UNIVERSITY AT ALBANY
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COLLEGE OF NANOTECHNOLOGY, SCIENCE, AND ENGINEERING
UNIVERSITY AT ALBANY | STATE UNIVERSITY OF NEW YORK

Toward Sub-10 ps Time Resolution in InAs/GaAs Quantum Dot Scintillation Detector

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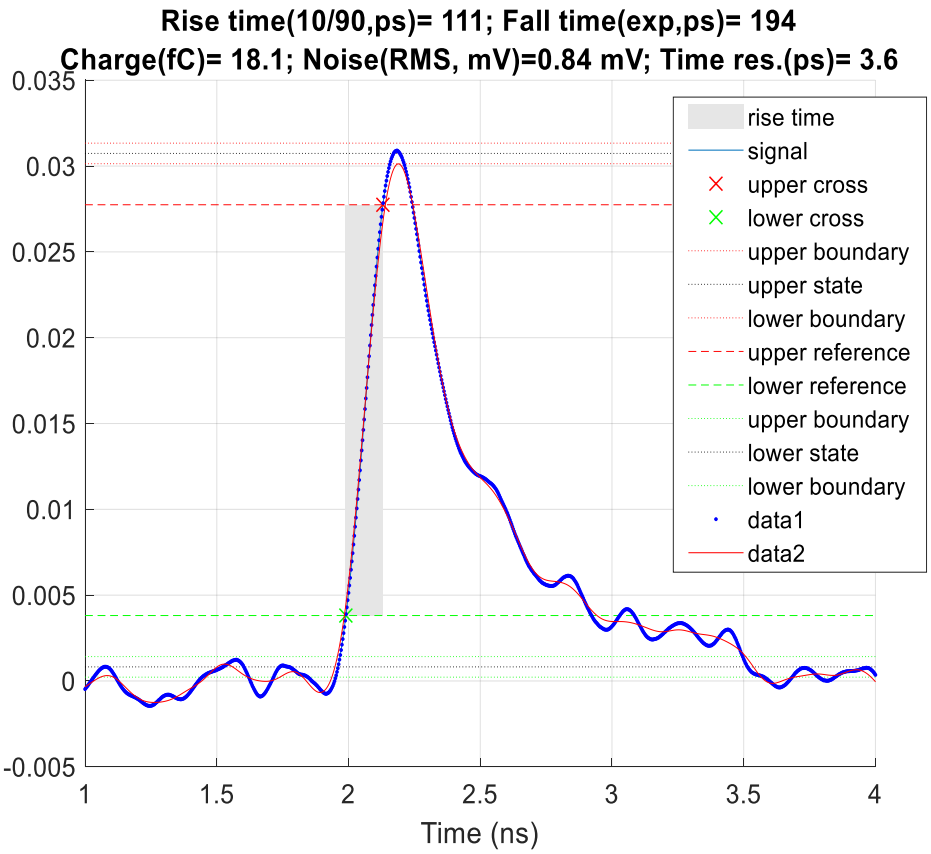
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We demonstrated novel device with InAs quantum dot base scintillator



We believe device has a lot more potential

- Fast scintillation process in semiconductor

~0.1 ns risetime (for apha)

~ 10 ps jitter

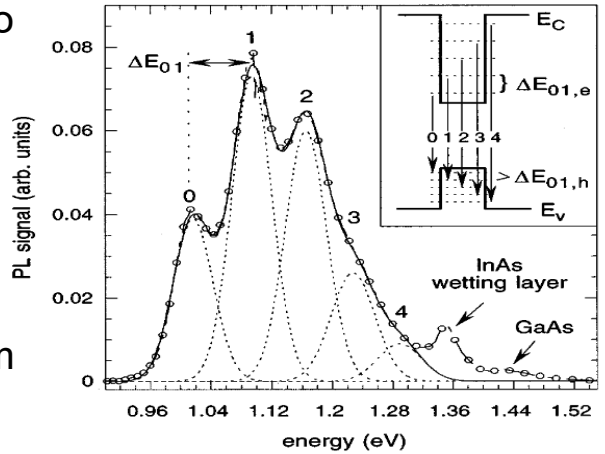
- Possible to achieve those parameters for MIP

Problems exit

InAs Quantum Dots

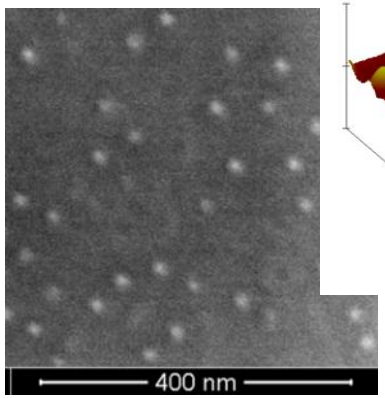
InAs Quantum dots:

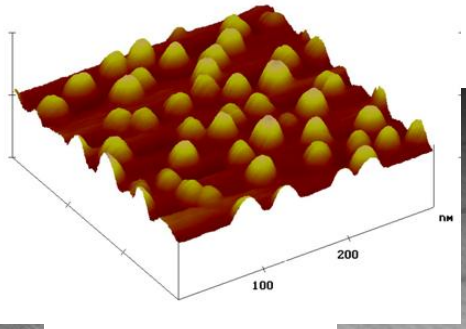
- Islands of InAs formed on GaAs surface during growth due to lattice mismatch
- Capped and embedded into GaAs / AlGaAs matrix
- Each dot is a potential well
  - electrons and holes 3D confined
  - Discrete energy levels are formed
  - Broadening in ensemble due to inhomogeneity in size
  - Electron-hole transitions produce light, ~1 eV or 1200 nm wavelength

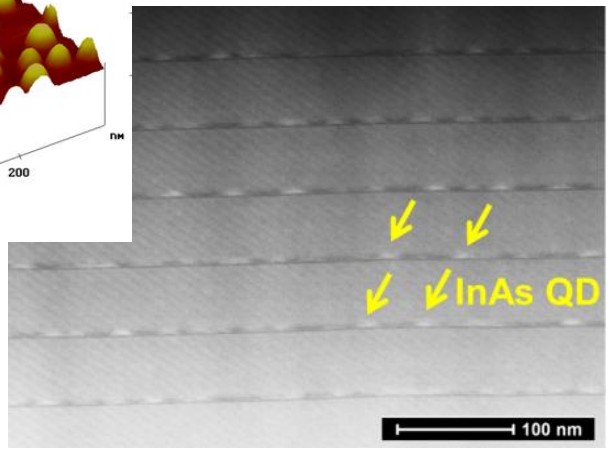


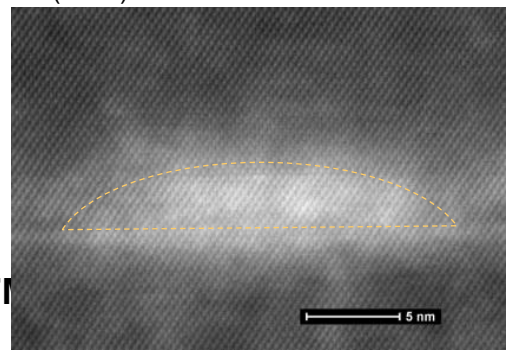
Photoluminesce spectra: Transitions between levels vs spectral lines

Figure from: Schmidt, Klaus H., et al. "Carrier relaxation and electronic structure in InAs self-assembled quantum dots." *Physical review B* 54.16 (1996): 11346.









Imaging of QDs: TEM, SEM, AFM

TEM cross-section of an individual InAs dot

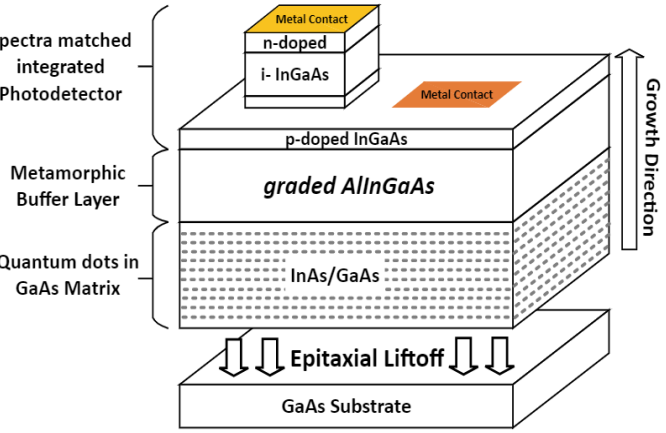
- QD diameter (FWHM)~ 18.7nm
- QD density (2.7-4.2) x 10^{10} cm^{-2}

Other applications of InAs QDs:

- QD semiconductor lasers
  - low threshold current, defect tolerance
  - considered for Si integration
- QD infrared photodetectors (QDIP) for mid-IR

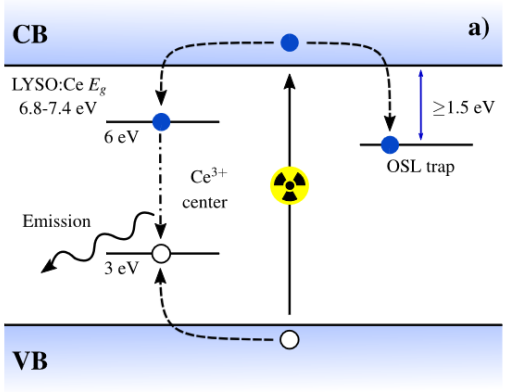
InAs QD scintillator

QD:
Fast scintillation, <0.50 ns



- Same basic physics as regular scintillator:
  - Generated carries captured by recombination center in a wide bangap matrix
    - Low matrix absorption of emitted light for both
    - different physical nature of recombination center
    - High quality semiconductor as a matrix vs oxide crystal
      - **High electron mobility in GaAs and fast recombination in QDs**
- GaAs/InAs structure has more engineering capabilities

LYSO:
Fast scintillation, <50 ns



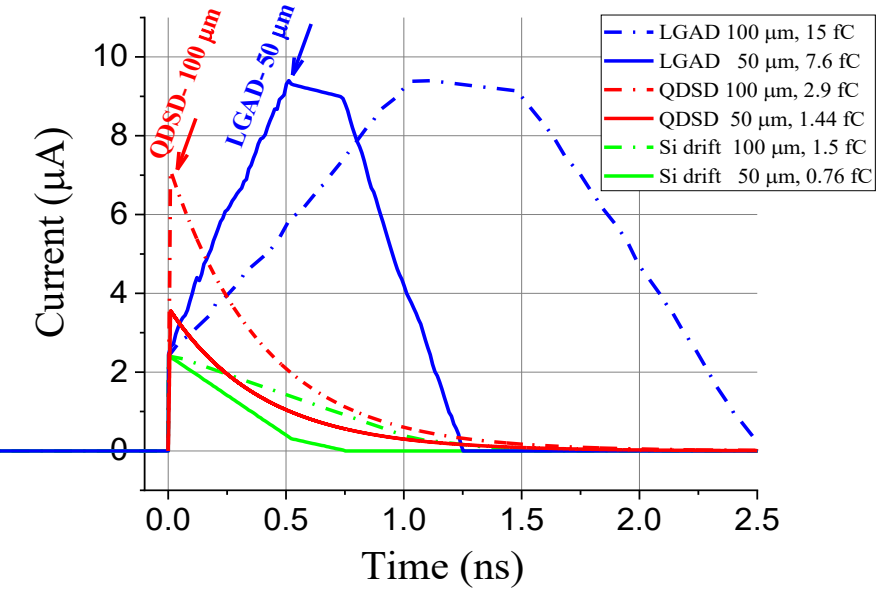
Jensen, Mads L., et al. "Optically stimulated luminescence in state-of-the-art LYSO: Ce scintillators enables high spatial resolution 3D dose imaging." Scientific Reports 12.1 (2022): 8301.

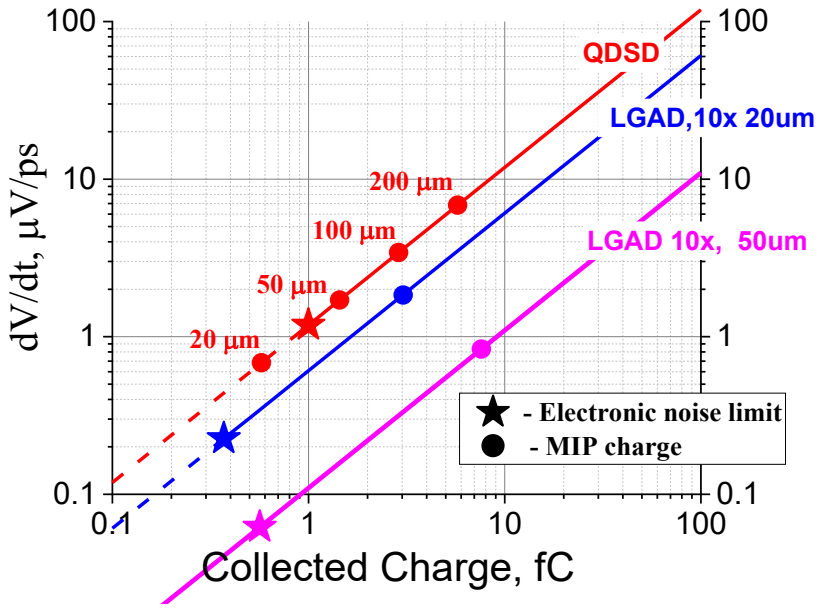
Device fabrication:

- Epitaxial structure is grown on GaAs, consisting of thick QD layer and integrated photodiode
- Photodiode is processed on top of scintillator
- Device is separated from the structure by epitaxial lift-off

Result:
- GaAs planar waveguide with embedded QD recombination centers and integrated photodetector

Modeled Response Comparison





Simulated MIP-induced currents from a QD scintillation detector with an integrated photodiode (this work), a Si LGAD (10× gain), and a non-amplified Si detector (Weightfield2)

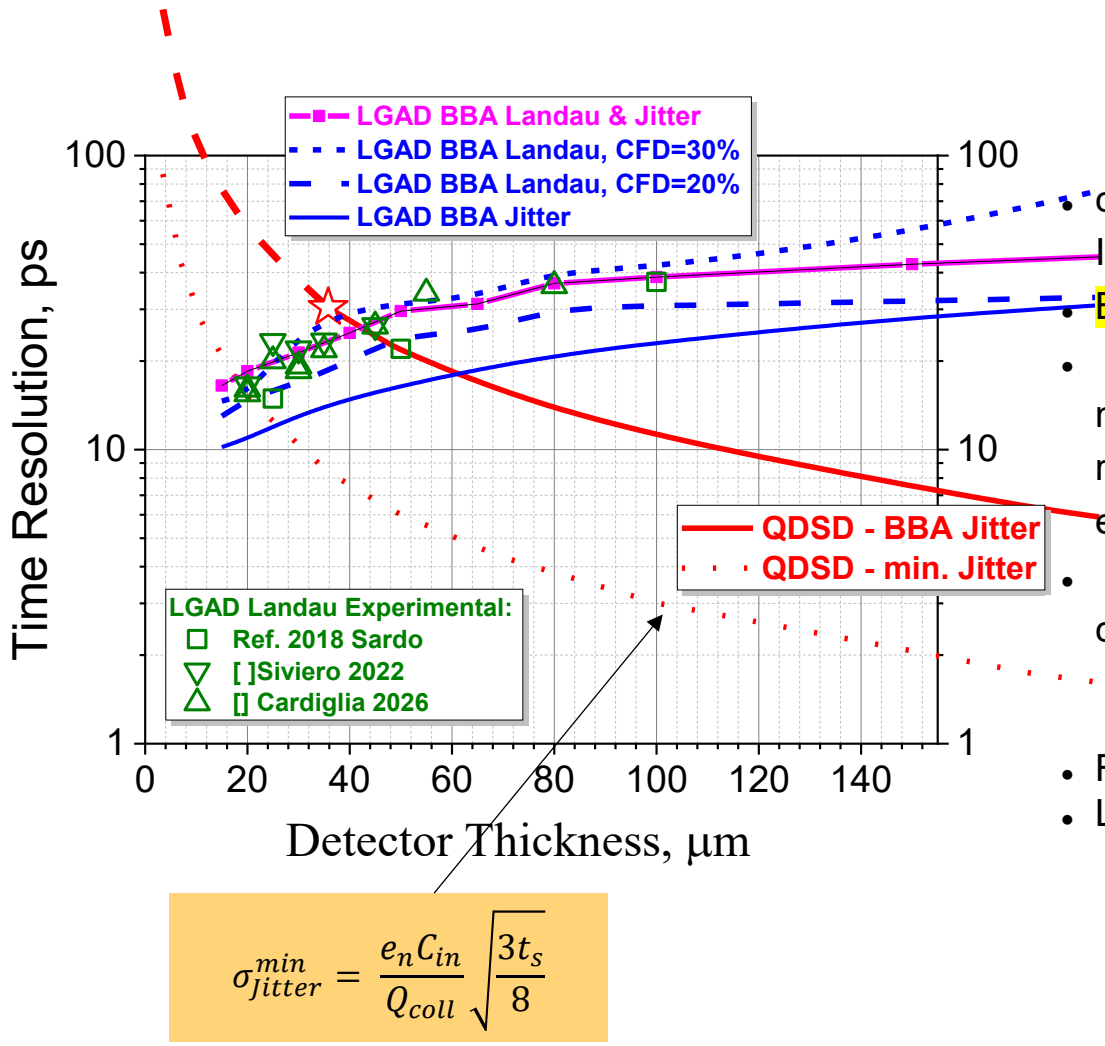
QD scintillator response:

- Total number of carriers generated in GaAs is similar to Si of the same thickness

- **High initial current output,** with a short risetime (few ps estimated)
- **Short pulse** – higher fraction of energy is processed per unit time
- **Pulse width independent of scintillator thickness**

- Signal in QD scintillator is collected from entire volume simultaneously
  - **Landau noise is averaged out.**

Modeled Thickness Scaling

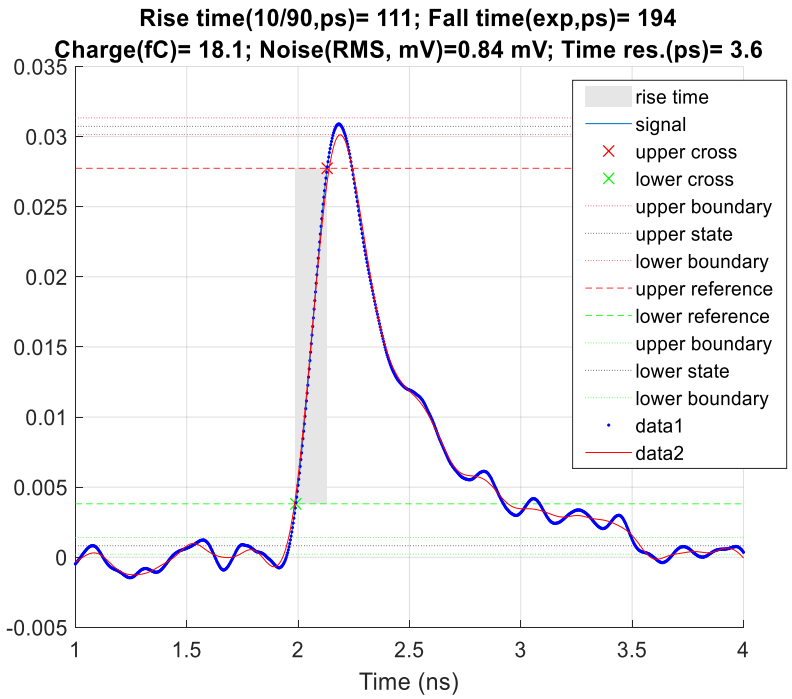


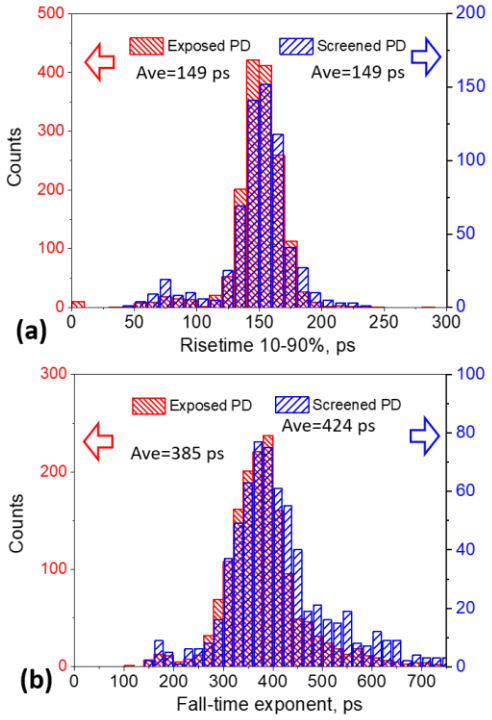
$$\sigma_{Jitter}^{min} = \frac{e_n C_{in}}{Q_{coll}} \sqrt{\frac{3t_s}{8}}$$

- comparison of the MIP time resolution of InAs/GaAs QDSD with Si LGAD (10× gain)
- Both detectors with 100% conversion efficiency
- Solid lines: jitter with BBA front end C_{in}=1 pF, noise bandwidth matched to the signal risetime. The star indicates the QDSD electronic noise-limited collected charge
- Dotted line: minimum achievable time jitter for centroid timing

- Ramo current times affect timinig
- Light propagation in the structure is fast
  - InGaAs photodiodeis the same

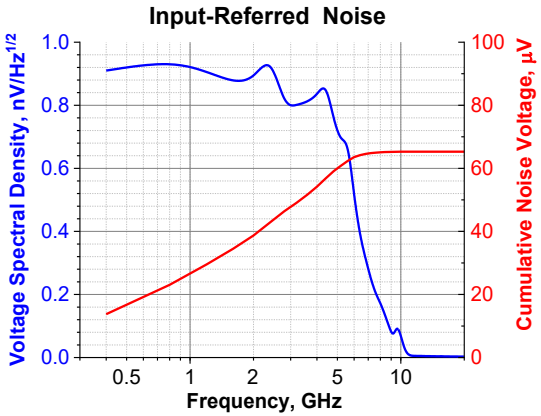
Experimental Timing: Alpha Particles



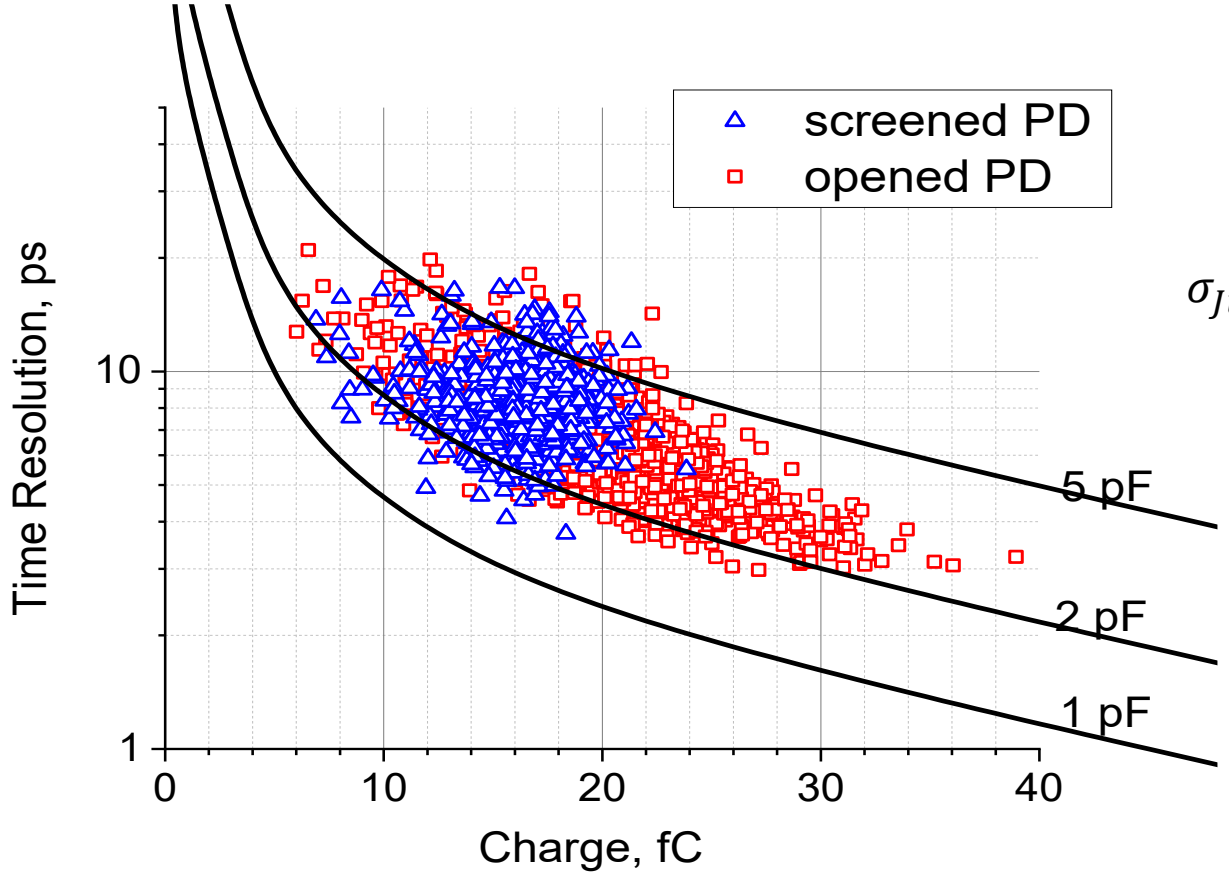


- Example of alpha particle detected pulse (BBA, 4 GHz, 22 dB, 5 dB noise figure
- More energy released than with MIP
  - can be tested on existing device

    ~150 ps for 10-90 risetime is observed
- Input referred noise 0.9 nV/Hz$^{1/2}$



Experimental Timing: Alpha Particles

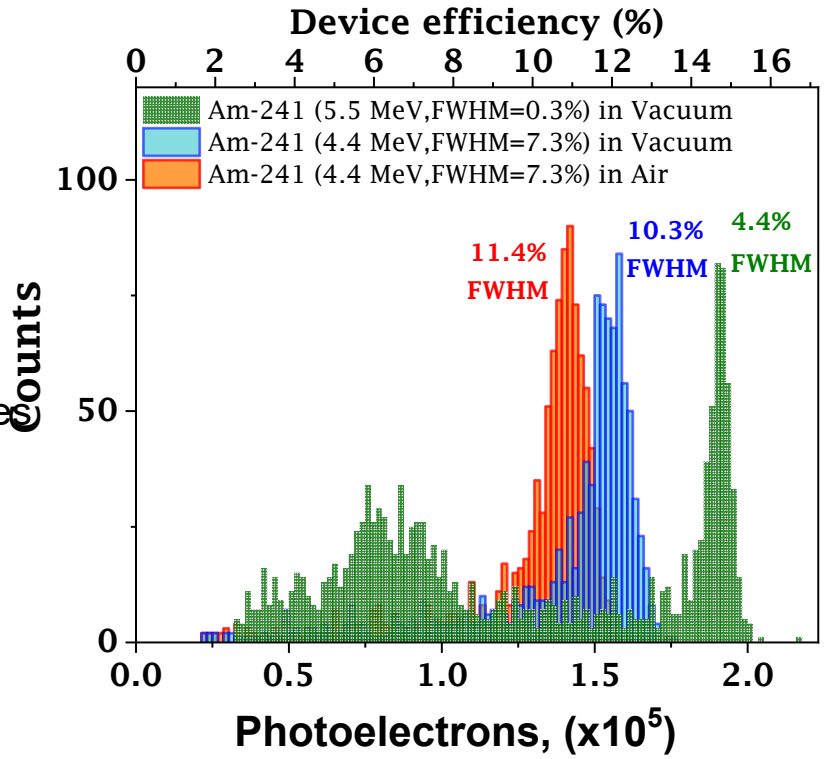


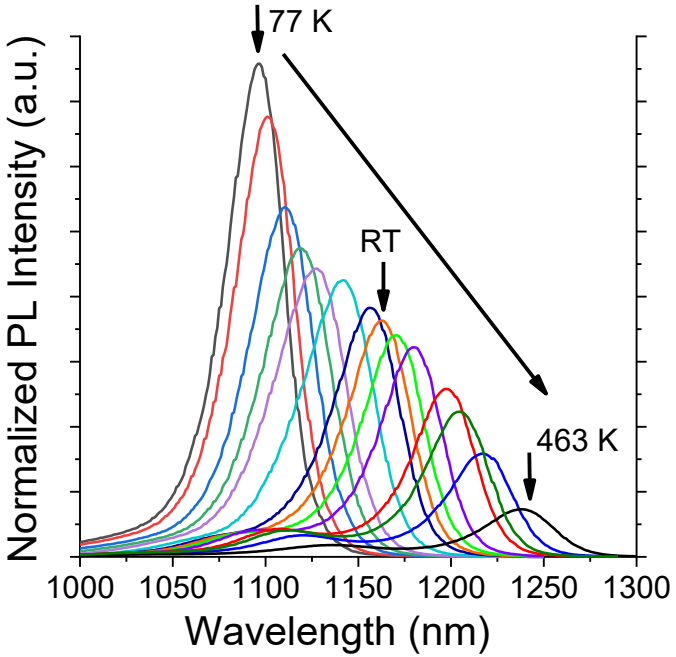
$$\sigma_{Jitter} \approx \left(\frac{v_n}{\Delta V/\Delta t}\right)$$

- Measurements with alpha-particle illumination in area including photodetector ("opened") and excluding diode area ("screened") shows <10ps-range timing
- Matches expected jitter values for the energy
- Input referred RMS noise 66 μV in 4 GHz BW
- Time resolution: <10 ps out of the box

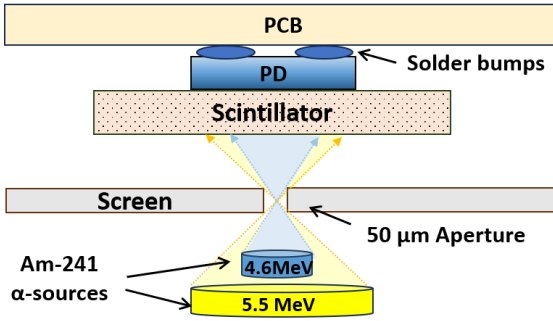
Energy Conversion Efficiency

- Textbook energy per e-h pair value: 2.8Eg = ~4 eV
- Expected pairs from 5.5 MeV alpha particle: >1e6
- Actually detected photons: <2e5
  - Device efficiency ~15% due to:
  - optical losses in waveguide and through backside
  - Low barrier around quantum dots in current devices
    - affects radiation hardness as well

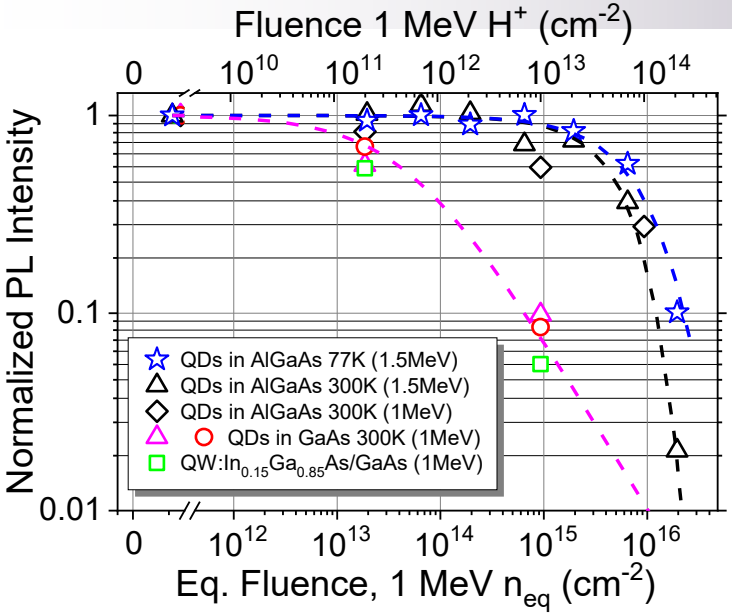




- timing estimates use 100% collection efficiency
- Current devices have 15% at room temperature

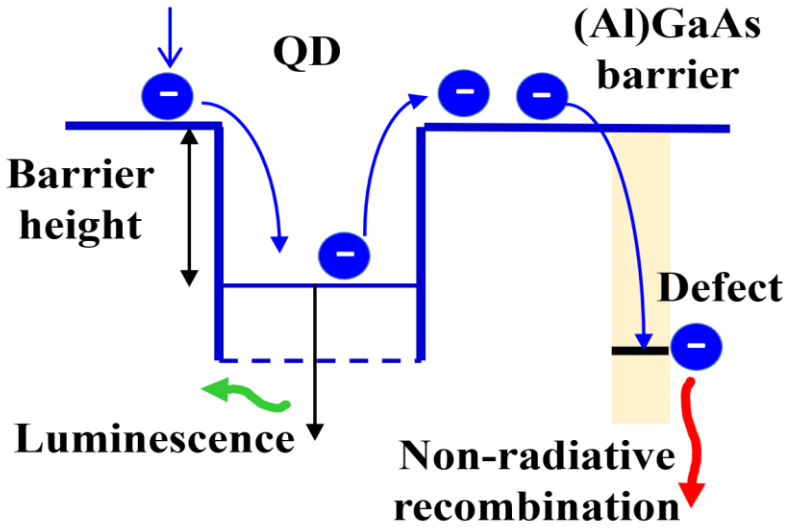


QD media: Radiation Hardness



$$\varphi_{n,1MeV} = \frac{NIEL_p}{NIEL_{n,1MeV}} \varphi_p = 93.2 \cdot \varphi_{p,1MeV}$$

- Quantum dot structures are more radiation tolerant than bulk semiconductors
- Confinement reduces defect recombination chances for captured carriers
- Quick capture and low escape probability are desired
- Low temperature and higher engineered barrier improve optical efficiency and defect tolerance
-
- Neutron transmutation:
  - Not addressed yet
  - Some extra n-type doping should be tolerated by p-doped media



, Summers, Geoffrey P., et al. "Damage correlations in semiconductors exposed to gamma, electron and proton radiations." *IEEE Transactions on Nuclear Science* 40.6 (1993): 1372-1379.

C. Baur, M. Gervasi, P. Nieminen, S. Pensotti, P. Rancoita, and M. Tacconi, "NIEL dose dependence for solar cells irradiated with electrons and protons," in Astroparticle, Particle, Space Physics and Detectors for Physics Applications: Proc. 14th ICATPP Conference, 2014, pp. 692-707.

Summers, G. P., et al. "Displacement damage in GaAs structures." *IEEE Transactions on Nuclear Science* 35.6 (1988): 1221-1226.

Akkerman, A., et al. "Updated NIEL calculations for estimating the damage induced by particles and γ-rays in Si and GaAs." *Radiation Physics and Chemistry* 62.4 (2001): 301-310.

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Summary

Fast scintillator based on InAs QDs in GaAs matrix is demonstrated
Technology of epitaxial growth gives a lot of knobs to tweak for optimizing device properties

Such system can naturally achieve <10 ps timing due to:

- **Fast optical collection of signal**
- **High electron mobility in GaAs and fast recombination in QDs enabling fast scintillation**
- **High initial output – maximum current is achieved within few ps of particle transit**
- **Landau noise is averaged out by collecting signal from entire device thickness.**

Present devices are a proof-of-concept with insufficient thickness and non-optimal parameters

Proof of timing viability is presented