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InAs/GaAs Semiconductor Quantum Dot Scintillation Detector: Real and Projected Performance for 4D Tracking

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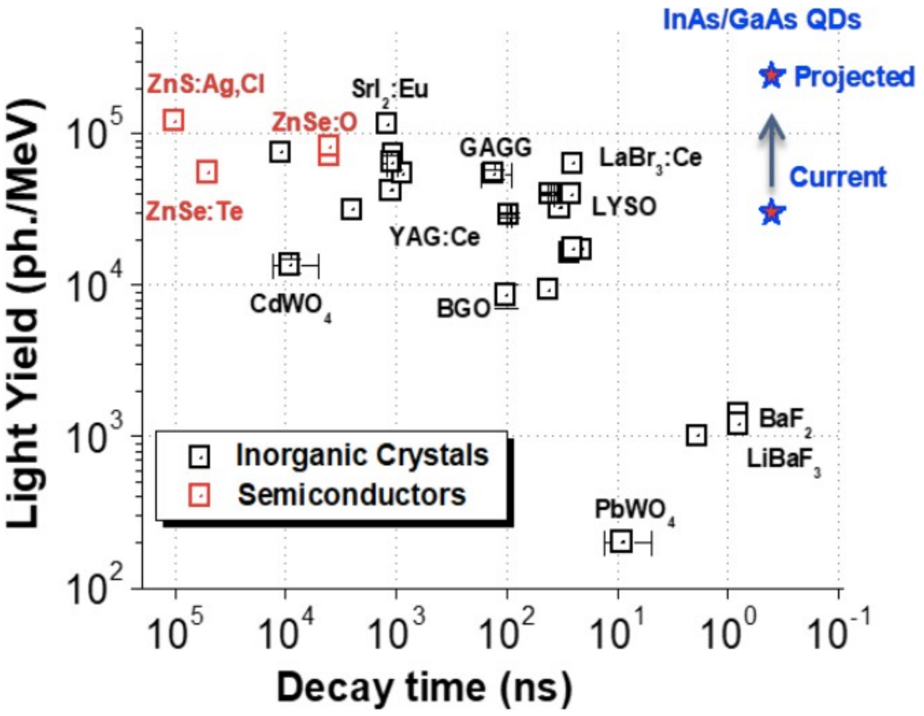
Outline

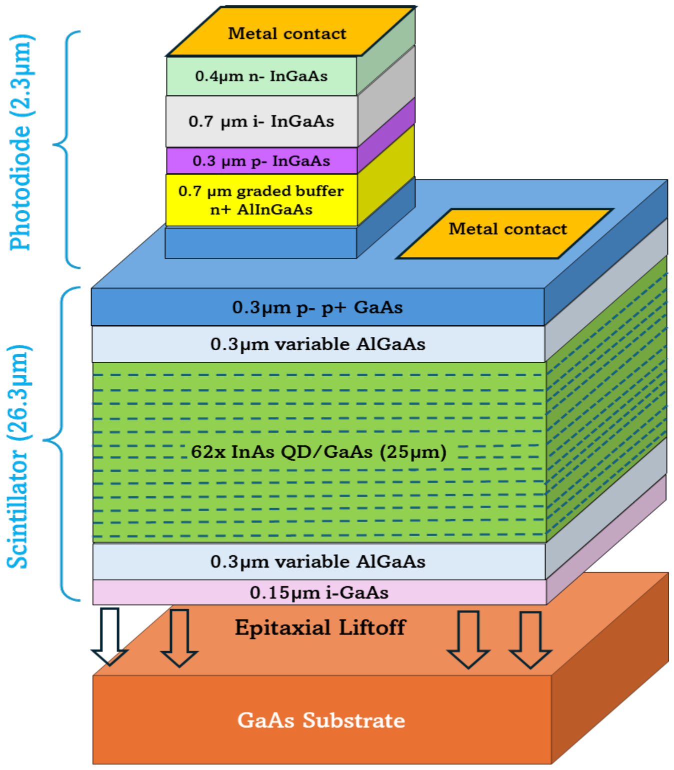
- **Quantum dot scintillation detector: Some physics and technology**
  - **Semiconductor QDs as luminescent centers**
  - **Integrated photodetector**
  - **Waveguiding**
- **QD Scintillator vs. LGAD**
- **Efficiency**
- **Hybrid detection**
- **Noise and timing**
- **Radiation hardness**
- **Challenges and Summary**

QD Semiconductor Scintillator: Properties and Technology

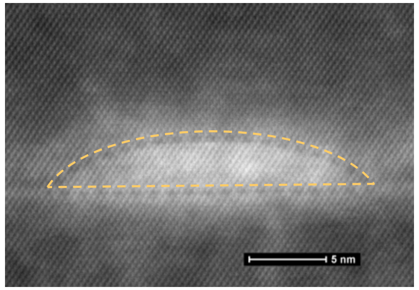
Comparison to some crystal inorganic scintillators



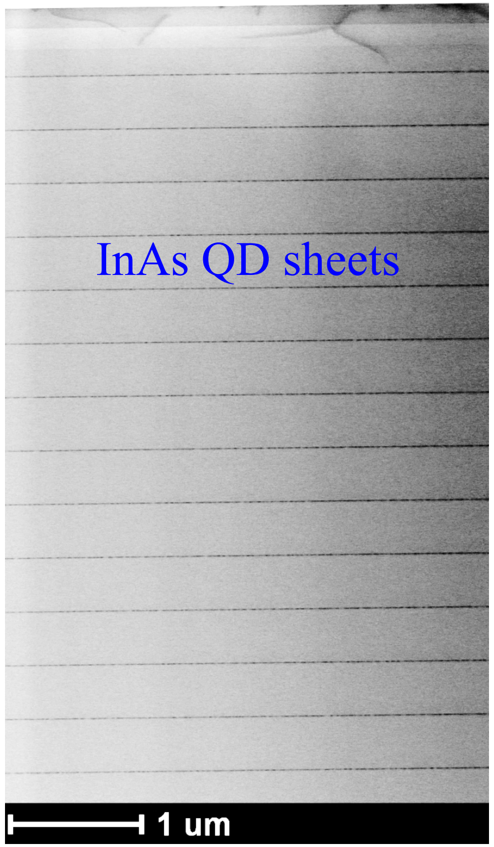
(Source: scintillator.lbl.gov)



Individual InAs QD: Artificial luminescence center



STEM of QD multilayer waveguide

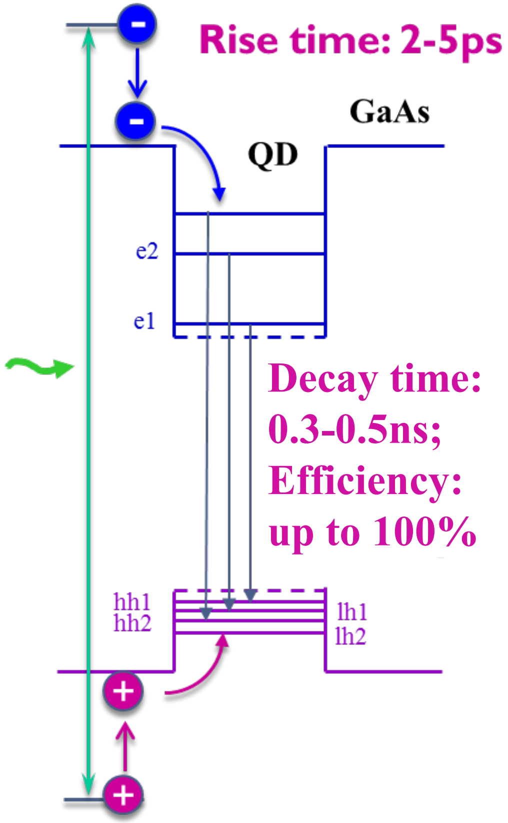


QD diam. (FWHM)~ 18.7nm
QD density (2.7-4.2) x 10^{10} cm^{-2}

QD Semiconductor Scintillator: Physics

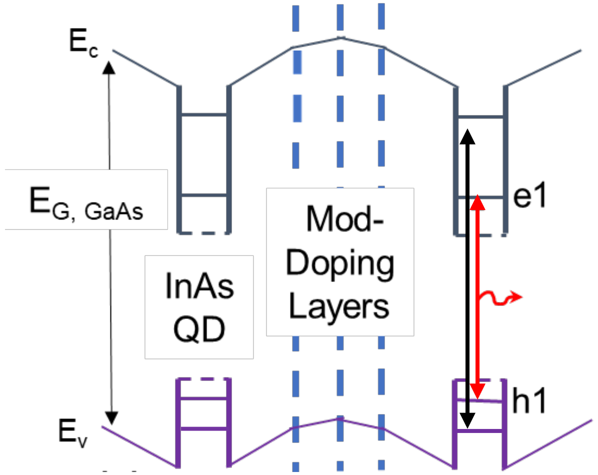
- **Ionization efficiency in bulk semiconductor (e.g. GaAs) with generation of e-h pairs :**
  - 4. 2 eV/pair (vs. ~20 eV per pair in inorganic scintillators) → 240,000 pairs/MeV
- **Capture of electrons by p-type QDs:**
  - Capture of minority carriers (electrons)
  - Typical time 2-5ps, field-enhanced
- **QD luminescence:**
  - λ~1µm, emission time <0.5 ns
  - Efficiency : up to 100%
  - High radiation hardness of QDs over bulk semiconductor

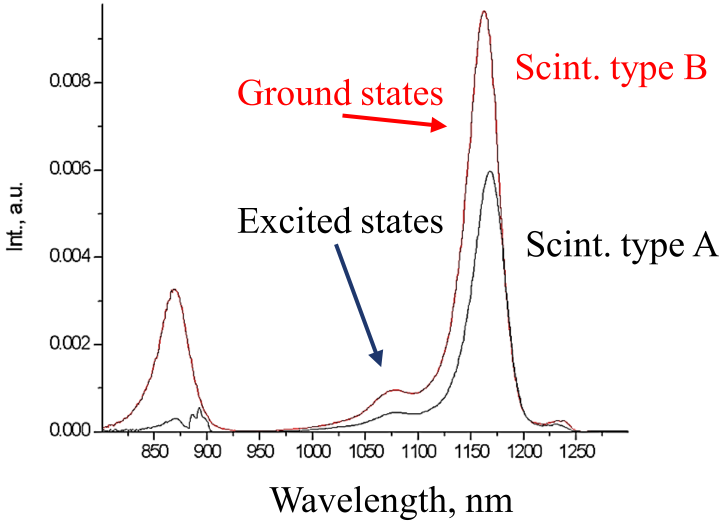
Band structure of a QD



Oktyabrsky et al. 2016, IEEE TNS
doi:10.1109/TNS.2015.2502426

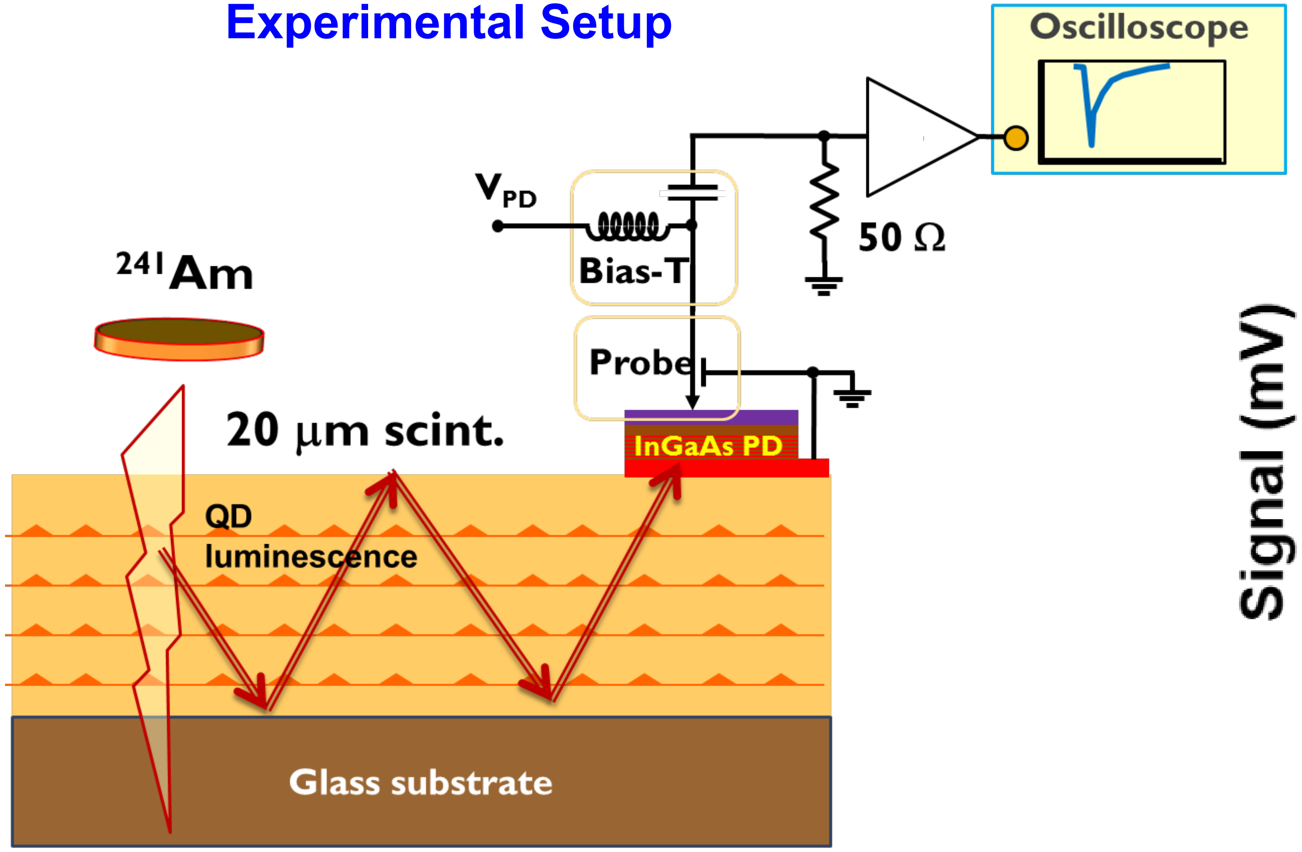
Band Structure and Luminescence Spectra



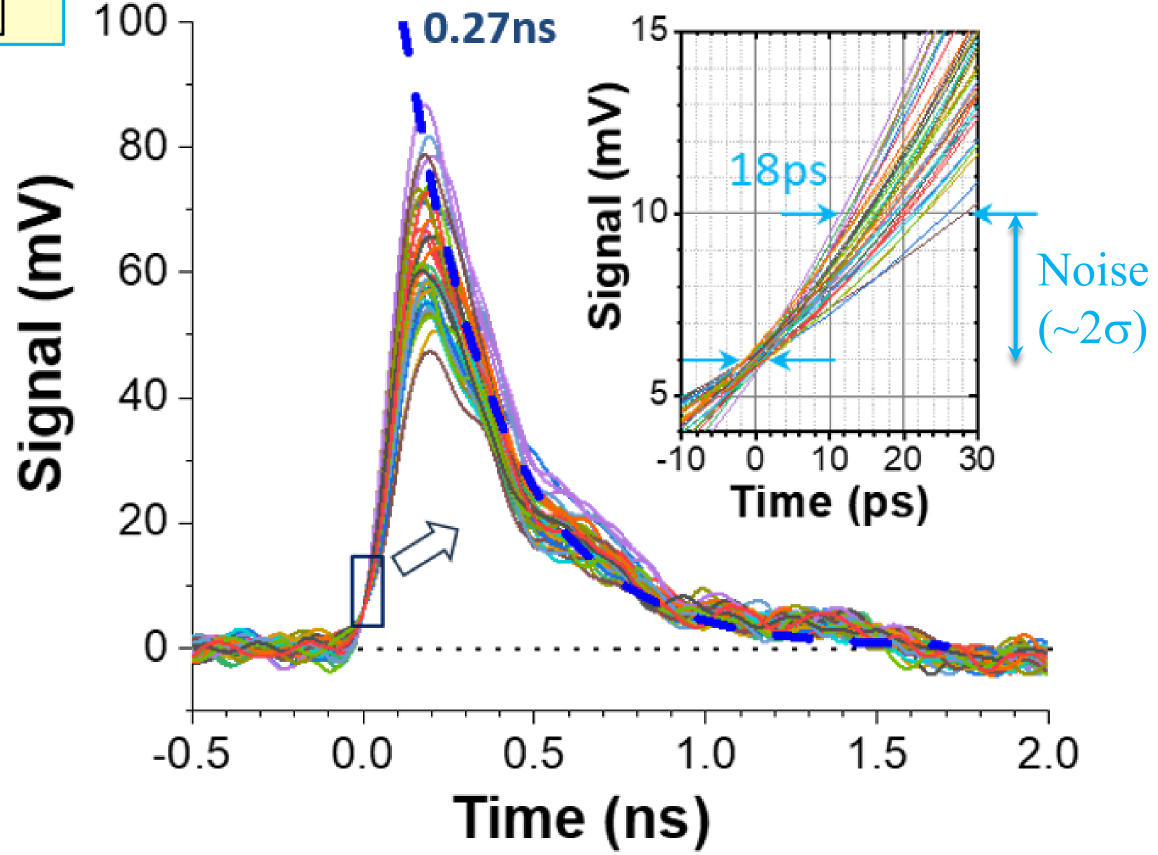


20 μm detectors: Charge collection from α-particles

Experimental Setup



4.5 MeV alpha-response with 6 GHz bandwidth

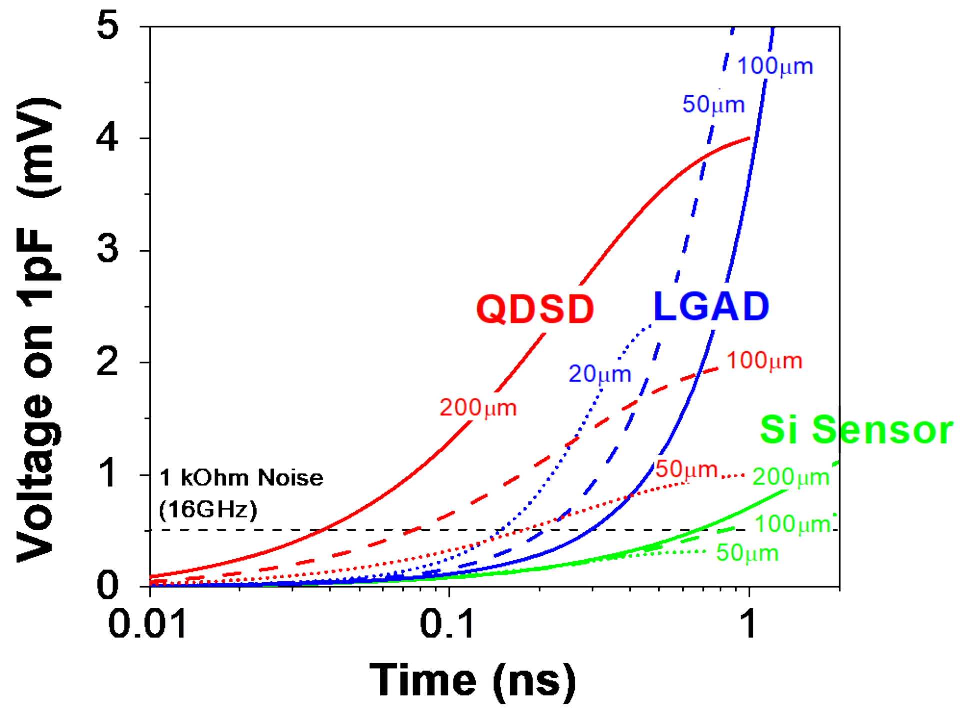


- **Decay time ~300 ps**
- **Time resolution ~ 20ps at ~4.5 MeV deposited energy**

K. Dropiewski,et al, "Ultrafast waveguiding quantum dot scintillation detector," Nucl. Instrum. Methods Phys. Res. A (2020).

Time Resolution of "4D" Trackers

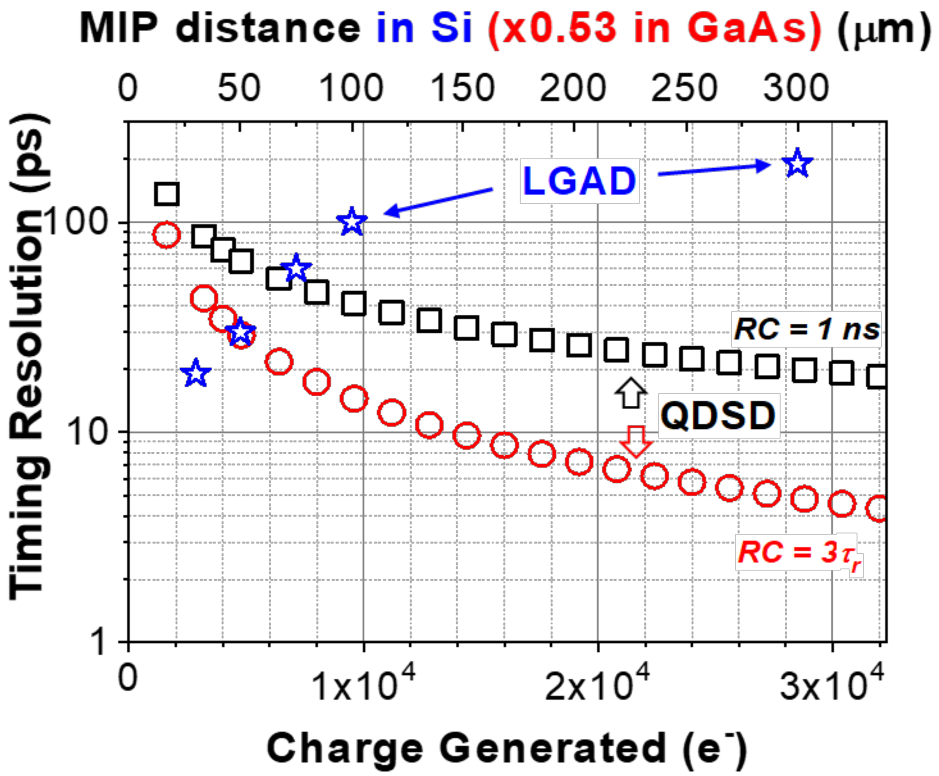
Simulated pulse leading edge generated by MIP:
In Si: 95 el./1µm
In GaAs: 180 el./1µm



- QD Detector (gain or efficiency=1)
- Si LGAD (gain = 20) - simulated with "Weightfield2"
- Traditional Si tracking sensor (gain=1)
- All with C=1 pF input capacitance

Time resolution is determined by signal slew rate and noise level

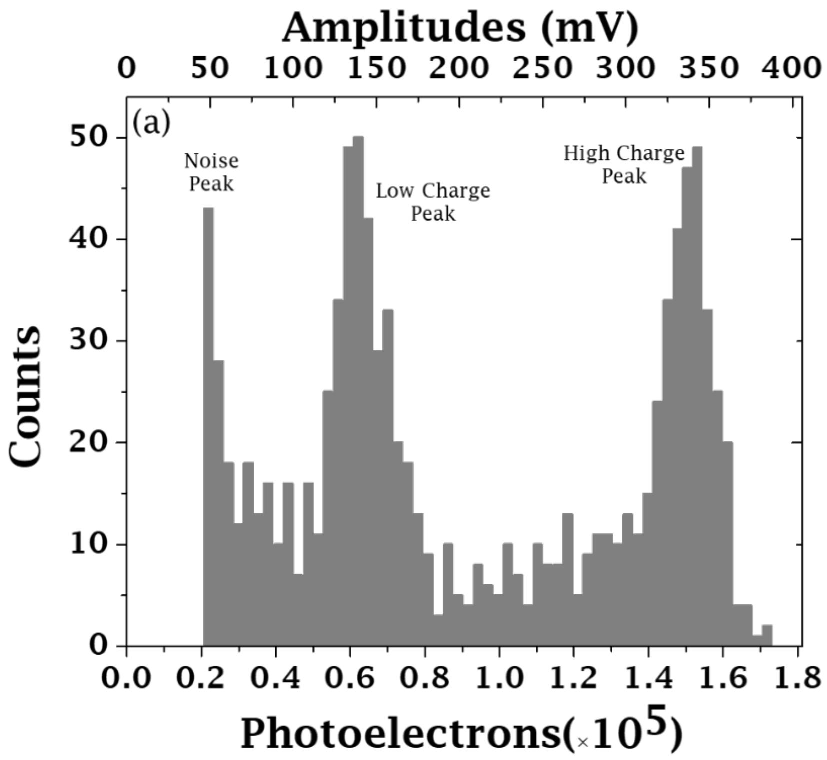
$$\sigma_t = \frac{v_{noise}}{dV_{signal}/dt}$$

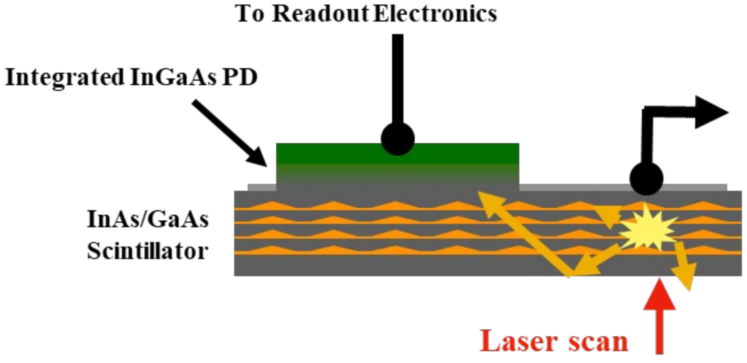


- Time resolution improves with increased thickness (opposite to an LGAD)
- Break-even thickness is 40-70 µm
- No bias overhead

Effect of device geometry on waveguiding

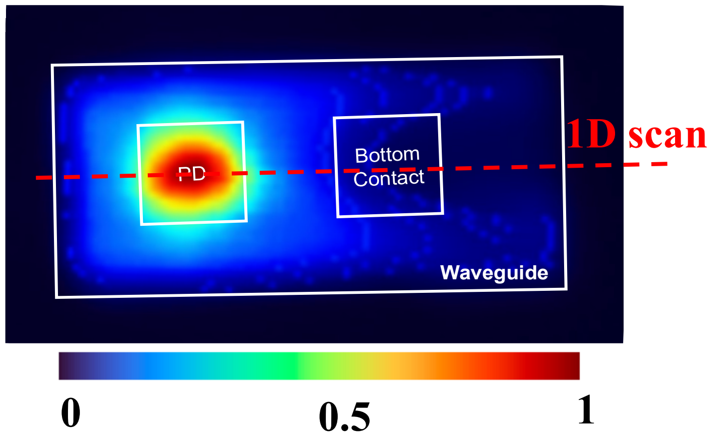
4.5 MeV alpha particle histogram



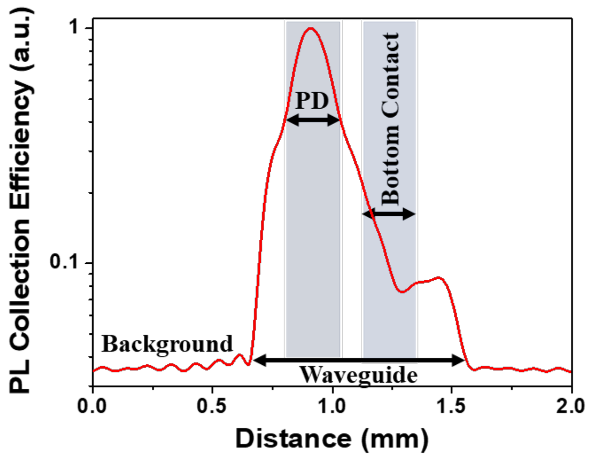


2D photoluminescence map

PD mesa is 300x300 μm^2



PL collection efficiency 1D profile

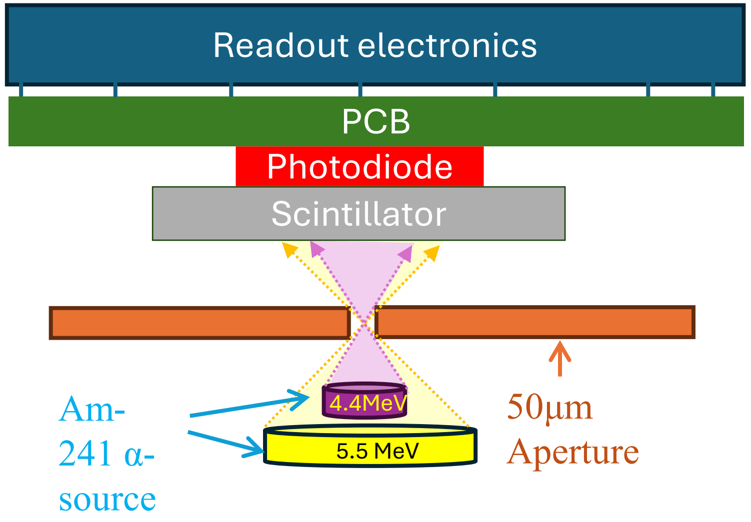


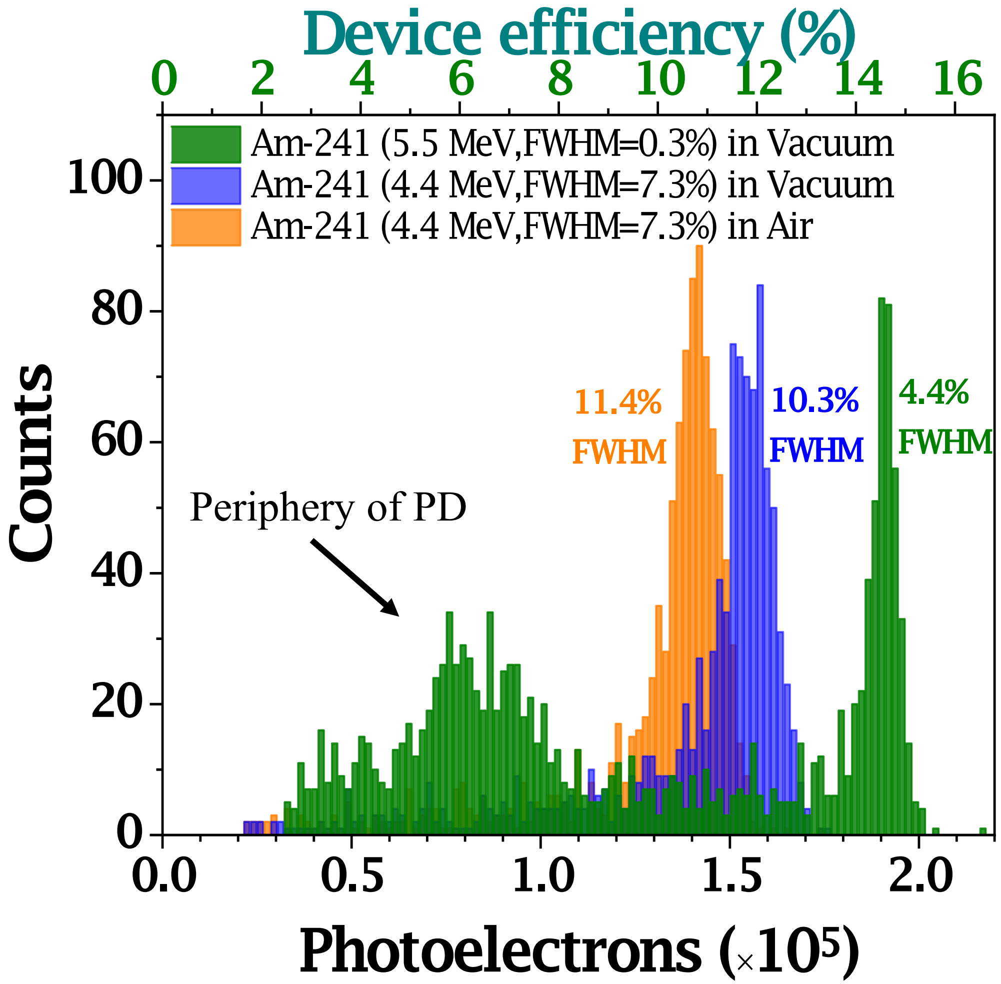
- **High charge peak: Maximum charge collection under the PD**
- **Low charge peak: 2-5x drop in PL efficiency at the periphery of PD**
- **Noise peak: <10% collection efficiency under and beyond the bottom contact**

Mahajan et.al. *Sensors*, *2024*, https://doi.org/10.3390/s24227178

Light Yield and Energy Resolution

Response to alpha particles

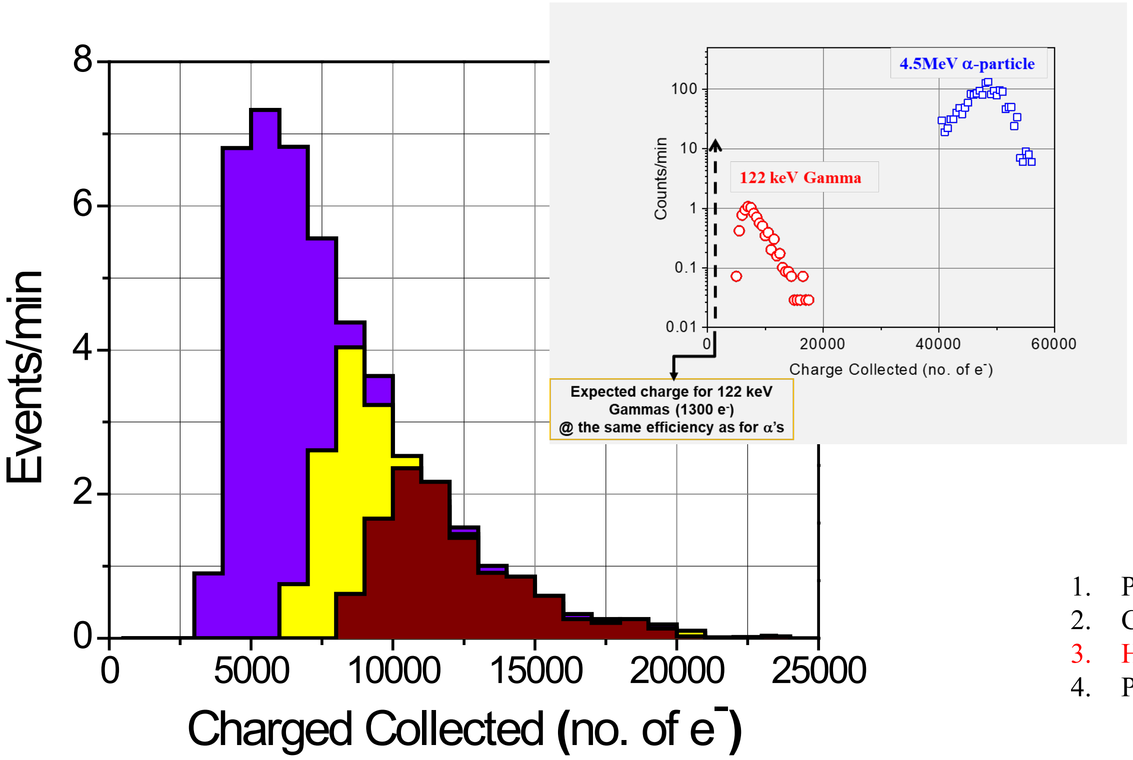




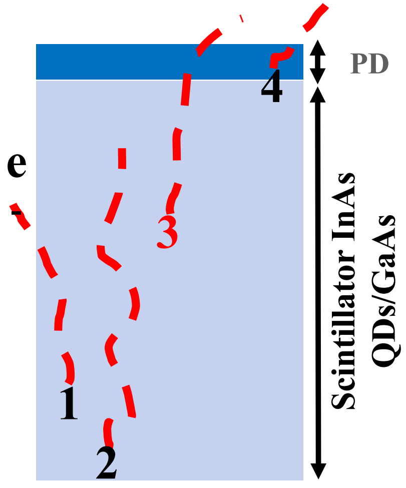
- **Improved 15% total device efficiency: 35 el./keV**
- **Energy resolution down to 4.4% (FWHM) or σ =1.9%**

Hybrid Mechanism of Photon Detection: ^{57}Co

122 keV gamma histograms for different trigger levels (CSA+ShA front end)

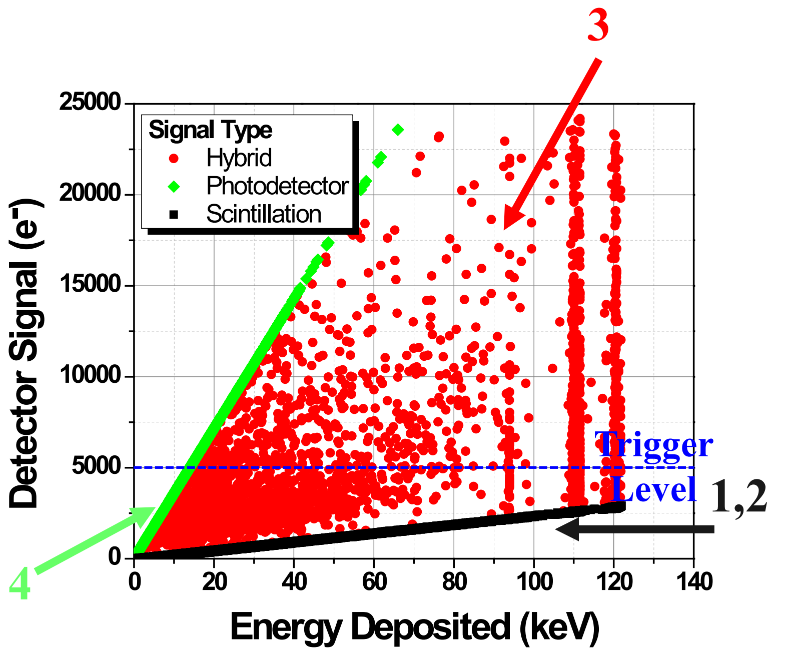


Mechanisms for energy loss



1. Partial energy loss in scintillator
2. Complete energy loss in scintillator
3. Hybrid energy loss in scintillator and PD
4. Partial energy loss in PD

Response Simulated by GEANT4 (Efficiency: scint.: 10%; PD: 80%



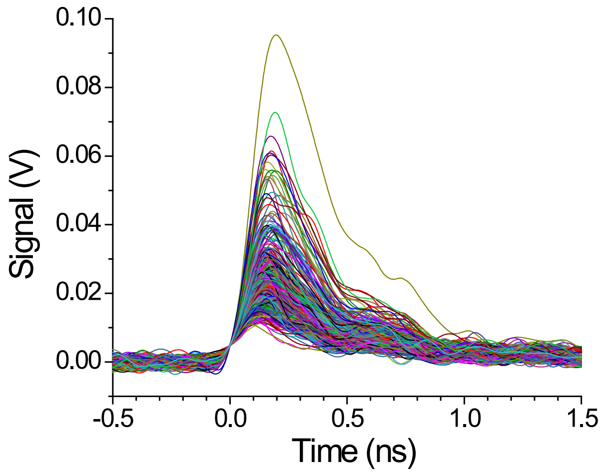
Mahajan et.al. *Sensors*, *2024*, https://doi.org/10.3390/s24227178

- S/N ratio is not enough to observe scintillation signal
- PD direct ionization is responsible for ~15% of events
- 85% of events is due to hybrid response
- Hybrid detection combines/optimizes fast response of the scintillator/PD and efficiency of direct conversion

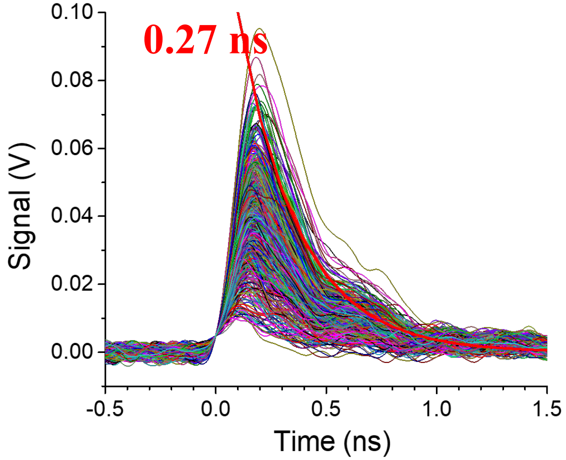
Time Resolution of Hybrid Response

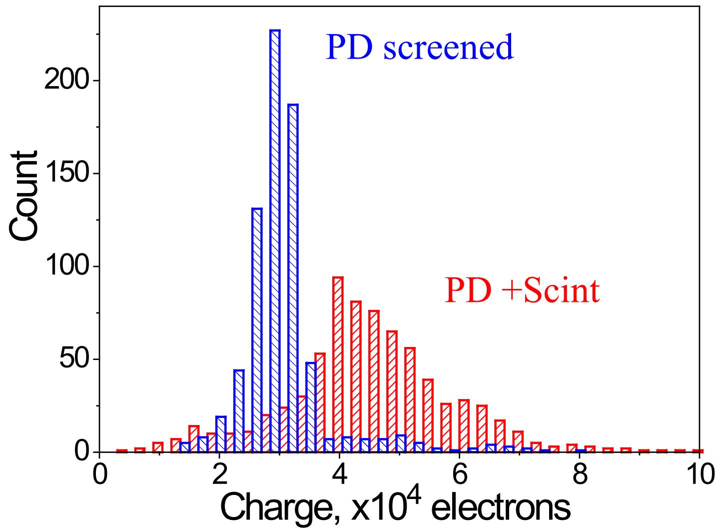
Response from ^{241}Am alphas

Waveguiding scintillator only

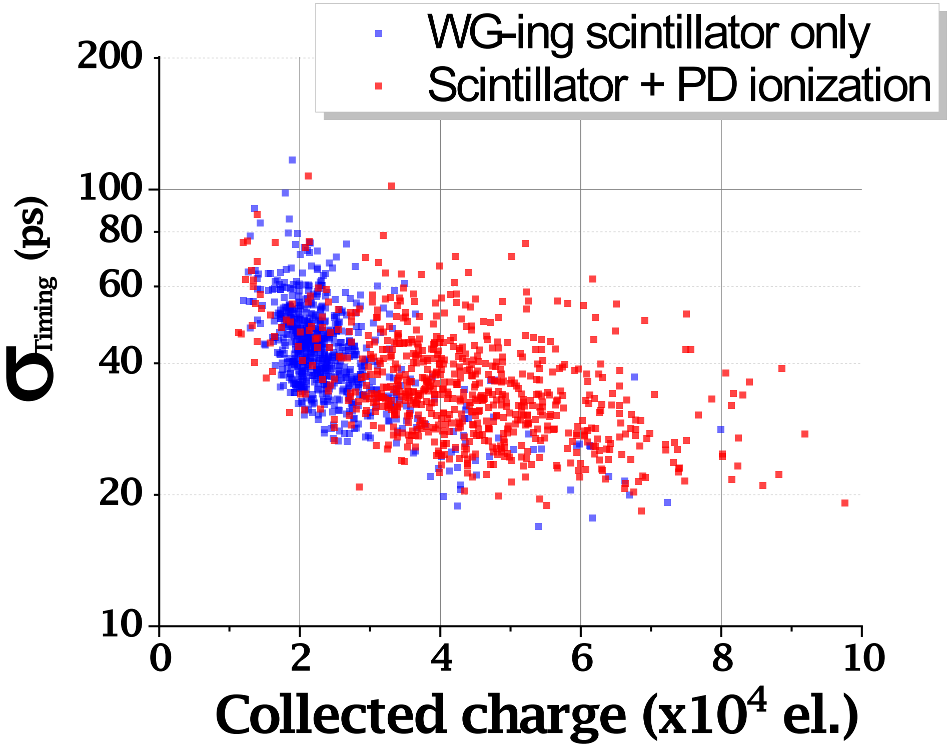


Scintillator + PD ionization





- **Hybrid response:**
  - **0.7 μm thick PD**
  - **20 μm thick scintillator**
- **Increases collected charge**
- **Improves time resolution**



$$\sigma_{Timing} = \sqrt{\left(\frac{V_{th}}{dV/dt}\right)^2 + \left(\frac{N_\Sigma}{dV/dt}\right)^2}$$

V_{th} = voltage threshold, N_Σ = RMS readout noise

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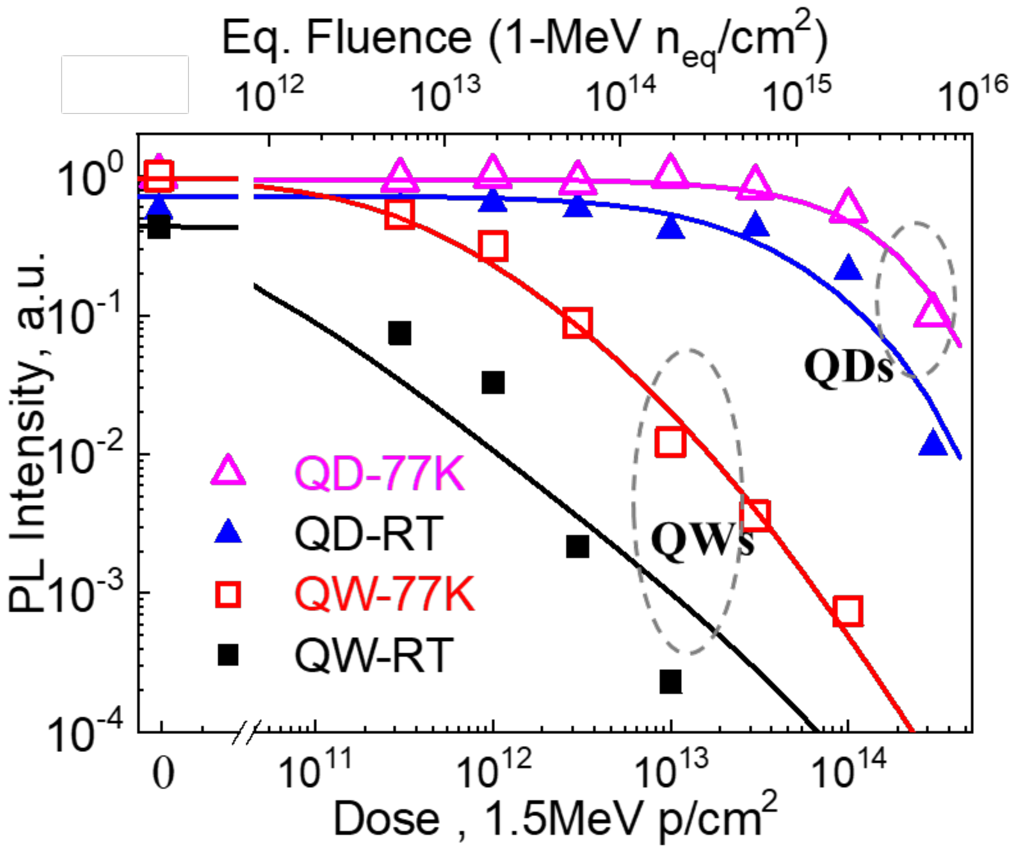
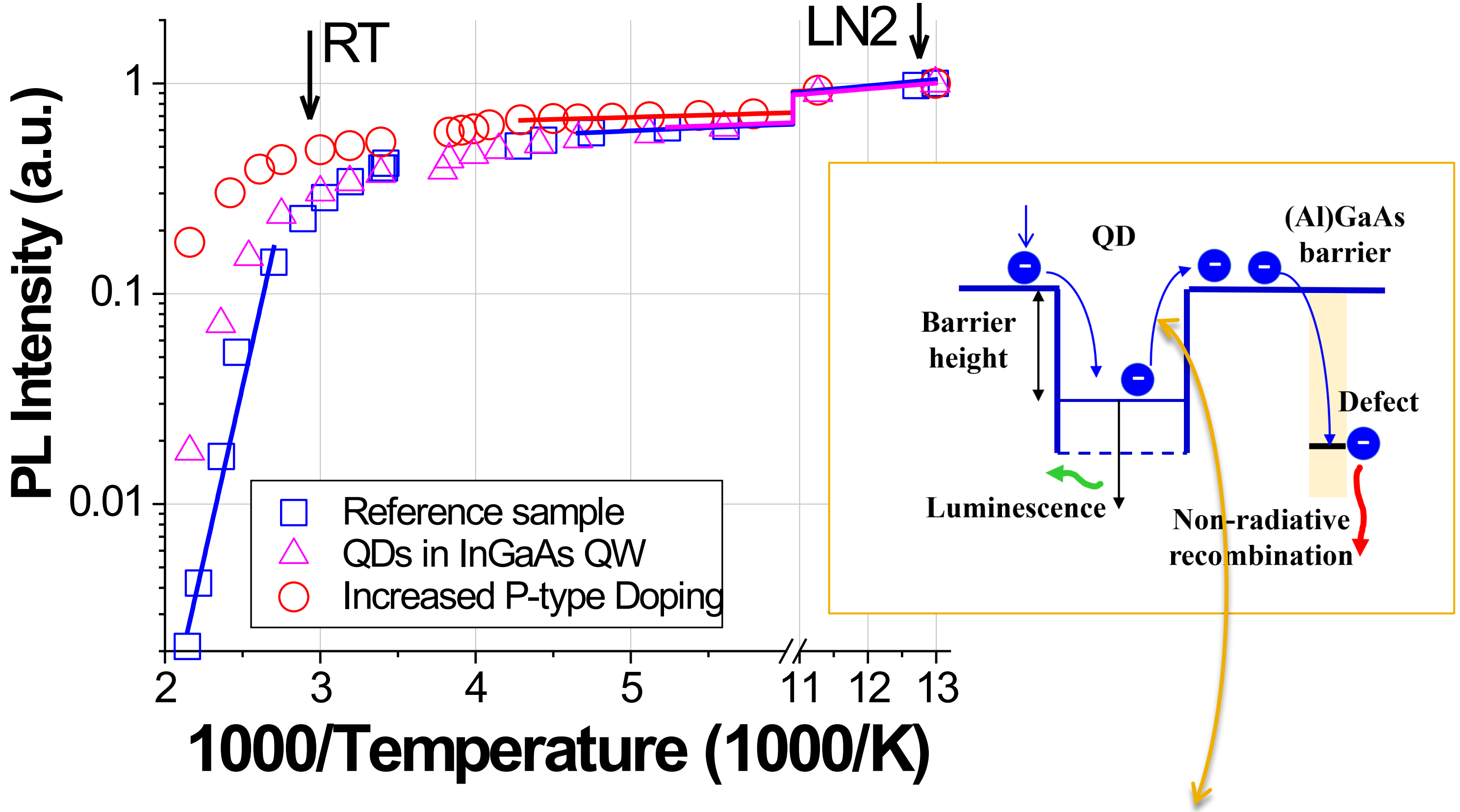
Radiation Hardness and Carrier Localization in QDs

InAs/AlGaAs QD Photoluminescence intensity vs.

H^+ implantation dose



Temperature

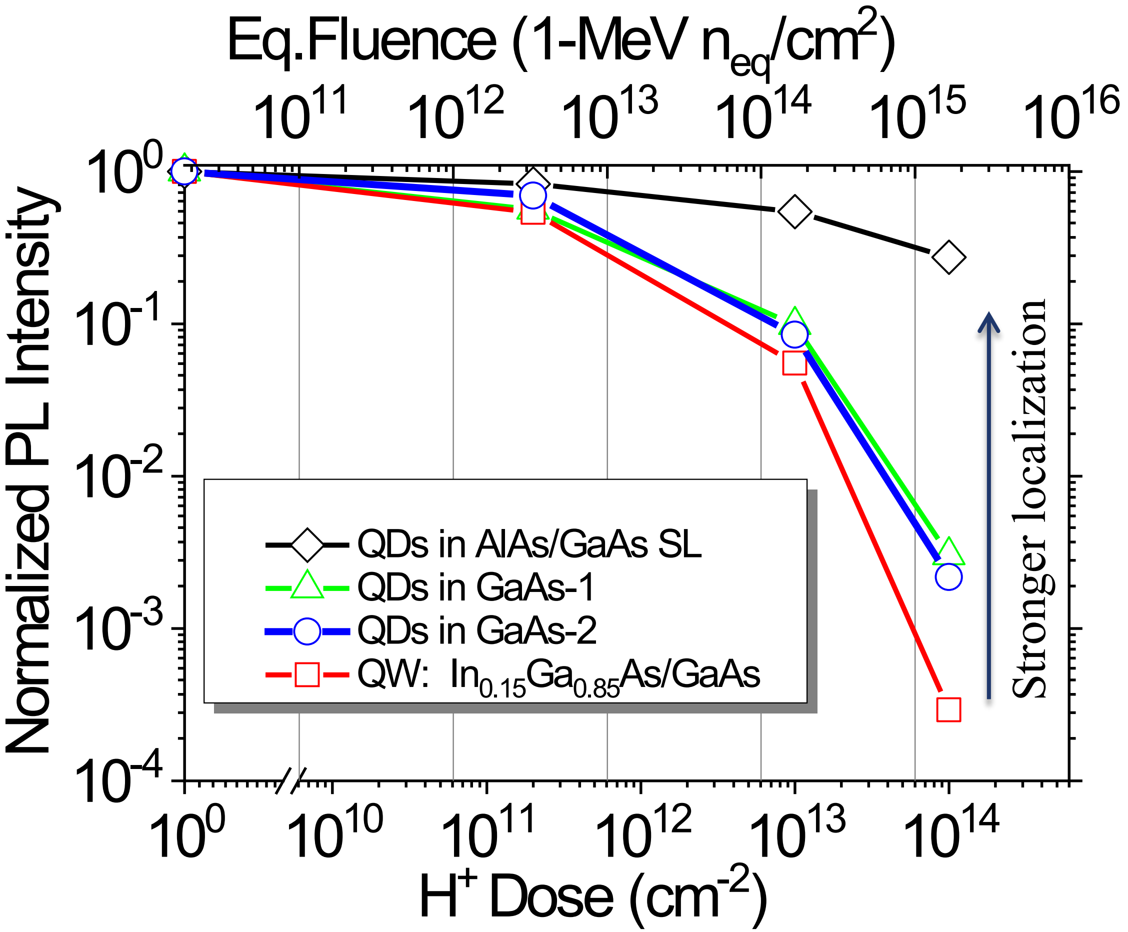


- Escape from QDs is determined by barrier height and temperature

Oktyabrsky et al.,2005, J. Appl. Phys. 10.1063/1.2037872

Radiation Hardness

QD Radiation hardness for different barriers (AlGaAs vs GaAs, room temp.)



Mahajan et.al. *Sensors*, *2024*,
https://doi.org/10.3390/s24227178

Rad hardness for Si strip detectors [Affolder, Proceedings of Science, 2011]

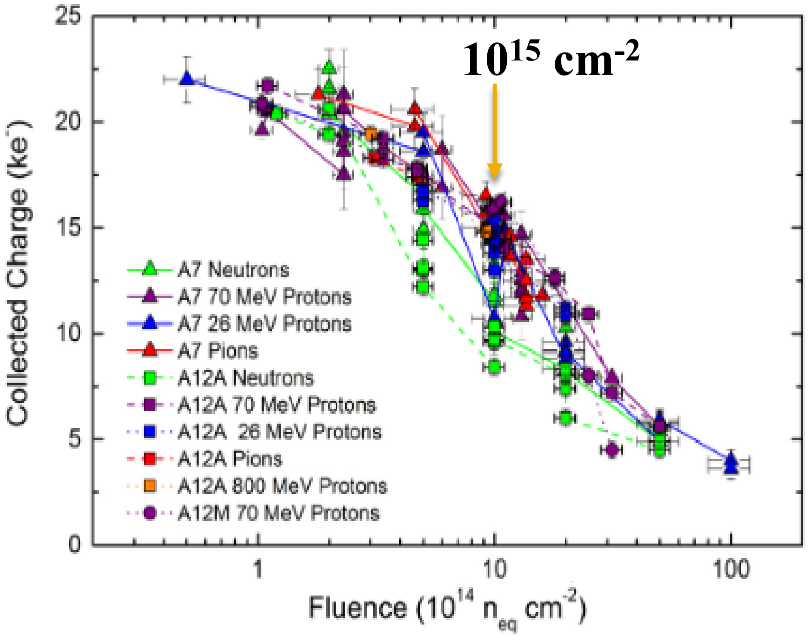
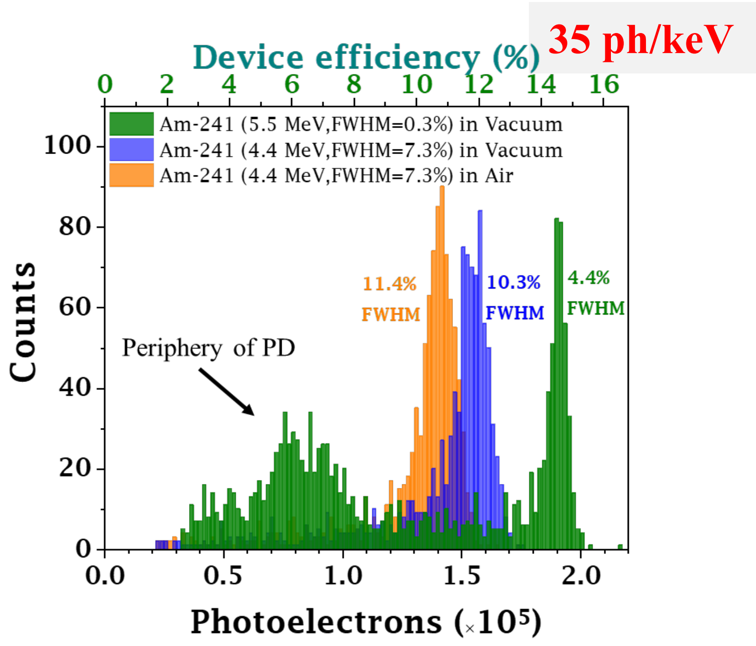


Fig. 10. Summary of collected charge measurements at 500 V for A07, A12A and A12M samples, shown separately for various irradiation sources.

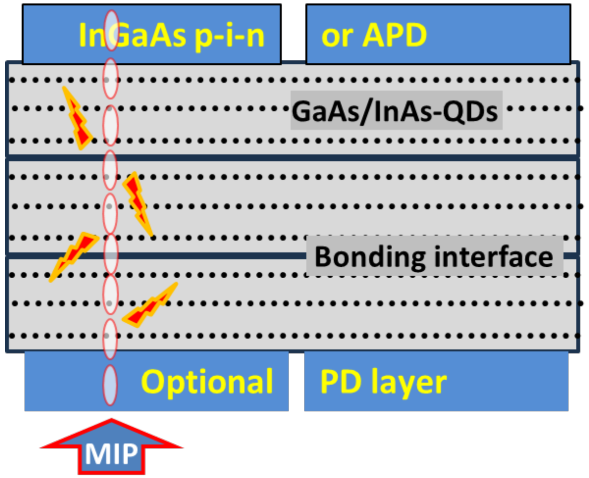
- Rad. Hardness is similar to Si detectors
- Improved with barrier height for electrons in QDs
- Further improved at low temperature
- QD decay time drops with impantation

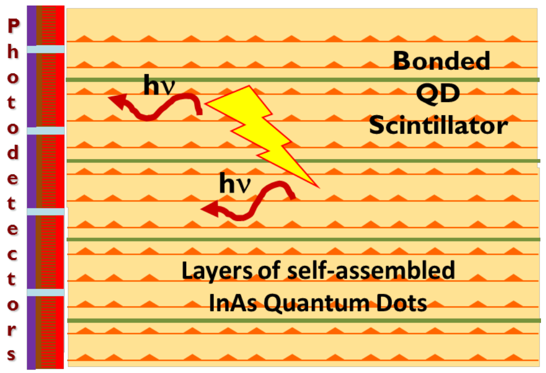
Current Challenges

- Charge collection efficiency is limited now by ~15% and mostly determined by the QD luminescence efficiency and PD light collection. Recently 3x improved.
    - Will be improved at low-T



- Limited thickness (now 25 μm) determined by the current semiconductor epitaxial growth technology: 1μm/hour
    - Bonding is an option:
        - Optically transparent bonding with hybrid PD
        - Polymer bonding with edge light extraction





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Summary

- **QD scintillating detector with unique properties**
  - Fast and efficient QD luminescence
  - Integrated PD
  - Low or no bias needed
- **Parameters extracted and modeled:**
  - Overall efficiency 30-40 el./keV, ~15% of the theoretical efficiency limit
  - Extremely fast scintillation (< 0.3 ns)
  - Time resolution of 18-40 ps for α-particles
  - Energy resolution (FWHM) down to ~4% (or σ =1.9%)
- **Hybrid detection of soft gammas**

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