Nuclear Physics Instrumentation: Position Sensitive Charge Particle and Gamma Ray Tracking Devices
(SBIR Topic: DOE 2013 – 42b)

Digital Silicon Photomultiplier Array Readout Integrated Circuits
Outline

• Brief Introduction to Voxtel
• Overview of Problem/Opportunity
• Readout Circuit Technical Discussion
  • SPAD device design and operation
  • Active quenching circuits
  • DSPAD prototype characterization results
  • Sensor specifications
• Summary and Questions
About Voxtel Companies

- Founded 1999
- 50 employees summer 2015 (30% PhD, 80% Advanced Degree)

**Voxtel Opto (Beaverton, Oregon)**
- Avalanche Photodiode (APD) and PIN Detectors and Arrays
- Eyesafe Pulsed Laser Transmitters
- Rangefinders, 3D Imaging, LADAR, and Electro-Optic Systems
- Readout Integrated Circuits (ROICs)
- Active & Act./Passive Focal Plane Array (FPA)

**Voxtel Nano (Eugene, Oregon)**
- Nanotechnology Technologies Group
- Nanocrystal VIS-SWIR-Thermal IP Imaging Products
- Analytical Facilities (HRTEM, SIMS, XRD, UPS/XPS)

**Vadient Optics (Corvallis, Oregon)**
- Spun out in 2013
- Inkjet Printed Solid Freeform Fabrication of GRIN Optics
Statement of Problem
The need for ever more sensitive, compact, rugged, and inexpensive optical sensors is particularly acute in the fields of homeland security, biological sciences, nuclear medicine, astronomy, and nuclear/high-energy physics.

- Applications like fluorescence and luminescence photometry, absorption spectroscopy, scintillation readout, charged particle detection, and Cherenkov imaging require extremely sensitive optical sensors to operate in space-limited and adverse environments.
- Existing detector technologies include: photomultiplier tubes (PMTs), microchannel plate photomultiplier tubes (MCPMTs), silicon photomultipliers (SiPM), and single photon avalanche detectors (SPAD)

Program Objectives
- Complete specification, design, and layout of the large format Digital SPAD sensor.
- Fabricate DSPAD readout, capable of being utilized as readout integrated circuit (ROIC) or monolithic sensor.
- Electrically and optically characterize the sensor.

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Geiger Mode SPAD Operation

1. Reverse bias is applied to photodiode beyond breakdown potential of device, arming the detector.
2. A photo- or thermally-generated carrier is collected in the junction, resulting in avalanche current in device.
3. Avalanche current is sensed and photodiode reverse bias is reduced (quench) to protect device.
DSPAD Pixel Architecture

- AQC modulates bias and controls quench time of the Gm-APD.
- In-pixel SRAM to disable individual pixels, improving dark count rate and device yield.
- Pixel output is either number of photons or time-of-flight (analog ramp).
- Local ramp generator may be utilized for improved timing resolution.

SPAD device development supported under DOE contract # DE-SC0006157 (Wafer-scale Geiger-mode Silicon Photomultiplier Arrays Fabricated Using Domestic CMOS Fab)

Prototype Pixel Layout (20% fill factor)
Prototype DSPAD and SiPM Sensors

Picture of VX-820A, VX-820B(1,2,3), and VX-820C prototype sensor designs.

**VX-820A**: 40 x 40 SPAD Array
*On-chip multiplexer*

**VX-820B (1,2,3)**: 8 x 8 SPAD Arrays
*Fan-out for integration with 64 channel TDC*

**VX-820C2**: 1mm$^2$ SiPM Devices

Block diagram of VX-820A sensor including 5 different SPAD arrays (A-E) and the select multiplexer that is utilized to characterize individual pixels within the array.
AQC and Multiplexer Operation

Laboratory demonstration of AQC APD quench and re-arm operation. Quench time is adjustable from 12 – 1200 ns.

Summary of key AQC timing parameters verified by measurement

<table>
<thead>
<tr>
<th>Description</th>
<th>Simulated Nom</th>
<th>Meas. Nom</th>
<th>Measured Max</th>
<th>Measured Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Nom Curr (µA)</td>
<td>Sim val. PD/Amp</td>
<td>Min Curr (µA)</td>
<td>PD/Amp</td>
</tr>
<tr>
<td>Pixel quench duration (qcap)</td>
<td>-20</td>
<td>149ns</td>
<td>-320</td>
<td>12ns</td>
</tr>
<tr>
<td>Quench Pulse duration on APD Anode</td>
<td>-20</td>
<td>540ns</td>
<td>-320</td>
<td>37.5ns</td>
</tr>
<tr>
<td>Pixel precharge/reset duration (nPr)</td>
<td>500</td>
<td>3.9ns</td>
<td>1</td>
<td>1000ns</td>
</tr>
<tr>
<td>Pixel Col pulse duration (PD)</td>
<td>-10</td>
<td>95ns</td>
<td>-1</td>
<td>460ns</td>
</tr>
<tr>
<td>Column pulse amplitude (test AQC)</td>
<td>100</td>
<td>(-15mV)</td>
<td>10</td>
<td>(-3mV)</td>
</tr>
<tr>
<td>Column pulse amplitude (SPADA)</td>
<td></td>
<td>(-15mV)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Breakdown Voltage

Target breakdown voltage was 13-25 V for wafers 1-5. Difference resulted from misplacement of annealing step in initial device process model. Upon changing the process simulation model to match the fabrication process flow, the measured breakdown voltages match the simulation results.
Dark Count Rate (DCR)

- Average DCR is 25-40 Hz at 2.25V over-bias (~9.2% $V_{OB}$).
- Roughly 2% screamer pixels.
- DCR scales roughly with active area.
- Negligible crosstalk and after pulsing effects.

The 14-µm diameter active area device has a reduced anode to guard ring spacing resulting in an early increase in DCR.
Quantum/Photon Detection Efficiency

- PDE is measured on single element SPAD (VX-820A sensor).
- Measurements at wavelengths below 450 nm are questionable (noise floor of ref. detector).
# DSPAD Array Specification Summary

<table>
<thead>
<tr>
<th>Specification</th>
<th>Goal</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel pitch, resolution</td>
<td>30 µm, 256 x 256</td>
<td>Baseline</td>
</tr>
<tr>
<td>Frame rate</td>
<td>500 Hz</td>
<td>Assumes 1 ms integration time, snapshot, integrate-then-read</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Single photon Gm-APD device</td>
<td></td>
</tr>
<tr>
<td>Dark count rate</td>
<td>&lt; 150 counts/pixel/sec</td>
<td>Based on measured VX-820 data, scaled to active area</td>
</tr>
<tr>
<td>Photon detection efficiency</td>
<td>&gt; 25% peak</td>
<td>At 500 nm, PDE &gt;10% from 400 – 650 nm</td>
</tr>
<tr>
<td>AQC quench time</td>
<td>10 – 50 ns</td>
<td>Active, adjustable through DSI</td>
</tr>
<tr>
<td>Counter dynamic range</td>
<td>12-bits</td>
<td>Integration mode</td>
</tr>
<tr>
<td>ToF minimum gate time</td>
<td>250 ns</td>
<td>37.5 m depth, can be longer</td>
</tr>
<tr>
<td>SPAD jitter</td>
<td>~100 ps</td>
<td>Current estimate, measurement in progress</td>
</tr>
<tr>
<td>Timing resolution</td>
<td>120 ps</td>
<td>In TOF mode, jitter + time-to-digital conversion (61 ps)</td>
</tr>
<tr>
<td>Timing dynamic range</td>
<td>12-bits</td>
<td>In TOF mode</td>
</tr>
<tr>
<td>Output channels</td>
<td>1 (6-bits parallel)</td>
<td>Digital output, 12-bit ADC, DDR</td>
</tr>
<tr>
<td>Output data rate</td>
<td>20 MSPS</td>
<td>LVDS</td>
</tr>
<tr>
<td>Pixel disable</td>
<td>Yes</td>
<td>For DCR reduction</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>300</td>
<td>Nominal</td>
</tr>
<tr>
<td>SPAD device</td>
<td>Silicon, p-on-n</td>
<td>Monolithic</td>
</tr>
<tr>
<td>SPAD area</td>
<td>20 x 20 µm</td>
<td>18-um diameter avalanche region - 30% fill factor</td>
</tr>
</tbody>
</table>
Lot turns at foundry are currently taking 4-5 months. Schedule is already tight so we are most likely going to need 6 month no-cost extension on the program.
Program Summary

• Technical risk related to monolithic SPAD design has been greatly reduced through VX-820 prototype arrays that were fabricated/characterized early in the program.

• Initial prototype lot had larger than expected SPAD breakdown voltage (>20 V), thus limiting available over-bias in sensor. Modeling error has been identified and was corrected in current fabrication lot – expected September 2015. Continued optimization of SPAD devices.

• DSPAD AQC circuits and readout were characterized to be fully functional with monolithic SPAD devices.

• Prototype DSPAD arrays have demonstrated DCR of <40 Hz at 10% over-bias at room temperatures, with a peak PDE of 26% (at 500 nm).

• Large format DSPAD array (256 x 256) is currently under development with fabrication scheduled for early 2016.

LOOKING FORWARD...

N-type wafers for improved PDE? Back-side illumination?
Thanks for your time.

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