of an SPMArray4 to 4 outputs (16:4 multiplexing).

The authors work optimized the resistor values and then tested the system in a variety of conditions, recording flood maps (Figure 11), energy resolution and timing.

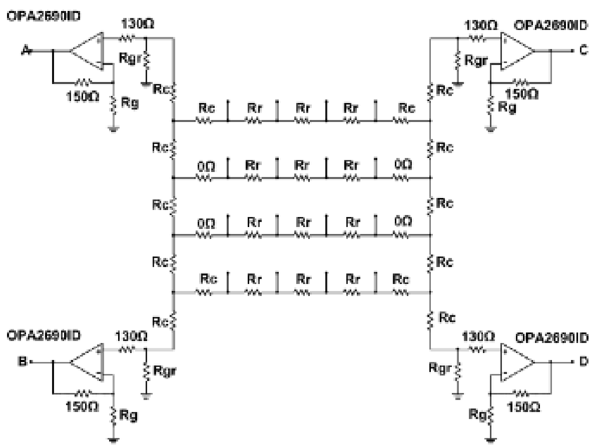


Figure 10. Charge Division Circuit used by Goertzen [4]

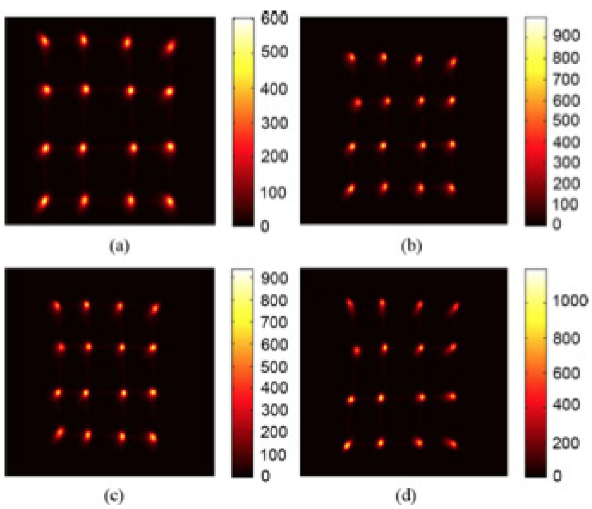


Figure 11. Flood Images with a) High, b) Medium 1, c) Medium 2 and d) Low Resistor Values [4]

The flood maps from four sets of resistor values (high, medium1, medium2 and low) are shown in Figure 11. It can be seen that the ‘high’ resistor values reproduce the pixel spacing most accurately. The other images all show some contraction in the X direction.

The work demonstrated that the use of high resistor values also gave the highest signal amplitude and best energy resolution (<15%), but the timing was severely compromised. This was because the high resistor values coupled to the capacitances of the SiPM pixels act like an RC filter. Using medium values of the resistors gave a timing resolution of 3 ns, while offering a good trade-off for the energy resolution and photopeak amplitude.

In the second part of the study, images were acquired using two layers of scintillator pixels that have a pixel pitch of 1.67 mm. The top array is offset from the bottom array by half a pixel width in each direction. In this dual layer version (Figure 12), the energy resolution measured was 15.2% for the top layer and 16.8% for the bottom layer. The timing resolution for the 350−750 keV energy window was 3.32 ns for the top layer and 3.26 ns for the bottom layer. These timing values are comparable to those achieved with the single-layer, 3 mm scintillation pixels. All 113 pixels are clearly resolved.

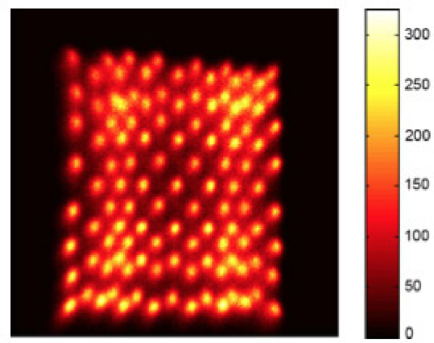


Figure 12. Flood Image of the Double Layer Scintillator Block. All 113 Pixels can be Identified [4]

The authors go on to compare their timing results with that of Schaart [13], who published a timing resolution of 960 ps for a similar SiPM device with LYSO scintillator in coincidence with a BaF sensor. Their work used 1:1 coupling and from this the researchers estimate that their resistive charge division multiplexing scheme contributes approximately 3 ns to the FWHM timing resolution.

In further work [14] to try to improve the timing resolution, and at the same time apply multiplexing to a larger area SiPM array, the authors compared two versions of a DPC network for a 12×4 arrangement of SiPM pixels (48:4 multiplexing). The first version is a typical, passive DPC as used for the work described above. The second version has a non-inverting voltage feedback op-amp at the output of each SiPM and before the input to the resistor network. The images below in Figure 13 compare the flood images achieved with both types of readout circuit, using LYSO crystals matched to the size of the SiPM pixels and obtained with 511 keV photons. The different spacing of the spots in the image of the active circuit is due to the different resistor values used in the active circuit. The energy resolution was found to be quite similar for each circuit, at around 14%. The active circuit did have the benefit of an improved timing resolution of ~4 ns, compared with the ~5 ns of the passive circuit. An alternative method of improving timing in multiplexed systems is described in Section D of this document.

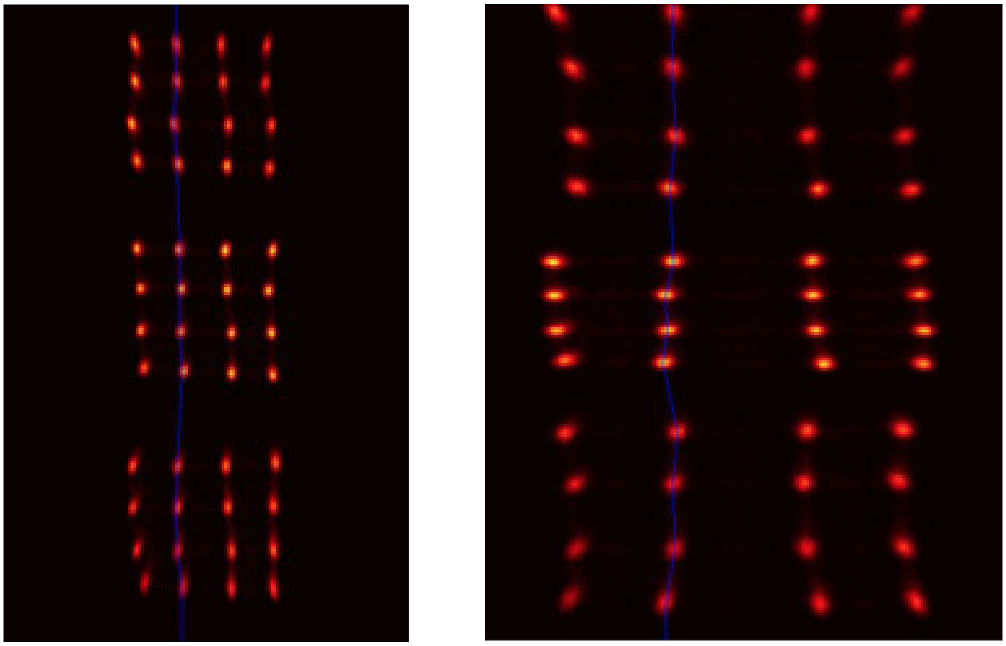


Figure 13. Flood Images of (Left) Passive DPC Circuit and (Right) Active DPC Circuit from [14]. ~3 mm LYSO Crystals were used on Three Linearly Tiled SPMArray4 Sensors

C. Matrix System Using Scrambled Crosswire Readout

Goal:	**Multiplex 144 pixels and maintain bias control**
Multiplexing:	**144:25**
Crystal pitch:	**1.5 mm**

The Matrix System from SensL [15], consisted of a large-area, sensor head and readout electronics. The sensor head consisted of a 12 × 12 array of 3 mm × 3 mm, SiPM pixels. The 12 × 12 array was conceptually arranged into 9 sub-arrays for the purpose of the novel readout scheme, named Scrambled Crosswire Readout (SCR), which was used in order to reduce the number of readout channels. The principle of the SCR scheme is shown in Figure 14, where each sub-array is designated as a different numbered ARRAY. This is consider ed a variation on the row/column format.

The Matrix sensor head is conceptually divided into nine 16-pix el ARRAYS with a total of 144 PIXELS. The entire Matrix sensor head can be readout with just 25 channels when SCR is employed.

- All 16 Cathodes of each 4 × 4 sub-array are joined together to provide 9 ARRAY detection channels. The 9 channels interface to simple threshold sensors that are used to determine which of the 9 arrays has detected an event.
- The corresponding Anode of each sub-array is joined together to produce 16 PIXEL detection channels. Each of these channels has threshold detection as well as an ADC for energy readout.

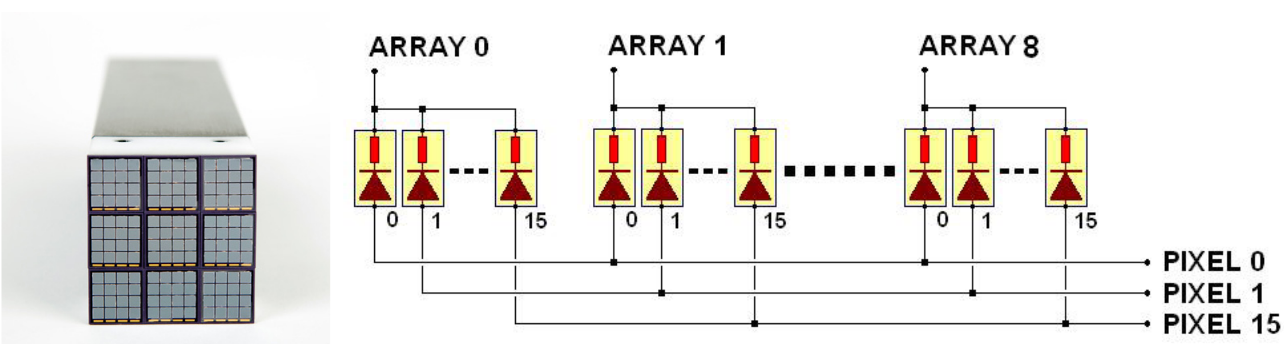


Figure 14. Matrix Sensor Head (Left) and Scrambled Crosswire Readout, from [15], (Right)

One important feature of this architecture, and what gives the name SCR to the design, is that the pixels on each energy channel are spatially separated by a 4×4 array. This means that, providing there is only one event at a given time, the energy measured on a particular PIXEL channel will be due to a single detector. Any light shared on the neighboring pixels will be measured on other PIXEL channels.

Although the SCR architecture was primarily designed for 1:1 coupling of SiPM and scintillation pixels, this technique does allow light sharing to resolve smaller crystal sizes. However, the SCR has the limitation of only being able to resolve when light sharing is limited to no more than 4×4 pixels (~12 mm × 12 mm on the Matrix sensor head), which is more than sufficient for typical PET applications but may be exceeded in other applications.

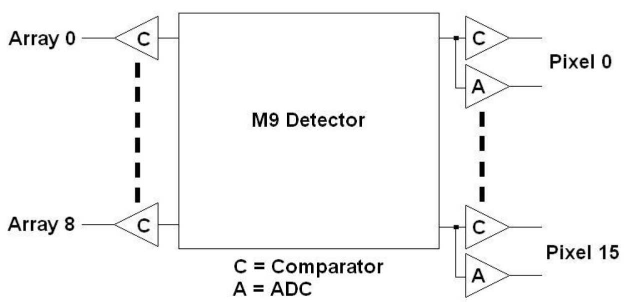


Figure 15. [15]

Du and his group at the University of California−Davis, tested the Matrix system for application to small-animal PET imaging using fine arrays of LSO or LYSO scintillator [16, 17].

For the accurate reconstruction of small scintillation pixel locations, light sharing across multiple SiPM pixels is required. The ability of the Matrix system to resolve small detection elements, down to 1 mm, was demonstrated via a flood histogram (allowing 511 keV gamma rays to illuminate the whole of the scintillation array).

In their initial work the authors used a Matrix9−SL detector head with the Matrix readout system [16], employing four different methods to reconstruct the gamma photon interaction position;

- M1) all energies method
- M2) all energies with offset calibration method
- M3) region of interest (ROI) method
- M4) ROI with offset calibration method. The “ROI method” uses the pixel with the maximum signal and its eight surrounding pixels. “Offset calibration” means that the signal offset was first subtracted from the signal.

Figure 16 shows flood histograms of LSO arrays with varying pixel pitch: 1 mm, 1.35 mm and 1.5 mm. They were reconstructed with the M4 method. Note that Figure 16 was acquired at 5°C. A timing resolution of 4.2 ns and an energy resolution of 14.3% were reported (@ 5°C).

Subsequent work from the UCD group used a 12×12 array of MicroFM−30035−SMT sensors, in conjunction with the Matrix readout boards [17]. Arrays of LYSO pixels with 1.05 mm pitch were used, and studies were carried out to optimize bias and this time, light guide thickness. A 1 mm thick light guide and a bias of 29.5 V were found to get the best results and using this, all pixels could be well resolved, as shown in Figure 17. In this paper, an energy resolution of 18.6% and a timing resolution of 6ns were achieved. All data was taken at 5°C in this study.

Although the timing and energy resolution results with the MicroFM sensors are somewhat worse than those found when using the previous SL silicon sensor (despite it having lower PDE), it should be pointed out that the $1.05 \times 1.05 \times 12\ mm^3$ LYSO crystals have a significantly poorer light collection efficiency (harder for photons to exit the crystal to reach the photosensor) than the $1.5 \times 1.5 \times 6$ mm3 crystals of the earlier study. The higher number of detected photons is likely the reason for the better timing and energy resolution in [16].

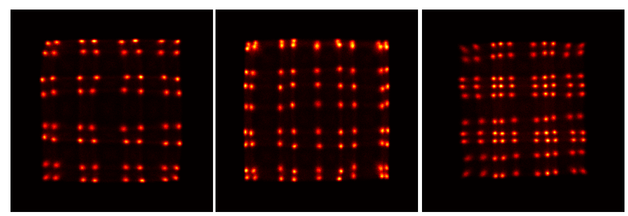


Figure 16. Flood Images Showing LSO Crystal Arrays of 1 mm (Left), 1.35 mm (Center) and 1.5 mm (Right) Pitch, from the Referenced Paper [16]

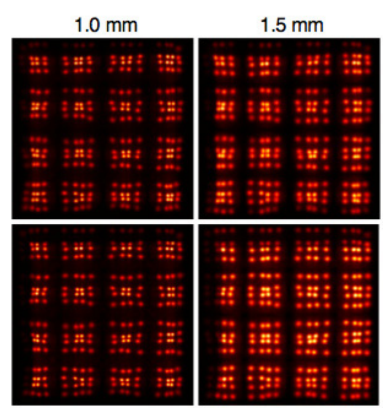


Figure 17. Flood Images of 1.05 mm Pixels [17]. The Values at the Top Refer to the Light Guide Thickness. Top Images are at 28 V and the Lower Ones at 30 V

Readout for Fast Timing and ToF PET

D. Signal Driven Multiplexing (SDM) for Improved Timing Performance

Multiplexing with arrays of SiPM sensors introduces specific problems. When multiplexing many channels together, the dark noise from each connected anode or pixel is summed together. This can result in significant dark current upon which the signal is superimposed. This could impact the detection of smaller signals and certainly worsen the signal-to-noise ratio of all signals.

Another limitation of multiplexing of SiPM pixels is that of the summed capacitive load connected to each readout channel. Connecting many SiPM pixels to a single readout channel can result in decreased signal rise times and pulse height.

ON Semiconductor C-, J- and R-Series SiPM sensors have a fast, capacitively-coupled output that gives a fast signal for timing applications. Multiplexing the fast output directly is not recommended. SPICE simulations have shown that standard multiplexing of the fast output results in poor rise time and pulse height. By introducing a diode pair (typically fast Schottky) as shown in Figures 18 and 19, each fast node is effectively isolated from the common node. Schottky diodes are non-linear, signal driven devices that differ from normal diodes in that they have a lower voltage drop (0.15 V−0.45 V compared with 0.6 V−1.7 V for a PiN), they are very fast (switching times of ~100 ps) and have minimal recovery time for high voltage sensors. Their main limitation is that of a 50 V rating. However, this is of no consequence for ON Semiconductor SiPM sensors which are biased in the range of < 50 V. SPICE simulations have shown that the presence of the Schottky diodes has minimal impact on the individual pixel readout, and preserves the performance when arrays of SiPMs are multiplexed together.

When a (C- or J-Series) SiPM sensor responds to incoming photons the fast output produces a signal pulse that turns the top Schottky diode on and at the same time turns the bottom Schottky diode off. When the top Schottky diode turns on, the fast pulse is transferred to the common output for readout. The effect of this positive signal on the common output also reverse biases the top Schottky diodes of the other sensors. This has the effect of suppressing the noise generated by the other sensors. The Schottky diode pair is used to create a symmetry whereby the sum of current at the fast node is constant.

In this way, Schottky diodes are used as a ‘signal driven multiplexor’ that will connect only the SiPM sensor that is activated by incident photons to the multiplexed readout channel. This approach significantly reduces the effective capacitance *and* noise at the common node such that the single pixel performance is preserved.

Unbiased Schottky diodes will provide the benefits described above, but additional benefits can be achieved by providing a separate bias to the Schottky diodes themselves (“Diode Bias” in Figures 18 and 19). This effectively holds the diodes just below their breakdown point with a standing current that allows the diode to respond faster and with greater sensitivity to a breakdown in the SiPM sensor, thus improving timing. This is also useful for applications where the signal output is weak.

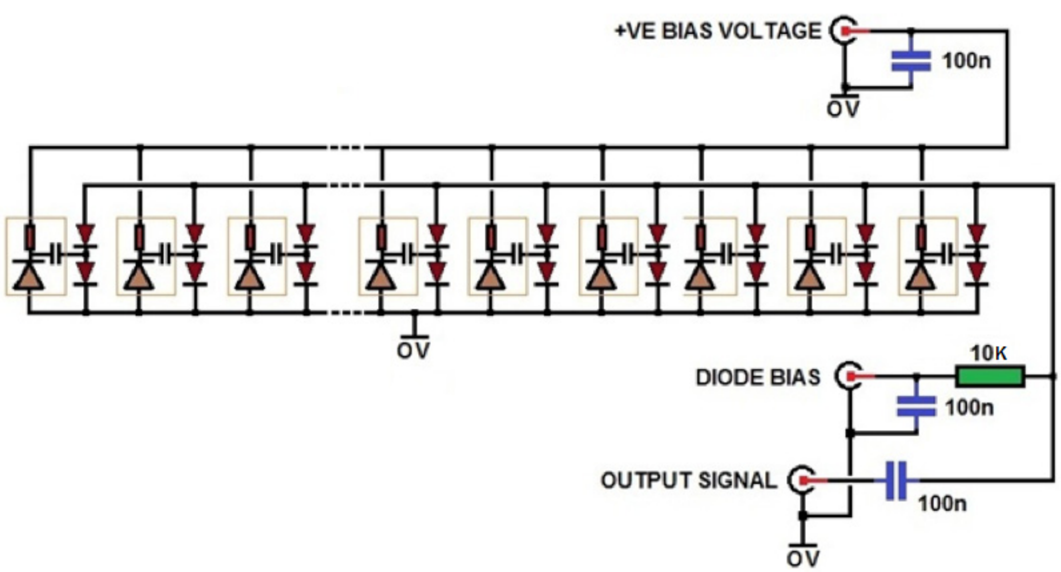


Figure 18. Signal Driven Multiplexing (SDM) Technique (R-Series Sensors)

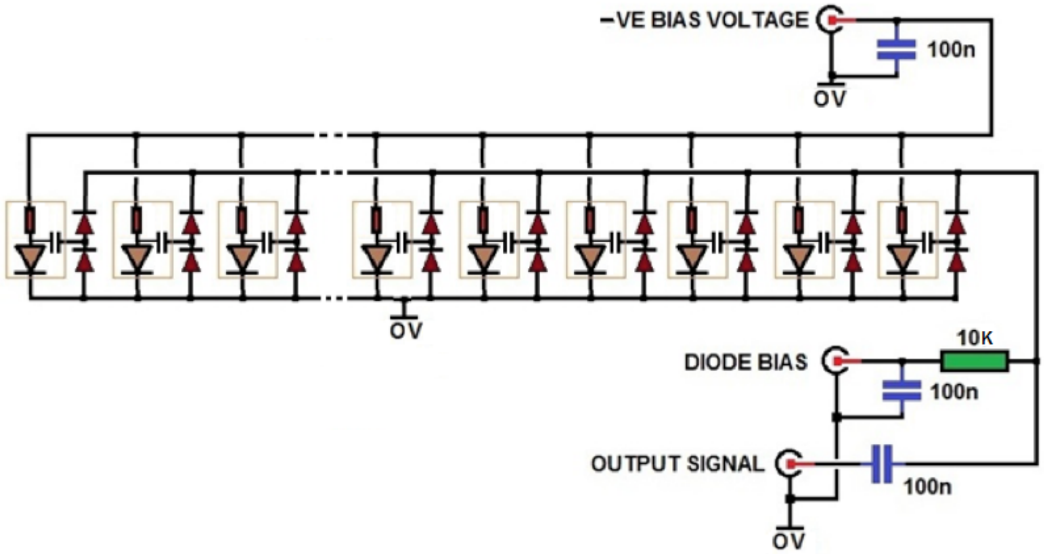


Figure 19. Signal Driven Multiplexing (SDM) Technique (J-Series and C-Series Sensors)

EXPERIMENTAL EVALUTION OF THE SDM READOUT

This section describes the testing of fast Schottky Diodes for multiplexing fast output signals from the now discontinued B-Series 3 mm SiPM devices. The same results would be expected with C-Series SiPM since it is pin-for-pin compatible with B-Series. The work was carried out to determine the scaling of achievable CRT (Coincidence Resolving Time) with the number of pixels per readout channel.

To study the effect of pixel count on the value of the CRT, three custom evaluation boards were designed with 16, 32 and 64 3 mm B-Series pixels. To avoid parasitics affecting the results, the boards only used the Fast Output. Amplification of the Fast Output was carried out using external amplifiers connected to the Fast Output SMA connector. Bias Voltage and Schottky Bias voltage were applied via 2 more SMA connectors. A picture of the three boards is shown in Figure 20.

Figure 21 shows the schematic for the 16-pixel version of the evaluation board. The summed Fast Output signal is capacitively coupled via the Schottky diodes to a standard SMA connector. The BIAS voltage is fed directly to the anode of all devices and the Schottky Bias voltage is fed via a 1 kΩ resistor to the summed Fast Output signal.

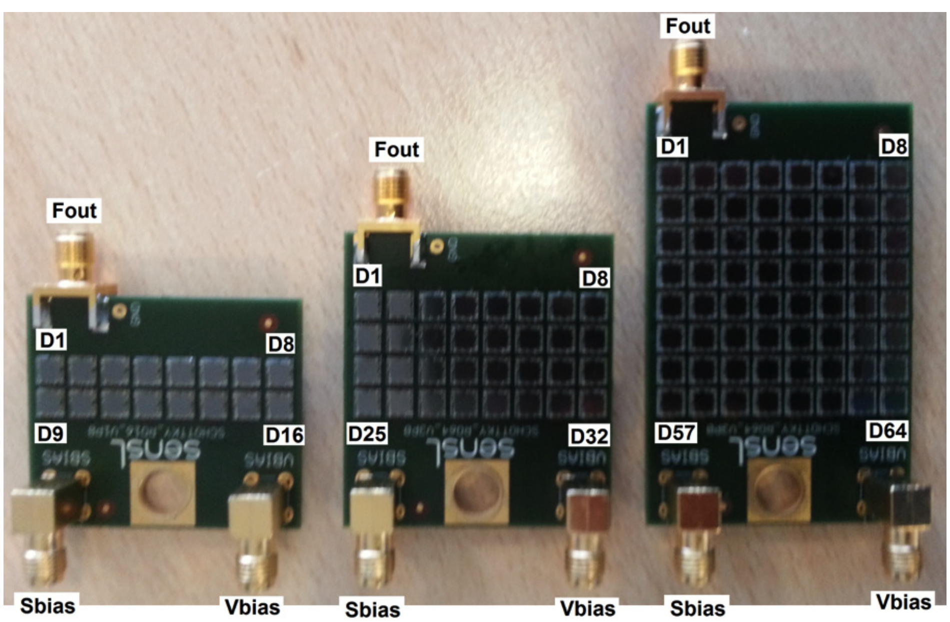


Figure 20. The Evaluation Boards Containing Arrays of 16, 32 and 64 SiPM Sensors with Schottky Multiplexed Readout

The test setup to measure the CRT used two $3 \times 3 \times 20\ mm^3$ LYSO crystals, coupled to a pixel on each of two identical evaluation boards (both either a 16, 32 or 64 pixels). A Na22 source of 511 keV gamma rays was mounted between the two crystals. The crystals, source and readout were mounted on X, Y, Z stages to allow for easy alignment of the crystals and source for various SiPMs on the board. To amplify the Fast Output signal two Microcircuits (ZX60−43 and ZFL−1000) amplifiers were used in series to give a gain of ~200. The output signal was then fed to the Wave Catcher, which in turn was sent, via a high speed USB interface, to the host computer for data analysis.

For each board type, the CRT was measured for a variety of pixels and Schottky Bias voltages. Table 1 shows a sub-section of the results giving the best CRT values that were obtained for each array. Full results and more information on the boards and testing can be found in the SDM Application Note.

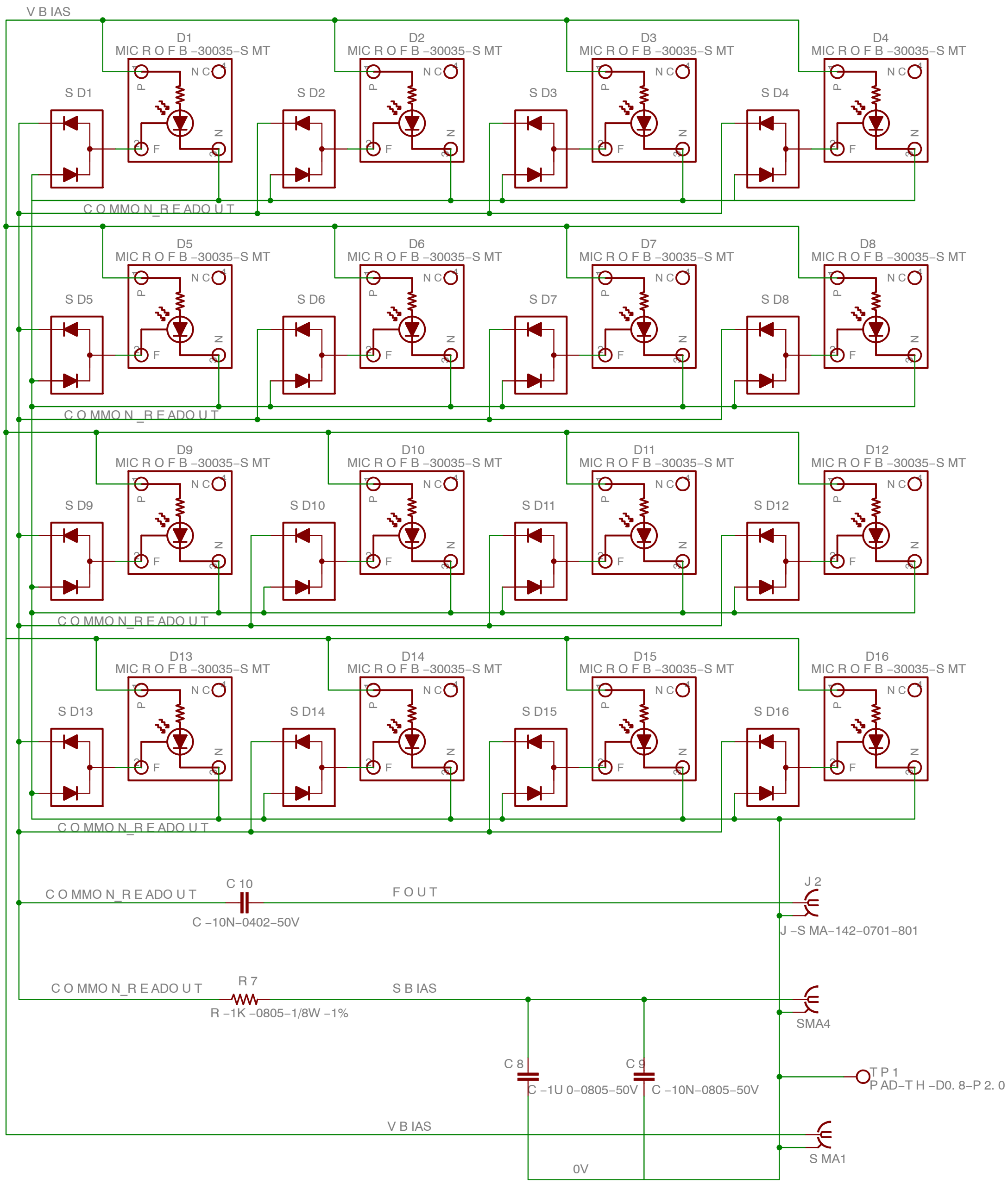


Figure 21. Schematic of 16-pixel Board. The SMA Input and Output Stage of the 32 and 64 Pixel Arrays are Identical to this Design. The Only Change is the Number of Pixels in the Array

Table 1. RESULTS SHOWING THE OPTIMUM CRT ACHIEVED WITH THE DIFFERENT ARRAY SIZE EVALUATION BOARDS

Board Type	Bias	Schottky Bias (–ve)	Measured CRT (ps)
16-pixel	29.5 V	12 V	304
32-pixel		20 V	371
64-pixel		30 V	473

CONCLUSIONS

- It was found that the optimum Schottky bias voltage increased as the size of the array increased.
- The positions of the tested pixels in the array were found to have minimal impact on the results, with only small variations between the CRT values obtained from the pixels nearest the fast output, and those furthest away.

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