New ROIC Developments at SUI

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ABSTRACT

Sensors Unlimited, Inc. (SUI), a Raytheon Company, advances infrared imaging technology through the development of next-generation Readout Integrated Circuits (ROICs) tailored for multi-modal, high-resolution imaging. This paper details innovations in smaller pixel pitch designs—under 10 microns—enabling high-resolution, cost-effective infrared imaging solutions. The new ROIC architectures support concurrent multi-modal operations including low-noise imaging, asynchronous laser pulse detection, and Time-of-Flight (ToF). Key challenges, novel techniques applied, and achieved performance metrics will be discussed, emphasizing the significance of pixel pitch reduction and processing technology advancements. The resultant ROICs address critical demands in defense, surveillance, and scientific research sectors while rigorously managing Size, Weight, Power, and Cost (SWaP-C) considerations.

1. INTRODUCTION

Readout Integrated Circuits (ROICs) are crucial components of modern infrared imaging systems, interfacing directly with infrared detectors to process incoming photons into usable electronic signals. The SWIR wavelength (typically 900 nm to 1700 nm) presents unique design challenges due to detector characteristics, required sensitivity, dynamic range, and operational conditions. ROICs designed for SWIR applications must efficiently handle low-photon-level signals, provide very low noise performance, and maintain stable operation over broad temperature ranges. Recent advancements in SWIR-compatible ROIC technology have focused primarily on pixel density improvement through pixel pitch reduction below 10 microns, significant noise reduction, and the development of highly integrated, power-efficient circuits.

2. OVERVIEW OF RECENT SWIR ROIC DEVELOPMENTS

Significant progress in SWIR ROIC technology includes innovations in pixel pitch reduction, noise reduction techniques, advanced detector integration, and high-speed ADC integration. Companies like Princeton Infrared Technologies, FLIR Systems, Attollo Engineering, and SCD Semi-Conductor Devices have demonstrated notable developments with pixel pitches as small as 10 µm, frame rates up to 120 FPS, dynamic range over 80 dB, and noise floors down to ≤5 electrons.

Table 1. Performance summary of State-of-the-Art ROICs for SWIR

Manufacturer	Pixel Pitch	Detector Type	Frame Rate	Dynamic Range	Noise Floor
Princeton IR	10 µm	InGaAs	100 FPS	80 dB	≤5 electrons
FLIR	12 µm	InGaAs	120 FPS	85 dB	≤8 electrons
Attollo	10 µm	InGaAs	120 FPS	85 dB	≤7 electrons
SCD	10 µm	InGaAs	60 FPS	70 dB	≤10 electrons

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PRINCIPLES OF THE SUI ROIC PIXEL

CMOS readouts are "active pixel" devices in which the photocurrent is buffered, amplified and stored in each pixel. A simplified SUI pixel schematic is shown in Figure 1. Each pixel contains a buffered gate modulated (B-GMOD) input circuit for converting current to voltage with continuously adjustable gain. In this circuit, the photodiode bias voltage is set through internally generated DSUB and VREF bias voltages. The photodiode current flows through M0 with a proportional amount of current mirrored in M1. The ratio of the currents through M1 and M0 is controlled though the externally set VBIAS and VGAIN voltages. The ROIC can derive all bias voltages necessary for operation of the focal plane array (FPA) without external sources.

The camera frame sequence consists of a global shutter exposure followed by digitization and rolling readout. During exposure, the integration reset switch is opened and the integration capacitor shown is discharged from its reset voltage by the mirrored photodiode current, converting the signal current to a voltage. At the end of the integration time, the sample switch is momentarily closed to sample the integration period's final signal voltage. After the signal is sampled, the integration reset switch is closed and held until the start of the next integration period. The exposure may or may not overlap the readout of the last frame depending on the user-configurable exposure period and the frame rate.

To generate the serialized digital video signal that is output from the FPA, each row is sequentially selected, and the analog pixel signals are passed to readout circuitry at the edge of the array. Embedded column-parallel ADCs convert the analog pixel signals to user-configurable digital values, which are then serialized and output on a highspeed digital bus. The above represents a classical imaging digital readout using SUI's proprietary pixel design.

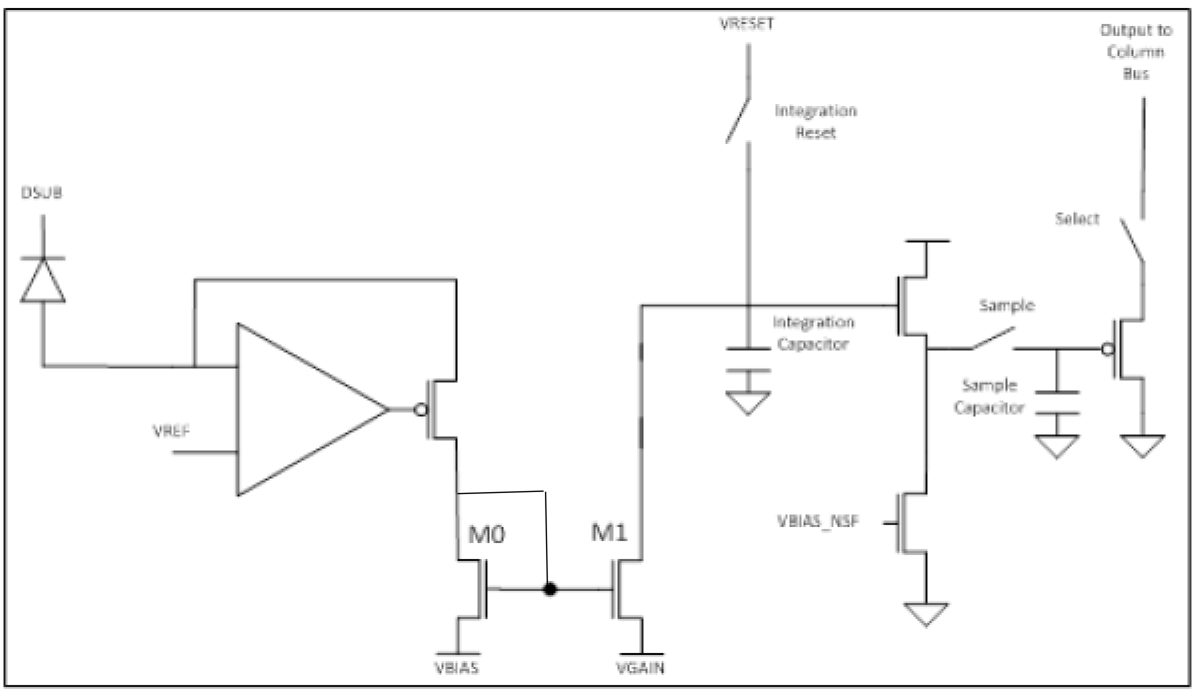

Figure 1: Schematic of BGMOD imaging pixel

Since 2017, SUI's ROICs also feature simultaneous full field of view (FOV) laser pulse detection, tracking, and decoding capabilities. This capability is enabled at the pixel-level through the inclusion of separate circuitry for laser event detection. The laser event detection portion of the pixel and readout operates independently and asynchronously from the imaging portion of the pixel and readout. This is particularly important for daytime laser spotting, as the focal plane can be configured for maximum signal collection, using a 99.9% exposure/frame time duty cycle, without compromising either the low-noise imaging performance or laser event capture performance, succeeding even when lasers have slow repetition rates and/or narrow pulse widths. This unique approach for maintaining high performance passive imaging, while offering overlaid asynchronous laser pulse detection (ALPD), tracking, and decoding capability is called SUI's multi-mode tracking (MMT) feature. The MMT function enables rapid identification of common battlefield targeting lasers, including those with covert eye-safe laser wavelengths, in both day and night conditions and is considered the gold standard in this domain.

Figure 2 shows the laser event data (binary) from a SUI MMT camera. Three images are shown: 2a) raw pulse bitmap from the FPA, 2b) filtered pulse data, 2c) filtered and threshold applied shows pulse frame data in raw form, after filtering, and post threshold as it is processed. These three images are 160x160 pixels as for tracking and decoding purposes windowing is utilized for higher pulse frame rates. The ROIC is capable of multiple pulse windows (> 3) operating concurrently at high frame rates (up to 20+ kHz). Although the laser event is clearly evident in 2a), one should also note the false triggers surrounding it. These need to be properly accounted for when performing tracking and decoding. 2b) highlights all the events of interest, while 2c) demonstrates the powerful noise filtering capabilities of SUI's MMT backend processing engine. The image in 2c) that is utilized for laser tracking and decoding is devoid of the false alarms present in the original raw image of 2a).

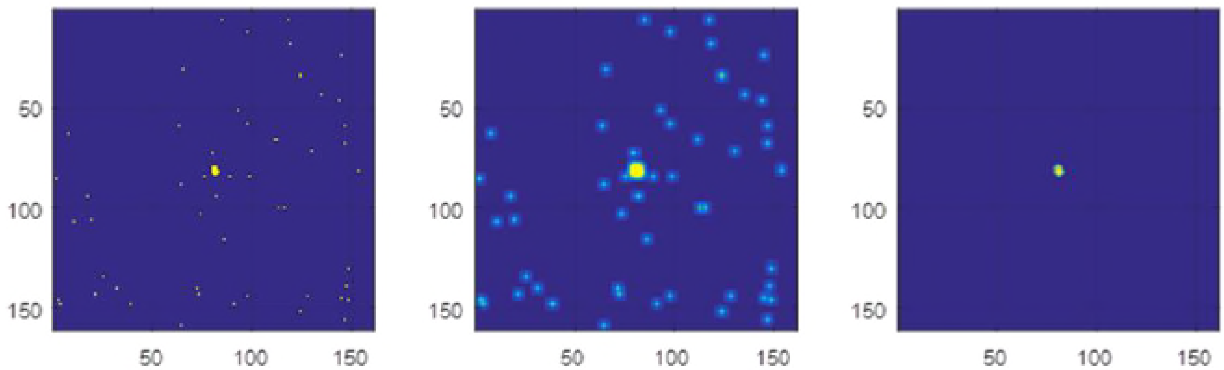

Figure 2: a) raw pulse bitmap b) filtered pulse data and c) filtered and threshold applied

SU640AM2 DEVELOPMENT

SUI's next-generation ROIC was, in part, developed based on the SU640AM2 ROIC, a 640×512 array with a 15 µm pixel pitch. This ROIC established critical baseline performance and provided a platform to validate multi-modal imaging, ALPD, and initial ToF capabilities. SUI's vanguard MMT ROIC technology, the SU640AB7, also has a 15 µm pixel pitch, and is considered the gold standard of VGA ALPD-capable sensor designs. In the same pitch, the SU640AM2 includes a separate ToF circuitry and supporting readout. Lessons learned and performance metrics from the SU640AM2 directly informed the advancements integrated into the new ROIC design. The following summarizes some of the salient ToF specific test and characterization results of the SU640AM2 ROIC to date.

Figure 3 shows the actual target distance and distance measured using the SU640AM2 in a laboratory environment with a stationary target and in the dark. As seen from Figure 3, the measured distance confirms the actual target distance up to ~25 m which is the designed target distance for this pixel design. In fact, up to ~23m, the error is < 10 cm. Although this result is from a controlled environment, it is also without complicated post-processing of the output data. It is envisioned that in camera form, this performance will be maintained if not improved with additional processing capabilities.

SUT9 (Sensor-Under-Test) PIXEL TEST CHIP

The next-generation ROIC pixel architecture originated from extensive testing and characterization using the SUT9 pixel test chip. This test chip allowed detailed evaluation of various pixel configurations to address challenges associated with reducing pixel pitch while maintaining or enhancing sensitivity and dynamic range. Insights from

SUT9 facilitated the development of optimized pixel architectures adopted in the next-generation ROIC. The SUT9 ROIC test vehicle included pixel variants compatible with different types of detectors. The purpose of the SUT9 was not only to explore reducing pixel pitch while maintaining the electro-optical performance of larger pitch designs, but to also explore different ToF architectures. The following summarizes the test and characterization results of the SUT9 pixel test chip to date.

True Distance (m)	Mean Est Distance (m)	Median Est Distance (m)	Stdev (cm)
5	5	5	6.8
7.25	7.25	7.25	6.6
9.5	9.5	9.5	6.3
11.75	11.75	11.75	6.1
13.99	13.99	13.99	6.2
16.24	16.24	16.24	6.2
18.49	18.49	18.49	5.9
20.74	20.74	20.74	6
22.99	22.99	22.99	6.6
25.24	25.24	25.24	12.5
27.48	27.52	27.5	38.8
29.73	29.82	29.77	80.5
31.98	31.74	31.97	93.7

Figure 3: Measured target distance using SUI's SU640AM2 next generation MMT pixel technology

A simple Geiger-mode avalanche photodiode (GmAPD) capable pixel design including passive quenching capability is shown in Figure 4. In this implementation the quenching and amplification/digitization circuitry are implemented as one of the test pixels of the SUT9. The detector operating voltage is adjusted through VQUENCH, which needs to be set to > 30 V for Geiger mode operation. The digital output, SPAD_out, of each pixel is conveyed to the readout circuitry. The purpose of this test pixel was to better explore the performance of SUI's APD technology, specifically in Geiger mode operation.

Figure 5 shows simulation results of digital pad driving a large capacitive load and sweeping the quench voltage. The purpose of the simulation is to observe the dependence of the passive quenching resistance on the digital output from this pixel. Increasing the quench voltage reduces the effective resistance resulting in shorter output pulse widths. Conversely, reducing the quench voltage increases the resistance resulting in wider output pulses. The importance of these output pulses in this configuration is that these pulses are utilized as part of the quenching processing. Longer or wider pulses result in a longer dead time where photons cannot be collected, while shorter pulse widths may not properly quench the avalanche process.

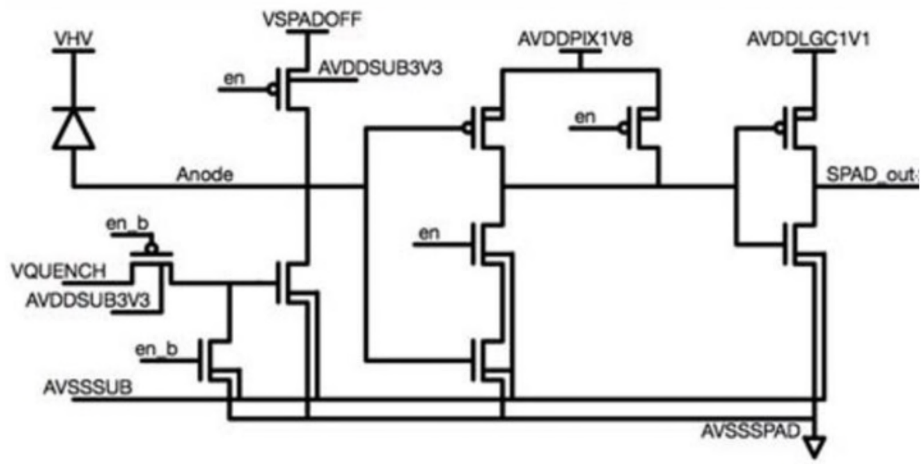

Figure 4: Schematic circuit of a GmAPD capable ROIC pixel utilized in the SUT9

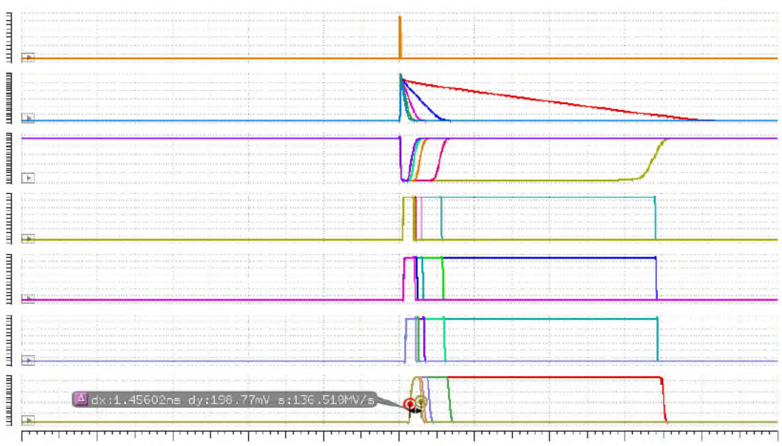

Figure 5: Simulated APD anode response Vs. quench voltage

SUI'S NEXT-GENERATION ROIC TECHNICAL DETAILS

The next-generation Readout Integrated Circuit (ROIC) developed by Sensors Unlimited Inc. (SUI) integrates multiple advanced architectural and circuit-level enhancements that address critical requirements for modern infrared imaging, laser pulse detection, and depth sensing. This ROIC features a pixel pitch under 10 µm, scalable imaging formats from 1k×1k to 2k×2k, and supports high-speed operation at ≥120 FPS, targeting both real-time imaging and multi-modal tracking systems.

The design supports spectral responsivity from 0.6 µm to 2.6 µm, enabling compatibility with a range of SWIR and extended SWIR detectors, including PIN, APD, and Geiger-mode arrays. A significant improvement is realized in intrascenic dynamic range, now exceeding 1900:1, made possible through adaptive gain pixel architectures and advanced column-level ADCs. The noise floor has been optimized to ≤10 electrons, due to improvements in pixel buffering, low-noise bias distribution, and temporal noise suppression schemes.

In addition to passive imaging, the ROIC offers support for high-speed, real-time asynchronous laser pulse detection (ALPD) with windowing capabilities and sampling frame rates up to 50 kHz, making it well-suited for battlefield laser designation and tracking applications. Its integrated Time-of-Flight (ToF) mode achieves depth accuracy ≤10 cm, with ongoing design targets for sub-centimeter resolution using novel dTOF signal processing techniques.

The ROIC architecture builds directly on lessons learned from the SU640AM2 and SUT9 test vehicles. These predecessors established key performance benchmarks and served as platforms for validating synchronous and asynchronous multi-modal imaging, ToF ranging, and Geiger-mode SPAD operation.

Core Advancements:

- Advanced Buffered-GMOD (BGMOD) Pixel Front-End: Uses variable-gain through user-programmable biasing to support both high sensitivity and large signal swing, improving full-well utilization and dynamic range.
- Integrated Linear-Mode APD Compatibility: Designed for seamless hybridization with InGaAs-based APD arrays, this allows internal signal gain and enhanced SNR under low-light or long-range scenarios, while maintaining low excess noise.
- High-Speed, Multi-Window Asynchronous Laser Pulse Detection: Capable of simultaneous detection and timestamping of multiple laser pulses across the full FOV, with adjustable sub-windowing for prioritized tracking of regions of interest.
- Field-Programmable Windowing and Gating: Enables real-time adaptation of integration times, readout windows, and gain modes for improved temporal response and lower power operation for all modes of operation independently (imaging, ALPD, and ToF).
- Full Field-of-View ToF Mode: Includes a separate ToF readout, enabling accurate rangefinding at high frame rates.

A summary of the salient features of this ROIC compared against the state-of-the-art is given in Table 2.

Table 2. Juxtaposition of State-of-the-Art ROICs and SUI's Next Generation ROIC specification

Mode/Feature	SUI Next-Gen ROIC	State-of-the-Art
Pixel Pitch	<10 μm	10-12 μm
Imaging Frame Rate	≥120 FPS	60-120 FPS
Dynamic Range	≥1900:1	~1000:1
Noise Level	≤10 e-	5-10 e-
ALPD Frame Rate	≤50 kHz	10-20 kHz
ALPD Sensitivity	≤1000 e-	~1500-3000 e-
ToF Depth Accuracy	≤1 cm	~2-5 cm
ToF Range	1000-3000 m	≤250 m

The ROIC enables significant situational awareness improvements through pixel-level innovations:

- Increased dynamic range and reduced noise improve image clarity in low-light conditions.

- High-frame-rate pulse detection allows rapid target acquisition and tracking.
- Precise ToF measurement provides real-time depth data critical for obstacle detection and target localization.
- SWIR capability penetrates atmospheric conditions better than visible or near-infrared wavelengths, ensuring reliable performance in fog, smoke, or low-visibility environments.

OVERVIEW OF TOF ROIC DEVELOPMENTS FOR DEPTH SENSING AND LIDAR/LADAR APPLICATIONS

Recent advancements in ToF-enabled ROIC architectures have transformed how systems capture depth and motion data, particularly in infrared regimes beyond 1 µm. Two primary methods—Amplitude Modulated Continuous Wave (AMCW) and pulse-based ToF—are used across consumer, industrial, and defense systems, with ongoing innovation in sensitivity, resolution, and integration complexity.

While visible- and NIR-based ToF systems dominate commercial markets, SWIR-based ToF systems offer enhanced range, reduced background interference, and eye-safe covert operation at 1550 nm—crucial for defense and secure industrial applications. These systems also benefit from SWIR's superior atmospheric penetration, enabling consistent performance in degraded visual environments.

SUI's ROIC platform targets these needs through hybrid support for linear-mode and Geiger-mode detectors, multi-window readout, and full-frame or sub-frame ToF support with <10 cm depth accuracy. A programmable quenching and thresholding architecture enables customization for SPAD arrays with single-photon sensitivity.

Table 3. Overview of commercial ToF offerings and their respective performance.

Manufacturer	Technology	Wavelength	Depth Accuracy	Max Range	Frame Rate	Application
Microsoft Azure Kinect	AMCW	850 nm	<1 cm	10 m	30 FPS	Robotics, AR
Intel RealSense L515	AMCW	860 nm	~1 cm	9 m	30 FPS	Robotics, Industrial
Luminar Iris	Pulse-based	1550 nm	~2 cm	250 m	20 FPS	Autonomous vehicles
Velodyne Alpha Prime	Pulse-based	903 nm	~2 cm	245 m	20 FPS	Autonomous vehicles

Competitive Analysis of SWIR-Capable ToF ROICs

Competitive SWIR-capable ToF ROIC designs include linear-mode APD arrays with high sensitivity and long-range performance, Geiger-mode APD technologies offering single-photon detection capability, and digital/computational pixel architectures enabling advanced real-time processing and adaptability. These technologies, documented extensively in IEEE and SPIE publications, highlight the competitive landscape and technological maturity of SWIR-based ToF systems. Table 3 offers a comparison of commercially available ToF technologies.

In the evolving landscape of depth-sensing technologies, SUI's ROIC platform demonstrates competitive advantages through:

- High Sensitivity Linear-Mode APD Arrays: Offering superior gain control with reduced excess noise for long-range applications (1–3 km), especially at covert wavelengths.
- SPAD/Geiger-Mode Pixel Integration: Enabling single-photon-level sensitivity and low-jitter timestamping critical for ultra-precise dToF mapping.
- Embedded processing: Capable of in-ROIC signal processing, reducing off-chip processing requirements.
- Flexibility and Scalability: ROIC formats ranging from VGA to 2k×2k with programmable pixel architectures allow tailoring to application needs from UAVs to fixed surveillance platforms.

These innovations position SUI's next-generation ROIC as a state-of-the-art platform for integrated imaging, tracking, and ranging in both active and passive SWIR-based systems.

CAMERA-SPECIFIC FEATURES ENABLED BY THE ROIC

The advanced capabilities of SUI's next-generation ROIC enable enhanced multi-modal imaging, precise depth sensing, robust performance in diverse environments, and significantly optimized SWaP-C. This facilitates high-speed imaging and real-time situational awareness crucial for defense, surveillance, and autonomous navigation.

3. CONCLUSION

The next-generation ROIC at SUI substantially advances infrared imaging technology through smaller pixel pitch, multi-modal functionality, and improved noise management. These ROICs effectively address critical imaging demands, maintain stringent SWaP-C considerations, and set new performance benchmarks for defense, surveillance, and scientific research applications.

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