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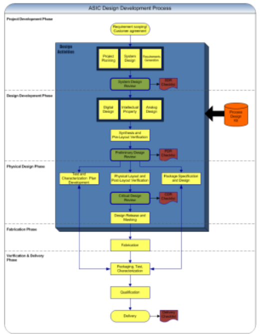

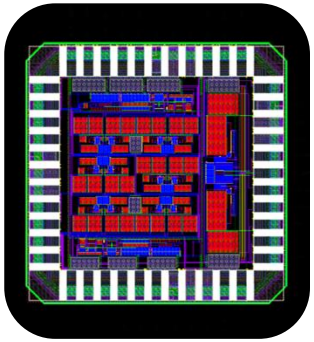


Direct Detection of >15 keV X-ray Photons on a Hybrid-CMOS Imager

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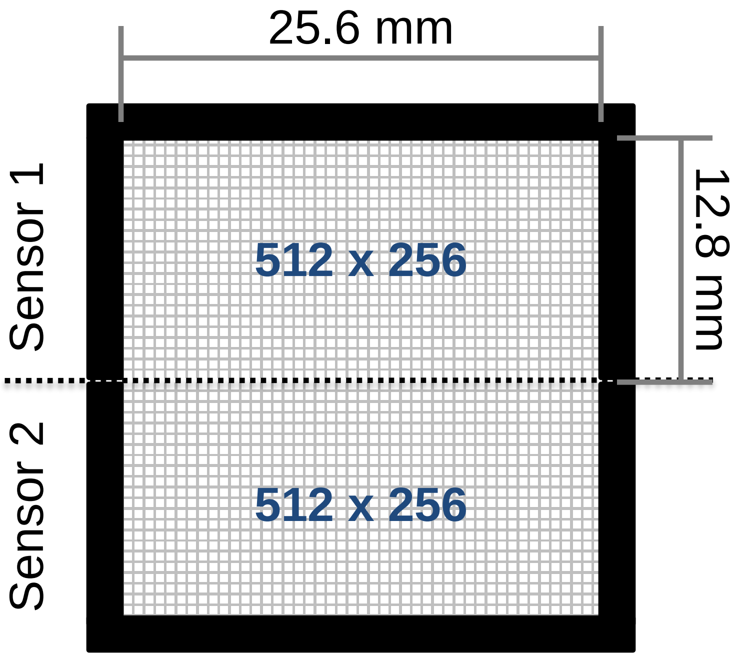
Gideon Robertson, Liam Claus, Rex Kay, Gordon Keeler, Jin Kim,
Quinn Looker, Joel Long, Marcos Sanchez, Doug Trotter, John Porter, Greg Rochau

Mixed Signal ASIC/SoC Products
Phone: 505-284-4393
Fax: 505-844-8480
Email: garobe@sandia.gov
http://www.sandia.gov/mstc/

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

A vision for a high energy sensor with the primary application of point-projection backlighting



ROIC (Hippogriff-like)

- 50 µm pixels
- 512 x 512 pixels with 2 tiled sensors
- 25.6 x 25.6 mm active area (2 tiled sensors)
- 2 frames or 4,8 frames interlaced
- ~2ns per frame
- Up to 6e6 electrons per pixel per frame (~1200 photons at 22 keV in GaAs)

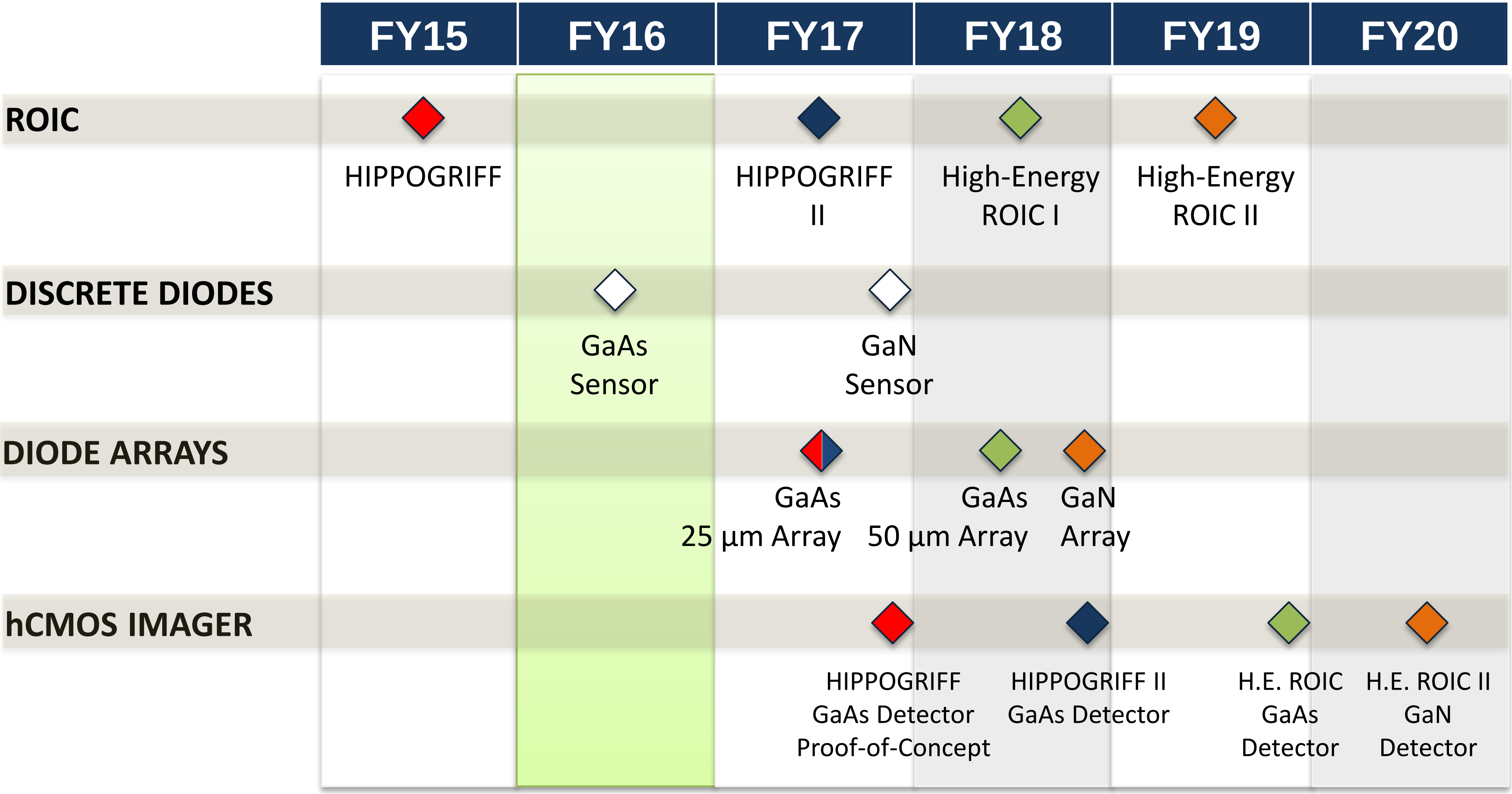
Detector

- 50 µm thick GaAs Absorber
- Photo-absorption > 50% at < 21 keV
- < 1 ns response time

Primary Challenges

- Pixelated GaAs arrays have been built before, but generally not at the required thickness
- Defects in GaAs need to be studied to determine yield (density of good pixels)
- Handling of potentially large currents needs to be studied
- ROIC needs to be re-designed for larger pixels and for 1-side abutment
- Speed of ROIC needs to be studied with larger pitch and higher capacitance per frame

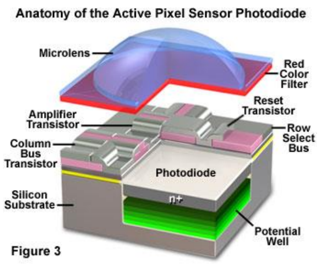
High energy imager roadmap with proof-of-concept GaAs imager complete in FY17



	FY15	FY16	FY17	FY18	FY19	FY20
ROIC	HIPPOGRIFF		HIPPOGRIFF II	High-Energy ROIC I	High-Energy ROIC II	
DISCRETE DIODES		GaAs Sensor	GaN Sensor			
DIODE ARRAYS			GaAs 25 µm Array	GaAs 50 µm Array GaN Array		
hCMOS IMAGER			HIPPOGRIFF GaAs Detector Proof-of-Concept	HIPPOGRIFF II GaAs Detector	H.E. ROIC GaAs Detector	H.E. ROIC II GaN Detector

A hybrid detector is probably the only viable direct detection imaging solution for > 15 keV X-rays

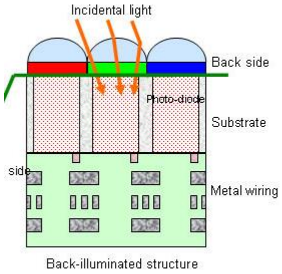
Front-Side Illuminated (FSI)



+ Inexpensive
+ Relatively Simple Processing

- Low fill-factor
- Requires Si detector

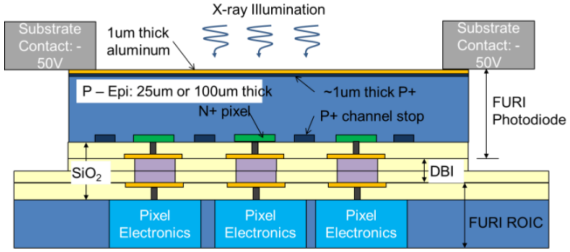
Back-Side Illuminated (BSI)



+ High fill-factor
+ Inexpensive compared to hybrid

- Expensive compared to FSI
- Requires Si detector
- Wafer thinning required, imager may be fragile

Hybrid



+ Independently optimize ROIC and detector
+ High fill-factor
+ Detector layer may enable additional functionality (capacitors, metal routes)

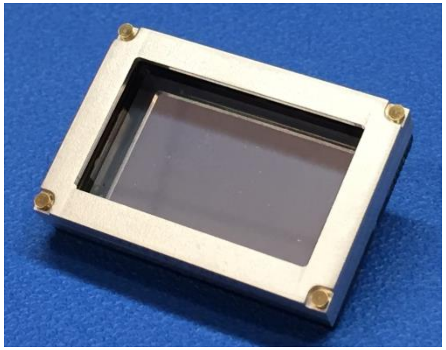
- Expensive (hybridization)
- Yield impact in hybridization process

The UXI program has developed or has experience in a number of key technologies that would be leveraged

ROICs

Under UXI program, SNL has developed a number of ROICs, but will leverage “Hippogriff”

- Imagers completed fabrication in FY15
- 25 µm x 25 µm pixel
- 512 x 1024 format
- ~ 2 ns per frame
- 2 frames native, 8 frames interlaced
- 1.5e6 e- full well



Hippogriff in SOP package w/ 25 um Si photodiodes

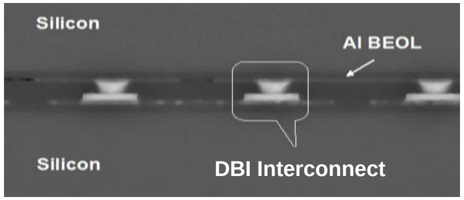
Detectors

Under UXI program, SNL has developed a number of silicon detectors:

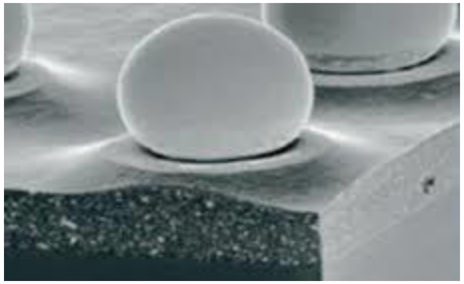
- **25 µm thick** –Vehicles for 4.7 & 6.1 keV detectors and hybridization development
- **100 µm** thick – Possibly useful for up to 13 keV X-ray detection (Absorption 30% @ 13 keV)

Hybridization

Oxide-to-oxide “Direct Bond Interface”



Indium Bump

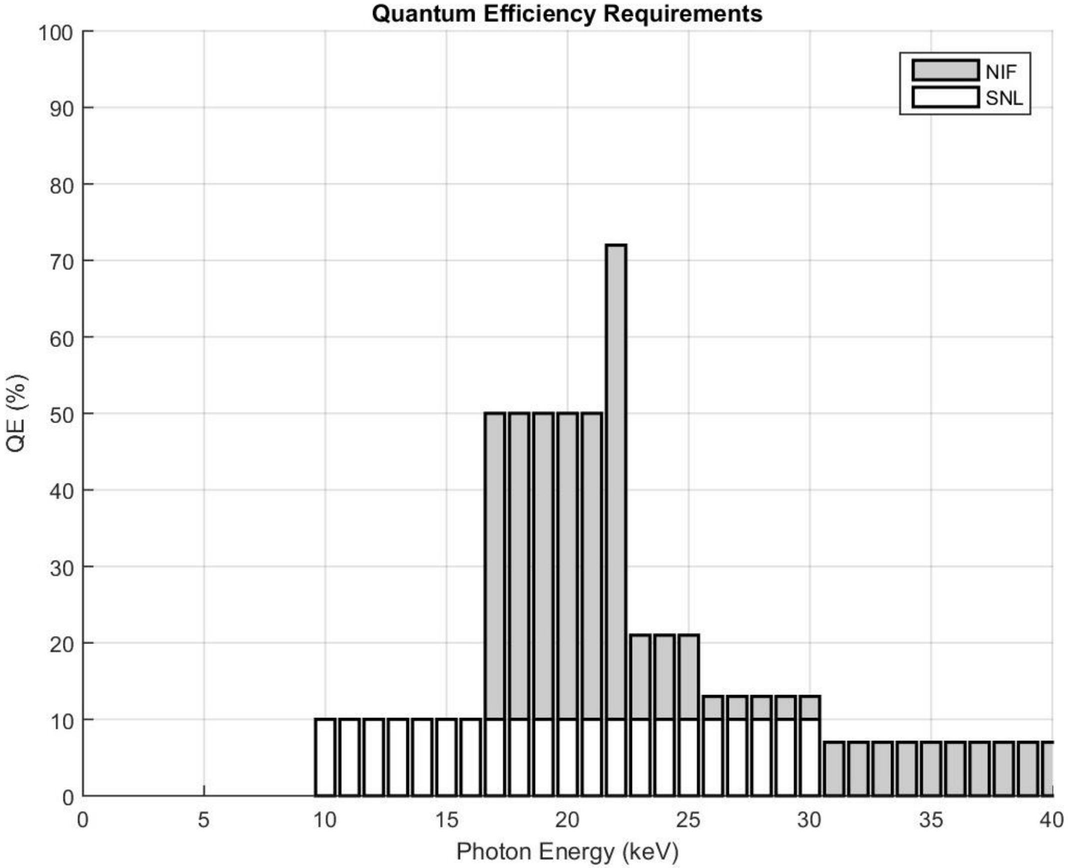


The high-energy imaging roadmap has been crafted to suit a number of programs at NIF

Customer / Application	QE	Energy (keV)
LLNL – NIF Strength Experiments	≥ 50%	17 – 22
LLNL – NIF "Toto"	≥ 72%	22
	≥ 21%	25
	≥ 13%	30
	≥7%	40
SNL – Multi-Frame X-ray Diffraction	≥ 10%	15
SNL – TiGHER	≥ 10%	10 – 25
SNL – Cold K-alpha Source Imaging - Wolter	≥ 10%	15 – 30

QE requirements for LLNL/NIF applications are very challenging - they largely drive design decisions.

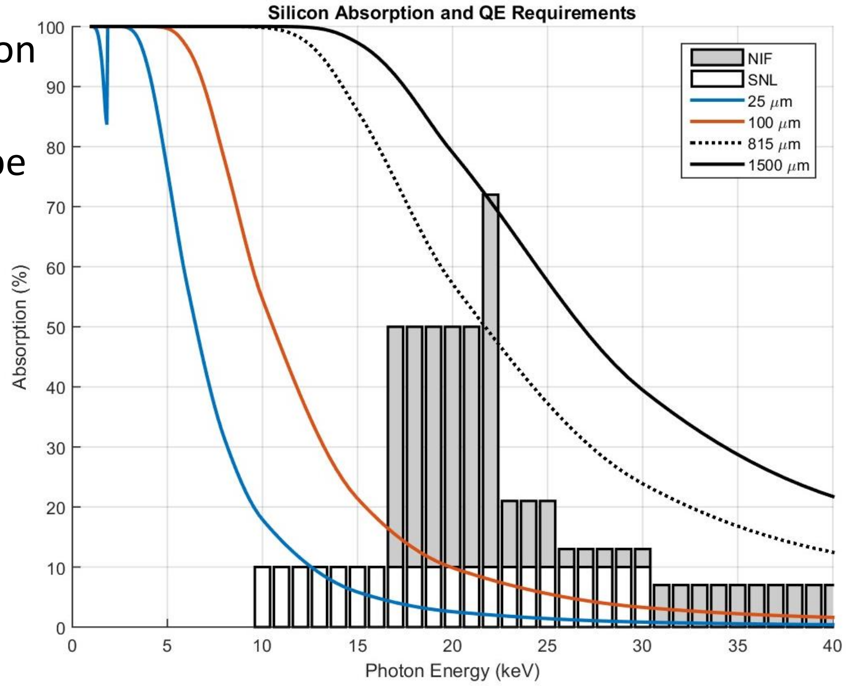
Note: Assumed that these environments are backlit



A silicon detector is incompatible with absorption and speed requirements

- In order to meet all absorption requirements, a silicon diode would have to be **1.5 mm** (!) thick.
- Even if outlier data point at 22 keV (72% QE) could be relaxed to 50%, a Si detector would have to be **815 µm** thick.

- Need to operate at velocity-saturation (~30 kV/cm)
  - 1.5 mm Bias = 4.5 kV
  - 815 µm Bias = 2.45 kV
- Worst-case, carrier (holes; electron transit time is about 40% faster) transit time at v_{sat}:
  - 1.5mm Thick: 21.4 ns
  - 815 µm Thick: 11.6 ns



Clearly, a silicon photodiode of appropriate thickness would be unsuitable for a 2-ns imager.

Electrical and mechanical requirements for a detector integrated with Hippogriff are relatively straightforward

- Physical/Mechanical Requirements

ID	Parameter	Current Hippogriff	Future High Energy ROIC
M1	Individual Pixel Size	25 µm x 25 µm	50 µm x 50 µm
M2	Array Format	512 x 1024 (12.8 mm x 25.6 mm)	256 x 512 (12.8 mm x 25.6 mm)
M3	Integration	Likely Indium	Likely Indium

- Electrical Requirements

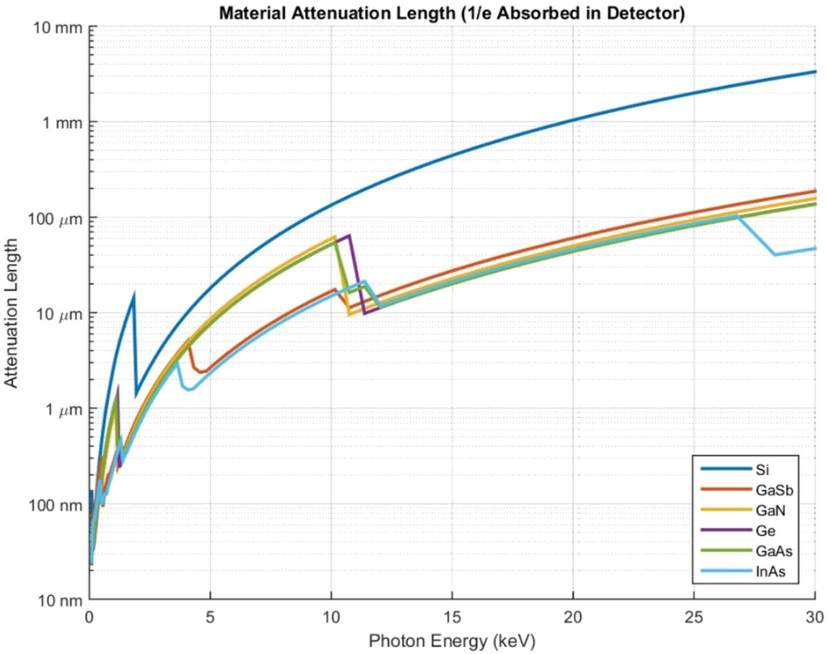
ID	Parameter	Value
E1	Pixel Depth	determined by photon energy and temporal response
E2	Temporal Response	Rise/Fall Times < 1 ns
E3	Quantum Efficiency	Variable
E4	Dark Current	< 2 mA/cm^2 – 2 mA is roughly equivalent to 1, 10 keV photon with t_{int} = 10 ns / 50 µm pixel
E5	Cooling Acceptable?	Possibly, with compelling justification
E6	Material Options	Preference for in-house materials, but not necessary
E7	Pixel Operability	> 99% (Low Priority)
E8	Cross-Talk	Minimize
E9	Diode Type	Common-cathode preferred (for compatibility with current ROICs), but could be changed with compelling justification

Material possibilities span both common and less common materials

- SNL has 8 MBE reactors, so strong preference for either epitaxially grown material:
  - GaAs Gallium-Arsenide
  - InAs Indium-Arsenide
  - GaN Gallium-Nitride
  - GaSb Gallium-Antimonide

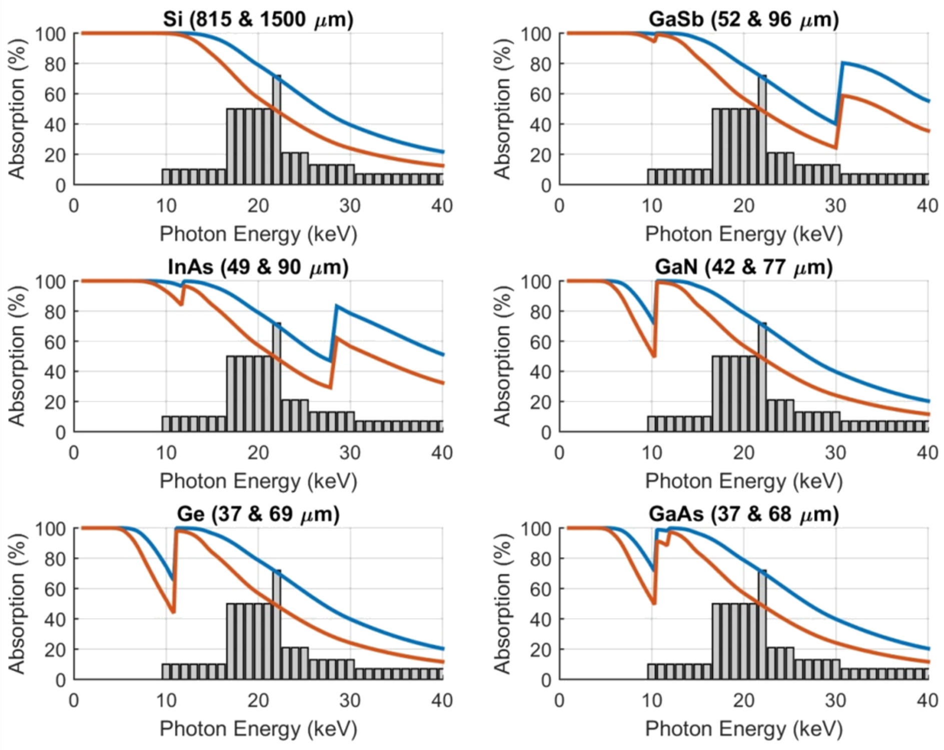
  or, commercially available material we can process:
  - Si Silicon
  - Ge Germanium

- Have Considered HgCdTe and CdZnTe ternary compounds, but:
  - In terms of characteristics we are interested in, no discernable benefit over a couple of the strong candidates
  - No manufacturing capability at SNL
  - Finding industrial partner willing to build one-off is challenging
  - Integration path is riskier
  - Ability to iterate is diminished
  - Loss of design flexibility



X-ray photon absorption for considered materials is at least an order of magnitude better than silicon

- Reduce Thickness by > Order of Magnitude



Material	PD Thickness 50% at 22 keV	PD Thickness 72% at 22 keV
Si	815 µm	1500 µm
GaSb	52 µm	96 µm
InAs	49 µm	90 µm
GaN	42 µm	77 µm
Ge	37 µm	69 µm
GaAs	37 µm	68 µm

Decreasing Required Thickness ↓

- However, unique challenges exist with high-energy X-ray detection

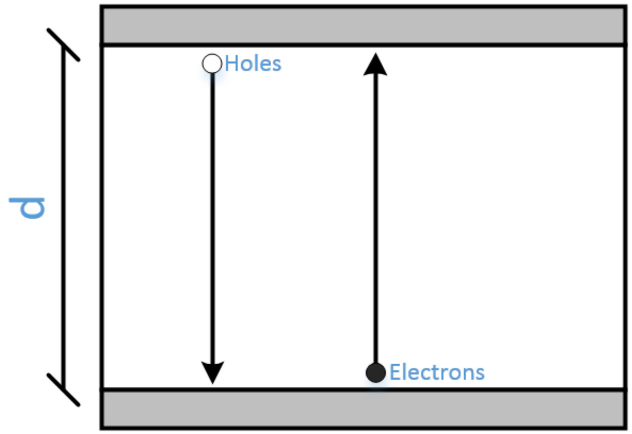
Photodiode speed is very sensitive to material properties, particularly carrier velocity saturation

- Photodiode Speed is Limited by:
  - **Carrier Diffusion** – Diffusion process is very slow, photodiode must be designed to eliminate it. We don't expect this to be material dependent.
  - **RC-Time Constant of Circuit** – This should be relatively insensitive to diode material, expect small changes in C_{JUNC} and R_S.
  - **Photocurrent Response Time** – Very sensitive to diode material, will operate device in velocity saturation
- Material Electron and Hole Transit Time
  - **Analysis is worst-case:** carrier must transit entire diode thickness ("d"). Most figures are quoted for holes as hole v_{sat} is almost always slower than electron v_{sat}

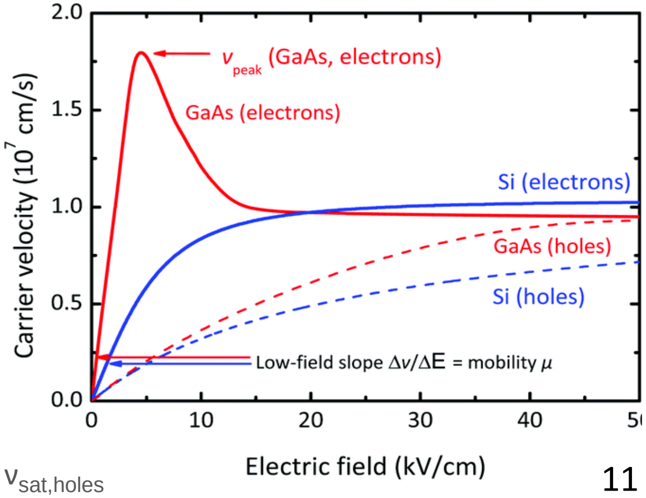
Material	Electron μ (cm²/V-s)	Electron υ_{sat} (cm/s)	Hole μ (cm²/V-s)	Hole υ_{sat} (cm/s)	Carrier 25 um Transit (ps)
Silicon	1400	1.0e7	450	**0.7e7**	**357**
GaAs	8500	**0.7e7**	400	0.9e7	**357***
Ge	3900	0.7e7	1900	**0.63e7**	**396**
InAs	40000	0.9e7	500	**0.5e7**	**500**
GaN	1000	2.7e7	350	**1.7e7**	**147**
GaSb	3000	0.6e7	1000	**0.3e7**	**833**

* Electron transit time used for GaAs since $v_{sat,electrons} < v_{sat,holes}$

Photodiodes designed to operate in velocity saturation and eliminate diffusion regions.



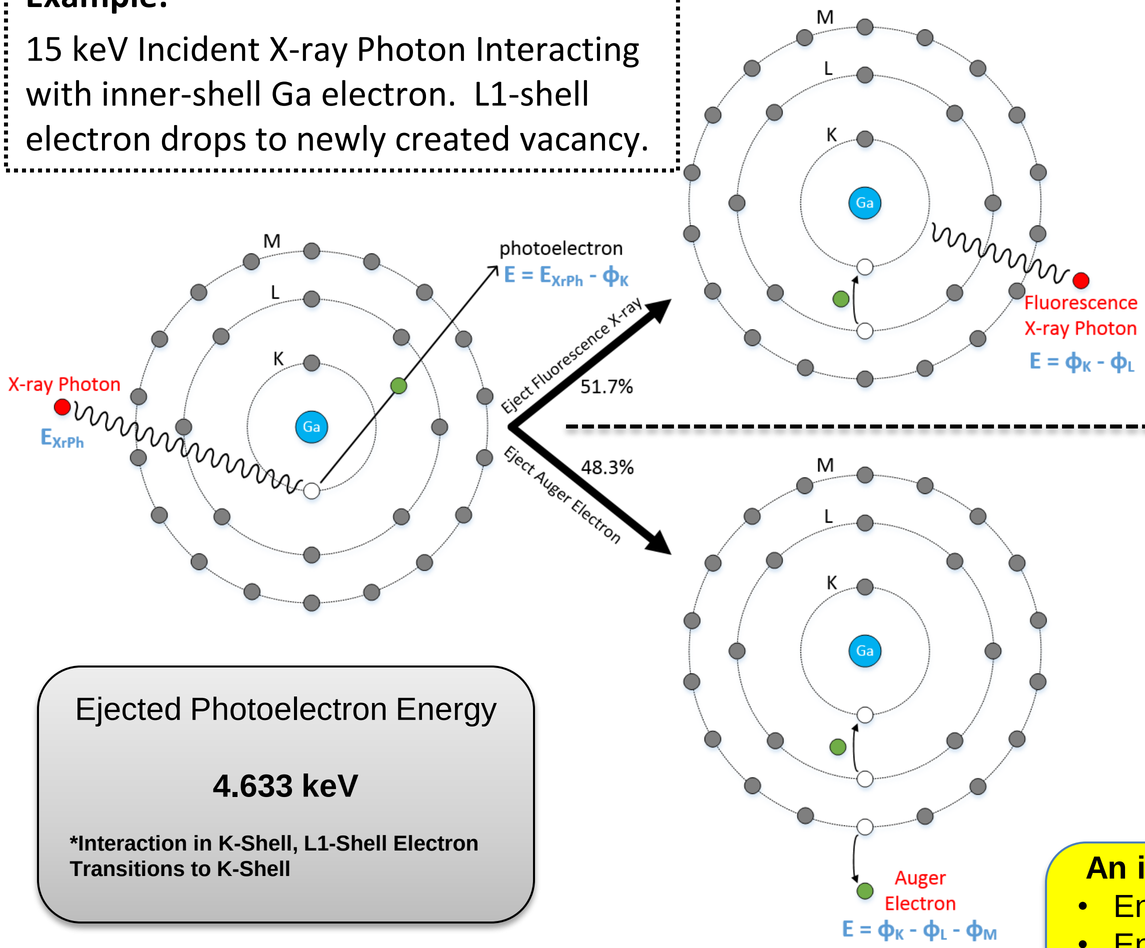
GaAs & Si carrier velocities are field dependent



Fluorescence is an unavoidable issue in high-Z semiconductors

Example:

15 keV Incident X-ray Photon Interacting with inner-shell Ga electron. L1-shell electron drops to newly created vacancy.



Ejected Fluorescence X-ray Photon

9.067 keV

Ejected Auger Electron

8.909 keV

***Assume M electron transitions to L1 vacancy**

Ejected Photoelectron Energy

4.633 keV

***Interaction in K-Shell, L1-Shell Electron Transitions to K-Shell**

An interacting X-ray photon generates:

- Energetic Photoelectron **AND**
- Energetic Fluorescence X-ray Photon

– OR –

- Energetic Photoelectron **AND**
- Energetic Auger Electron

Secondary electrons and X-ray particles have vastly different ranges and have to be accounted for in non-Si detectors

- At similar energies:

  Fluorescence Photon Range >> Auger Electron Range

- Silicon detectors aren't problematic because:
  1. Silicon K-edge is at 1.84 keV – fluorescence range is sub-pixel
  2. Silicon fluorescence yield is low ~ 5%

- Non-silicon detectors we are considering are likely problematic:
  1. Non-Si detectors have much higher K-edge energies → fluorescence photons have much higher energy than those in Si
  2. Fluorescence yields are > 10x Si

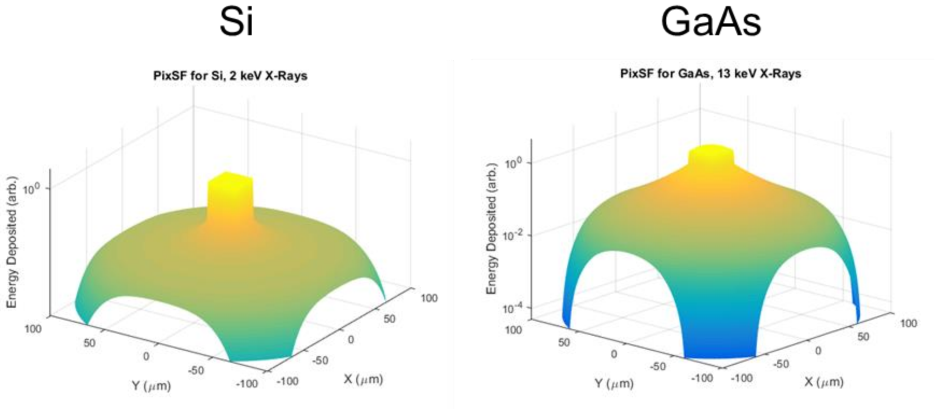
Material	K-Edge (keV)	K-Edge Electron Range (µm)	K-Edge X-ray Photon Range (µm)
Si	1.84	0.09	13.8
As	11.9	1.00	67

Material	K-edge (keV)	Fluorescence Yield	K-edge X-ray Photon Range (µm)
GaSb	10.4, 30.5	52%, 86%	18, **187**
InAs	11.9, 27.9	57%, 85%	27, **142**
Ge	11.1	55%	**65**
GaN	0.4, 10.4	0.4%, 52%	~1, **61**
GaAs	10.4, 11.9	52%, 57%	**55**, 17
Si	1.84	5%	**14**

↓ Decreasing Fluorescence Range

Fluoresced photons propagate in all directions and can blur the image

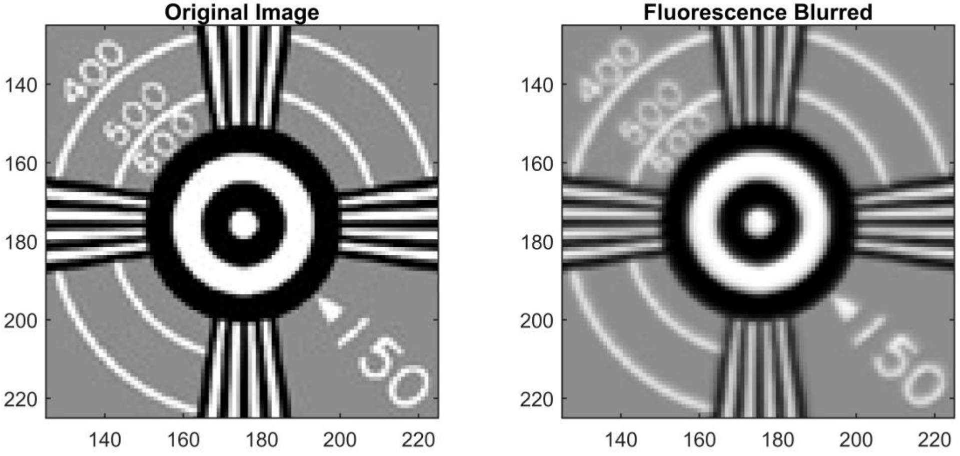
Point-spread function of Si and GaAs with incident X-ray photons just above K-edge


Si

GaAs

Region	Energy Deposited Si	Energy Deposited GaAs
Pixel	69%	24%
Pixel + 8 Neighbors	84%	63%
Pixel + 24 Neighbors	90%	86%

Image representing blur in a 25 μm x 25 μm, 100 pixel x 100 pixel array as a result of fluorescence in GaAs


Original Image

Fluorescence Blurred

Higher bandgap materials are required to mitigate room-temperature thermal excitation and are desired for larger pair creation energies

Thermal Noise

- Thermal noise in Ge is well know, detectors are typically cooled to mitigate.
- Unclear at what bandgap thermal noise becomes an issue

Material	Bandgap (eV)
InAs	0.354
Ge	0.661
GaSb	0.726
Silicon	1.120
GaAs	1.424
GaN	3.200

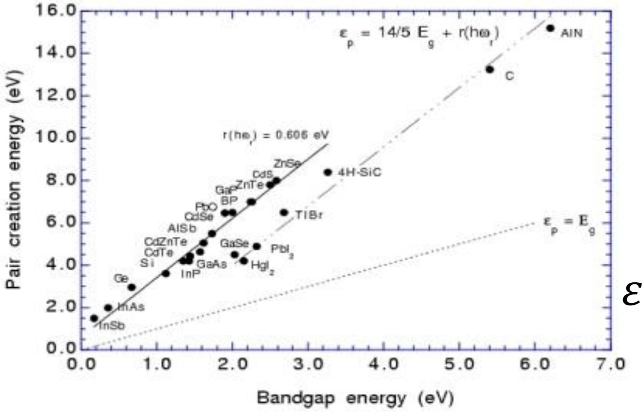
↓ Increasing Bandgap

Pair Creation Energy

- **Pair creation energy:** This value is used to determine how many electron-hole pairs are created by an X-ray photon. Can be approximated as ~3X a semiconductor's bandgap.

Material	Pair Creation Energy (eV)
InAs	2.0
GaSb	2.70
Ge	2.96
Silicon	3.62
GaAs	4.4
GaN	8.9

↓ Increasing Pair Creation Energy



$$\varepsilon_P = \frac{14}{5} \cdot E_g + c$$

For a single photon, high-energy X-rays result in comparably larger photocurrents

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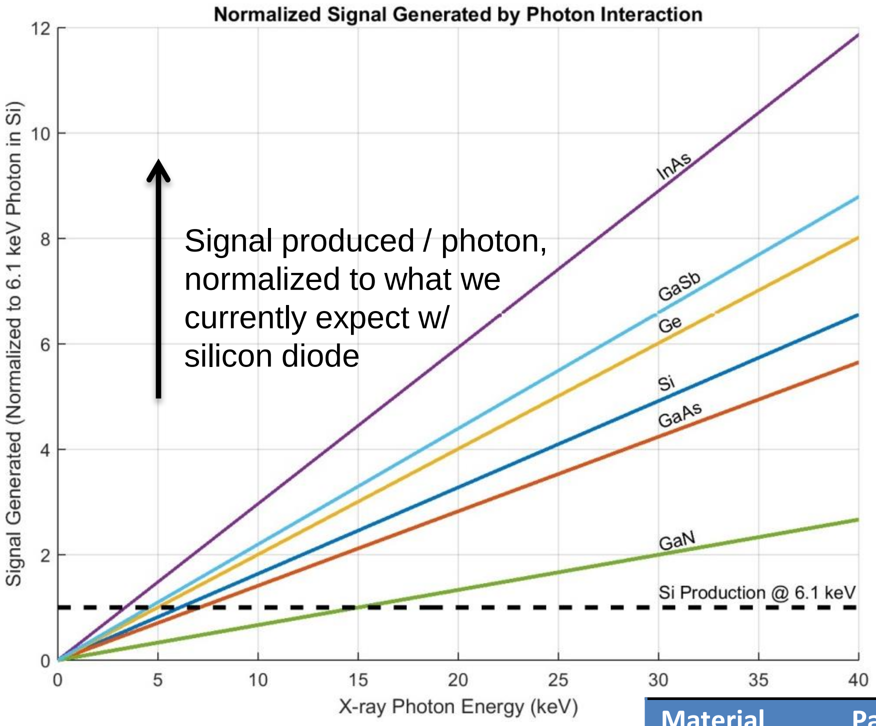


Signal produced / photon, normalized to what we currently expect w/ silicon diode

- As ASIC designers, we generally struggle with not having enough signal
- In this particular case, large signals are challenging

- Current ROICs can only store a finite amount of charge:
  - Current 1.5e6 e- Full Well is Filled by:

    890, 6.1-keV Photons with Si Detector, or

    136, 40-keV Photons with Si Detector, or

    334, 40-keV Photons with GaN Detector

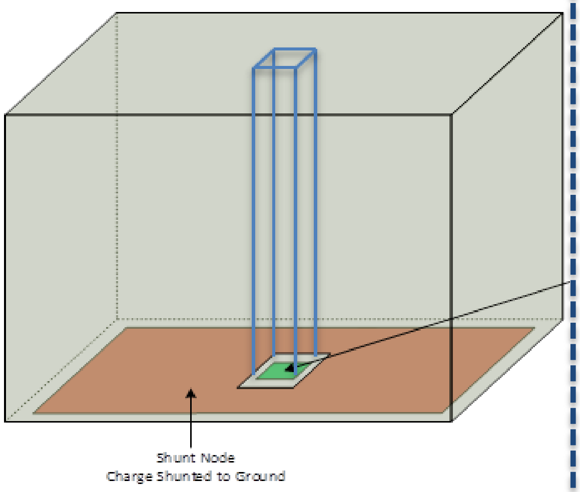
GaN is likely the best that we'll get, but dynamic range would still be very limited at 20+ keV with current ROICs.

		Number of Photons for Full Well			
Material	**Pair Creation Energy (eV)**	**1.5M e- Full Well @ 6.1keV**	**1.5M e- Full Well @ 13keV**	**1.5M e- Full Well @ 22keV**	**1.5M e- Full Well @ 40keV**
InAs	2.0	**492**	**231**	**136**	**75**
GaSb	2.7	**664**	**312**	**184**	**101**
Ge	2.96	**728**	**342**	**202**	**111**
Si	3.62	**890**	**418**	**247**	**136**
GaAs	4.4	**1033**	**508**	**300**	**158**
GaN	8.9	**2189**	**1027**	**607**	**334**

MIXED SIGNAL ASIC/SoC PRODUCTS

Unfortunately, it is unlikely that large photocurrents can be mitigated in the detector layer

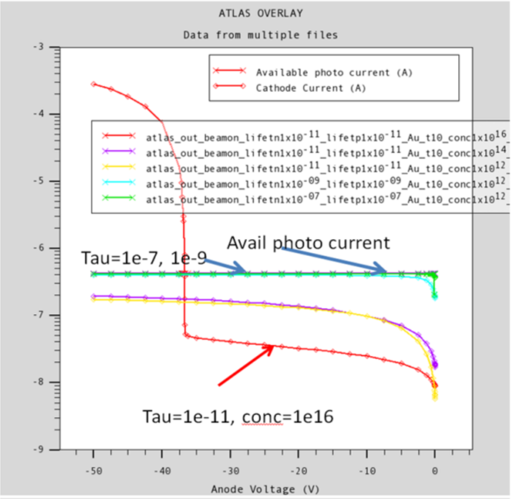
Multiple Charge Paths



Multiple contacts – charge collected based on geometry of contacts?

(-) Charge is generally collected from volume immediately above collection contact – substantially reduces fill-factor.

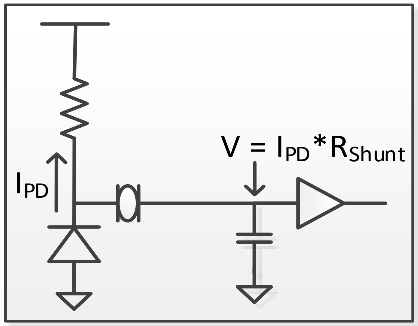
Recombination Rate Eng.



Reduce quality of material and induce high recombination rates within photodiode volume (dope w/ Au, irradiate w/ neutrons).

(-) Undesirable since amount of charge collected per photon is dependent on depth of photon interaction. Carriers generated far from collection node have more chance to recombine than those generated close to node.

Passive Charge Bleed

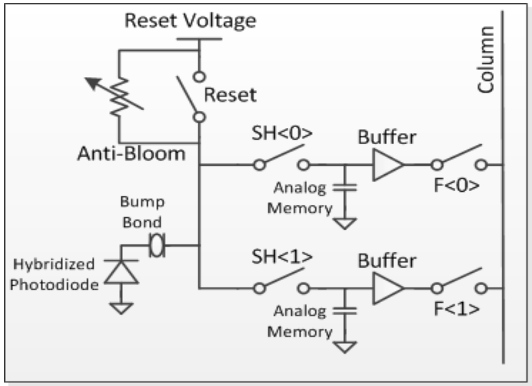


Introduce a "bleed" resistor in photodiode layer.

(-) Changes the function of the pixel from integrating to sample and hold. Unlikely that this is desirable behavior.

There are at least two obvious solutions to dealing with large photocurrents in the ROIC layer, both of which need further study to mitigate performance impact

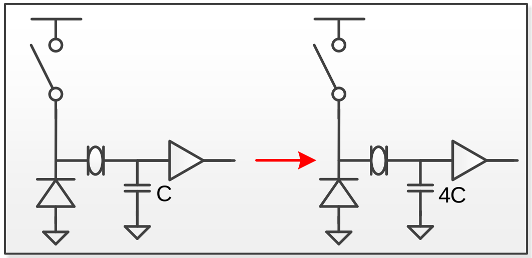
Anti-Bloom



Introduce/utilize anti-bloom transistor to compress signal at large signal levels.

(-) Might be a reasonable first candidate, however, it will induce a non-linearity, especially at upper end of signal

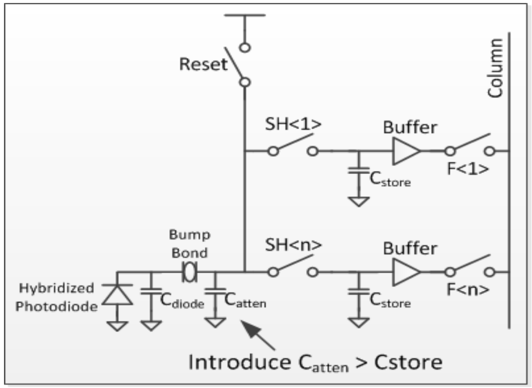
Increase Full-Well



Increase the size of the analog storage capacitor.

(+) This solution is a good candidate, however, speed and area impacts need further study

Capacitive Charge Division



Introduce a charge dividing capacitor on the front-end of the ROIC.

(+) This solution is a good candidate, however, will need to look at impacts to reset and analog signal levels.

A viable near-term solution couples an existing ROIC to a relatively low-risk detector array, while an optimal solution incorporates a moderately modified ROIC with GaN

Material	Bandgap (eV)	Pair Creation Energy (eV)	PD Thickness 50% at 22 keV	Slow Carrier Transit (ps)	K-edge X-ray Photon Range (µm)
Si	**1.120**	**3.62**	**815 µm**	**11,640**	**14**
GaSb	**0.726**	**2.70**	**52 µm**	**1,733**	**18, 187**
InAs	**0.354**	**2.0**	**49 µm**	**980**	**27, 142**
GaN	**3.200**	**8.9**	**42 µm**	**156**	**~1, 61**
Ge	**0.661**	**2.96**	**37 µm**	**529**	**65**
GaAs	**1.424**	**4.4**	**37 µm**	**529**	**55, 17**

Near-Term Solution

- Hippogriff ROIC
  - 25 µm x 25 µm Pixels
  - 512 x 1024
  - 1.5e6 e- full-well
  - ~2-ns / frame
- 37 - 50 µm (thick) GaAs Detector
  - Meets all absorption requirements except 72% at 22 keV
  - Slow carrier transit 529 - 715 ps
  - 1033, 350, 210, and 158 photons to fill well at 6.1, 18, 30, and 40 keV
- FY17 Proof-of-concept

Long-Term Solution

- "High-Energy ROIC I"
  - 50 µm x 50 µm Pixels
  - 256 x 512
  - 6e6 e- full-well
  - ~2-ns / frame
- 42 – 50 µm (thick) GaN Detector

  Same benefits as GaAs except:

  1. Dramatically improved pair creation energy allows doubling of dynamic range
  2. Dramatically higher transit speed would allow a thicker detector for improvements in absorption
- FY19-20 Proof-of-concept