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Sub-ns Response GaAs X-Ray Detectors for Pulsed Power Applications

Q. Looker, M. G. Wood, D. K. Serkland, J. K. Kim, G. A. Keeler
Sandia National Laboratories, Albuquerque, NM 87185, USA

Abstract

For pulsed power applications, such as experiments at Sandia's Z-machine, the National Ignition Facility, or the OMEGA facility at Rochester, detectors with fast (often sub-nanosecond) response are required to capture the rapidly changing signals of interest. Historically, Si diodes or diamond photoconductors have been widely utilized for time-resolved x-ray detection in these applications, but the x-ray absorption efficiency of these detectors decreases rapidly for energies above 10 keV. Furthermore, a tradeoff with detector size and speed places a limit on sub-ns detection efficiency with Si. Given the strong dependence of x-ray absorption efficiency on atomic number, GaAs detectors provide a method of significantly increasing detector efficiency with the same geometry and similar response time. We have fabricated GaAs detectors with a 20 µm absorber thickness and <1 mm cross-sectional area which are capable of sub-ns x-ray response and 13x stronger absorption at 15 keV than an equivalent Si detector. As a comparison to available Si diodes, we present x-ray absorption data, pulsed x-ray data, and relevant material properties along with potential impacts on pulsed power experiments.

Pulsed Power Experiments

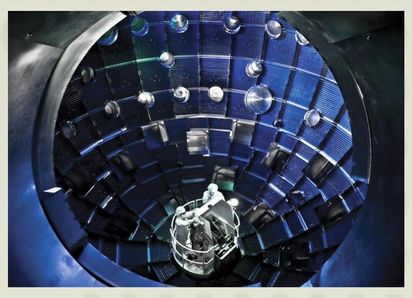
Radiation Effects Science

Understanding the effects of intense radiation on electronic, material, and biological systems. High intensity is often achieved by compressing energy into a short period of time.

Inertial Confinement Fusion

Seeking to achieve ignition (energy out > energy in) by means of rapidly compressing light nuclei to achieve extremely high pressure. Confinement times are short, and physics evolves rapidly.

Facilities

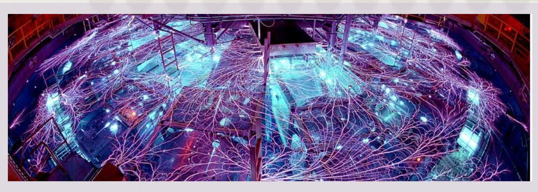


The National Ignition Facility precisely directs 192 laser beams, each with multi-kJ energy content delivered over the period of a few ns.

Rochester's OMEGA facility directs 60 laser beams with a total of 40 kJ of energy into a central target chamber in the period of ~1 ns.

Sandia's Hermes III facility generates ~MeV x-ray pulses by brehmsstrahlung radiation in a few ns.

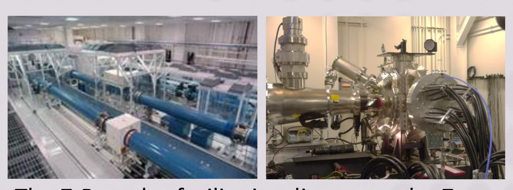
Example Applications



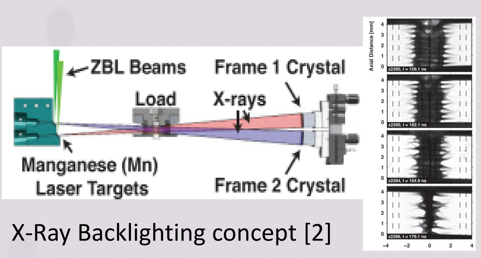
Sandia's Z-machine utilizes a capacitor Marx bank to supply 26 MA of current in order to magnetically compress targets on the time scale of ~10^{-8} s. A z-pinch plasma can produce 2.7 MJ of x-rays or rapidly compress targets.

Monitoring x-ray output from a target as a function of time.

MagLIF fusion concept [1]



The Z-Beamlet facility is adjacent to the Z-machine and can deliver kJ of laser energy to z-pinch targets with sub-mm accuracy. There are also several target chambers for laser-only experiments.



X-Ray Backlighting concept [2]

X-Ray backlighting of imploding targets. Laser irradiation of a metal foil produces a short flash of x-rays to allow short exposure radiography.

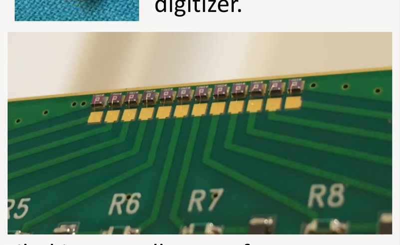
Detectors for higher energy X-Rays are needed in order to monitor hard X-Ray emission and allow more penetrating radiography

Current Detectors

Individual photon counting untenable – numerous photons arrive simultaneously

Time-resolved

Small Si diodes or diamond photoconductors are read out in current mode directly to a digitizer.



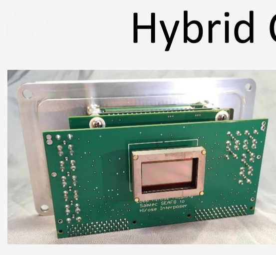
Tiled into small arrays for rudimentary time-resolved imaging

Imaging

Image plate captures a time-integrated image of the entire experiment.

Evolving signals are not resolved

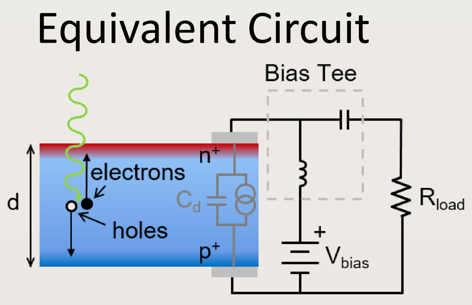
Hybrid CMOS



A newer development uses a Si diode array coupled to a ~ns exposure burst mode CMOS camera.

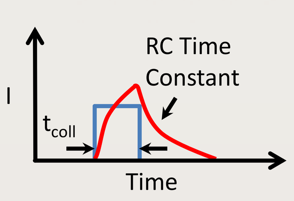
Temporal response is a product of charge carrier collection time and RC time constant

Si Diode Equivalent Circuit



$$t_{coll} = \frac{d_{coll}}{v_{sat}}$$

$$C_{det} = \varepsilon \frac{A}{d}$$



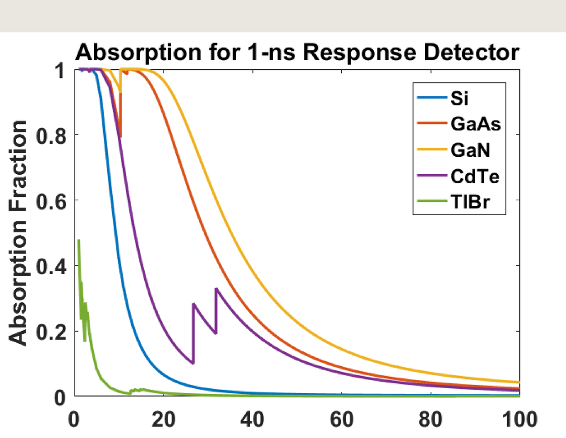
Example:
1 ns RC time constant at 50 Ω, C ≤ 20 pF
1 ns charge collection time at $v_{sat}=10^7$ cm/s is 100 µm thickness

Tradeoff between detector speed and sensitivity:
A larger area increases RC time constant
A thicker absorber increases collection time

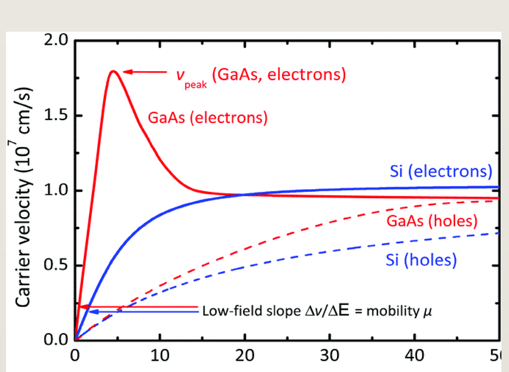
Benefits of GaAs

Higher atomic number absorber allows bypass of tradeoff between thickness and speed

$$\sigma_{pe} \propto \frac{Z^{4-5}}{E_\gamma^{3.5}}$$



GaAs has similar absorption to Ge – but no cooling required
GaAs has higher material maturity than CZT



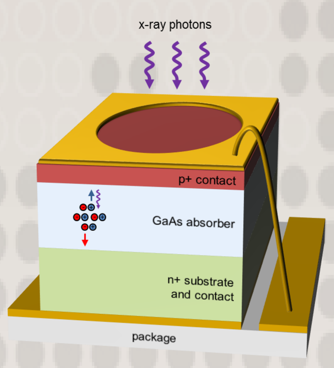
GaAs carrier velocity comparable to Si for high electric fields

	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

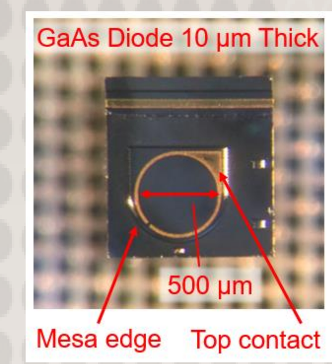
Device Characterization

GaAs detectors were fabricated at Sandia

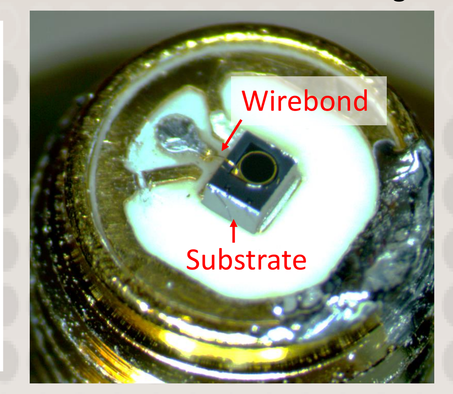
1. Molecular Beam Epitaxy (MBE) growth of low-doped GaAs grown on GaAs substrate
2. Top metal electrode deposited and patterned
3. Mesa etch through MBE-deposited absorber layer
4. Add backside electrode, passivation



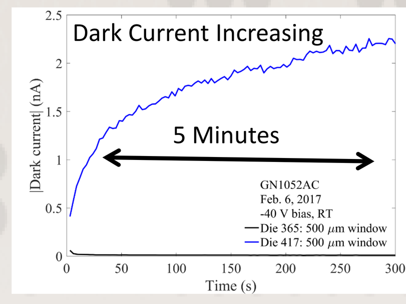
GaAs Detector Die



GaAs Detector in SMA Package



Encountered initial issues with leakage current increasing over the period of minutes to hours

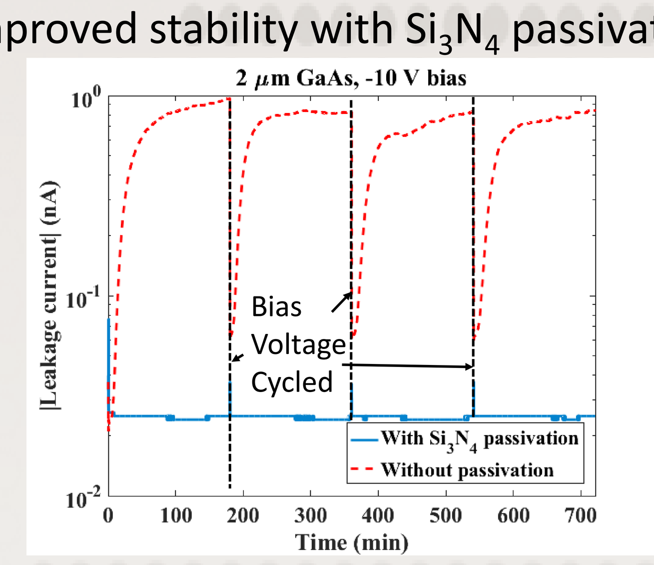


Detectors must operate fully depleted for fast timing

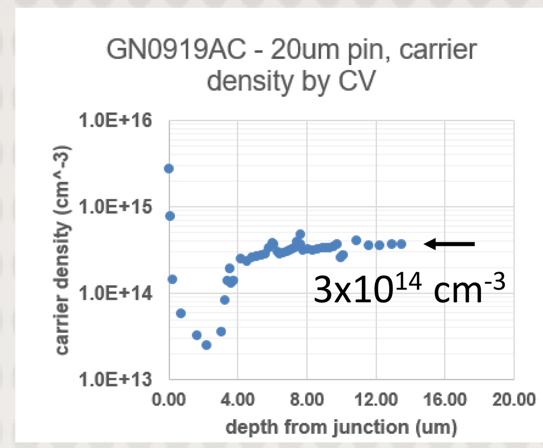
Depletion depth: $x_d = \sqrt{\frac{2\varepsilon V}{qN_d}}$

x_d: Depletion depth (cm)
ε: Dielectric constant (F/cm)
V: Applied bias (V)
q: electronic charge (C)
N_d: Dopant concentration (cm^{-3})

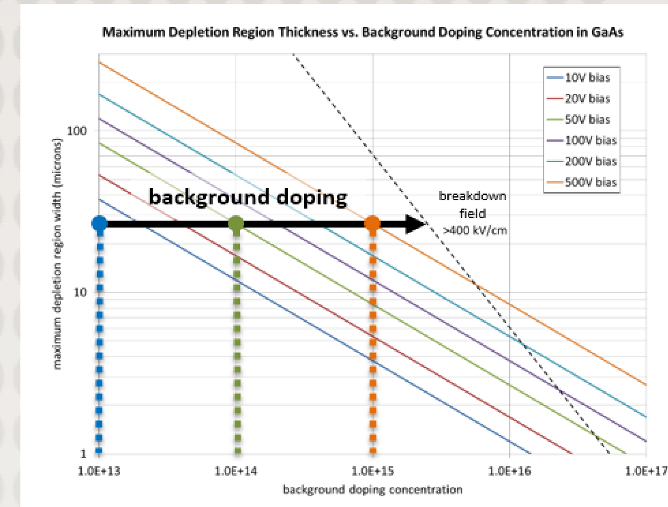
Small devices (2 µm thickness) showed improved stability with Si_3N_4 passivation



Background dopant concentration is critical to increasing thickness



Measured in 20µm MBE layer: $3x10^{14}$ cm^{-3}
Full depletion expected around 90 V



Absorption Efficiency Measurements

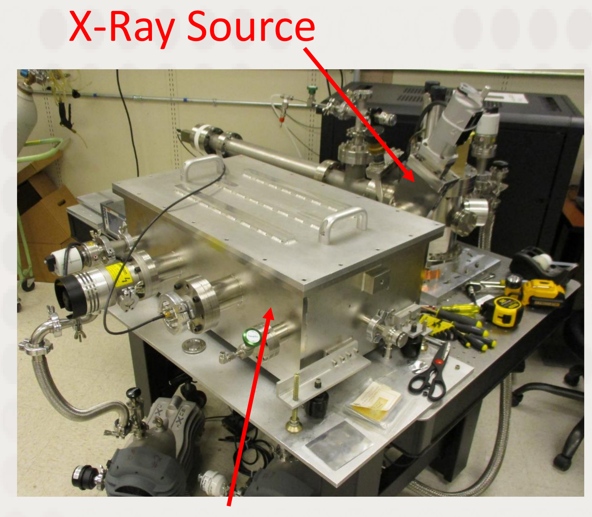
DC X-Ray absorption verification using Manson source

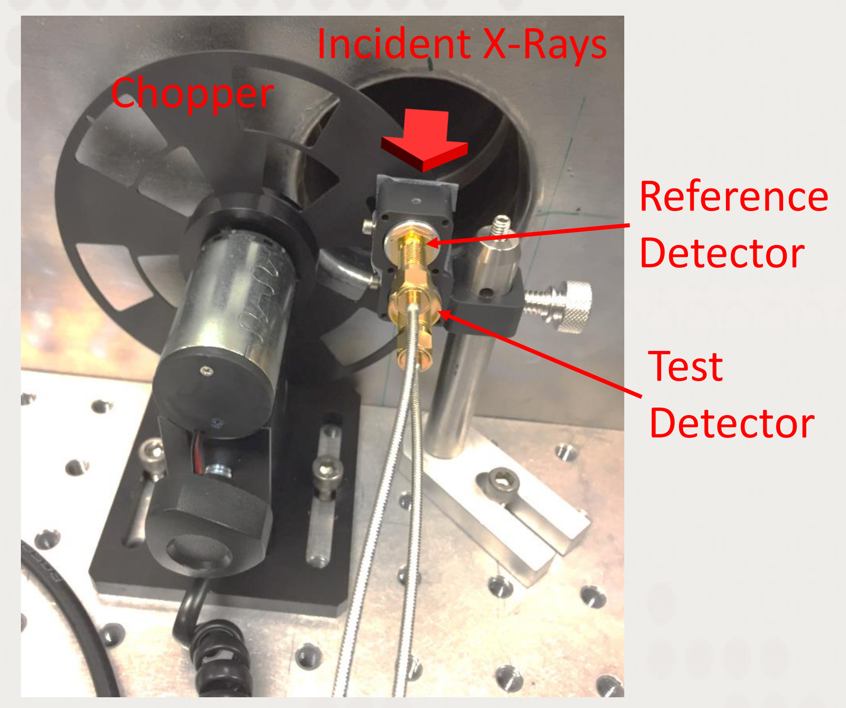
e^- beam (20 keV)

Anode Material

K_α, K_β, L x-rays

Anode Material	K_α Energy (keV)	K_β Energy (keV)	L Energy (keV)
Fe	6.403	7.057	0.705
Cu	8.047	8.904	0.930
Ge	9.885	10.98	1.186



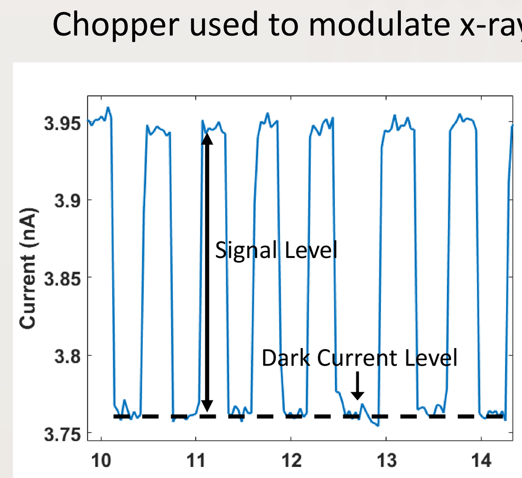


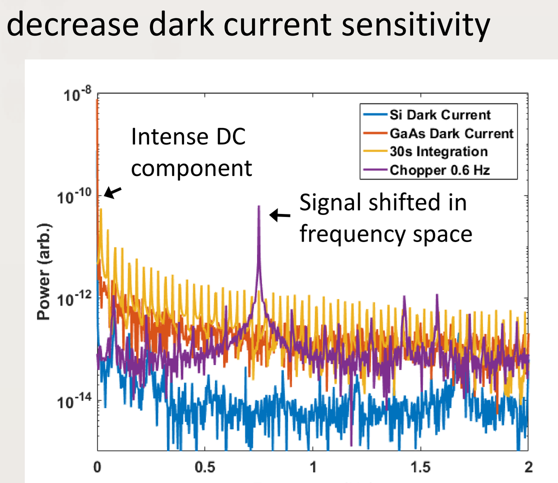
Dark current:
Si ~0.6 nA
GaAs ~4-7 nA

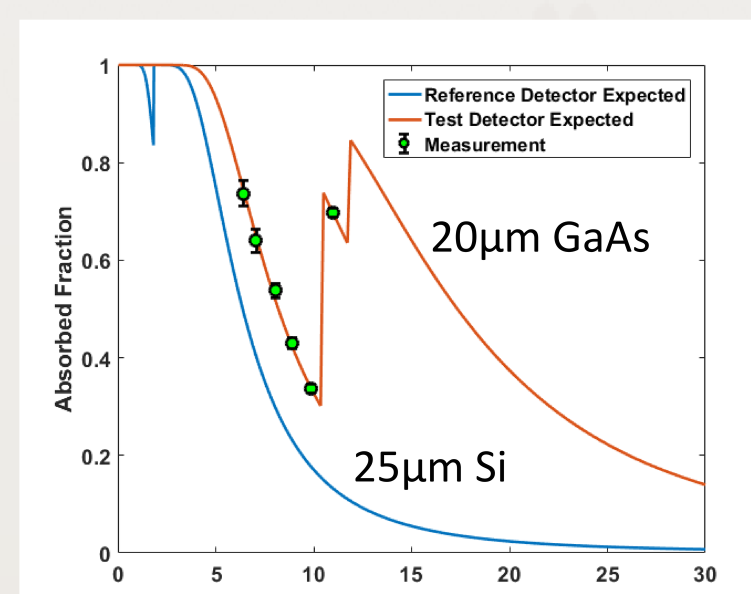
$$I_{signal} = \frac{\Phi_{inc} A_{det} E_{inc} q}{w}$$

Φ_{inc}: Incident photon flux
A_{det}: Detector absorption fraction
E_{inc}: Incident photon energy
q: electronic charge
w: electron-hole pair creation energy

Chopper used to modulate x-ray flux, decrease dark current sensitivity







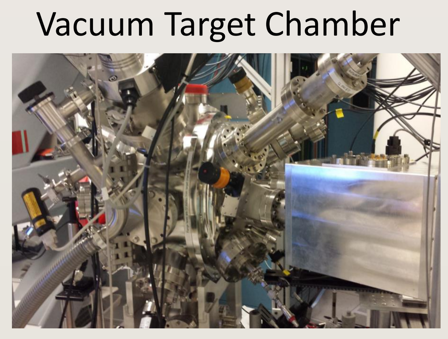
X-Ray attenuation length data from [3]

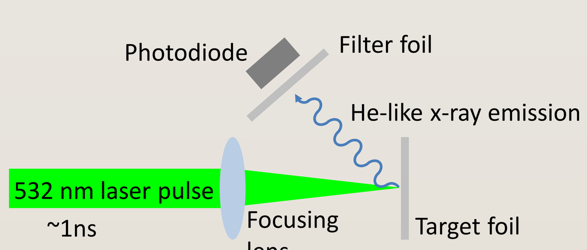
We verified our fast GaAs detectors are absorbing x-rays with the expected increased efficiency

Pulsed Measurements

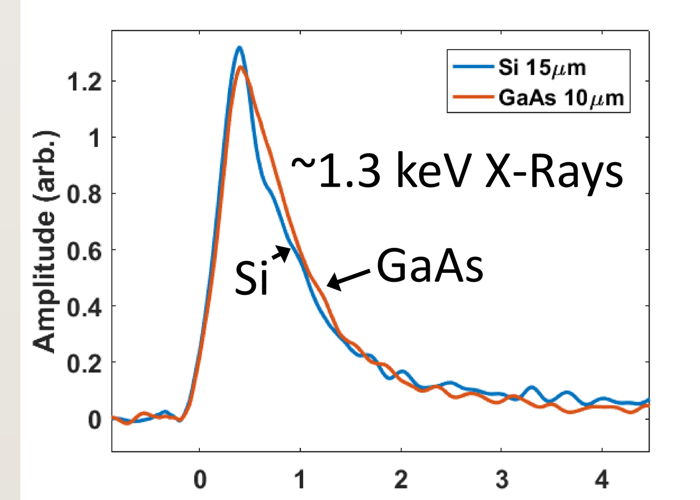
Pulsed x-ray measurements conducted by focusing intense laser radiation on a target foil

Vacuum Target Chamber



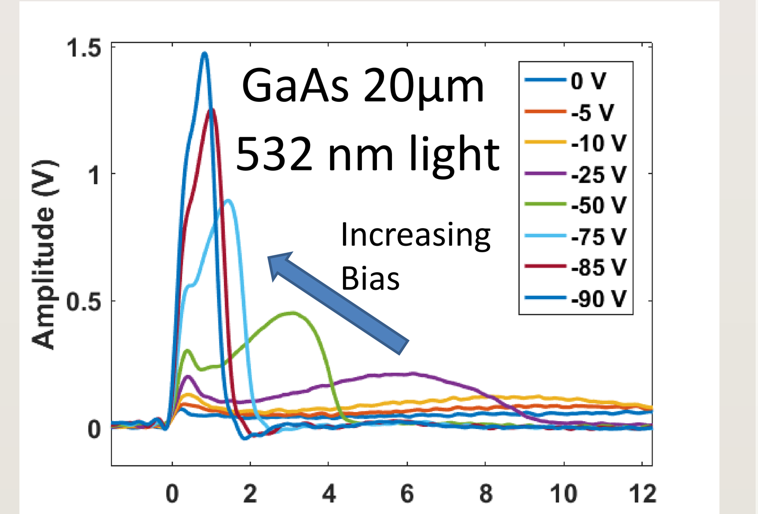


Readout from Si and GaAs diodes



Pulses scaled by relative device area and e-h pair creation energy show equally fast time response

Green Laser Illumination



Illumination by green light pulses shows device approaching full depletion

Conclusion

- GaAs diodes provide an alternative to Si diodes that bypasses tradeoff between detector size and speed
- Sandia has fabricated fast (~ns response time) GaAs diodes with up to 20µm absorber thickness
- These have been demonstrated to respond to fast x-ray pulses as fast as a similar Si diode
- Higher hard x-ray absorption properties have been demonstrated with the same GaAs detectors

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[1] S. A. Slutz et al, Phys. of Plasmas Vol. 17, p. 056303 (2010)
[2] R. D. McBride et al, Phys. of Plasmas Vol. 20, p. 056309 (2013)
[3] LBL CXRO database: http://henke.lbl.gov/optical_constants/atten2.html