Geiger-mode avalanche photodiode focal plane arrays for three-dimensional imaging LADAR

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ABSTRACT
We report on the development of focal plane arrays (FPAs) employing two-dimensional arrays of InGaAsP-based Geiger-mode avalanche photodiodes (GmAPDs). These FPAs incorporate InP/InGaAs(P) Geiger-mode avalanche photodiodes (GmAPDs) to create pixels that detect single photons at shortwave infrared wavelengths with high efficiency and low dark count rates. GmAPD arrays are hybridized to CMOS read-out integrated circuits (ROICs) that enable independent laser radar (LADAR) time-of-flight measurements for each pixel, providing three-dimensional image data at frame rates approaching 200 kHz. Microlens arrays are used to maintain high fill factor of greater than 70%. We present full-array performance maps for two different types of sensors optimized for operation at 1.06 μm and 1.55 μm, respectively. For the 1.06 μm FPAs, overall photon detection efficiency of >40% is achieved at <20 kHz dark count rates with modest cooling to ~250 K using integrated thermoelectric coolers. We also describe the first evaluation of these FPAs when multi-photon pulses are incident on single pixels. The effective detection efficiency for multi-photon pulses shows excellent agreement with predictions based on Poisson statistics. We also characterize the crosstalk as a function of pulse mean photon number. Relative to the intrinsic crosstalk contribution from hot carrier luminescence that occurs during avalanche current flows resulting from single incident photons, we find a modest rise in crosstalk for multi-photon incident pulses that can be accurately explained by direct optical scattering.

Keywords: avalanche photodiode, single photon detector, photon counting, Geiger-mode, ladar, three-dimensional imaging, InP, InGaAsP

1. INTRODUCTION
Through the use of laser radar (LADAR) to obtain high-resolution range measurements at each pixel of an imager, it is possible to obtain image data in three spatial dimensions that provides information about imaged scenes and objects which is superior to that provided by traditional two-dimensional intensity images. Whereas intensity images require that object shapes be inferred from edge examination and complex image processing algorithms that generally require assumptions that are not implicit in the image data, three-dimensional data removes the ambiguity of edge determination and provides far more definitive information concerning imaged objects. Such three-dimensional imaging techniques [1,2] enable the acquisition of data that is generally not obtainable using two-dimensional imaging technology, including the imaging of objects behind camouflage netting, tree foliage, or other foreground obscurants.

The use of arrays with pixels consisting of Geiger-mode avalanche diodes (GmAPDs) provides several benefits for LADAR three-dimensional imaging applications. [3] These detectors have single photon sensitivity and thus provide high efficiency detection for highly attenuated return signals. With single photon sensitivity at the imager pixels, the pulse energy requirements for launched LADAR pulses are greatly reduced (on the order of 100X) and lead to much more deployable and reliable system solutions. Moreover, the the Geiger mode detection process is inherently digital: in these detectors, a single photon induces a macroscopic pulse of current that can be readily sensed with appropriate threshold detection circuitry. Given the digital nature of this detection mechanism, the detection process is noiseless;

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the only FPA-level noise is from the shot noise associated with false counts resulting from background or dark count mechanisms. This imager architecture is also realized with efficient “photons-to-bits” digital pixel circuitry that provides excellent prospects for scaling to smaller pitch and larger formats. A constraint of current implementations of GmAPDs in 3-D imaging FPA is the limitation to 1 bit of intensity information per pixel per frame—any given pixel can count no more than one single photon per frame. Although this prevents the collection of scene image intensity information with a single pulsed laser “flash”, intensity information can be readily obtained by collecting multiple frames. This multi-frame operation is aided by the very high frames rates that we have designed for our FPAs.

In this paper, we describe focal plane arrays (FPAs) for 3-D imaging systems with single photon sensitivity employing two-dimensional arrays of InGaAsP-based Geiger-mode avalanche photodiodes (GmAPDs). In Section 2, we describe the FPA design, in which GmAPD arrays are hybridized to CMOS read-out integrated circuits (ROICs) that enable independent laser radar time-of-flight measurements for each pixel, providing three-dimensional image data at frame rates approaching 200 kHz. Other module design elements include a microlens array (MLA) used to maintain high fill factor of greater than 70%, a thermoelectric cooler to establish chip operating temperatures of 240 K, and hermetic packaging to provide a high reliability for use in harsh environments. In Section 3, we present a summary of fundamental FPA performance parameters. This summary includes full-FPA performance maps for dark count rate (DCR) and photon detection efficiency (PDE) for two different types of sensors optimized for operation at 1.06 μm and 1.5 μm, respectively. DCR distributions are also shown for both types of FPAs. For the 1.06 μm FPAs, the dependence of DCR on PDE illustrates that PDE >40% is achieved at <20 kHz dark count rates, even with all optical losses associated with MLA fill factor and other transmission losses. In Section 4, we describe the performance of the FPAs when multi-photon pulses are incident on single pixels. The effective PDE for multi-photon pulses shows excellent agreement with predictions based on Poisson statistics. We also characterize the pixel-to-pixel crosstalk as a function of the average photon number in incident pulses. Relative to the intrinsic crosstalk contribution from hot carrier luminescence that occurs during avalanche current flows resulting from single incident photons, we find a modest rise in crosstalk for multi-photon incident pulses that can be accurately explained by direct optical scattering. Finally, in Section 5, we summarize this work.

2. FOCAL PLANE ARRAY DESIGN CONCEPT

The GmAPD FPA sensors described in this paper consist of a number of essential components. Single photon detection is enabled by a photodiode array (PDA) with GmAPD detectors in each pixel. A CMOS readout integrated circuit (ROIC) provides pixel-level electrical interfacing, such as GmAPD biasing and active quenching circuitry; in-pixel counters for time-of-flight timestamp data; and the control of FPA-level functions such as clock generation and distribution and frame readout. A GaP microlens array (MLA) is aligned and attached to the back-illuminated PDA to ensure high fill factor, and various packaging sub-components are used to define electrical, mechanical, and optical interfaces to the overall sensor module. To enable flexible, turnkey operation of the module using a standard personal computer, we have also designed an FPGA-based evaluation interface board. In this section, we discuss some details of the PDA, the ROIC, the overall module construction, and the interface board.

2.1 Geiger-mode avalanche photodiode (GmAPD) array

When an avalanche photodetector is biased above its breakdown voltage \( V_b \), the creation of a single electrical carrier can induce a run-away avalanche that gives rise to a detectable macroscopic current. In this mode of operation, often referred to as Geiger mode, the detector is sensitive to the absorption of a single photon. (For this reason, these detectors are also often referred to as single photon avalanche diodes, or SPADs.) We have developed InGaAs/InP avalanche diode structures specifically for single photon detection in the wavelength range of 0.92 to 1.67 μm [4], and we have optimized this structure for shorter wavelength operation 1.06 μm by employing a quaternary InGaAsP absorber in place of the longer wavelength ternary InGaAs absorber. [5] We have described in detail the design, simulation, and characterization of discrete GmAPD devices employing both InGaAs and InGaAsP absorption regions in previous publications. [4 – 9]

A schematic depiction of the GmAPD device structure is illustrated in Figure 1. Photon absorption occurs in either a ternary InGaAs layer (\( E_g \sim 0.75 \text{ eV} \)) or a quaternary InGaAsP layer (\( E_g \sim 1.03 \text{ eV} \)) for optimized detection of single
photons at either ~1.55 μm or 1.06 μm, respectively. The absorption layer is spatially separated from a wider bandgap InP region (E_g ~ 1.35 eV) in which avalanche multiplication occurs. A primary goal of the design — the separate absorption and multiplication (SAM) region structure [10] — is to maintain low electric field in the narrower bandgap absorber (to avoid dark carriers due to tunneling) while maintaining sufficiently high electric field in the multiplication region (so that impact ionization leads to significant avalanche multiplication). The creation of a single electron-hole pair by photoexcitation in the absorber layer results in the injection of the hole into the high-field InP multiplication region in which impact ionization results in avalanche gain. With the GmAPD biased above V_b in its armed state, the resulting avalanche gives rise to a macroscopic current pulse that is sufficiently large to be sensed by a threshold detection circuit contained in the readout integrated circuit, described below. Unlike linear mode APDs operated below V_b, the GmAPD detection process is inherently digital, and with appropriately designed detectors and threshold circuits, the detection process is noiseless.

Figure 1. Schematic representation of InP-based planar-geometry diffused-junction GmAPD photodiode array hybridized to a CMOS readout integrated circuit by indium bump flip-chip bonding. The composition of the absorber layer determines the spectral response of the detectors, with InGaAsP used for 1.06 μm operation and InGaAs used for 1.55 μm operation. Avalanche multiplication takes place in an InP multiplier between the diffused region and the absorber.

The lateral structure of our design employs a buried p-n junction to guarantee edge breakdown suppression, low perimeter leakage, and high reliability. The active area of this planar geometry device [11] is determined by the patterning of a SiN dielectric passivation layer to create a diffusion mask for a subsequent diffusion of Zn dopant atoms to create a p'-InP region within the i-InP cap layer. To suppress electric field enhancement at the edge of this planar structure, we use two diffusions to tailor the p-n junction profile [12] so that the junction is deeper in the central part of the active area than it is in the junction periphery. This design ensures that the gain profile across the center part of the active region is uniform and that the gain is reduced in the peripheral region of the device. For the 32 x 32 format arrays described in this paper, the optical active region diameter was 34 μm in each 100-μm pitch pixel.

In the fabrication of arrays of GmAPD devices, a key consideration that does not play a role in discrete device performance is that of optical crosstalk. An avalanche of electrical carriers in one pixel gives rise to hot carrier luminescence, and even if the number of emitted photons is small (previous studies indicate 1 emitted photon for every ~10^5 to 10^6 avalanche carriers), the single photon sensitivity of neighboring pixels makes them susceptible to correlated crosstalk counts triggered by these luminescence photons. To reduce the line-of-sight coupling between nearest-neighbor pixels, we have etched isolation trenches along the pixel boundaries, as shown schematically in Figure 1. The GmAPD array fabrication also includes back-side anti-reflection-coated apertures aligned to the pixel active regions and front-side patterning of indium bumps to facilitate hybridization of the detectors to mating 32 x 32 CMOS ROICs; see Figure 1.

In addition to our work on planar-geometry GmAPD FPAs described here and in other papers [13,14], arrays of related mesa-geometry InP-based GmAPD have been extensively studied in pioneering work by researchers at MIT-Lincoln Laboratory [15 –17], and significant additional work on mesa-geometry devices has also been recently reported. [18,19] These devices are based on an epitaxial structure similar to that used for our planar geometry devices, but instead of
using dopant diffusions to define the active region p-n junctions, mesa-geometry devices have active areas defined by the etching of mesas in which all epi-grown material is removed outside the intended active region.

2.2 CMOS Readout integrated circuit (ROIC) functionality

The basic functions of our 3-D imaging FPA are performed by a custom CMOS ROIC mated to the GmAPD PDA by indium bump hybridization. In the disarmed state, every pixel of the detector array is biased slightly below the breakdown voltage of the GmAPD using a single external low-noise voltage supply with voltages on the order of 70 to 80 V. Each imaging frame begins with the arming of all of the detector pixels by the ROIC, which applies an excess bias of up to 5 V. The period during which the pixels remained armed is the range gate, which is typically on the order of a few microseconds. In a LADAR imaging system, the beginning of the range gate is synchronized (perhaps up to a fixed delay) with the launch of an optical pulse from which reflected photons will be detected. Every pixel contains a pseudorandom counter that provides detection timing information on a per-pixel basis. Upon asserting the master clock enable (MCE) signal, all pixel counters begin counting. Within each ROIC pixel, there is a threshold detection circuit that is triggered when an avalanche event occurs in the corresponding armed pixel of the photodiode array. When a detection occurs, an active quenching circuit removes the excess bias from the fired GmAPD pixel to disarm it, and the in-pixel counter is stopped so that the time of detection within the range gate is recorded. At the end of each range gate, pixels that do not sense an avalanche event record the terminal counter value, indicating that no event has occurred at that pixel. The frame readout then consists of scanning out all of the pixel counter values. This FPA architecture provides range resolution corresponding to the timing resolution of the pixel counters, whereas the intensity resolution is one bit per frame since each pixel can return only a single time-stamp value per frame. Intensity information is obtained by accumulating multiple frames.

The ROIC incorporates a phase lock loop (PLL) circuit to generate highly stable clock signals for all timing operations. An overall 13-bit timing resolution is obtained using 11-bit pseudorandom counters with two additional vernier bits created by using a copy of the clock with a 90 degree phase shift. [3] At the end of each range gate, frame data is scanned out using dedicated I/O ports for each of the 32 rows in the array, and high-speed scan circuitry achieves the read-out of the 32 pixels in each row in 3.36 µs. With a typical range gate duration of 2 µs, the full frame duration of 5.36 µs corresponds to a very high frame rate of 186 kHz. The range gate duration is user-selectable and can have any value between 1 ns and 2 µs. For very short (i.e., ns scale) range gates, the frame rate is determined entirely by the 3.36 µs readout and is on the order of 300 kHz. In addition to the internally supplied clock, the FPA can also be run with an external clock input if desired for system synchronization.

The design strategy of the pixel-level circuitry for this ROIC emphasized forward compatibility with a next generation of higher resolution 50 µm pitch 32 x 128 FPAs currently under development. Scaling considerations dictated the use of a 0.18 µm CMOS technology as well as the use of the very space-efficient pseudorandom counter in each pixel. The ROIC design also targeted minimal power dissipation, and for conventional 3-D imaging frame rates on the order of 20 kHz, the ROIC dissipates less than 40 mW. Even for frame rates as high as 200 kHz, the power dissipation is only ~320 mW. The power dissipation of the entire FPA module is therefore dominated by the dissipation of the integrated two-stage thermoelectric cooler used to establish a temperature differential ΔT between the ambient case temperature and the operating temperature of the hybridized chip stack. The thermal design of the FPA will support ΔT up to 55°C, and to operate the FPA with the PDA chip at -35°C, the FPA module dissipates about 5 W.

2.3 Module design summary

Following the hybridization of the GmAPD photodiode array (PDA) to the CMOS ROIC (see Figure 1), we align and attach a GaP microlens array (MLA) to the exposed back surface of the PDA. Based on the characterization of FPA pixel-level photon detection efficiency before and after MLA attachment, we estimate that the effective fill factor for broad illumination of the FPA is ~75%. (Note that the fill factor in the absence of the MLA is given by the ratio of the 34 µm diameter GmAPD active region to the 100 µm pitch pixel area, or ~9%.) Once the MLA has been attached to the PDA, the resulting chip stack of ROIC+PDA+MLA is attached to a ceramic interposer, which provides electrical routing of signals from the ROIC to the package interconnection pins. The interposer is then placed on a two-stage thermoelectric cooler (TEC), which has been previously mounted to the ceramic housing. A schematic illustration of this FPA architecture is given in Figure 2(a). The solid body cut-away diagram in Figure 2(b) shows a scale model of the module, including additional elements such as a CuW heat sink, the housing pin grid array with 175 pins for electrical connections, and a hermetically sealed lid with an anti-reflection coated sapphire window. As with the ROIC
design, the design of this housing incorporated elements to ensure forward compatibility with future FPA generations, including sufficient pins for ROICs with a larger number of I/O connections.

![Figure 2](image1.png)

**Figure 2.** (a) Notional concept for GmAPD focal plane array, consisting of the hybridized chip stack with readout integrated circuit (ROIC), Geiger-mode APD photodiode array (PDA), and microlens array (MLA) attached to a ceramic interposer for electrical signal routing and cooled by a thermoelectric cooler (TEC). (b) Solid body model of FPA prototype module with cut-away showing, from bottom to top, CuW heatsink (gold), ceramic package (gray), TEC (white), interposer (light blue), hybridized ROIC+PDA+MLA chip stack (dark blue), and package window (clear).

![Figure 3](image2.png)

**Figure 3.** Photograph of evaluation interface board providing full control to the GmAPD focal plane array (FPA) via a National Instruments card in a personal computer. Firmware in the FPGA provides on-board high-speed control of the FPA, and high data throughput is managed using a 200 MB/s digital I/O port. Additional electrical interfaces provide low-noise high voltage dc bias for the GmAPD array, control of the thermoelectric cooler, and auxiliary signals for the FPGA and ROIC.

### 2.4 Evaluation interface board

To provide for flexible, turn-key operation of the FPA with camera-level functionality, we have designed an interface board (see Figure 3) to control all features of the FPA and manage interfaces with support instrumentation. Primary interface board functions are managed by an Altera Cyclone III FPGA controller and include: FPA clock generation and scaling; data de-convolution, buffering, and high-speed output to a digital I/O card; programmable timing and pulse
width of FPA control signals; device configuration registers; and laser trigger output. This board manages real-time data retrieval from the FPA, and the FPGA executes all required buffering and formatting of the pseudorandom counter timestamp data obtained from the sensor. The board also has simple electrical connections for support instrumentation (specifically, a high-voltage power supply to provide the APD bias voltage and a standard TEC controller). The board is operated by a comprehensive graphical user interface on a personal computer (PC), and communication between the board and the computer is via National Instruments digital I/O cards. The high frame rate capability of the FPA is supported by a 200 MB/s digital I/O port to establish high-throughput data transfer from the FPGA to a PC.

3. FUNDAMENTAL PERFORMANCE PARAMETER SUMMARY

FPA sensors were characterized in a dark enclosure via computer control using the interface board just described in subsection 2.4. Fixturing within the enclosure provided for array illumination at either 1.06 \( \mu \)m or 1.55 \( \mu \)m. Photon detection efficiency (PDE) measurements could be obtained with optical pulses focused to a single pixel or using broad illumination that uniformly filled an entire 32 x 32 array. Single-pixel measurements were facilitated by an automated three-axis translation system used to scan the focused output of an optical fiber (8 \( \mu \)m at the 1/e^2 points) with translations as small as 1 \( \mu \)m. For array-level PDE characterization under broad illumination, the fiber source was backed away from the FPA and collimated so that the optical intensity variation across the array was no more than ±5%. Dark count rate (DCR) measurements were obtained with no illumination.

Measurements reported in this section were taken with the FPA case temperature at ~293 K and the GmAPD PDA stabilized at temperatures close to 250 K using the two-stage TEC inside the hermetic FPA module. Data presented below was obtained as a function of excess bias voltage for values up to 4.0 V. Illuminated measurements were made using pulsed lasers with a pulse width of ~150 – 200 ps. The optical pulse timing could be set to have pulse arrivals at any time within the 2 \( \mu \)s range gate, and most data was acquired with pulse arrivals near the midpoint of the range gate (i.e., for pixel counter timestamps corresponding to ~ 1 \( \mu \)s). For single pixel measurements, the pulse intensity was typically attenuated to a mean photon number of \( \eta = 0.1 \) so that the Poisson probability of there being two photons in any given pulse was less than 1%. For some measurements, \( \eta = 1 \) was used to increase the data acquisition rate, in which case the resulting illuminated count measurements were corrected by assuming Poisson statistics to calculate the intrinsic PDE. To reduce statistical uncertainty in DCR and PDE measurements, the data presented below are based on the collection of between 10,000 and 25,000 frames of data.

3.1 Dark count rate (DCR) and photon detection efficiency (PDE) characterization

The most important characteristic of the GmAPD FPA is the fundamental tradeoff between DCR and PDE. Higher PDE can be achieved by operating the GmAPD array pixels at higher excess bias voltage, but only at the expense of increased DCR. The optimal operating point for managing this trade-off depends on various factors dictated by the specific imaging application. As an example, for operation with high background count rates (such as daytime imaging), higher dark count rates will be tolerable as long as they do not exceed the background count rate. In this case, FPA operation with higher PDE will be desirable since the accompanying increase in DCR will not negatively impact image quality (i.e., as long as it remains background-limited). Conversely, in dark conditions with no background, DCR will dominate the noise performance of the FPA, and a different operating point for PDE may be optimal.

3.1.1 DCR and PDE performance for InGaAsP/InP FPAs at 1.06 \( \mu \)m

To characterize the DCR and PDE performance of our GmAPD FPAs, we record array-level data to create performance maps of all 1024 pixels of the 32 x 32 array. The map in Figure 4(a) illustrates DCR performance for a FPA designed for detection at 1.06 \( \mu \)m, with the quantitative value of DCR for each pixel indicated in kHz. The map in Figure 4(b) illustrates accompanying PDE performance for the same FPA, with quantitative values for each pixel indicated in percentage (%). Data were obtained at an operating temperature of 253 K and an excess bias voltage of 3.5 V. These data demonstrate perfect yield, with 100% hybridization (i.e., all connections between PDA and ROIC are present) and 100% pixel operability (i.e., all pixels within target specifications for DCR and PDE performance).
Table 1. Number of Pixels

<table>
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<th>T = 253 K</th>
<th>DCR (kHz)</th>
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<tr>
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<td>0.5</td>
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(a) Histogram of pixel dark count rates for the DCR map data presented in Figure 4 for InGaAsP/InP FPA at 1.06 μm. This FPA has no leaky or open pixels. The DCR distribution at 253 K has an average of 13.6 kHz with a standard deviation of 2.2 kHz. Data were obtained at an excess bias of 3.5 V, which corresponds to an average PDE of 39%. This FPA has no leaky or open pixels. The DCR distribution at 253 K has an average of 13.6 kHz with a standard deviation of 2.2 kHz. Data were obtained at an excess bias of 3.5 V, which corresponds to an average PDE of 39%. (b) Dependence of DCR on the effective PDE for a random sample of pixels from the performance maps presented in Figure 4. Regardless of position on the FPA, pixels show very consistent DCR vs. PDE behavior.

The DCR distribution for the entire array has an average of 13.6 kHz and a standard deviation of 4.2 kHz. Additionally, all 1024 pixels in the array exhibit a DCR of less than 20 kHz for the specified operation conditions. Details of the DCR distribution are illustrated by the histogram in Figure 5(a). The average PDE across the entire array is 39%, and the standard deviation of the distribution of PDE values is 6.3%. From the maps in Figure 4, it is apparent that variation in DCR and PDE across the array is quite systematic, with very little random fluctuation. This suggests that non-
uniformities are the result of systematic variation in device properties, with the most important factor being the variation in APD breakdown voltage \( V_b \). Since a single applied voltage \( V_a \) is supplied to the entire array, the excess bias \( V_{ex} = V_a - V_b \) will vary among different pixels if they have different values of \( V_b \). A smaller \( V_{ex} \) will result in smaller values for both DCR and PDE, and we see that the two variables tend to trend together at different locations across the array. Other sources of performance variation are also possible and may affect DCR and PDE differently. For instance, the rotational misalignment of the microlens array lenses relative to the PDA active areas can induce gradients in the PDE performance but has no impact on the DCR values. We note that the non-uniformity in PDE giving can be easily corrected using non-uniformity correction factors. However, in many applications, the FPA is scanned within the scene being imaged, and the scanning tends to remove the impact of PDE non-uniformity without additional correction.

As described above, the relationship between DCR and PDE presents the most fundamental tradeoff in GmAPD operation. To illustrate this relationship in more detail, we have plotted in Figure 5(b) the dependence of DCR on PDE for a random selection of pixels from the FPA maps in Figure 4. Although there is some variation among these pixels, at any given value of PDE, they all exhibit DCR values consistent to within a factor of \( \sim 2 \). Each point on a DCR vs. PDE curve is obtained by measuring these two parameters at a single value of the excess bias. The collection of DCR vs. PDE curves in Figure 5(b) shows even more consistent behavior than is apparent in the full-array performance maps in Figure 4 because the mapping data includes the additional variation imposed by spatial non-uniformities in \( V_b \) (and therefore \( V_{ex} \)) across the array. For the DCR vs. PDE curves, since both parameters are measured at the same \( V_{ex} \) for a given pixel, array-level variation in \( V_{ex} \) is not a factor.

### 3.1.2 DCR and PDE performance for InGaAs/InP FPAs at 1.55 \( \mu \)m

In addition to FPAs intended for use with 1.06 \( \mu \)m laser sources, we have also designed and fabricated very similar FPAs for use at 1.55 \( \mu \)m. Three-dimensional imaging at this wavelength is preferred for a variety of applications in which the relative eye-safety of the pulsed laser source is of concern as well as cases in which greater coverage is provided by the use of a wavelength that is beyond the spectral sensitivity of many imagers in use today (e.g., visible and near-infrared). Because the longer wavelength sensitivity of these FPAs requires a smaller bandgap absorber (i.e., InGaAs), these devices are more prone to thermal carrier excitation and thus have higher DCR for any fixed set of operating conditions (e.g., excess bias and operating temperature) relative to the 1.06 \( \mu \)m FPAs. Aside from the difference in GmAPD Pdas, all other module elements (ROIC, MLA, packaging sub-components, etc.) used to fabricate FPAs for use at 1.55 \( \mu \)m are identical to those used for the 1.06 \( \mu \)m FPAs.

![Figure 6. Performance maps of all 1024 pixels of a 32 x 32 InGaAs/InP (1.55 \( \mu \)m) GmAPD FPA operating with an excess bias of 3.25 V at 253 K. (a) Dark count rate (DCR) in kHz for all pixels. All pixels are < 50 kHz; there are no high DCR pixels in this FPA. (b) Photon detection efficiency (PDE) in % for all pixels, where the average pixel PDE of 22% includes all optical losses related to the microlens array and other sources of insertion loss.](image)
As seen in the performance maps in Figure 6, we have established excellent performance for these longer wavelength FPAs. Just as in the case of the 1.06 \( \mu \text{m} \) FPAs, these maps demonstrate perfect yield, with 100% hybridization and 100% pixel operability. The DCR map in Figure 6(a) shows that all 1024 pixels have DCR less than 50 kHz, and the average DCR is 28 kHz with a standard deviation of 6.5 kHz. The detailed DCR distribution is illustrated by the histogram in Figure 7(a). For the PDE performance map in Figure 6(b), the mean PDE is 22.2%, with a standard deviation of 4.6%. The array-level non-uniformity in DCR and PDE for these FPAs is comparable to that found for the 1.06 \( \mu \text{m} \) FPAs; somewhat lower values of DCR and PDE near the edges of the FPA are explained by process-related variations in \( V_b \), as opposed to the wafer-level variability in \( V_b \) described above caused by epi-growth parameter gradients.

In Figure 7(b), we have plotted the dependence of DCR on PDE for a random selection of pixels from the 1.55 \( \mu \text{m} \) FPA maps in Figure 6. This characteristic is similar to that shown in Figure 5(b) for the 1.06 \( \mu \text{m} \) FPA, with the primary difference being that the longer wavelength pixels show DCR to be larger by about a factor of 5X.

![Graph showing pixel dark count rate vs. number of pixels](image_url)

**Figure 7.** (a) Histogram of pixel dark count rates for the DCR map data presented in Figure 6 for InGaAs/InP FPA at 1.55 \( \mu \text{m} \). This FPA has no leaky or open pixels. The DCR distribution at 253 K has an average of 28 kHz with a standard deviation of 6.5 kHz. Data were obtained at an excess bias of 3.25 V, which corresponds to an average PDE of 22%.

(b) Dependence of DCR on the effective PDE for a random sample of pixels from the performance maps presented in Figure 6. Regardless of position on the FPA, pixels show consistent DCR vs. PDE behavior.

### 3.2 Summary of crosstalk performance

Another GmAPD FPA performance parameter that is generally of considerable importance to 3-D imaging applications is crosstalk. The detection of single photons in GmAPDs involves macroscopic current flows that can cause optical crosstalk due to hot carrier luminescence, in which the acceleration of charge in a high-field avalanche region gives rise to photon emission at the rate of one photon per \( 10^5 - 10^6 \) carriers that flow through the avalanche region. Because all pixels of the FPA are sensitive to single photons, the coupling of emitted photons to neighboring active areas can cause correlated spurious dark counts at these neighbors that are defined as crosstalk events. With reference to Figure 1, luminescent photon emission can couple from an avalanching pixel to a nearest neighbor pixel by direct “line-of-sight” paths or to more distant neighbors by back-reflection from the rear surface of the GmAPD chip. Etched trenches between nearest neighbor pixels are fabricated to reduce the probability for direct line-of-sight coupling.
Crosstalk characterization can be obtained from wafer-level frame data for avalanches of any origin, so dark or lit measurements can be used. Spatial correlations between avalanches are readily determined from pixel positions, and temporal correlations are provided by the pixel-level timestamp data. To obtain crosstalk data from DCR measurements, we store 1000 frames of DCR data from the entire 32 x 32 FPA and search each frame for “trigger” events and any correlated neighboring events occurring with 10 ns of the “trigger”. From this analysis, we can compile the probability of a crosstalk event as a function of the distance between the “trigger” pixel and the crosstalk pixel. The highest probability exists for crosstalk events at neighboring pixels (i.e., nearest neighbors) and is just under 1% for an operating point at which PDE \sim 35% for the full FPA. The data show a decrease in crosstalk with increasing interpixel distance D that is roughly consistent with an expected 1/D^2 rolloff, although there is non-monotonic behavior that depends quite sensitively on the precise location of a particular crosstalk pixel. [13] The probability that more than one crosstalk event occurs in response to a primary avalanche is \sim 2% when PDE \sim 35%; and the total integrated crosstalk probability—i.e., the probability that any crosstalk event takes place at any pixel in response to a primary avalanche—is under 15% when PDE \sim 35%. [14]

For avalanche events induced by intentional single photon illumination at a specific “trigger” pixel, we can apply the same analysis as used for the DCR data, although we can restrict our search to a much narrower range of pixels surrounding the illuminated pixel. To within measurement uncertainties, the resulting crosstalk for this “lit pixel” scenario is identical to that found for the dark count data. [13] This is expected since there is no difference between dark carrier-induced and photon-induced avalanches. More details pertaining to crosstalk performance will be described in the next section with reference to multi-photon pulse illumination experiments.

4. FPA PERFORMANCE WITH MULTI-PHOTON PULSES

Although GmAPD FPAs provide the distinctive capability of having pixels sensitive to single photons, they can be employed to great advantage in applications for which LADAR pulse returns may consist of multiple photons arriving simultaneously at a given pixel. The principle performance improvement in such a scenario is much higher detection efficiency for these pulses since any single photon in a multi-photon wave packet can trigger a detectable avalanche event. With appropriate operating conditions, “pulse detection efficiency” (PuDE) can be well over 90% for multi-photon pulses with 10 or more photons, and even for photon numbers less than 10, PuDE values are markedly higher than the intrinsic PDE for single photon detection. In this section, we analyze the expected behavior of GmAPD pixels in response to multi-photon pulses and compare experimental measurements with model expectations. We also report measurements of the FPA crosstalk with multi-photon pulse detection and explain these results using a theoretical model that describes the quantitative impact on crosstalk of direct optical scattering.

4.1 Theoretical response to multi-photon pulses

To calculate the effective pulse detection efficiency (PuDE) for multi-photon pulses, we assume that multiple photons arrive simultaneously and conform to Poisson statistics with optical pulses having a mean photon number \mu. In this case, the probability of any given pulse containing N photons is given by the Poisson distribution P(N;\mu) = (\mu^N e^{-\mu})/N!.

We then consider that since the probability of detecting one photon is given by PDE, the complementary probability of not detecting one photon is (1 – PDE). For an optical pulse containing N photons, the probability of not detecting any of the N photons is (1 – PDE)^N. Next, the complementary probability of detecting at least one of the N photons is P_{det}(N) = 1 – (1 – PDE)^N. Finally, to find the pulse detection efficiency PuDE(\mu) for pulses described by mean photon number \mu, we consider the sum over N for the product of P(N;\mu) and P_{det}(N):

\[
PuDE(\mu) = \sum N P(N;\mu)P_{det}(N) = \sum N \frac{\mu^N e^{-\mu}}{N!} [1 – (1 – PDE)^N].
\]

4.2 Measured multi-photon pulse detection efficiency

To experimentally determine PuDE for multi-photon pulses, we used the apparatus described earlier that allows us to focus an incident optical pulse onto a single pixel with an optical fiber with appropriate focusing optics at the fiber facet. With calibrated adjustable attenuation following a calibrated 1.06 \mu m optical source, we set the optical pulse.
intensity to any desired mean photon number $\mu$. We then used the FPA to measure the detection probability for various values of $\mu$ to determine PuDE($\mu$). The filled data points in Figure 8 show the measured PuDE for $\mu = 1, 2, 3, 4, 5,$ and 10 at three different excess bias values of $V_{ex} = 1, 2,\text{ and } 3 \text{ V}$ corresponding to DCR values of 0.6, 3, and 12 kHz, respectively. The figure shows that PuDE increases dramatically for $\mu$ increasing from 1 to 10, with ~98% detection probability for a 10-photon pulse at operating conditions that given 12 kHz DCR. With multi-photon pulses incident on the detector, it is also possible to operate at much lower DCR values while maintaining reasonably high PuDE if specific applications benefit from lower DCR.

The solid lines in Figure 8 indicate the model prediction described by Eq. (1) and show excellent agreement with the experimentally measured data points. The value of PDE was determined by independent measurement of the pixel being tested at a low $\mu$ value of 0.1.

![Figure 8](image)

**Figure 8.** Effective pulse detection efficiency for multi-photon pulses as a function of the mean photon number $\mu$ per pulse for three different excess bias voltages, with corresponding dark count rates indicated. Filled data points are experimental measurements, and solid curves are from model calculations described in the text.

### 4.3 Measured crosstalk with multi-photon pulses

To further characterize the performance of our GmAPD FPAs in illumination by multi-photon pulses, we measured the crosstalk as a function of mean photon number $\mu$. Given our previous measurement of the dependence of PuDE on $\mu$, we then plotted the total probability for all crosstalk events as a function of the multi-photon pulse detection efficiency PuDE. Each set of solid points of a specific shape and color corresponds to illumination with a particular value of $\mu$ and shows the expected increase in total crosstalk and PuDE for increasing excess bias voltage. The solid lines are a phenomenological fit to these sets of points to better illustrate the trend in the data for each $\mu$. The dashed lines indicate the trend in the data for increasing $\mu$ at a fixed excess bias. The increase in multi-photon PuDE with increasing $\mu$ is expected based on the results presented in Figure 8.

However, these data show that the total crosstalk probability also increases with increasing $\mu$. This is an effect that can not be related to hot carrier luminescence described above in sub-section 3.2 because the GmAPD bias circuitry dictates the size of a detection avalanche. This avalanche magnitude will not be dependent on how many photons are absorbed by the pixel, and so hot carrier emission and its consequent crosstalk effects can not depend on photon number $\mu$. We therefore consider the impact of optical scattering—e.g., from the seams of the microlens array in the FPA—to determine whether such scattering could quantitatively account for the observed increase in total crosstalk with increasing $\mu$. 
Since crosstalk events are defined by their correlation to an initial primary avalanche, crosstalk detection can only occur if a detection event has occurred at a primary pixel. If a particular input optical pulse contains only one photon, it is not possible to detect optical scattering. If the one photon triggers a primary avalanche, then it is annihilated and any crosstalk must be from photon re-emission. If the one photon is scattered before it can trigger a primary avalanche, then even if it is absorbed elsewhere, it will not be counted as a crosstalk event because there was no primary avalanche to correlate with. So optical scattering can only be detected if a particular input pulse contains two or more photons. (Note that this corresponds to the case of $N \geq 2$, which is still possible with finite probability for mean photon number $\mu \leq 2$.) Additionally, even for multi-photon input pulses with $N \geq 2$, the total crosstalk probability $P_{xt}$ will still contain a contribution $P_{xt,0}$ from hot carrier luminescence.

To calculate the total crosstalk probability including the effects of optical scattering with multi-photon incident pulses, we again assume Poisson statistics for the pulses with probability $P(N; \mu)$ of having $N$ photons given a mean photon number of $\mu$. Of the $N$ photons in any given pulse, we then assume that $m$ photons are scattered with a 1-photon scattering probability $\beta$. To observe a crosstalk event, we must have a primary avalanche, which requires that we detect one of the $(N - m)$ non-scattered photons; this probability is $1 - (1 - PDE)^{N-m}$. At the same time, we must also detect one of the $m$ scattered photons at a neighboring pixel; this includes the likelihood that scattering occurs in the first place as well as the likelihood that one of the $m$ photons is then detected. This total probability is $\beta^m[1 - (1 - PDE)^m]$. The total crosstalk probability is then $P_{xt,0}$ added to a term that sums over all possible photon numbers $N$ for $N \geq 2$ with a nested sum over all possible scattered photon numbers $m$ of the product of probabilities describing the detection of a primary avalanche and the detection of a scattered photon at a neighboring pixel.

![Figure 9](image.png)

**Figure 9.** Total crosstalk probability as a function of the effective multi-photon pulse detection efficiency for different excess bias voltages and over a range of mean photon number $\mu$ per pulse (i.e., $\mu = 1, 2, 3, 4, 5,$ and 10). Filled data points are experimental results, and the solid curves in phenomenological fits to indicate data trends for each mean photon number $\mu$. The dashed lines indicate trends across different values of $\mu$ for fixed excess bias voltages.

Using this model, for which additional details will be published in another paper, we find that we can accurately fit the total crosstalk dependence on PuDE illustrated in Figure 9 with a single value of $\beta \sim 15\%$ for the optical scattering probability. Both the model and experimental measurements show that the total crosstalk probability for 10-photon pulses is $\sim70\%$ larger than it is for 1-photon pulses. Extracted values of the hot carrier luminescence contribution $P_{xt,0}$ for specific excess bias values (and consequent single photon PDE values) agree well with results for low mean photon number measurements (i.e., $\mu = 0.1$) [13]. The consistency of these results for the two free parameters $\beta$ and $P_{xt,0}$ suggest that optical scattering is in fact responsible for the observed increase in crosstalk with mean photon number for multi-photon pulses. It is also interesting to compare the experimentally determined microlens array fill factor loss of
~25 – 30% with the value of ~15% determined for the optical scattering probability $\beta$. These results suggest that about half of the photons lost due to the imperfect fill factor are being scattered to neighboring pixels at which they can be detected as spurious counts. This finding warrants further consideration relative to the performance of GmAPD FPAs even with single photon incident pulses. We believe that this optical scattering originates at the seams between individual lenses in the microlens array where the lens geometry deviates from the intended aspheric design and can misdirect incident photons to PDA active areas other than the active area corresponding to the illuminated microlens.

5. CONCLUSIONS

In this paper, we have described the performance of focal plane arrays based on Geiger-mode APDs with single photon sensitivity that function as the sensor engine for 3-D LADAR imaging systems. Time-of-flight measurements are captured on a per-pixel basis using a custom CMOS ROIC which also controls GmAPD avalanche quenching and reset operations and can read out 3-D image data at frame rates as high as 186 kHz for 2 $\mu$s range gates. These 32 x 32 x 100 $\mu$m pitch arrays include GaP microlens arrays to provide high fill factors of ~75%. Robust hermetic packaging ensures reliable operation in harsh environments, and FPGA-controlled interface boards have been developed to provide turnkey camera-level electronic functionality.

We have designed two different versions of the basic FPA. One version employs a quaternary InGaAsP absorber in the GmAPD photodiode array optimized for use in systems with 1.06 $\mu$m laser sources, which the other employs a ternary InGaAs absorber for longer wavelength operation near 1.55 $\mu$m. For both versions of this FPA, we have demonstrated perfect yield for FPAs, with 100% operable pixels and excellent FPA-level distributions of dark count rate and photon detection efficiency. For the 1.06 $\mu$m FPA, the mean DCR was 14 kHz at 39% PDE and 250 K operation, with all pixels having less than 20 kHz DCR. For the 1.55 $\mu$m FPA, the mean DCR was 28 kHz at 22% PDE and 250 K operation, with all pixels having less than 50 kHz DCR.

We have also reported the first evaluation of GmAPD FPAs for the detection of multi-photon optical pulses with mean photon numbers in range from $\mu = 1$ to $\mu = 10$. For 10-photon pulses, the pulse detection efficiency is ~98% under operating conditions consistent with just 12 kHz DCR. We model the PuDE assuming Poisson statistics for the optical pulses and find excellent agreement between the measured and calculated values for any photon number and excess bias condition. We have also analyzed the dependence of the total crosstalk probability on photon number, and we have found that we can accurately describe the increase in crosstalk with $\mu$ with a model based on direct optical scattering in the presence of multi-photon pulses. Fitting of this model to our measured data yields an optical scattering probability of ~15%, which accounts for approximately one-half of our measured fill factor loss. The model also indicates a crosstalk contribution from photon emission due to hot carrier luminescence of ~10% at an operating PDE ~35%, consistent with earlier crosstalk results focused on the characterization of these hot carrier emission effects.

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