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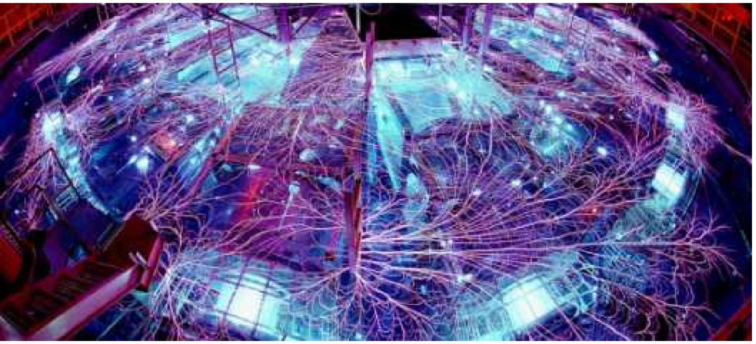
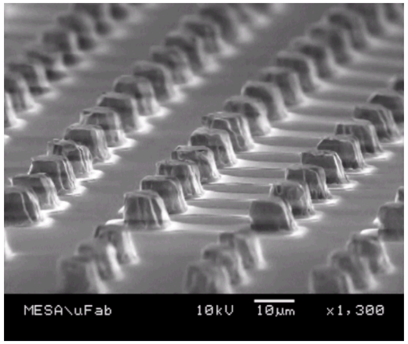

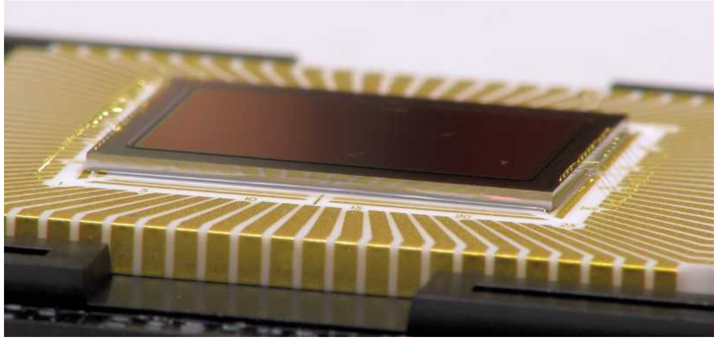

Semiconductor Detectors for Sub-ns Detection of 20-70 keV X-Rays

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

11/29/2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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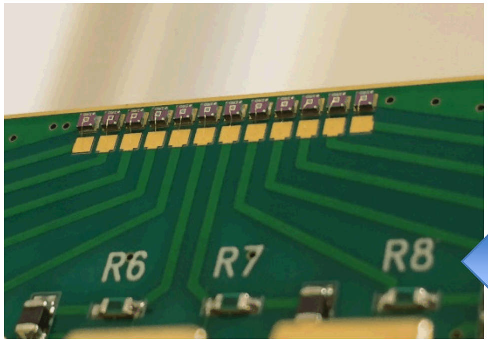
Outline

- Detector Physics
- Hard X-Ray Detector Progress at SNL
- Path Forward to UXI Cameras More Sensitive to 20-70 keV X-Rays

Si Diode Detectors - Applications

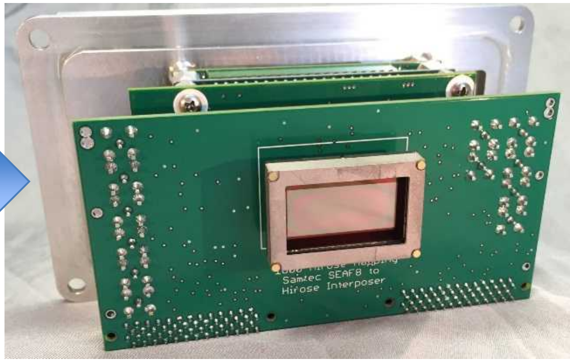
- Fast, versatile x-ray detectors
  - Sub-ns temporal resolution possible; continuous time history
  - Possibility of absolute calibration; relative uniformity among devices
  - Small size, simple readout, low cost
- Easily extended to diode arrays
  - 1-D or 2-D arrays for imaging, spectroscopy, dynamic diffraction, and other applications
  - Large hybrid arrays on UXI cameras

Commercial Si Diode and Associated Readout



Custom Si Diode Array

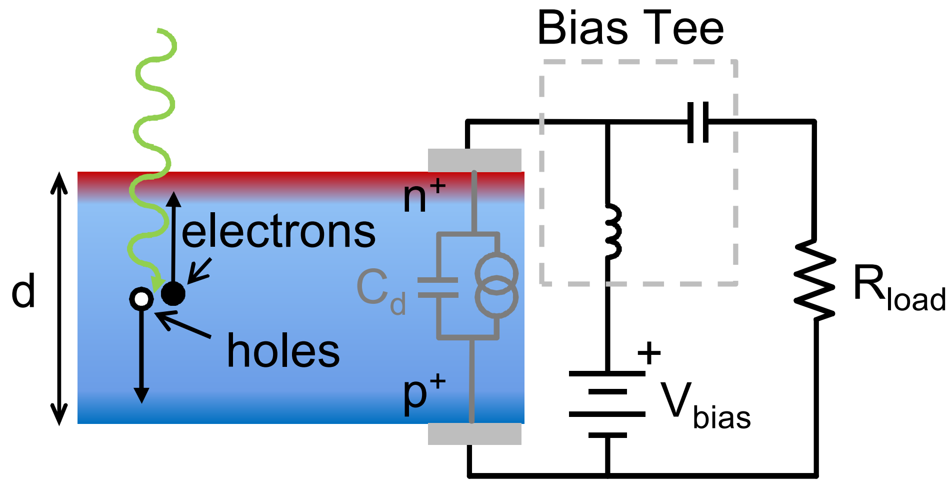
UXI Camera



Semiconductor Detector Readout

- Reverse-biased diode
  - Depletion region is sensitive to x-rays – Need full depletion for fast timing
  - Current mode readout from one electrode

$$C_d R_{load} \ll t_{coll}$$



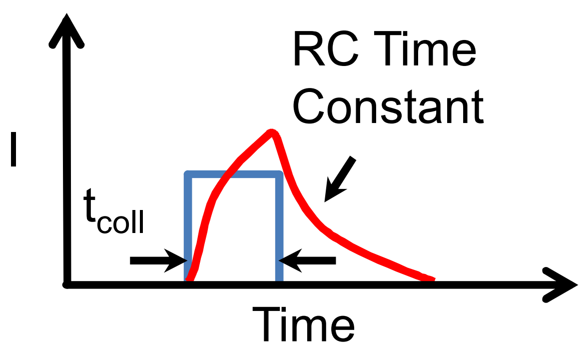
- Temporal resolution
  - Charge collection time – charge carrier drift across detector thickness

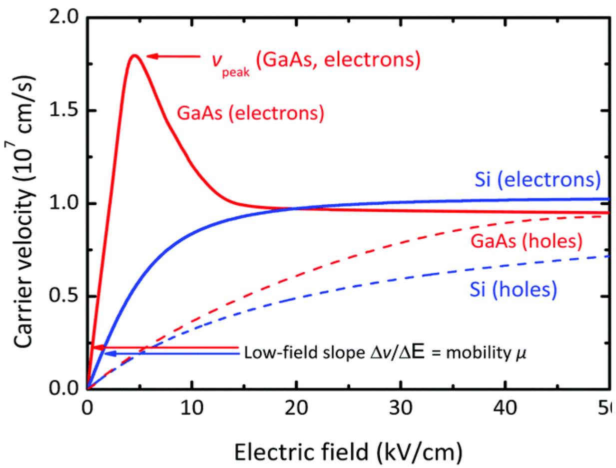
$$t_{coll} = \frac{d_{coll}}{v}$$

  - Circuit response time

$$\sim R_{load} C_d$$

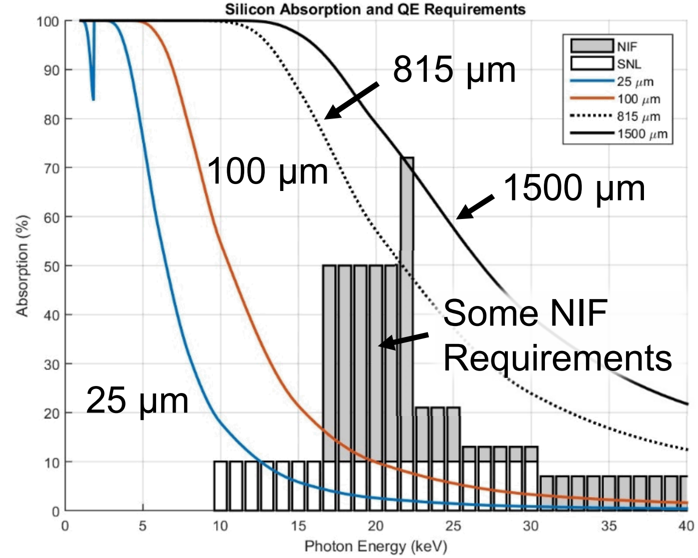
$$C_d = \varepsilon \frac{A}{d}$$

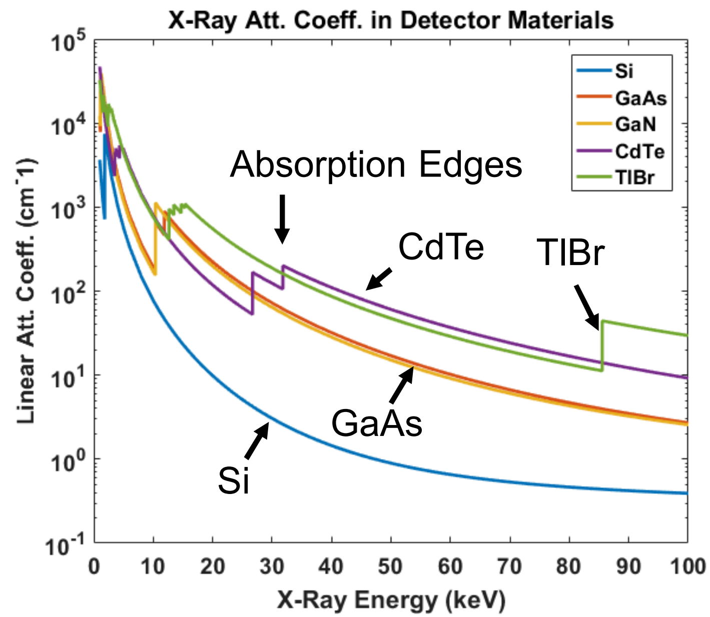




Semiconductor Detector X-Ray Absorption

- Increasing x-ray energy => fewer photons absorbed
  - Need larger area => increase C_d (slower response)
  - Need thicker absorber => increase t_{coll} (slower response)
- Increasing absorber atomic number is a way to opt out of the compromise
  - X-ray absorption ~ $Z^4/E^{3.5}$
  - Photoelectric absorption more dominant





Absorber Material Options

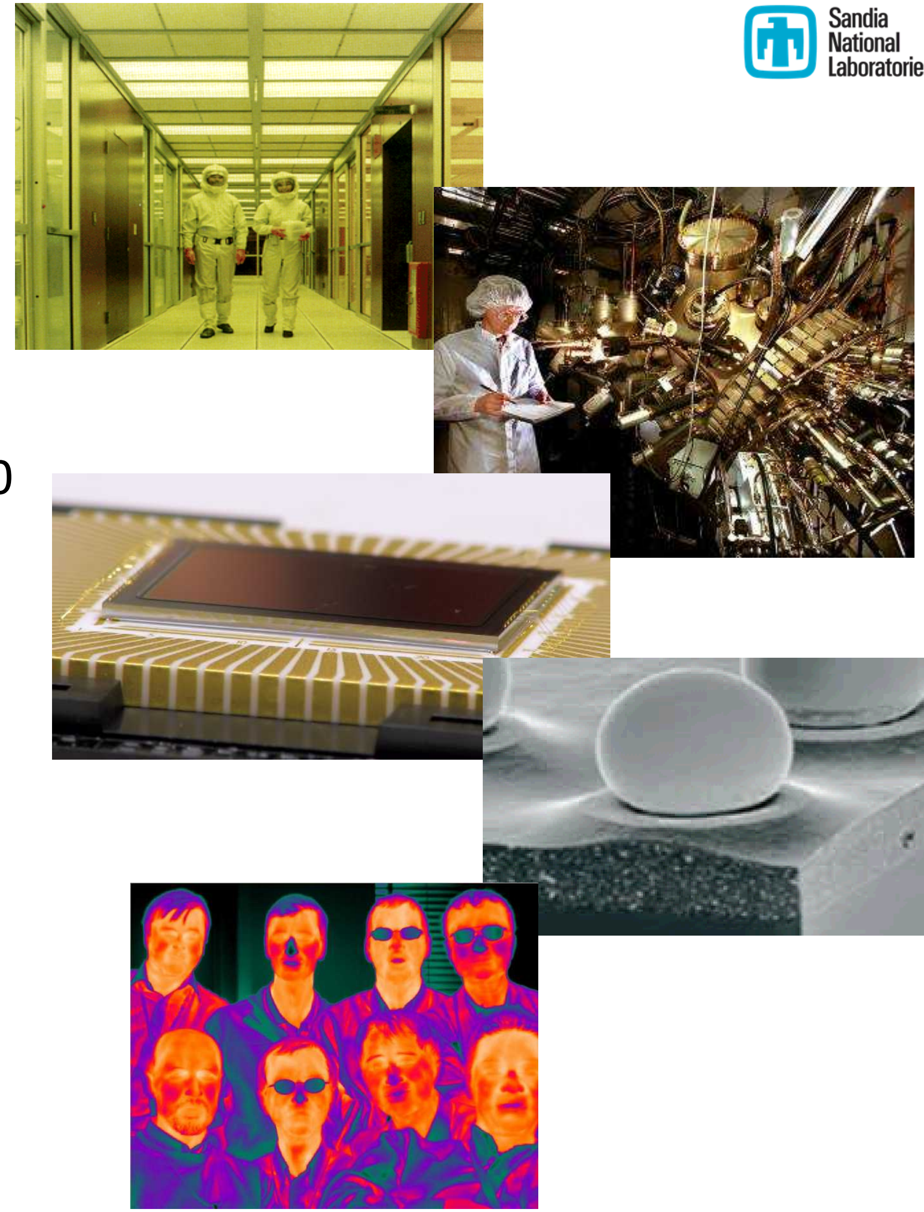
- Requirements
  - Semiconductor – *reduce scope of study to manageable size*
  - Able to obtain material of sufficient size and quality – *need large detector sizes, minimal carrier trapping*
  - Low background dopant concentration – *must fully deplete detector*
  - Higher Z preferred – *greater x-ray absorption for fixed thickness*
  - High carrier velocity preferred – *greater thickness tolerated for necessary time response*
  - Higher bandgap preferred – *reduce magnitude of collected charge*

	Bandgap (eV)	Electron-hole pair creation energy (eV)	ε_r	Z	Electron υ_{sat} (cm/s)	Hole υ_{sat} (cm/s)	1ns thickness (microns)
Si	1.12	3.6	11.7	14	1.0e7	0.7e7	70
Ge	0.67	3.0	16	32	0.6e7	0.6e7	60
GaAs	1.43	4.2	12.8	31,33	0.9e7	0.9e7	90
GaN	3.4	8.9	9.7	31,7	2.7e7	1.7e7	170
GaSb	0.73	2.7	15.7	31,51	0.6e7	0.3e7	30
InAs	0.35	2.0	15.2	49,33	0.9e7	0.5e7	50
CdTe	1.44	4.4	10.9	48,52	1.0e7	0.2e7	20
CZT	1.57	4.6	10	48,30,52	0.3e7	5e5	5
TlBr	2.68	6.5	30	81,35	4e4	2e4	0.2

Hard X-Ray Detector Development Progress at Sandia

SNL Capabilities

- MESA Semiconductor Fabrication Facility
  - SiFab: 11,900 ft^2 Class 1 for Rad Hard CMOS, MEMS
  - MicroFab: 14,230 ft^2 Class 10/100 handling a variety of materials including III-V
- Photonics Group
  - Extensive experience creating leading edge III-V semiconductor focal plane arrays
  - 8 epitaxy tools for material growth, MicroFab for device fabrication, mature flip chip process flow, testing infrastructure

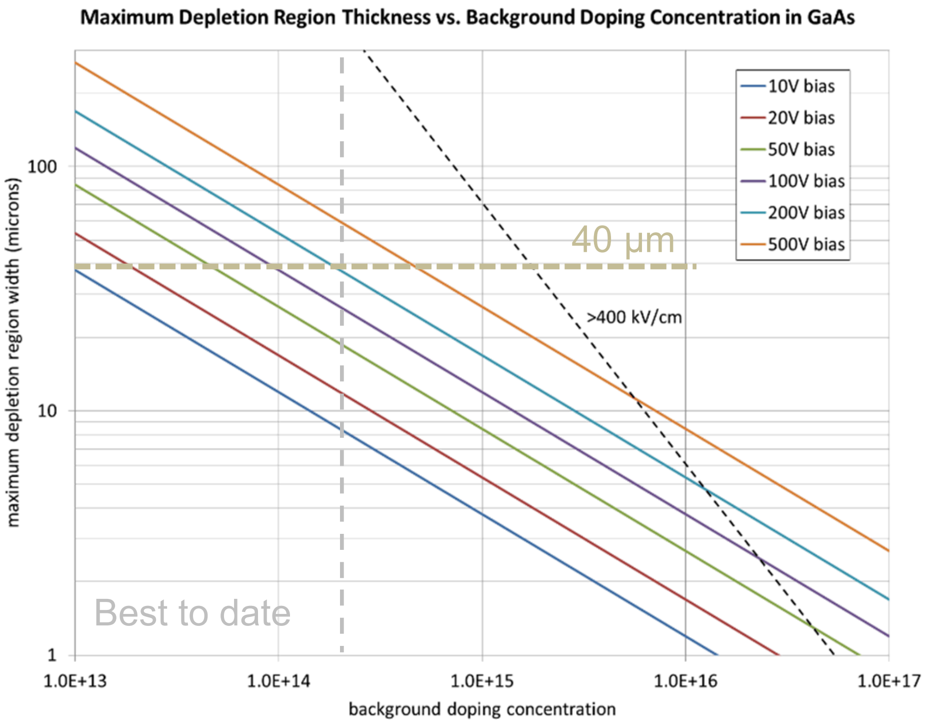


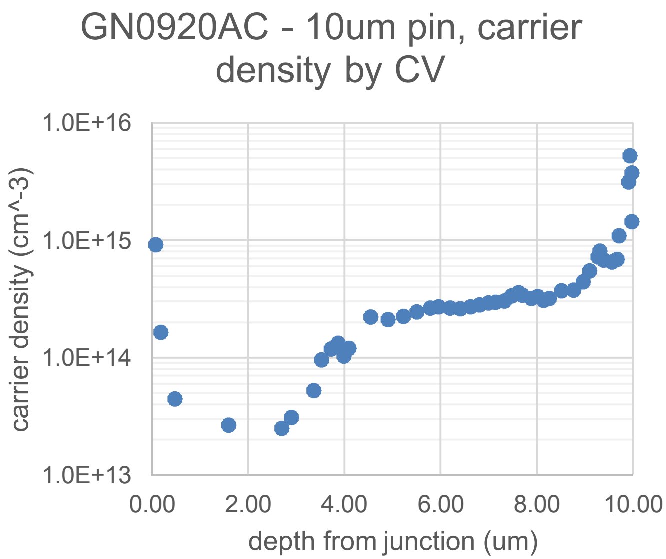
Hard X-Ray Detector Development Plan

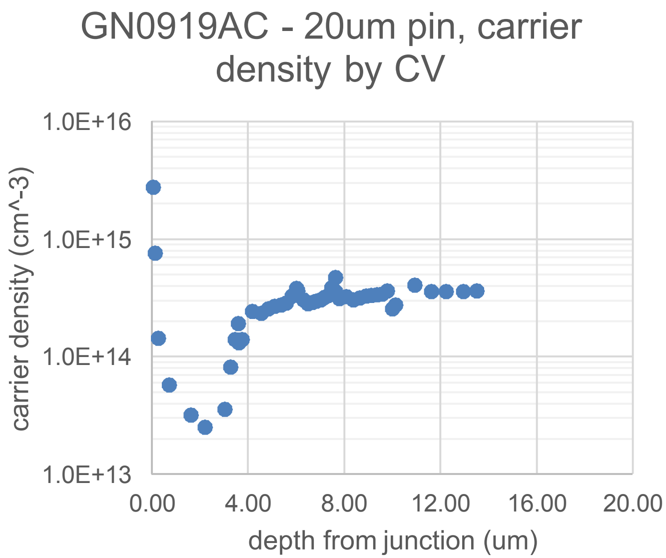
- Exploratory Study – Complete
  - Many requirements not possible with Si
  - GaAs provides best chance of success with significant improvement
- Phase 1: Discrete Diodes – In Progress
  - Material growth – initial success. Reproducibility?
  - Demonstration of equivalent Si timing, improved QE >10 keV
- Phase 2: Diode Arrays – Beginning this FY
  - Packaging development for closely spaced arrays
  - Layout and fabrication process development for single-die arrays
- Phase 3: hCMOS Integration – Funding Dependent
  - Port indium bump process to GaAs arrays on UXI ROICs
  - New packaging and testing strategies

GaAs Detector Development

- Start material
  - SNL MBE growth
  - Key challenge: background dopant concentration
  - Low growth rate, single 3” wafer

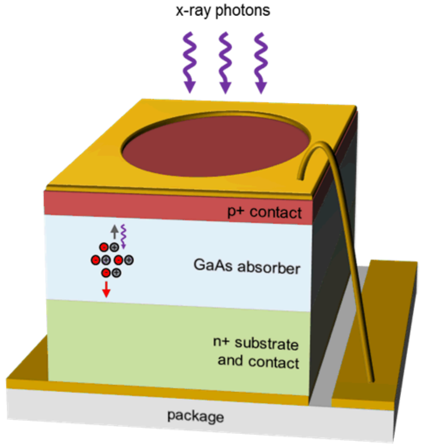


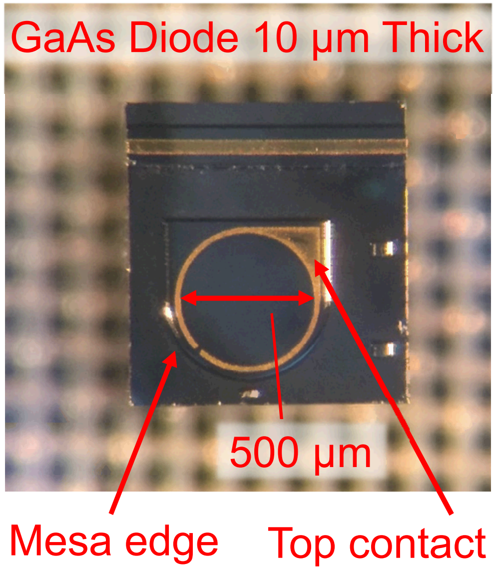


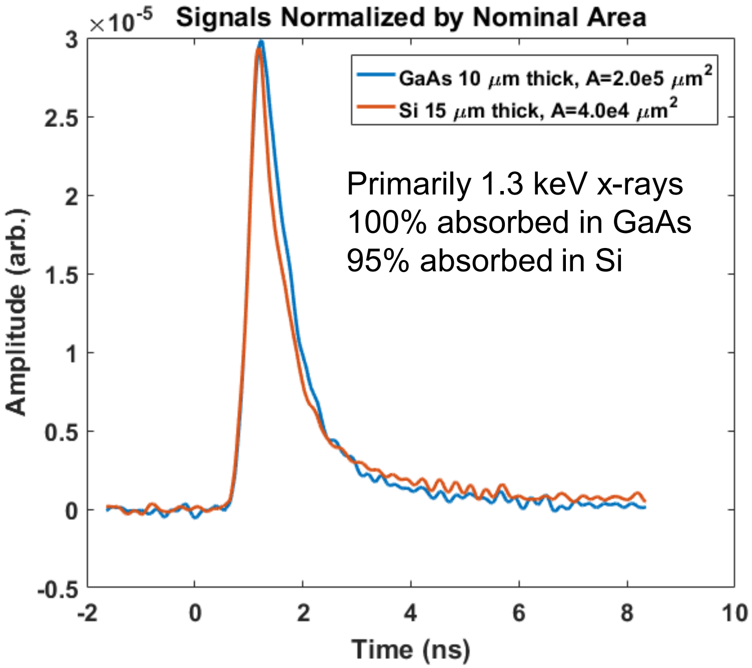


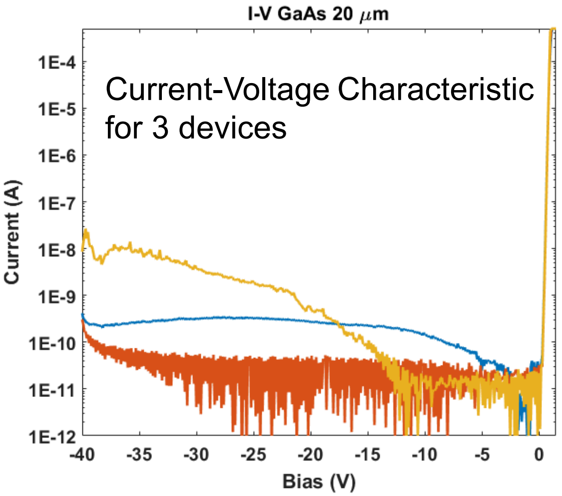
GaAs Detector Testing

- Devices
  - Epitaxial absorber layer isolated by mesa etch
  - Single metal layer forms top contact
  - Bottom contact formed by highly doped handle, backside metal



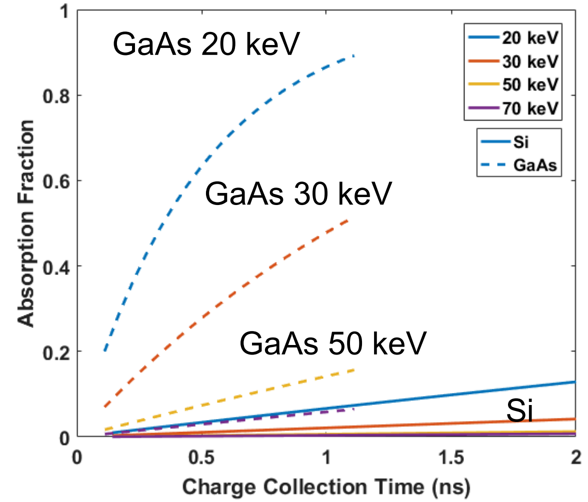




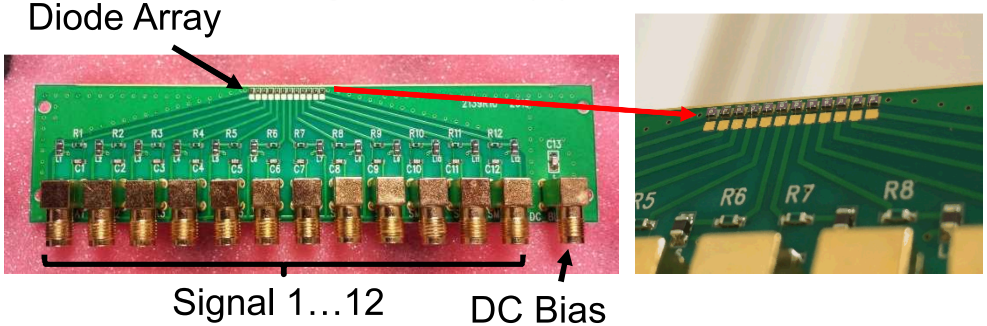


GaAs Diode Applications

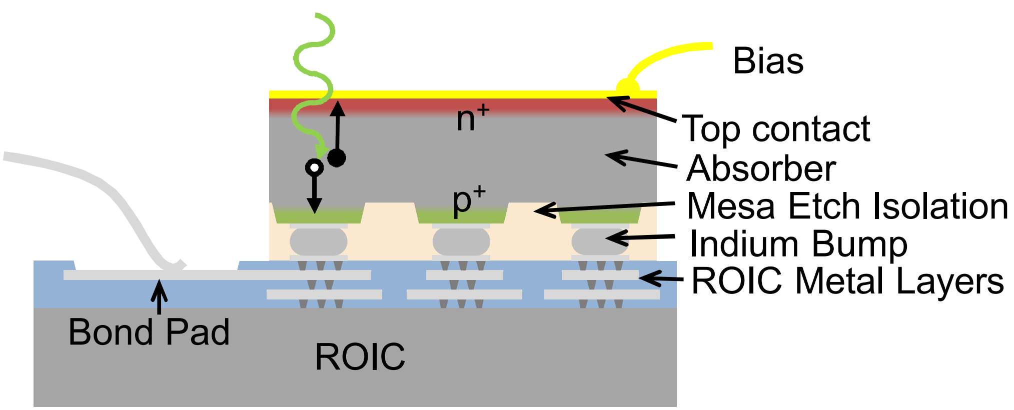
- Discrete diodes – higher QE for warm x-ray source development



- 1-D Arrays – dynamic diffraction, spectroscopy
- 2-D Arrays – simple imaging with continuous time history



- Diode array on UXI ROIC
  - Single-chip diode array
  - Flip chip bonding to ROIC



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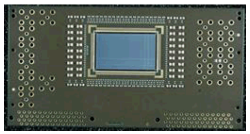
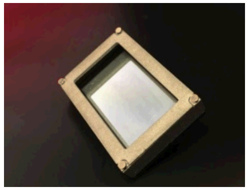
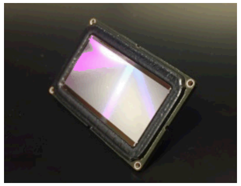
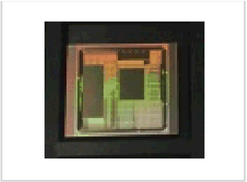
Path Forward for UXI Cameras More Sensitive to 20-70 keV X-Rays

UXI ROICs

	'High' Full Well Sensors			'Low' Full Well Sensors	
	In Use		New Design	In Testing	
	Furi	Hippogriff	Daedalus	Icarus	Acca (test chip)
Year	FY14	FY15	FY17	FY16	FY18
Min. Gate	~1.5 ns	~2 ns	~1.0 ns	~1.5 ns	~1 ns
Frames	2	2 (full resolution) 4 or 8 (Row interlaced)	3 (full resolution) 6+ (Row interlaced)	4 (full resolution) 8 (L/R interlaced)	8
Tiling Option	No	No	One Side	No	Linear Tiling
CMOS Process	350 nm (SNL)		350 nm (SNL)	350 nm (SNL)	130 nm (G.F.)
Pixels	448 x 1024		512 x 1024	512 x 1024	512 x 512
Pixel Size	25 μm x 25 μm		25 μm x 25 μm	25 μm x 25 μm	
Capacitor Full Well	1.5 million e^-		1.5 million e^-	0.5 million e^-	

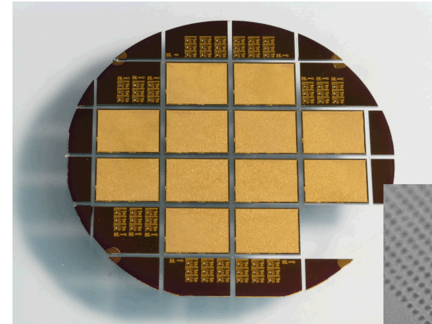
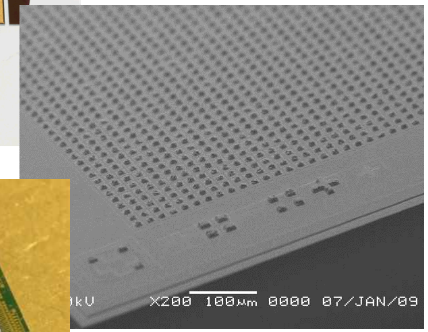
TBD

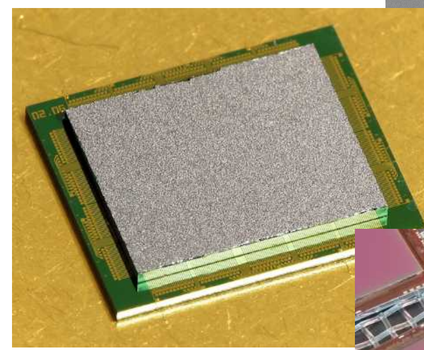
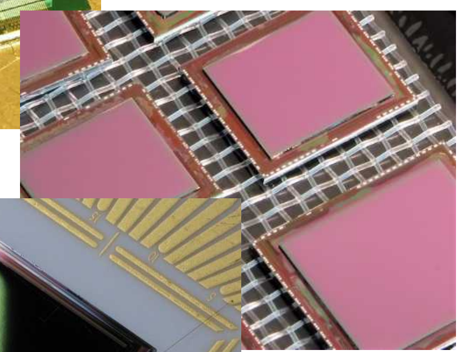
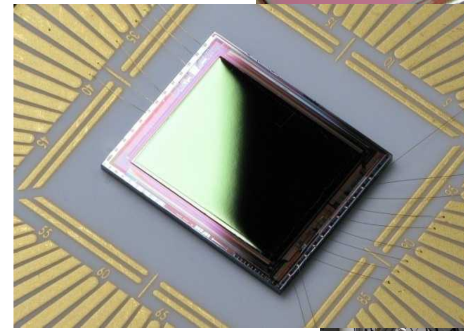
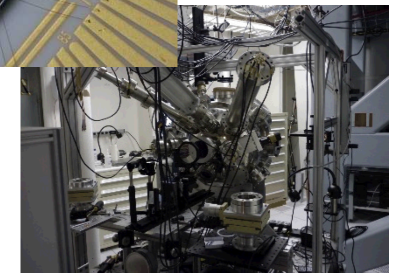



Daedalus is best candidate for first GaAs array

Hybrid Array Flow

- Epitaxial material growth
  - SNL has extensive infrastructure, experts in III-V epitaxy; unique capability
  - Must monitor material for trapping, impurity concentration; challenging to grow thick layers needed for x-ray detection
- Device fabrication
  - Mesa etch, metallization, dielectric layers
  - Fine features of Si CMOS not possible
- Indium bump bond
  - Established flow for IR FPAs; very similar for x-ray
- Detector layer thinning
  - Necessary for x-ray absorption, high-fidelity readout
- Backside processing
- Device packaging
  - Very similar to existing UXI cameras
- Testing
  - Need bright x-ray sources in 10-100 keV range

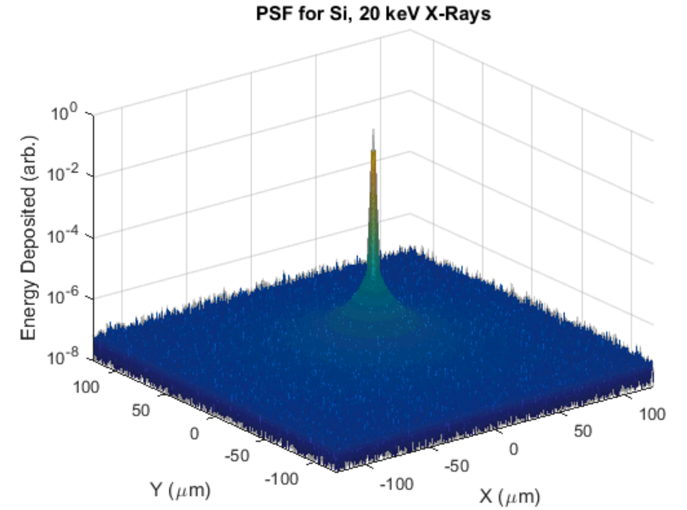



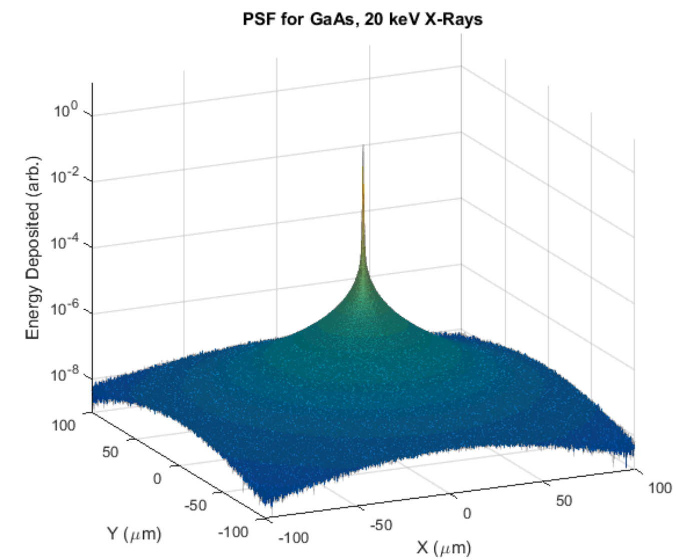





Energy Deposition Spatial Spreading

- Secondary energy cascade process is material dependent
- Higher Z => More x-ray fluorescence, higher energy fluorescence x-rays
- Result is larger spatial distribution of energy deposited by a single primary x-ray

Region	Si	GaAs
Pixel (25 µm)	94.1%	89.3%
Pixel + 8 nearest neighbors	99.8%	97.8%
Pixel + 24 nearest neighbors	99.8%	99.3%





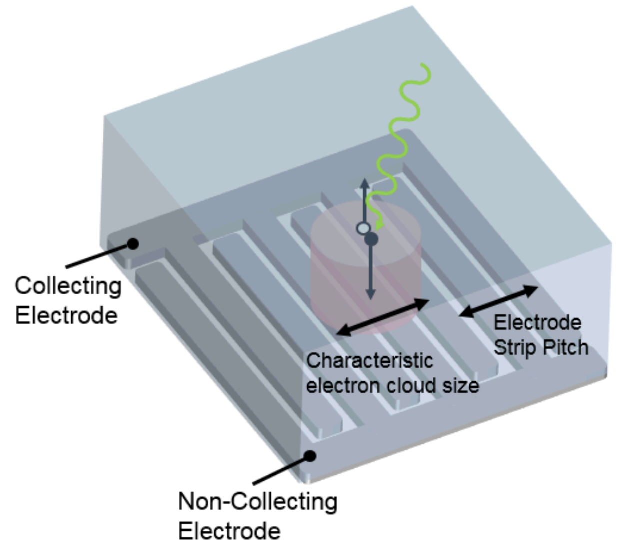
Excessive Charge Collection

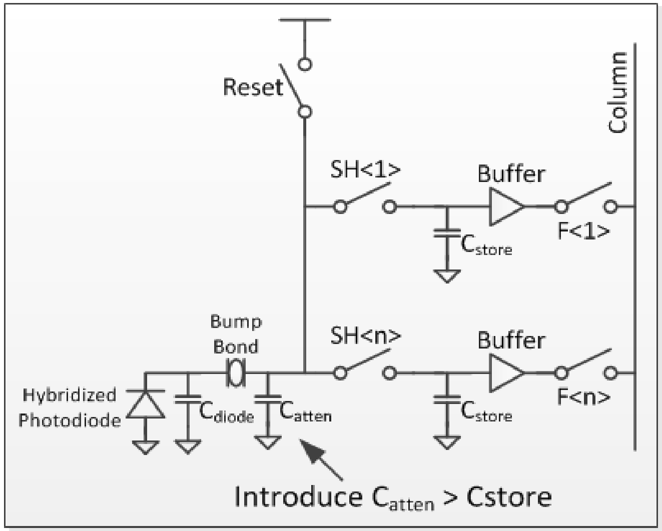
- UXI ROIC design limits each pixel-frame to a maximum charge
  - 1.5 million electrons for Furi, Hippogriff, and Daedalus
- Absorber material dictates conversion ratio of x-ray energy to charge carriers
- Increasing x-ray energy => fewer x-rays saturate pixel
- Fewer x-rays => increase in shot noise
- Higher bandgap absorber preferred for this reason
- Seeking alternate methods of reducing detector signal

Material	Carrier Creation Energy (eV)	Number of Photons to Fill 1.5M e^- Well				
		6.1 keV	20 keV	30 keV	50 keV	70 keV
Si	3.6	885	270	180	108	77
Ge	3	737	225	150	90	64
GaAs	4.2	1032	315	210	126	90
GaN	8.9	2188	667	445	267	190
GaSb	2.7	663	202	135	81	57
InAs	2	491	150	100	60	42
CdTe	4.4	1081	330	220	132	94
CZT	4.6	1131	345	230	138	98
TlBr	6.5	1598	487	325	195	139

Collected Charge Division

- With a goal of 1000 photons at 30 keV, need ~5X reduction in collected charge
- Charge per photon would then be ~1400 e^{-}, about the same as 6.1 keV photon in Si – signal-to-noise ratio not a significant issue
- Approaches in two categories:
  - Reduce collected charge in detector
    - Difficult to accomplish noiselessly
    - May slow response
    - May introduce spatial non-uniformity
  - Electronically divide signal
    - Prefer no ROIC changes ($$$$)
    - May slow response
    - Less maturity on non-Si





Summary

- Semiconductor detectors operated in current mode provide a fast, versatile x-ray diagnostic capability
- Inherent tradeoff in detector thickness between greater absorption and faster time response
- A method of bypassing the conflict is a higher atomic number absorber
- SNL has extensive experience with UXI ROIC development and III-V semiconductor focal plane arrays – combining these two could provide fast framing cameras sensitive to hard x-rays
- Significant progress in GaAs single detector development
- Path forward and challenges identified for UXI ROIC with GaAs diode array

Expanded Discussion

Si Diode Detectors - Applications

- Fast, versatile x-ray detectors
  - Sub-ns temporal resolution possible; continuous time history
  - Possibility of absolute calibration; relative uniformity among devices
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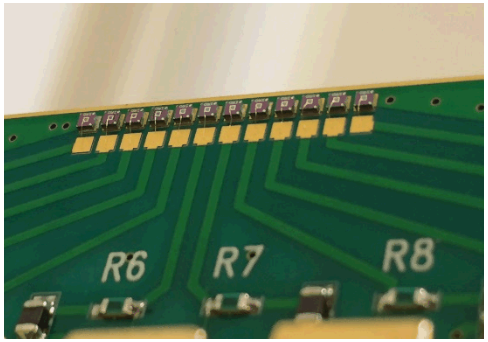

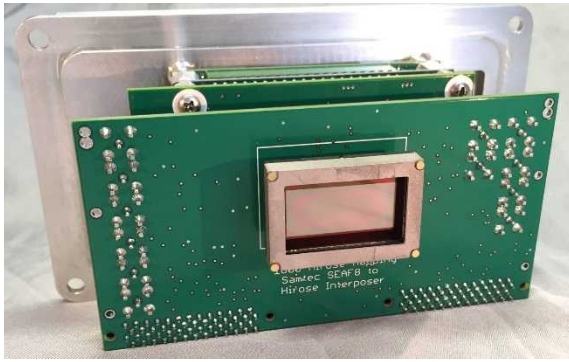

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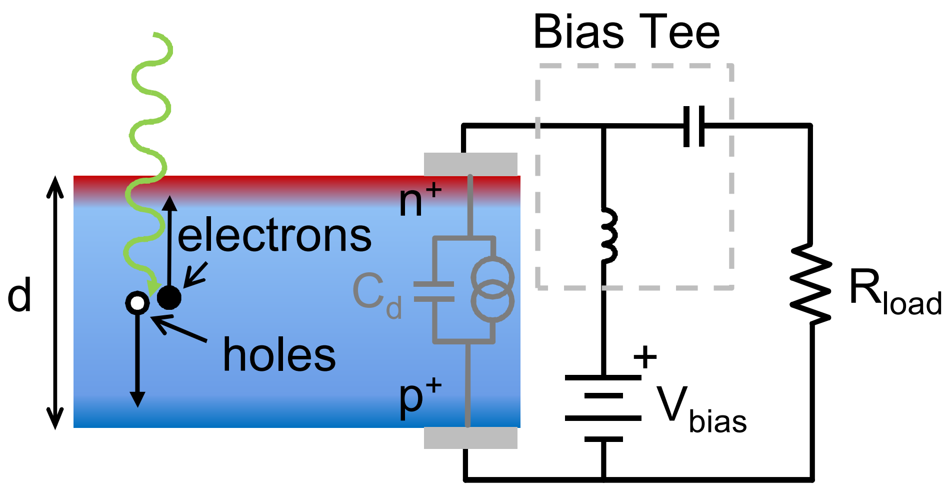

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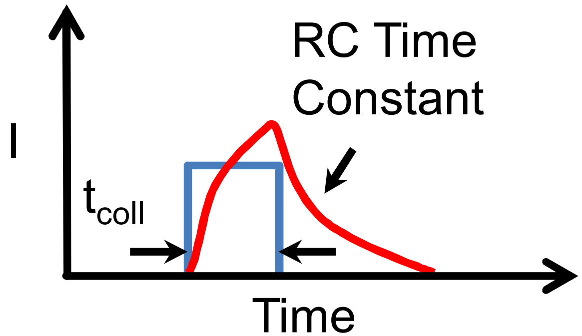
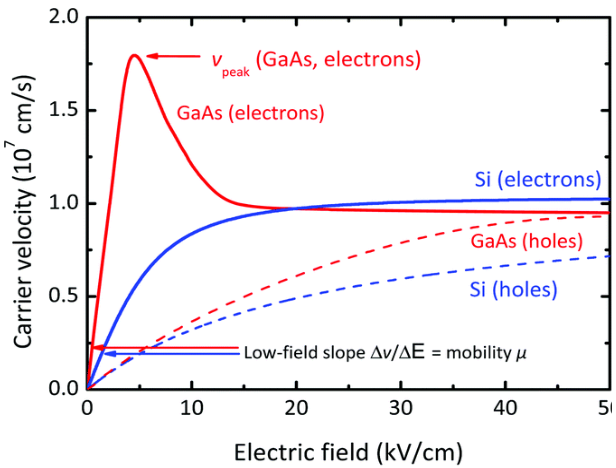
$$\sim R_{load} C_d$$

$$C_d = \varepsilon \frac{A}{d}$$





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  - Need larger area => increase C_d (slower response)
  - Need thicker absorber => increase t_{coll} (slower response)
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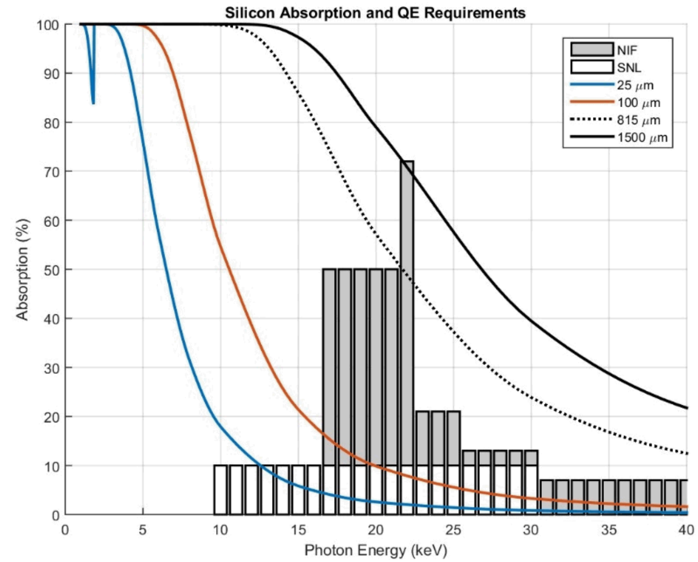
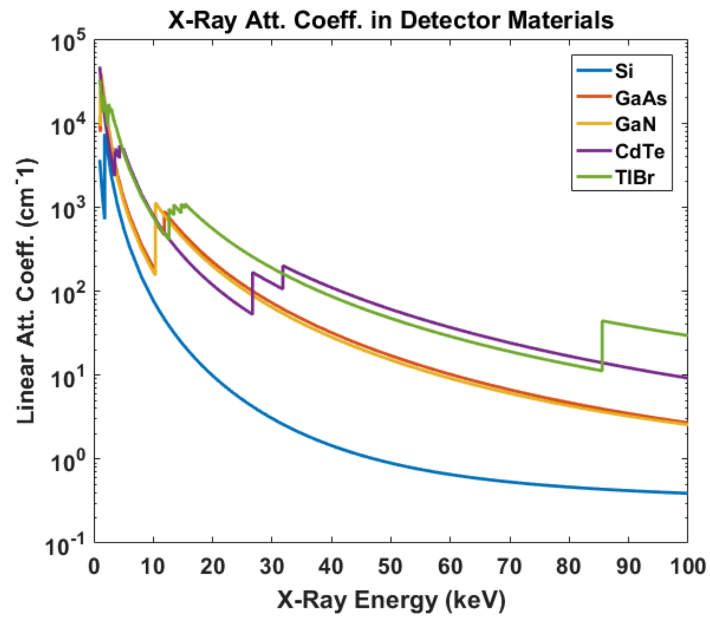
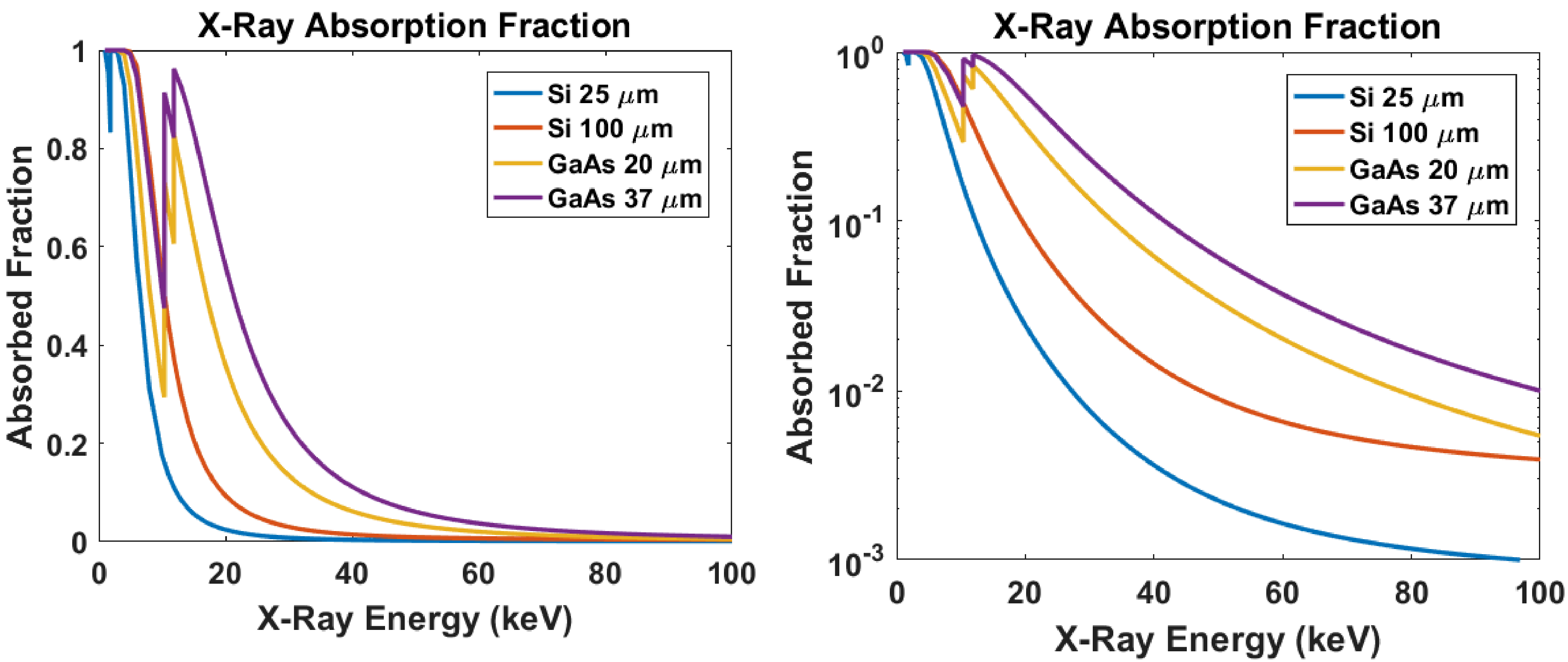
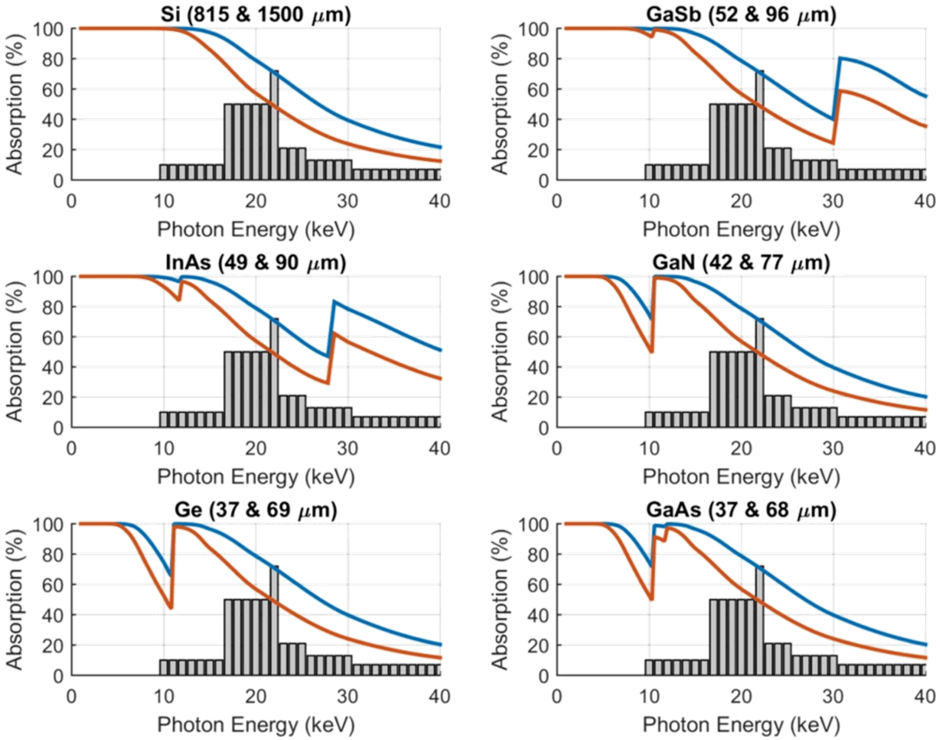





X-Ray Absorption Fraction
Absorbed Fraction
X-Ray Energy (keV)
Si 25 μm
Si 100 μm
GaAs 20 μm
GaAs 37 μm
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
X-Ray Absorption Fraction
Absorbed Fraction
X-Ray Energy (keV)
Si 25 μm
Si 100 μm
GaAs 20 μm
GaAs 37 μm
10^0
10^-1
10^-2
10^-3
0
20
40
60
80
100

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

Absorber Material Options

- Requirements
  - Semiconductor – *reduce scope of study to manageable size*
  - Able to obtain material of sufficient size and quality – *need large detector sizes, minimal carrier trapping*
  - Low background dopant concentration – *must fully deplete detector*
  - Higher Z preferred – *greater x-ray absorption for fixed thickness*
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	Bandgap (eV)	Electron-hole pair creation energy (eV)	ε_r	Z	Electron υ_{sat} (cm/s)	Hole υ_{sat} (cm/s)	1ns thickness (microns)
Si	1.12	3.6	11.7	14	1.0e7	0.7e7	70
Ge	0.67	3.0	16	32	0.6e7	0.6e7	60
GaAs	1.43	4.2	12.8	31,33	0.9e7	0.9e7	90
GaN	3.4	8.9	9.7	31,7	2.7e7	1.7e7	170
GaSb	0.73	2.7	15.7	31,51	0.6e7	0.3e7	30
InAs	0.35	2.0	15.2	49,33	0.9e7	0.5e7	50
CdTe	1.44	4.4	10.9	48,52	1.0e7	0.2e7	20
CZT	1.57	4.6	10	48,30,52	0.3e7	5e5	5
TlBr	2.68	6.5	30	81,35	4e4	2e4	0.2

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

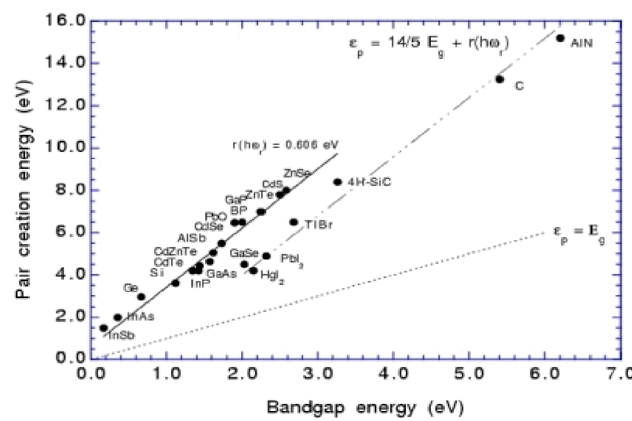
Increasing Bandgap ↓

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 ↓

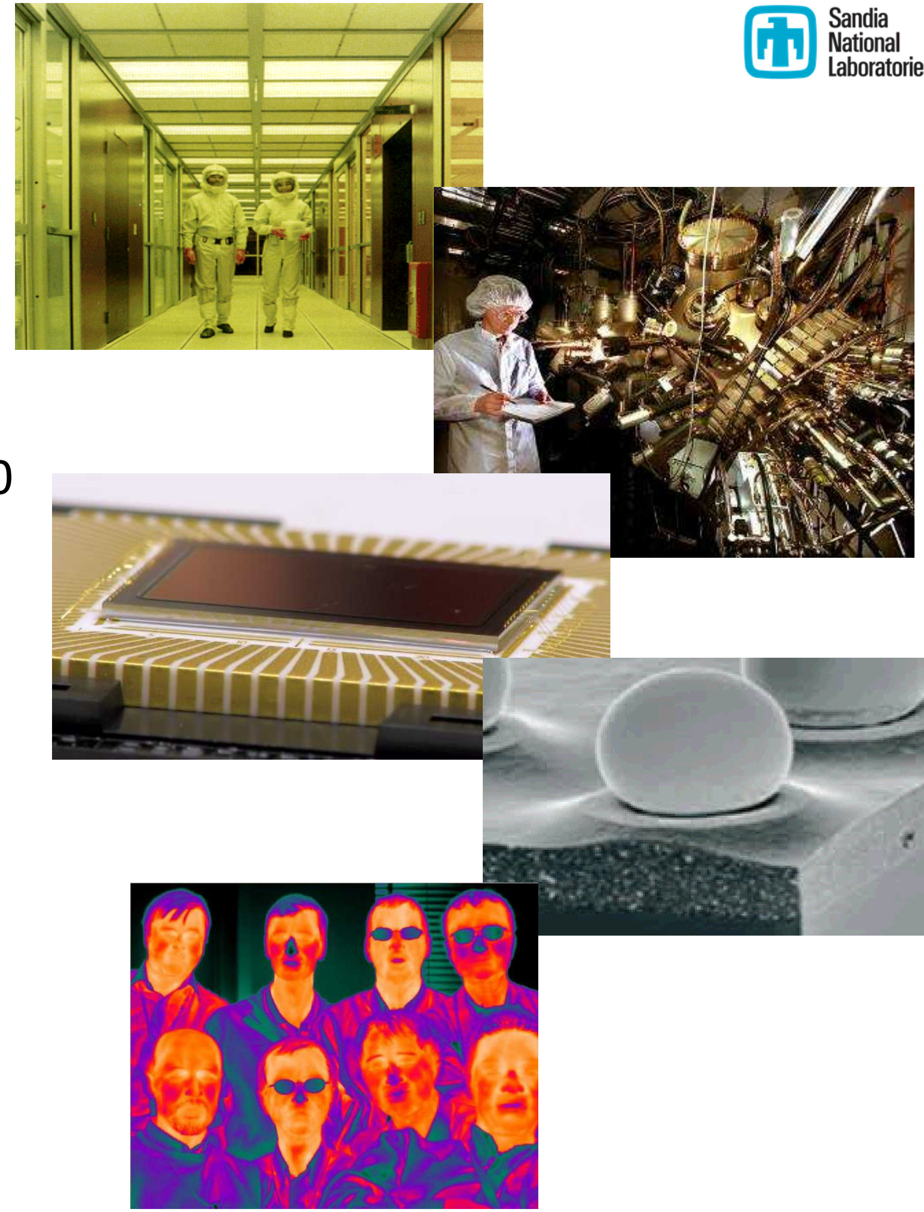


$$\varepsilon_P = \frac{14}{5} \cdot E_g + c$$

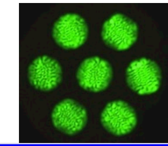
Sandia National Laboratories

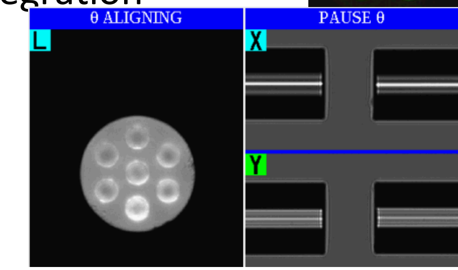
SNL Capabilities

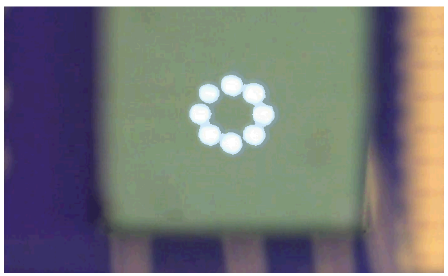
- MESA Semiconductor Fabrication Facility
  - SiFab: 11,900 ft^2 Class 1 for Rad Hard CMOS, MEMS
  - MicroFab: 14,230 ft^2 Class 10/100 handling a variety of materials including III-V
- Photonics Group
  - Extensive experience creating leading edge III-V semiconductor focal plane arrays
  - 8 MBE tools for material growth, MicroFab for device fabrication, mature flip chip process flow, testing infrastructure

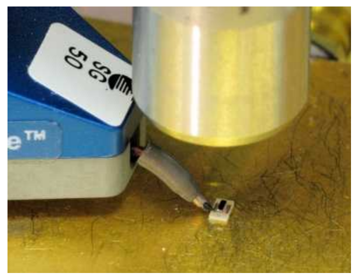


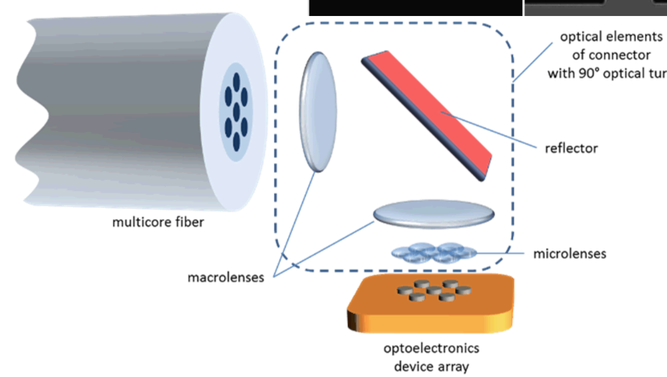
- development of high-density optoelectronics arrays
  - low-power VCSELs designed for high BW at low drive current
  - photodiodes >40Gb/s with very low capacitance through flip-chip integration
- Micro-optics designed for coupling to multicore fibers
  - custom micro-optics developed for multicore fiber links

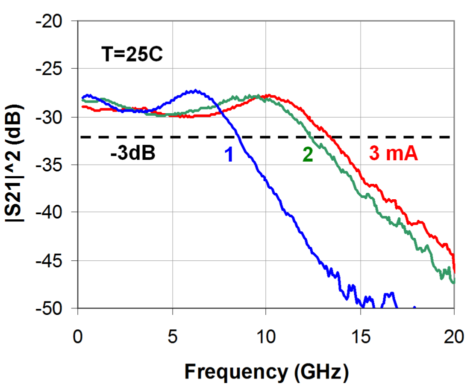




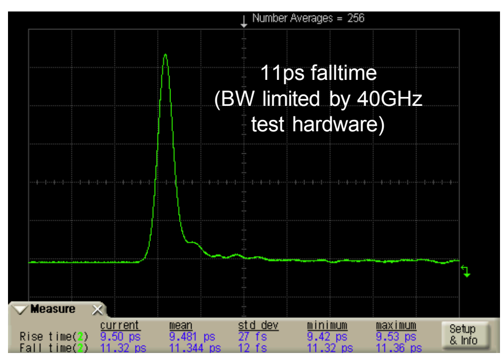




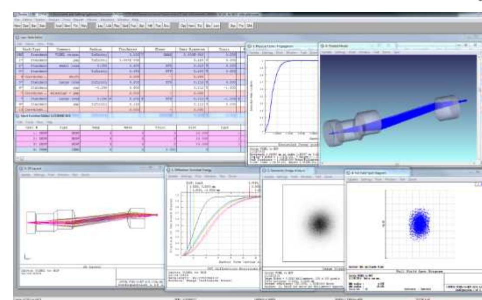


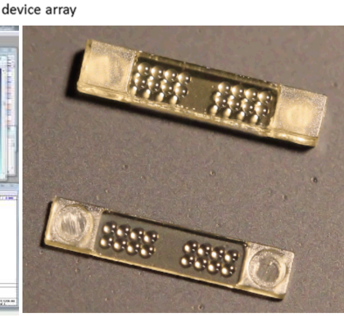


VCSEL performance



InGaAs photodiode performance





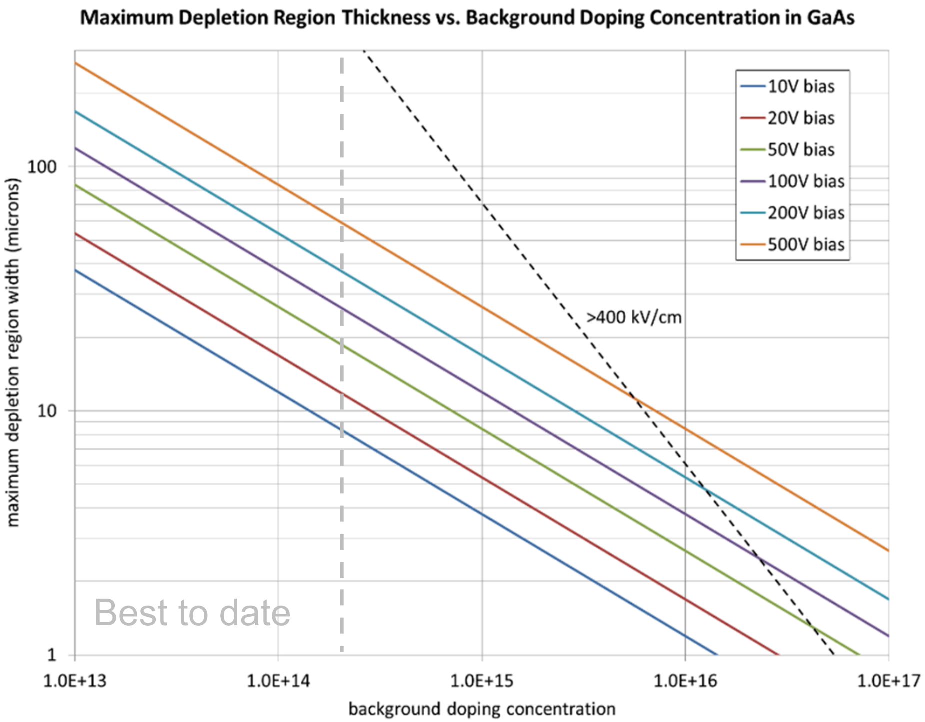
micro-optics and multicore fibers

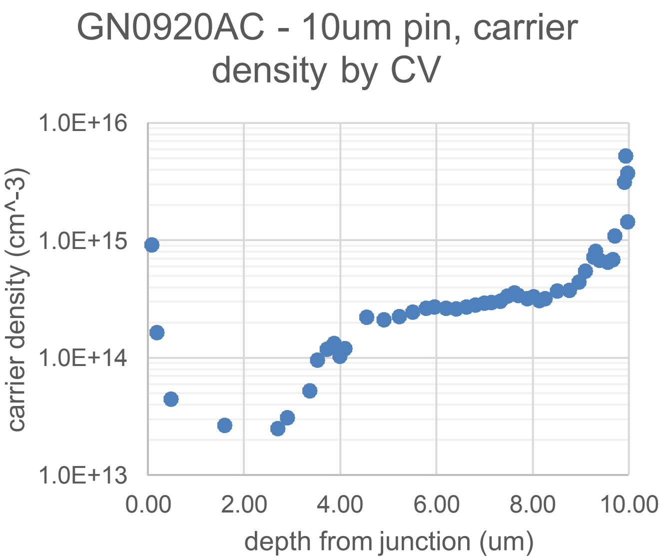
Hard X-Ray Detector Development Plan

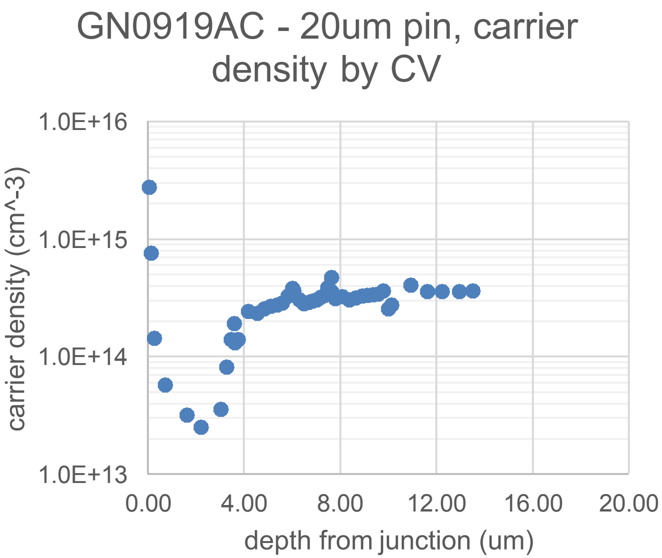
- Exploratory Study – Complete
  - Many requirements not possible with Si
  - GaAs provides best chance of success with significant improvement
- Phase 1: Discrete Diodes – In Progress
  - Material growth – initial success. Reproducibility?
  - Demonstration of equivalent Si timing, improved QE >10 keV
- Phase 2: Diode Arrays – Beginning this FY
  - Packaging development for closely spaced arrays
  - Layout and fabrication process development for single-die arrays
- Phase 3: hCMOS Integration – Funding Dependent
  - Port indium bump process to GaAs arrays on UXI ROICs
  - New packaging and testing strategies

GaAs Detector Development

- Start material
  - SNL MBE growth
  - Low growth rate, single 3” wafer
  - Key challenge: background dopant concentration

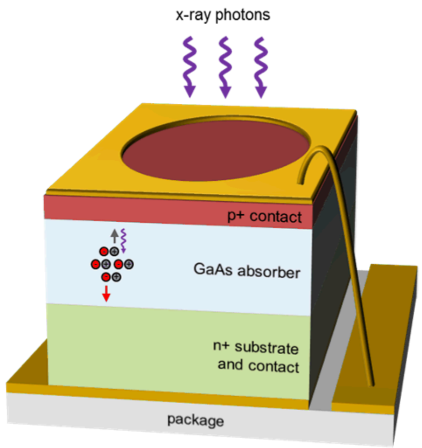


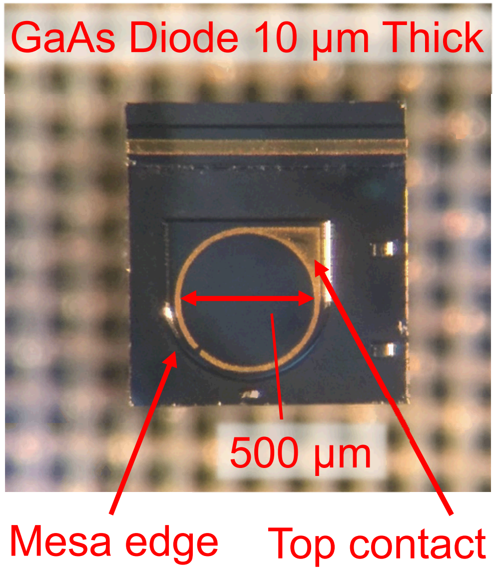


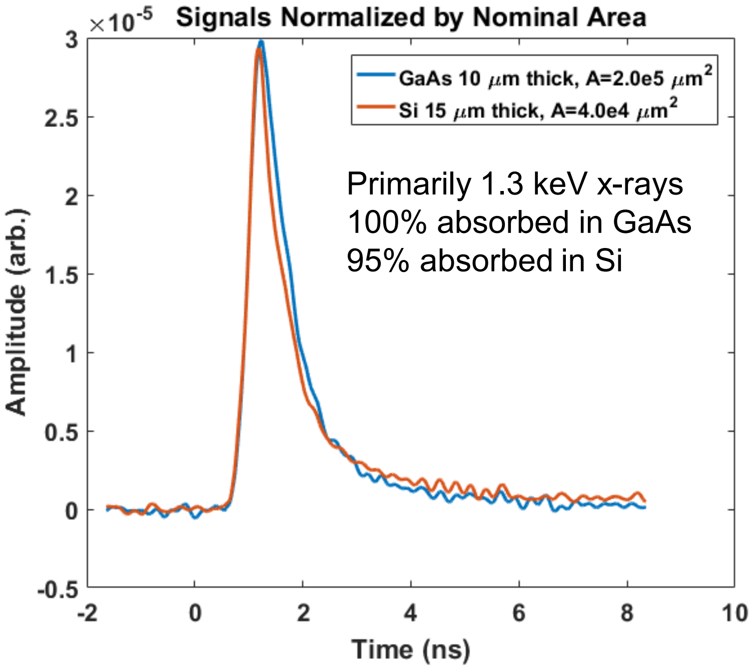


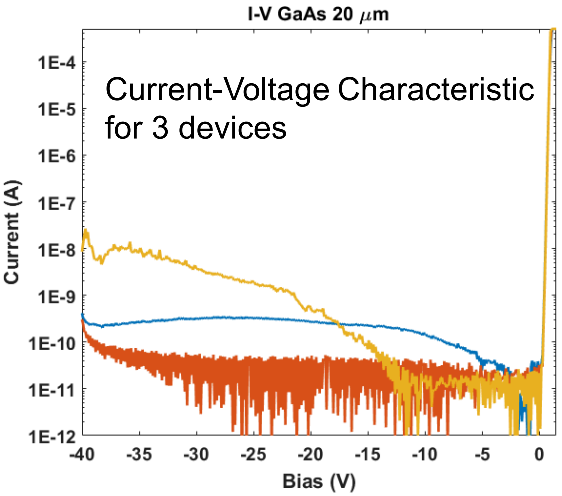
GaAs Detector Testing

- Devices
  - Epitaxial absorber layer isolated by mesa etch
  - Single metal layer forms top contact
  - Bottom contact formed by highly doped handle, backside metal





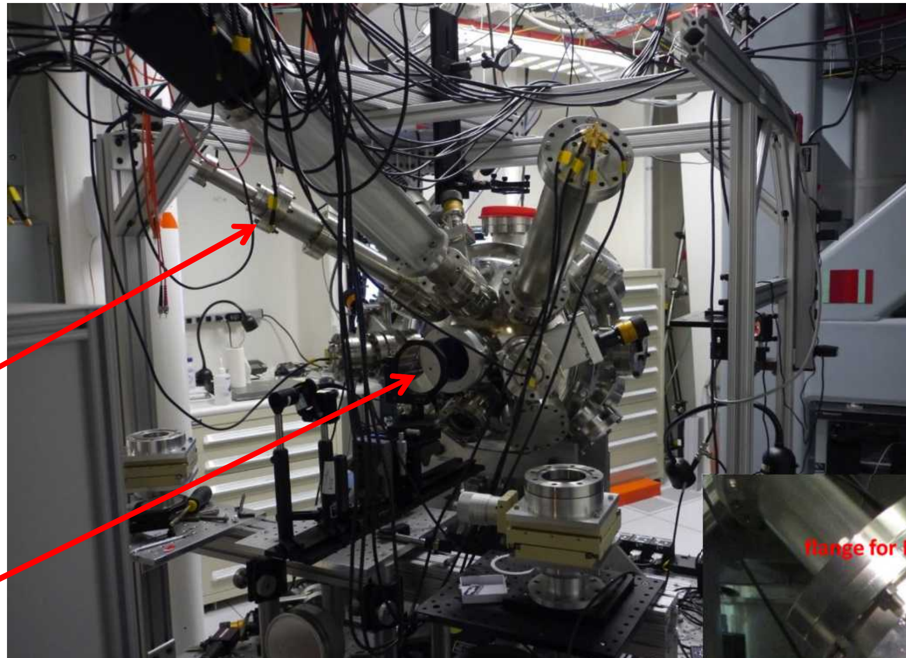




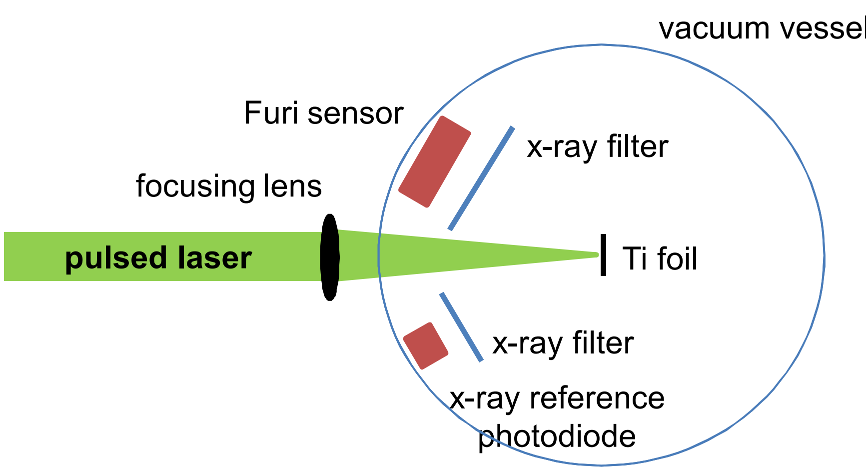
X-Ray Testing in Chaco Target Chamber

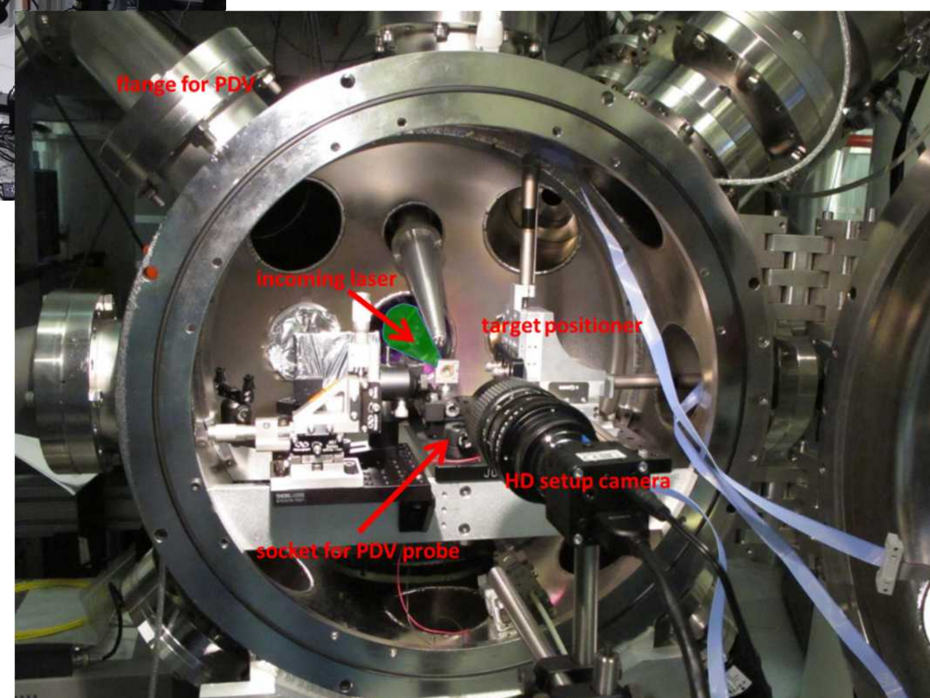
X-ray diodes

Laser beam input lens



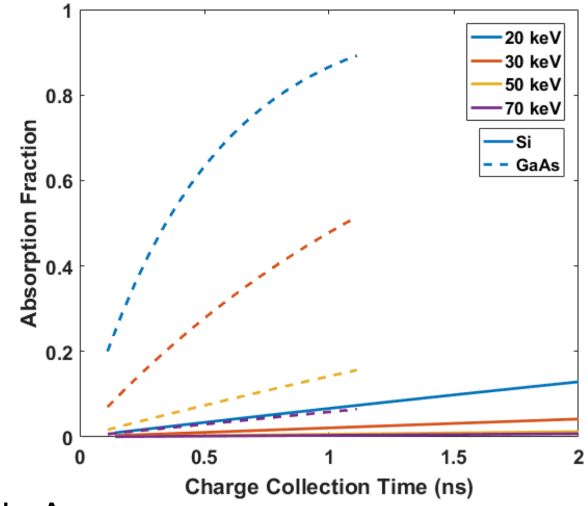
Wavelength: 532 nm (frequency doubled)
Laser energy: 15 J (max. at 2ω)
Pulse duration: 0.3 – 4 nsec (variable)
Target material: Ti (4.7 keV x-rays)



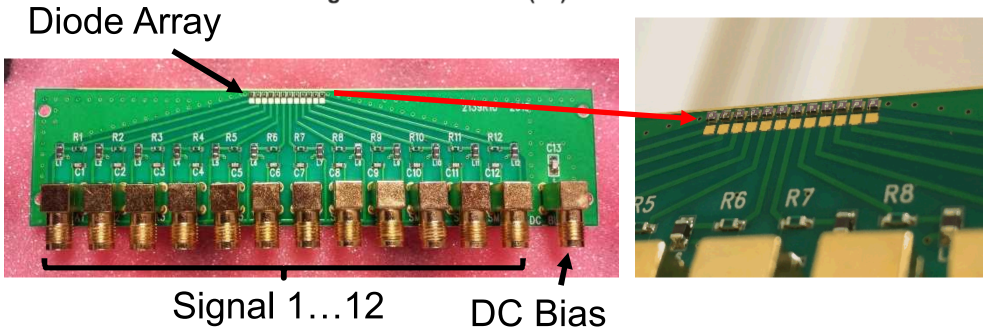


GaAs Diode Applications

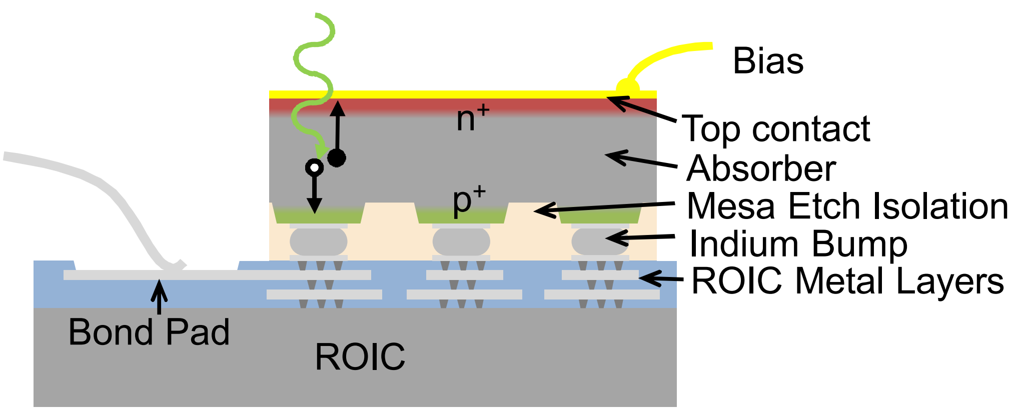
- Discrete diodes – higher QE for warm x-ray source development



- 1-D Arrays – dynamic diffraction, spectroscopy
- 2-D Arrays – simple imaging with continuous time history

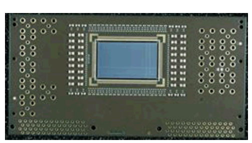


- Diode array on UXI ROIC
  - Single-chip diode array
  - Flip chip bonding to ROIC

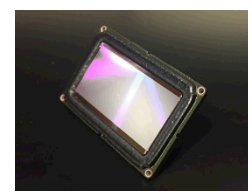
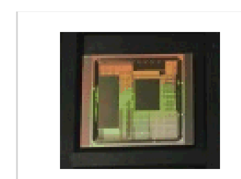


UXI ROICs

	'High' Full Well Sensors			'Low' Full Well Sensors	
	In Use		New Design	In Testing	
	Furi	**Hippogriff**	**Daedalus**	**Icarus**	**Acca** (test chip)
Year	FY14	FY15	FY17	FY16	FY18
Min. Gate	~1.5 ns	~2 ns	~1.0 ns	~1.5 ns	~1 ns
Frames	2	2 (full resolution) 4 or 8 (Row interlaced)	3 (full resolution) 6+ (Row interlaced)	4 (full resolution) 8 (L/R interlaced)	8
Tiling Option	No	No	One Side	No	Linear Tiling
CMOS Process	350 nm (SNL)		350 nm (SNL)	350 nm (SNL)	130 nm (G.F.)
Pixels	448 x 1024		512 x 1024	512 x 1024	512 x 512
Pixel Size	25 µm x 25 µm		25 µm x 25 µm	25 µm x 25 µm	
Capacitor Full Well	1.5 million e^-		1.5 million e^-	0.5 million e^-	



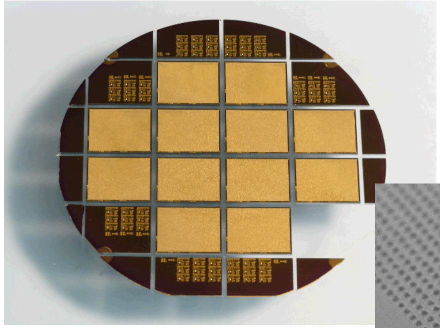
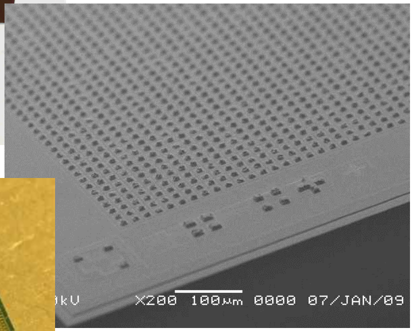

TBD

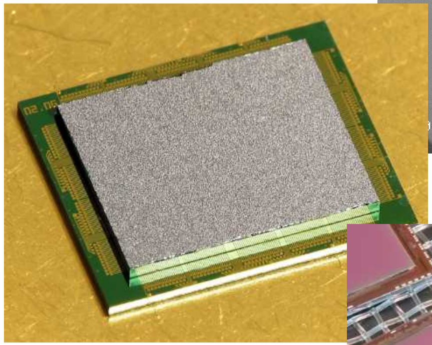
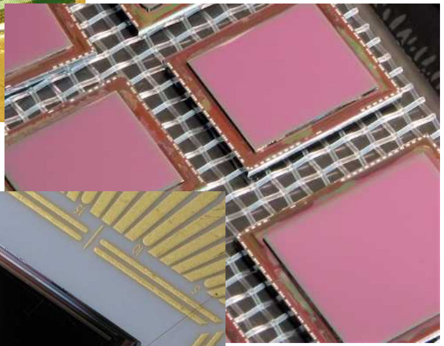
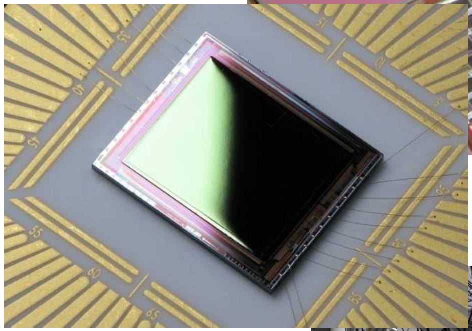
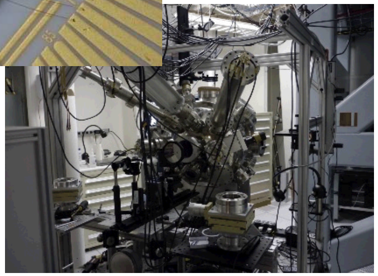



Daedalus is best candidate for first GaAs array

Hybrid Array Flow

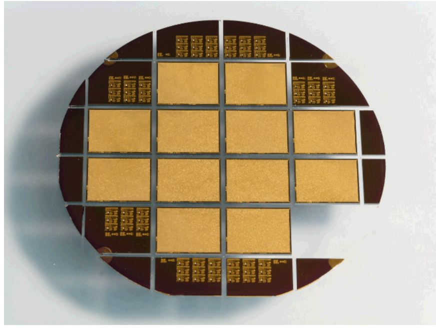
- Epitaxial material growth
  - SNL has extensive infrastructure, experts in III-V epitaxy; unique capability
  - Must monitor material for trapping, impurity concentration; challenging to grow thick layers needed for x-ray detection
- Device fabrication
  - Mesa etch, metallization, dielectric layers
  - Fine features of Si CMOS not possible
- Indium bump bond
  - Established flow for IR FPAs; very similar for x-ray
- Detector layer thinning
  - Necessary for x-ray absorption, high-fidelity readout
- Backside processing
- Device packaging
  - Very similar to existing UXI cameras
- Testing
  - Need bright x-ray sources in 10-100 keV range

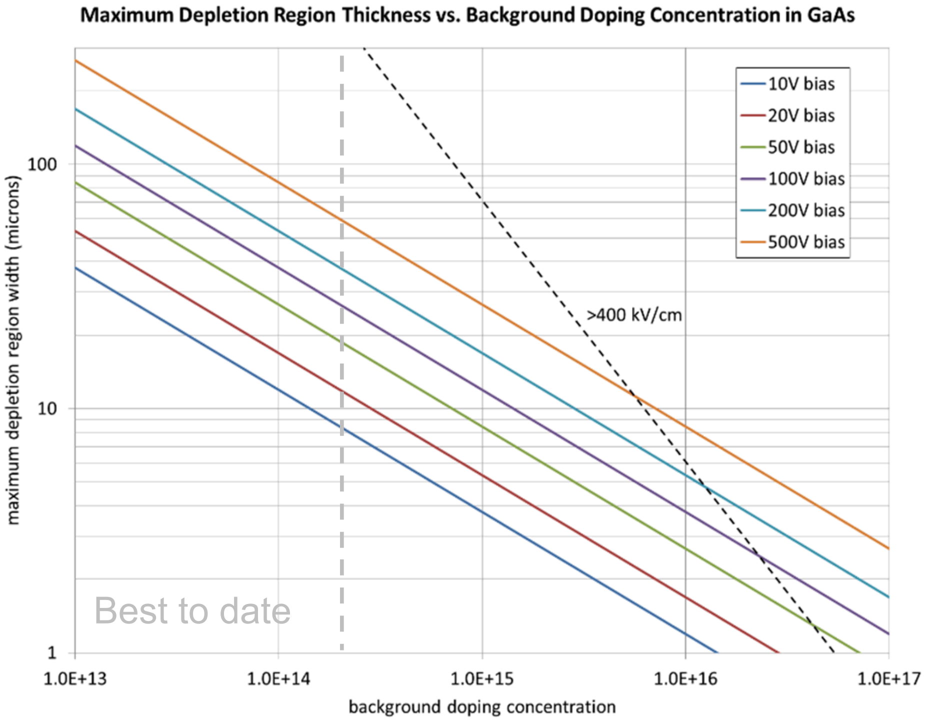



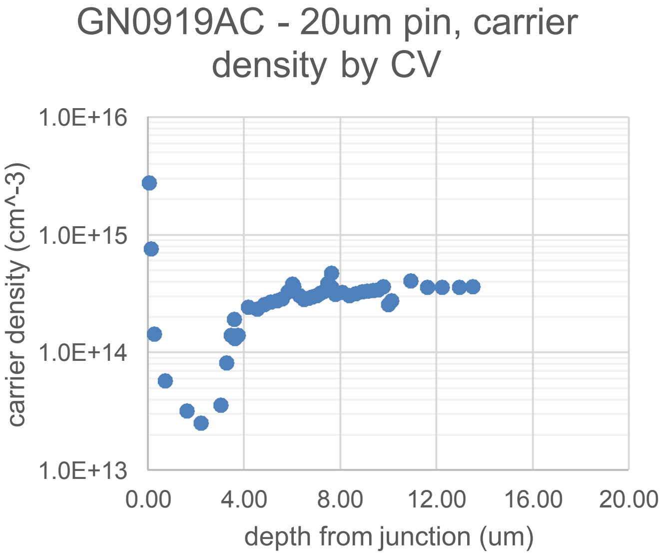





Hybrid Array Flow

- Epitaxial material growth
  - At current background concentrations, need over 200 V to overbias ~40 µm!
  - Possible non-uniformity in background concentration across wafer
  - Potentially use semi-insulating GaAs – thick wafers, need thinning

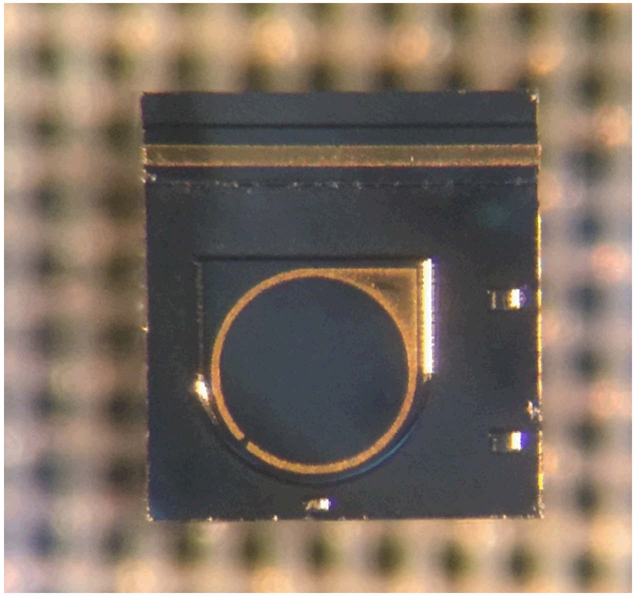






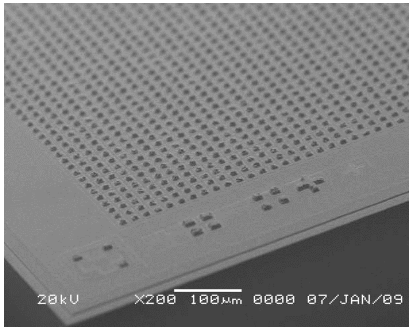
Hybrid Array Flow

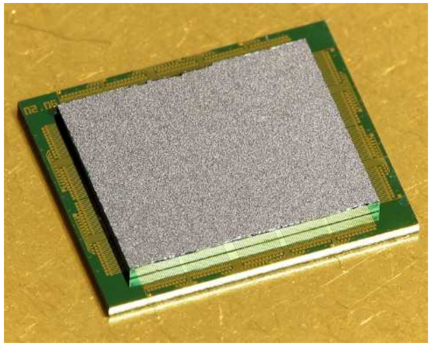
- Device fabrication
  - Fine features of Si CMOS not possible
  - Mesa etch depth targeting; passivation needed?
  - Pixel isolation
  - Metal contacts – barrier height?

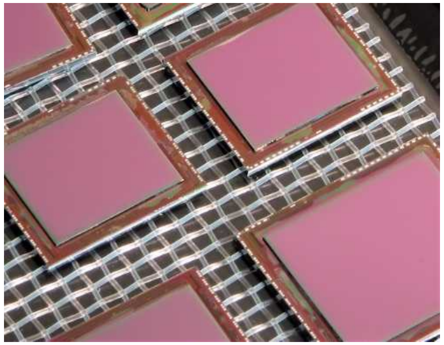


Hybrid Array Flow

- Indium bump bond
  - Established flow for IR FPAs; very similar for x-ray
  - New for UXI cameras
- Detector layer thinning
  - Necessary for x-ray absorption, high-fidelity readout
  - Significantly different than current UXI flow; done for IRA FPAs on other Si CMOS ROICs
- Backside processing
  - No more complex than current backside processing

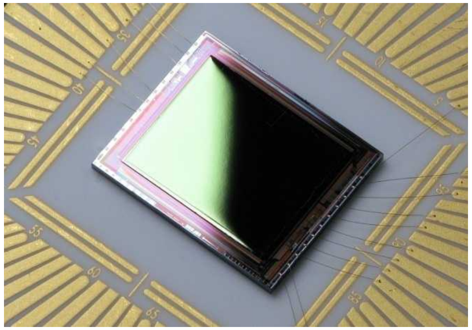




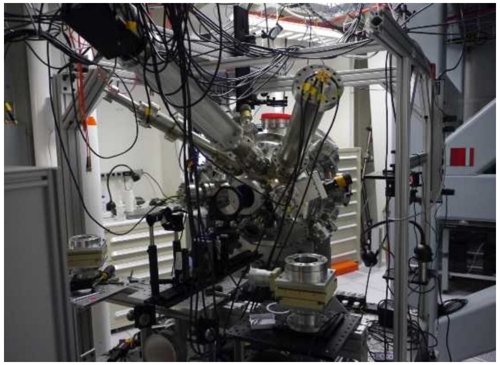


Hybrid Array Flow

- Device packaging
  - No significant process differences anticipated
  - Hybridized device potentially less robust
  - Lower thermal budget



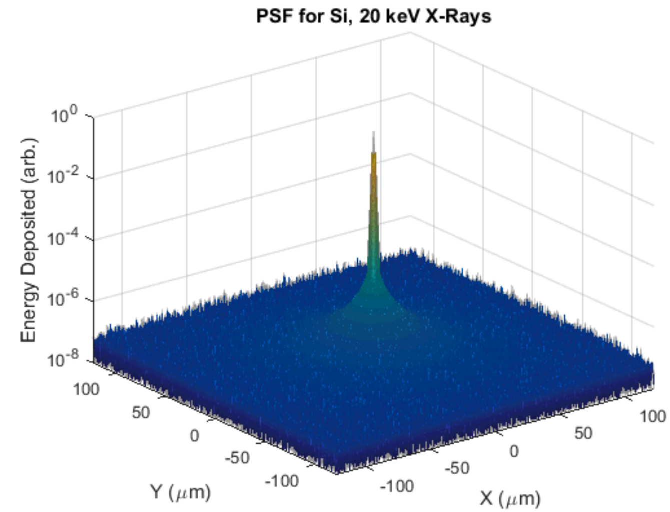
- Testing
  - Need bright x-ray sources in 10-100 keV range
  - Slightly greater absorption in GaAs-coupled camera should be observable in current capability up to 6.1 keV
  - May need to move to short-pulse laser for 10-20 keV x-ray source
  - Synchrotron

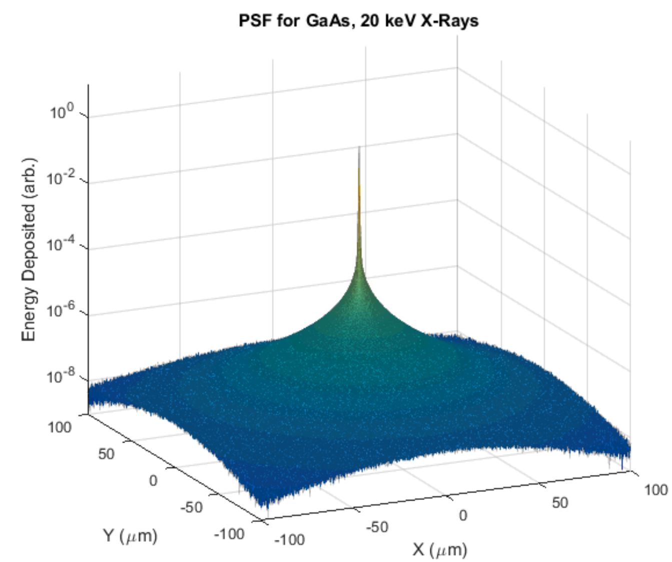


Energy Deposition Spatial Spreading

- Secondary energy cascade process is material dependent
- Higher Z => More x-ray fluorescence, higher energy fluorescence x-rays
- Result is larger spatial distribution of energy deposited by a single primary x-ray

Region	Si	GaAs
Pixel (25 µm)	94.1%	89.3%
Pixel + 8 nearest neighbors	99.8%	97.8%
Pixel + 24 nearest neighbors	99.8%	99.3%



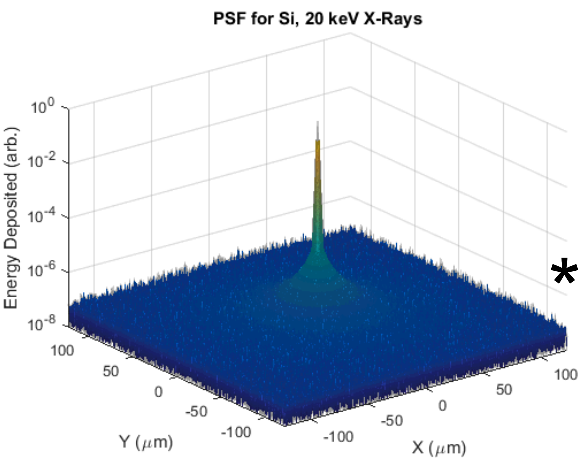


Process of Defining "Pixel Spread Function"

- Camera designed for uniform illumination across entire pixel
  - Point spread function not necessary ideal metric
  - What proportion of energy incident on a pixel ends up in other pixels? How much charge in a pixel is due to energy deposited in other pixels?
- Geant4 simulation
  - 20 keV x-ray pencil beam
  - 50 µm thick Si absorber
  - Caresian bins cube 0.2 µm on a side

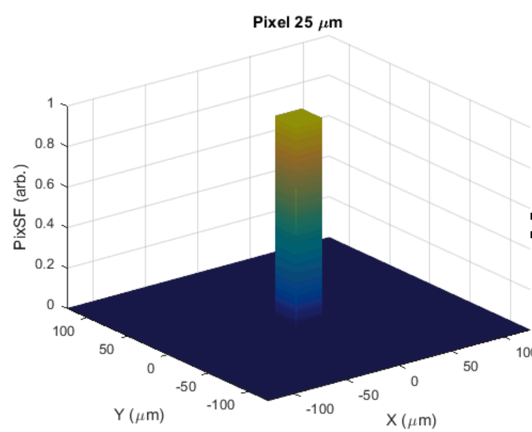
For a 25 µm pixel:

Energy deposited in the same pixel on which the x-ray was incident 94.1%
In same pixel + 1 ring 99.8%
In same pixel + 2 rings 99.8%



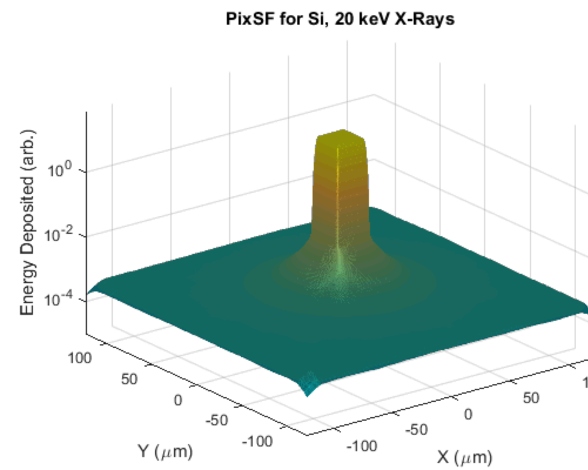
Point spread function, or spatial impulse response

*



Uniform illumination of a single 25 µm pixel

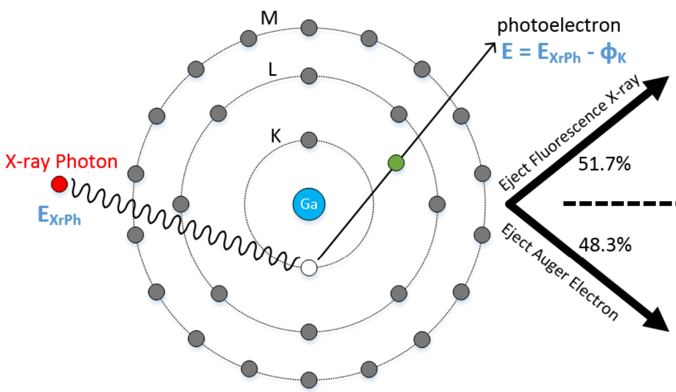
=

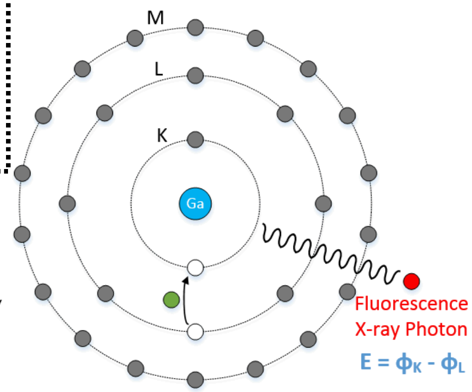


Pixel spread function

Fluorescence is an unavoidable issue in high-Z semiconductors

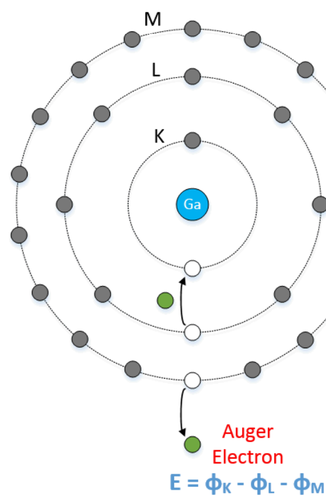
Example:
15 keV Incident X-ray Photon Interacting with inner-shell Ga electron. L1-shell electron drops to newly created vacancy.





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 ↓

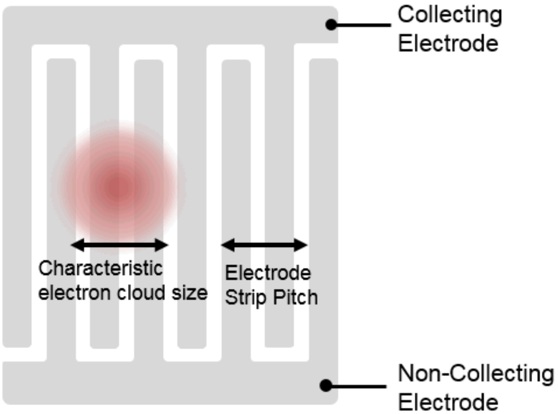
Excessive Charge Collection

- UXI ROIC design limits each pixel-frame to a maximum charge
  - 1.5 million electrons for Furi, Hippogriff, and Daedalus
- Absorber material dictates conversion ratio of x-ray energy to charge carriers
- Increasing x-ray energy => fewer x-rays saturate pixel
- Fewer x-rays => increase in shot noise
- Higher bandgap absorber preferred for this reason
- Seeking alternate methods of reducing detector signal

Material	Carrier Creation Energy (eV)	Number of Photons to Fill 1.5M e^- Well				
		6.1 keV	20 keV	30 keV	50 keV	70 keV
Si	3.6	885	270	180	108	77
Ge	3	737	225	150	90	64
GaAs	4.2	1032	315	210	126	90
GaN	8.9	2188	667	445	267	190
GaSb	2.7	663	202	135	81	57
InAs	2	491	150	100	60	42
CdTe	4.4	1081	330	220	132	94
CZT	4.6	1131	345	230	138	98
TlBr	6.5	1598	487	325	195	139

Excessive Charge Collection

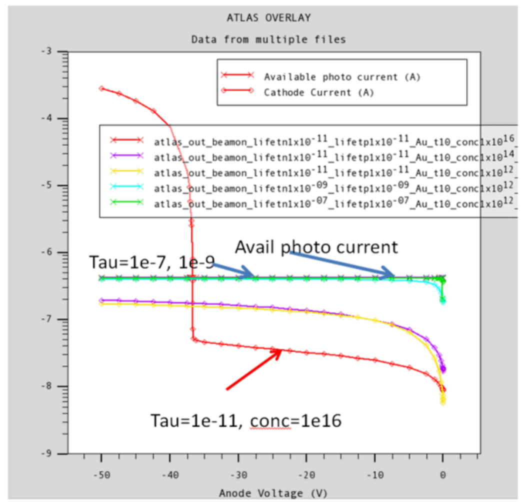
Multiple Charge Paths



Multiple contacts – charge collected based on geometry of contacts?

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

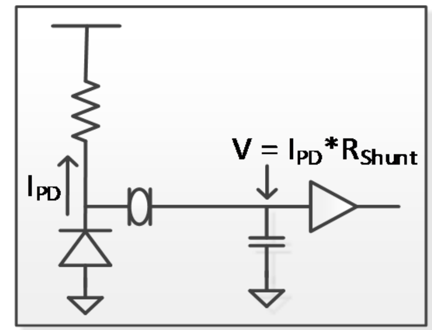
Recombination Rate Eng.



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



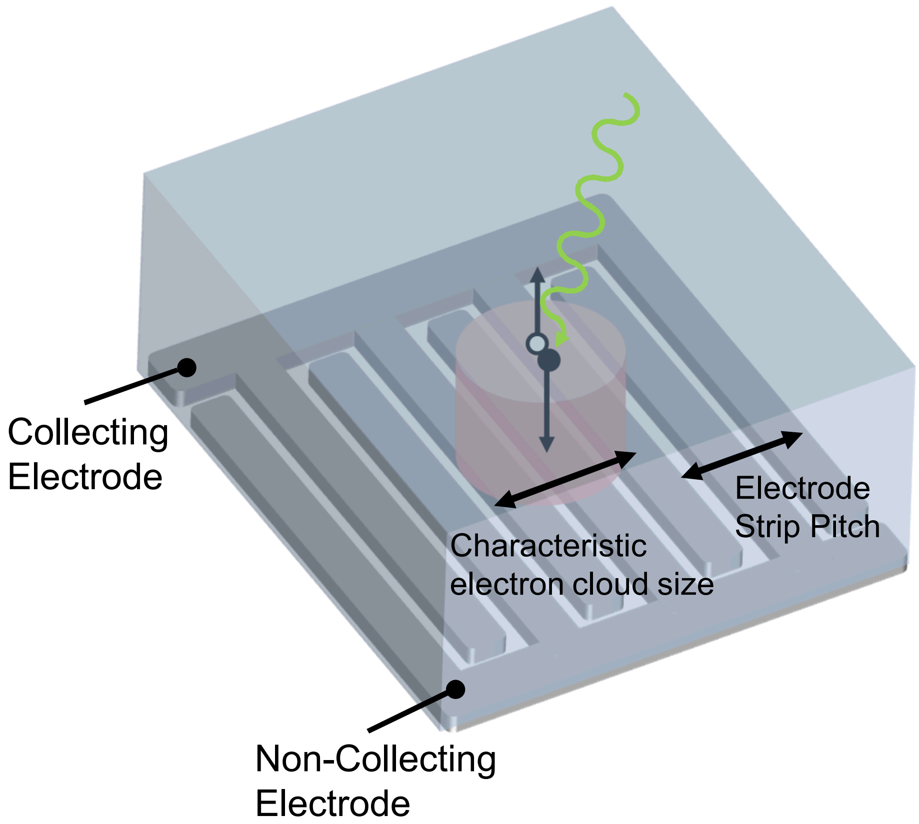
Introduce a “bleed” resistor in photodiode layer.

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

Also ROIC redesign solutions **expensive

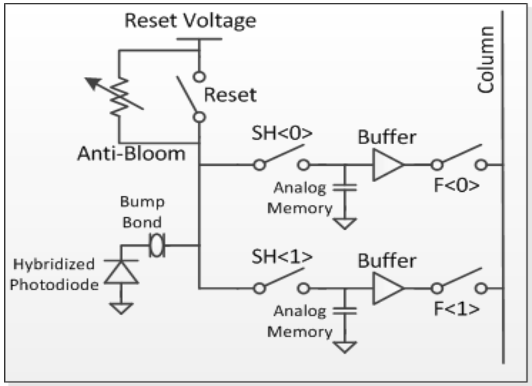
Coplanar Grid Electrodes

- Adjust charge division ratio based on relative strip sizes of collecting and non-collecting electrodes
- Electrodes must remain at same potential
- Increased capacitive shunt path of sense electrode
- Limited minimum metal feature size on GaAs



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

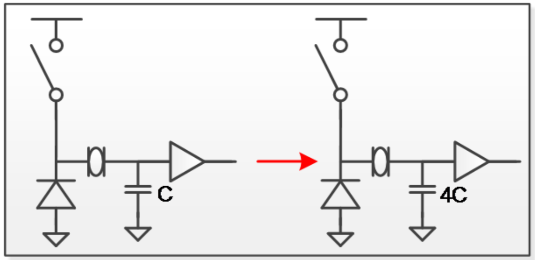
Anti-Bloom



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

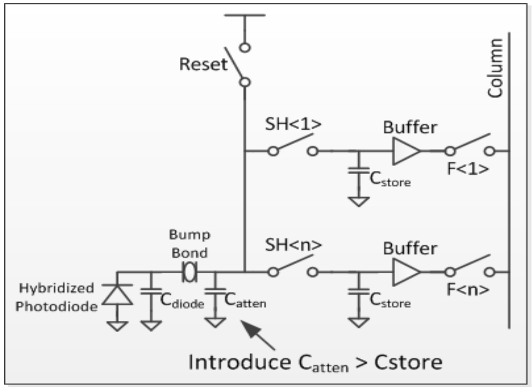
Increase Full-Well



Increase the size of the analog storage capacitor.

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

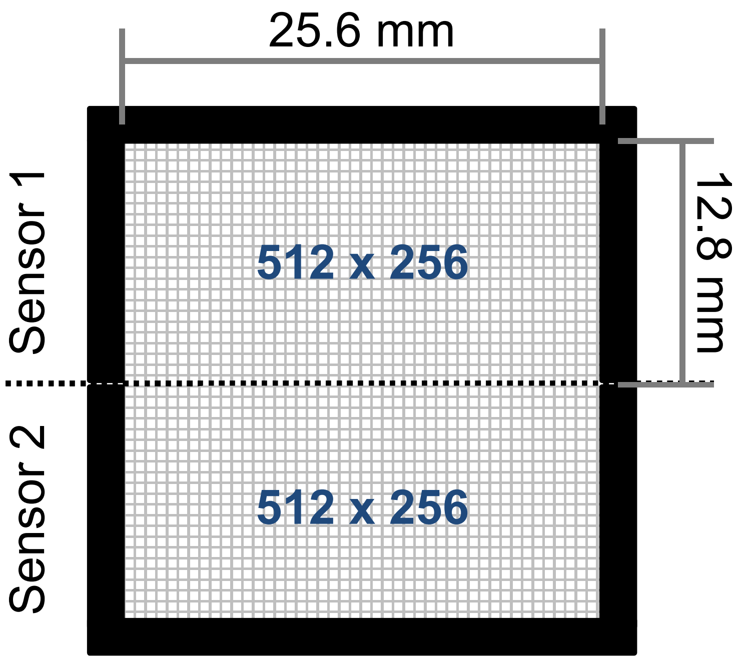
Capacitive Charge Division



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 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

Summary

Sandia National Laboratories

- Semiconductor detectors operated in current mode provide a fast, versatile x-ray diagnostic capability
- Inherent tradeoff in detector thickness between greater absorption and faster time response
- A method of bypassing the conflict is a higher atomic number absorber
- SNL has extensive experience with UXI ROIC development and III-V semiconductor focal plane arrays – combining these two could provide fast framing cameras sensitive to hard x-rays
- Significant progress in GaAs single detector development
- Path forward and challenges identified for UXI ROIC with GaAs diode array