Single-photon imaging camera development for night vision

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ABSTRACT

Single-photon imaging in infrared will add a new valuable tool to night imaging cameras. Despite years of development, high-sensitivity SWIR cameras are still expensive and not ready for large-volume production. Germanium (Ge) is a promising semiconductor to convert SWIR radiation and it has seen extensive development in conjunction with high-speed optical communications.

We are demonstrating a new low-light level infrared array technology based on the single-photon sensitive Geiger avalanche PhotoDiode (Si-GPD) array technology developed at aPeak and low-dislocation Germanium processing developed at MIT. The core of the imaging camera is a Ge:Si photon-counting GPD pixel with CMOS readout. The primary technology objective is to demonstrate through prototyping and semiconductor process development the technical feasibility of single-photon detection cameras sensitive in the SWIR and set the performance specifications. We report on prototype Ge:Si structures compatible with the GPD operation and technology. We demonstrate >80% quantum efficiency at 1310nm and 45%-60% quantum efficiency at 1550nm. Dark current measurements indicate that single-photon sensitivity (2.6x10^{-18} W/pixel) is achievable by cooling the detector at cryogenic temperatures down to 53K.

A digital developed to provide adjustable dynamic range and frame rate is reported. Because the GPD detectors have intrinsic excellent gating and ranging capability, the pixel architecture is developed to enable the dual mode operation - passive illumination two-dimensional imaging (night vision) and active illumination three-dimensional imaging.

Keywords: avalanche, Geiger, night vision

1. INTRODUCTION

Single-photon detection technology with silicon Geiger avalanche PhotoDiode (GPD) arrays has demonstrated maturity and has been already used in a wide variety of applications like biomedical, defense, nuclear physics and space.\textsuperscript{1,2,3,4} Silicon is weakly absorbing photons at 1550nm through processes which do not generate e-h carriers. To overcome this disadvantage and still benefit from silicon’s Geiger avalanche performance, infrared converters with high absorption in infrared could be used to inject carriers into silicon-based p-n junction GPDs. Ge is an effective SWIR absorber. If deposited on silicon GPDs with a well-controlled layer thickness and doping concentration, it could yield high quantum absorption efficiency over the SWIR spectral range. Previous research on Ge photodetectors deposited on Si has demonstrated quantum efficiency >80% from 1000 nm to 1550 nm.\textsuperscript{5} Lattice engineering (strained Ge) has resulted in extended response to 1600 nm, an important feature to match the camera sensitivity to nightglow spectra.\textsuperscript{6} It would be therefore desirable to capitalize on the progress of Si GPD technology and explore whether heterojunction Ge-Si:GPD pixel based cameras could operate in SWIR and beyond 1550nm with single-photon sensitivity. In such structures, Ge will absorb efficiently the infrared photons and will inject photo carriers in to the Si:GPD avalanche region – the concept has been used before for other materials and it is known as SAM GPD - Separate Absorption and (avalanche) Multiplication GPD.

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The proposed Ge-Si:GPD array and pixel structures are shown in Figure 1a and Figure 1b. Large-area photon counting GPD detectors and readouts are monolithically CMOS processed in silicon on the front side of the wafer. The quantum efficiency in SWIR is extended by depositing on the backside low-defect density Ge islands with a structure engineered to achieve low-noise and high-quantum efficiency. Free carriers, generated in the Ge infrared converters by SWIR photons, will be injected across the GPD Geiger junction and will generate avalanche events. The internal gain of the Si-GPD yields 0.5-1 volt signals for single-photon triggered events and therefore no low-noise amplification is needed to process single-photon induced signals.

As opposed analog photo-pixels, in GPD pixels responsivity and noise performance parameters are replaced with the single-photon detection efficiency SPDE, and respectively the dark count rate DCR. The generally accepted equations governing the detection efficiency SPDE in Geiger detectors are:

\[
SPDE = 1 - \exp(-QE \cdot P_{be})
\]

and:

\[
DCR = Idark \cdot (1 - \exp(-P_{be})) / q
\]

where \(QE\) is the quantum efficiency, \(P_{be}\) is the single-carrier breakdown probability, \(Idark\) is the dark (leakage) current/pixel and \(q\) is the electron charge. Single-photon detection sensitivity at \(QE=50\%\) and \(SNR=3\) converts to \(2.6 \times 10^{-18}\) W/pixel minimum detectable power.

![Figure 1. (a) Cross-section through the SWIR camera. Ge:Si-GPD pixels detect SWIR photons; (b) Ge:Si-GPD pixel detail. The Si Geiger p-n junction collects the carriers injected through the Ge-Si heterojunction and initiates Geiger avalanche breakdown events.](image)

2. PROCESS DEVELOPMENT AND QUALIFICATION

The primary difficulty in depositing Ge epi-layers on Si is the 4% lattice mismatch between Si and Ge. This lattice mismatch must be accommodated through either strain or dislocations. The critical thickness before layer relaxation through the introduction of dislocations is only a few atomic layers for pure Ge on Si and it is too thin to absorb the infrared photons with acceptable absorption efficiency (target is 50%). For thicker layers, upon relaxation, dislocations are introduced at the interface in the growth plane (misfit dislocations). Because a dislocation cannot terminate within the bulk, it must terminate at the edge or surface of a material, or else close upon itself, forming a closed loop. Consequently, many dislocations leave the growth plane and propagate through the film to the film surface (threading dislocation). These threading dislocations degrade the device performance by reducing the carrier lifetime.

The method to deposit micron thick Ge is using a two-step Ultra-High Vacuum Chemical Vapor Deposition (UHVCVD) direct growth of Ge on Si substrates followed by cyclic annealing to produce high quality Ge epitaxial films with \(<10^7\) /cm² dislocation densities. This method produced Ge films suitable for high quality photo detectors without the need of thick graded buffer layers.
The UHVCVD systems accommodate by now 6” wafers – scaling up to larger silicon diameter is feasible – this makes the method suitable for prototyping and volume production. The competitive advantage of the Ge-Si:GPD array technology using this process is its capability to produce dies on large scale and at potentially low cost.

The major difference between this process development and previous Ge process developments on UHVCVD for Ge/Si based photodetectors is that in the Ge-Si:GPD the Ge-Si heterojunction is part of the active volume through which photo generated carriers in Ge are injected and collected by the avalanche region in Si, as opposed to homojunction Ge photodetectors deposited on Si.

### 2.1 Tests Structures

Ge deposition quality was evaluated first on Ge-Si photodiodes (Ge-Si:PD) with the same base resistivity as Ge-Si:GPDs. After the Ge process development has been completed, Ge-Si:GPDs fabricated in custom bipolar process, have been etched in KOH at the back side to create a thin membrane in front of the Geiger junction located on the opposite side. Low defect density Ge was selectively deposited (using the process previously developed at MIT) into small silicon oxide windows that were photo lithographically defined at the bottom of the KOH etched cavity. **Figure 2a** shows a micrograph of the KOH etched cavity and **Figure 2b** shows a schematic cross-section through the Si:GPD prior to the deposition of the Ge converter in the KOH etched cavity. These Ge-Si:GPDs have shown avalanche multiplication but at a higher breakdown voltage – more accurate process simulation is needed to correctly control the breakdown voltage and account for the extra thermal budget during Ge deposition and subsequent post processing steps.

![Figure 2. A deep cavity KOH anisotropic etching was created on the opposite side of the fabricated Si:GPD to allow Ge growth. (a) Micrograph of KOH etch pattern after etch. (b) Cross section through a GPD structure with etched cavity on the backside prior to Ge deposition in the KOH etched cavity.](image)

### 2.2 Current –Voltage Characteristics in Ge-Si:PDs

Prior to fabricating Ge-Si:GPD photodetectors, Ge-Si:PD (PhotoDiode) test structures have been fabricated and used to test the quality of the Ge-Si heterojunction. Photodetector current-voltage characteristics (I-Vs) with different ratios of area/perimeter have been measured at room temperature. The area current density (normalized to the photo detector area) and peripheral current density (normalized to photo detector perimeter) were calculated for diodes ranging from 10um x 10um to 300um x 300um. The results (**Figure 3a** and b) show a large spreading of the area reverse current density for small versus large diodes (smaller diodes show actually higher area current density) and a relatively low spreading of the peripheral dark current density. We conclude that for both diode sizes the peripheral reverse current is dominant and that process modifications are needed to further decrease the peripheral dark current.
Figure 3. The comparison of area and peripheral reverse currents indicates a dominant conduction at the diode periphery. (a) Area current density - if the current were controlled by the bulk current, smaller diodes (10um x 10um) should have the lowest current density as earlier studies at MIT have shown a complete annealing of the Ge growth in small diodes. In fact, they show higher area current density; that points to the peripheral current as a dominant contribution. (b) Peripheral current density (current/diode perimeter) shows similar dark (reverse) currents for both 10um and 300um diodes.

2.3 Dark current and operation temperature

Field operated SWIR cameras require minimizing the operational power. Camera cooling, for noise considerations, may add to the total power budget. Determining the operation temperature should allow estimating the contribution of the cooling to the overall power. There are reports of un-cooled Ge-Si:GPDs in SOI technology but without targeting single-photon imaging. Ge is a low band gap semiconductor with high thermal carrier generation at room temperature and requires cooling of Ge-Si:GPDs to achieve thermal generation low enough to detect single photons. Previous activation energy measurements on Ge-Si junctions have shown that the activation energy at temperatures lower than 200K is not constant. In order to avoid underestimating the camera cooling requirements, we measured the Ge-Si photodiodes down to 100K. Ge-Si p-n junction photodiodes with 10um x 10um Ge islands were tested from 293K to 100K at different reverse voltages covering the reverse bias developed in Ge-Si:GPD at the operation conditions (approximately 0.1 - 0.3V bias drop on the Ge-Si heterojunction). The reverse current at different reverse bias is plotted in Figure 4. If the data are extrapolated down to 1e/s noise, the reciprocal operation temperature 1/kT ranges from 145-220 ev⁻¹, i.e. T = 53-80K. Data clearly show a two-activation energy process with a crossover at 50-69 ev⁻¹. The results presented in section 2.2 indicate that even in small area detectors the peripheral currents dominate the bulk currents (normal to the Ge-Si junction). As only the bulk currents start the Geiger avalanche, we expect meeting the single-photon condition at higher temperatures – the estimated range T=53-80K is therefore corresponding to the worst-case condition.
Figure 4. Arhenius plot of the dark current measured at constant voltage. Extrapolation of the data to $1/e/s$ indicates an operation range of 53-80K.

2.4 Dark current improvement

We have evaluated the dark currents of differently grown and fabricated Ge photodiodes. We have initially used a wet etch process to open windows in the oxide in order to expose the single crystalline Si for Ge growth. The wet oxidation step was chosen because the wet etched Si surface allowed an excellent quality for Ge growth. Earlier tests using RIE only (reactive ion etching) produced poor Si surfaces and therefore resulted in poor Ge growth. A SEM cross section is shown Figure 5 for Ge growth in a wet etched oxide window.

![Figure 5. Ge mesa grown in a wet etched oxide window. The wet etch resulted in sloped oxide sidewalls.](image)

The deposited Ge island shows faceting due to exposed crystallographic surfaces - [111] and [311] are slow growing surfaces that prevent the complete filling of the oxide window. Because of the sloped oxide sidewalls, the Ge layer is relatively thin at the edge of the mesa. The dark current densities for these small Ge diodes (smaller than 10 x 10 µm) at -1V bias were of the order of $10^1$ to $10^2$ A/cm$^2$. The main source of dark current appears to be due to peripheral leakage from the Ge mesa edge. Larger Ge diodes (100 x 100 µm) show dark current densities of $\sim10^3$ A/cm$^2$. Since the peripheral contribution to the dark current for the larger Ge diodes is smaller relative to the bulk contribution, the measured dark current is mainly attributed to bulk leakage.

It has been previously shown that the bulk contribution to dark current of Ge diodes is dominated by leakage due to threading dislocations.\(^9\) For large diodes, the threading dislocation density is larger than for small diodes. The difference
in misfit dislocation densities for different diode sizes is due to the thermal treatment that increases the mobility of threading dislocations and drives them to the edges of the mesa. For small Ge mesas (10 x 10 µm), the thermal treatment removes most of the threading dislocations, while for large mesas (100 x 100 µm), interaction between dislocations limits the total reduction. We therefore expect the bulk leakage current for small mesas to be below $10^{-4}$ A/cm$^2$.

In order to improve the peripheral leakage of small diodes, a new oxide etching process has been implemented – the process resulted in near vertical sidewalls while providing a high quality Si surface prior to Ge growth. The process combines reactive ion etch (RIE) to partially remove the oxide and with wet oxide etch to remove the remaining oxide and expose the Si surface for growth. Sharp vertical walls were anisotropically etched in silicon dioxide windows on Ge-silicon photodiodes using RIE - Figure 6 shows the resulting Ge growth. Due to the steep oxide sidewalls, we were able to suppress faceting during growth sufficiently so that the oxide sidewalls were completely covered with Ge. As shown in Figure 7, the dark (reverse) current on pin diode Si-Ge heterojunctions improved dramatically. This improvement should further relax the cooling needs and it will decrease the power required to cool the camera.

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**Figure 6.** Ge growth in oxide window with near vertical sidewalls.

**Figure 7.** Comparative dark current density in homojunction Ge/Si photodiodes for wet etched (tapered wall window) and RIE etched (vertical wall window) silicon oxide (positive for forward bias).
3. PERFORMANCE EVALUATION

3.1 Ge-Si:PD (photodiode) testing - Quantum Efficiency

The quantum efficiency over the 1000-1600nm was measured on 300um x 300um Ge-Si photodiodes at room temperature using lock-in techniques. The quantum efficiency spectra shown in Figure 8, demonstrate a peak QE>80% and QE=45% at 1550nm. It was found that the quantum efficiency is higher for smaller size pixels (<50um), which is consistent with the defect-annealing model developed at MIT/MPC (more efficient defect annealing in smaller Ge structures).

![Figure 8. Measured spectral quantum efficiency of Ge-Si photodiodes](image)

3.2 Ge-Si:GPD fabrication and testing

Ge-Si:GPD fabrication flow has involved 67 process steps, out of which 34 process steps have been used for the fabrication of the Ge converter and the contact electrode on Ge. The process flow has used conventional thinning KOH methods prior to Ge island deposition as describe in section 2.1. A micrograph of the final device is shown in Figure 9a, and a packaged die (aperture in the center is located on the Ge side) is shown in Figure 9b.

![Figure 9. Micrograph of the Ge-Si:GPD at the completion of the fabrication flow (Ge side). The four rectangles indicate the walls of the cavity etched in KOH. The darker dot at the bottom of KOH etched cavity is the Ge converter.](image)
Ge-Si:GPD structures were tested at 1550nm in a collimated laser beam. Ge converters (approximately 15 um diameter), deposited in the KOH etched cavity have shown a relatively wide spreading of the QE (mainly due to photolithography limitations in 500um deep wells etched by KOH) and have peaked at QE=60%.

3.3 Timing jitter

Night vision cameras operate as two-dimensional cameras, usually in passive illumination mode. The fast response of the GPD avalanche to single photons and its extremely short integration time (few ns) would allow developing cameras with ranging capability in active illumination mode with pulsed lasers (flash-LADAR like) for three-dimensional imaging (third dimension is the range measured by the two-way trip time of the laser pulse). For these applications the timing jitter performance at pixel level indicates the maximum range resolution.

This section reports on the timing jitter measured on the native Si:GPD design with an overall 300um base thickness. The timing performance of the Ge-Si:GPD with a thinner GPD base in Ge-Si:GPDs (target is thinner than 30um) should be superior to the native Si:GPD design due to faster carrier collection and a decreased contribution of the slow carriers propagating through diffusion to the GPD junction. A collimated 1050nm laser, emitting 35ps pulses, was used for timing measurements. GPD pixels actively quenched by off-chip ASICs developed at aPeak have been tested for timing jitter (rise time fluctuations or RTF) in multi-photon and single-photon regimes. The intrinsic RTF (corrected for the measurement system RTF, ASIC RTF, and laser pulse width) was 130ps for single-photon registered photon hits and 20ps for multi-photon hits (Figure 10). A timing jitter of 130ps translates into 2 cm range resolution.

![Figure 10. Measured RTF versus the GPD detection efficiency at 1050nm.](image1)

3.4 Camera readout

GPD has a digital output and therefore for selected applications it should be advantageous to design digital readouts of the Geiger detection event. GPD outputs a binary signal corresponding to a photon detection event – the detector pixel acts like a photon counter. As compared to an analog readout, the digital readout has the advantage of higher compatibility with available CMOS processing technologies, thus allowing design portability to lower technology nodes. The second advantage is that it could be processed in pure digital CMOS technologies. Figure 11a shows the selected digital readout to be implemented at pixel level. One flip-flop stores the GPD photon detection state, while the second flip-flop when enabled with SEL, shifts out serially the data along the array row. The first flip-flop DFF1 (leftmost DFF) is continuously monitoring the photon detection event, and therefore during the frame read sequence no events are missed. The second D flip-flop DATA_IN and DATA_OUT are connected to the neighboring pixels and forms a row-
long shift register. Once the photon event is registered, the output of DFF1 is locked until the RESET (at the end of frame) is enabled. This simple readout should allow maximum photon imaging yield (close to 100%) and fast data transfer rates. High photon yield utilization is critical for operations at nighttime, as the camera operates in photon-starved regime. The layout of the digital read at pixel level is shown in Figure 11b. SPICE simulation indicated that maximum readout clock is 500MHz in 180nm CMOS. Ring oscillators using the layout shown in Figure 11b have been fabricated and have shown systematically shorter propagation delays as compared to the simulation. Therefore we expect readout rates in fabricated cameras in 180nm CMOS in excess of 500MHz. Fast pixel interrogation (1/500MHz = 2ns) at low-light levels will prevent photon hit pile-up in DFF1. Based on this readout rate, a camera with 1K x 1K pixels and row-column addressing should be capable of approximately 500 Hz frame rate.

![Figure 11](image)

Figure 11. (a) Pixel level digital readout designed for the single-photon SWIR camera. GPD_DIN is the Ge-Si:GPD pulse stored in the first flip-flop DFF and routed through the second MUX 2 to the second DFF. In SEL mode, the stored state in the second DFF is shifted serially to the output column buffer. The second flip flop performs the shifting function similar to that designed in CCDs with the difference that digital states are shifted out instead of charge packets
NOTE: the first MUX is for functional and performance testing; (b) Pixel level digital read layout.

4. CONCLUSIONS

This work, focused on process and design development of Ge-Si:GPD detectors for night vision applications, has demonstrated the feasibility of cameras with single-photon imaging capability at 1550nm. High quantum efficiency of the Ge converter has been demonstrated. A simple digital readout has been simulated and the primitive cells have been fabricated and tested for readout speed. Based on primitive cell simulation and propagation delay data extracted from fabricated cells, we expect 500 Hz frame rates in 1Kpixel x 1Kpixel cameras. The camera operation temperature required to achieve single-photon sensitivity ranges from 53-80 K. Dark current improvements, reported in section 2.4, and the immunity of the multiplication Geiger process to peripheral currents in GPD junctions should further decrease the equivalent noise (DCR) and increase the camera operation temperature.

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6. REFERENCES


