# Study of the Properties of Quantum Dot InAs/GaAs Scintillator for Future 4D Trackers

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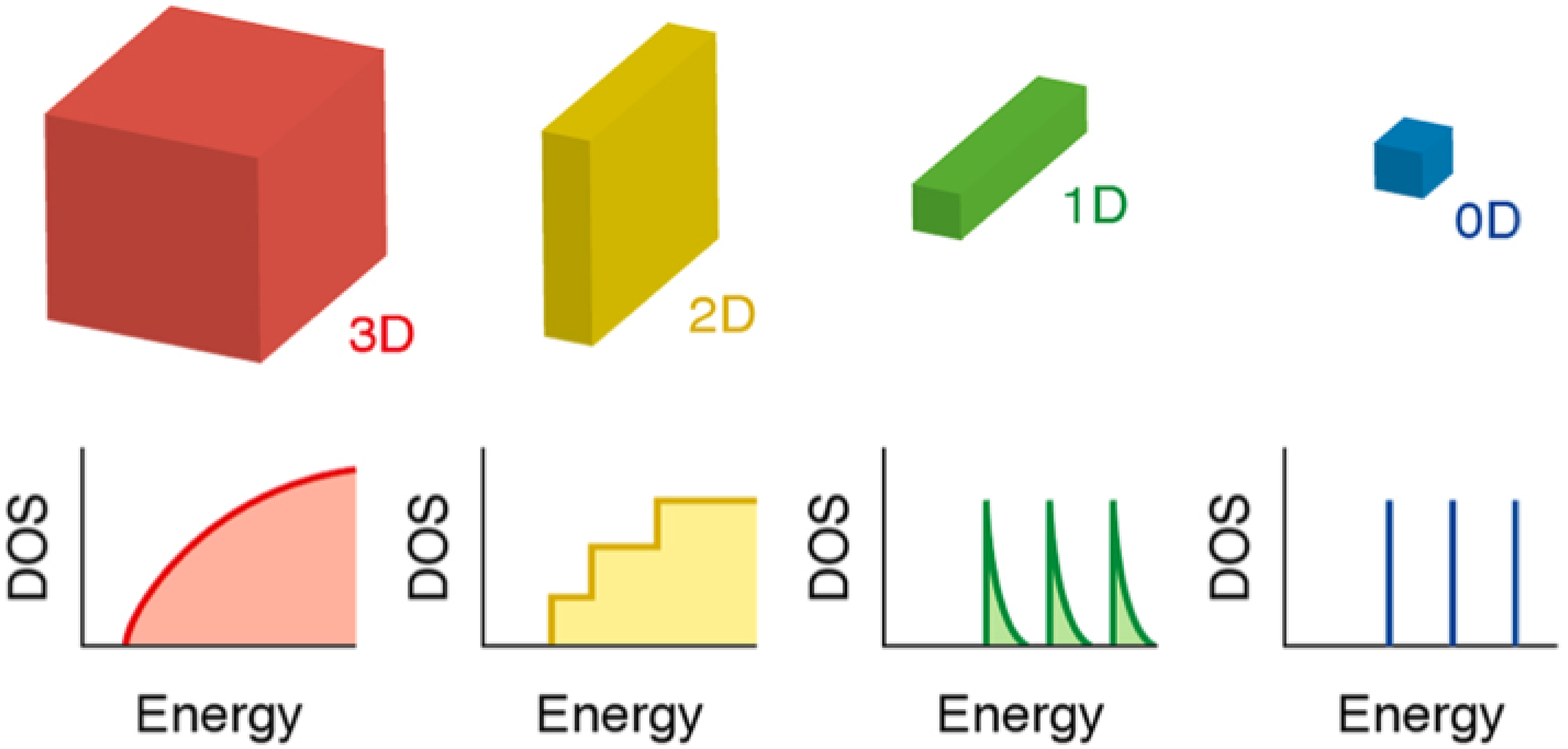
# Need for Nanomaterial Based Scintillator

Bulk Semiconductor | Quantum Well | Quantum Wire | Quantum Dot

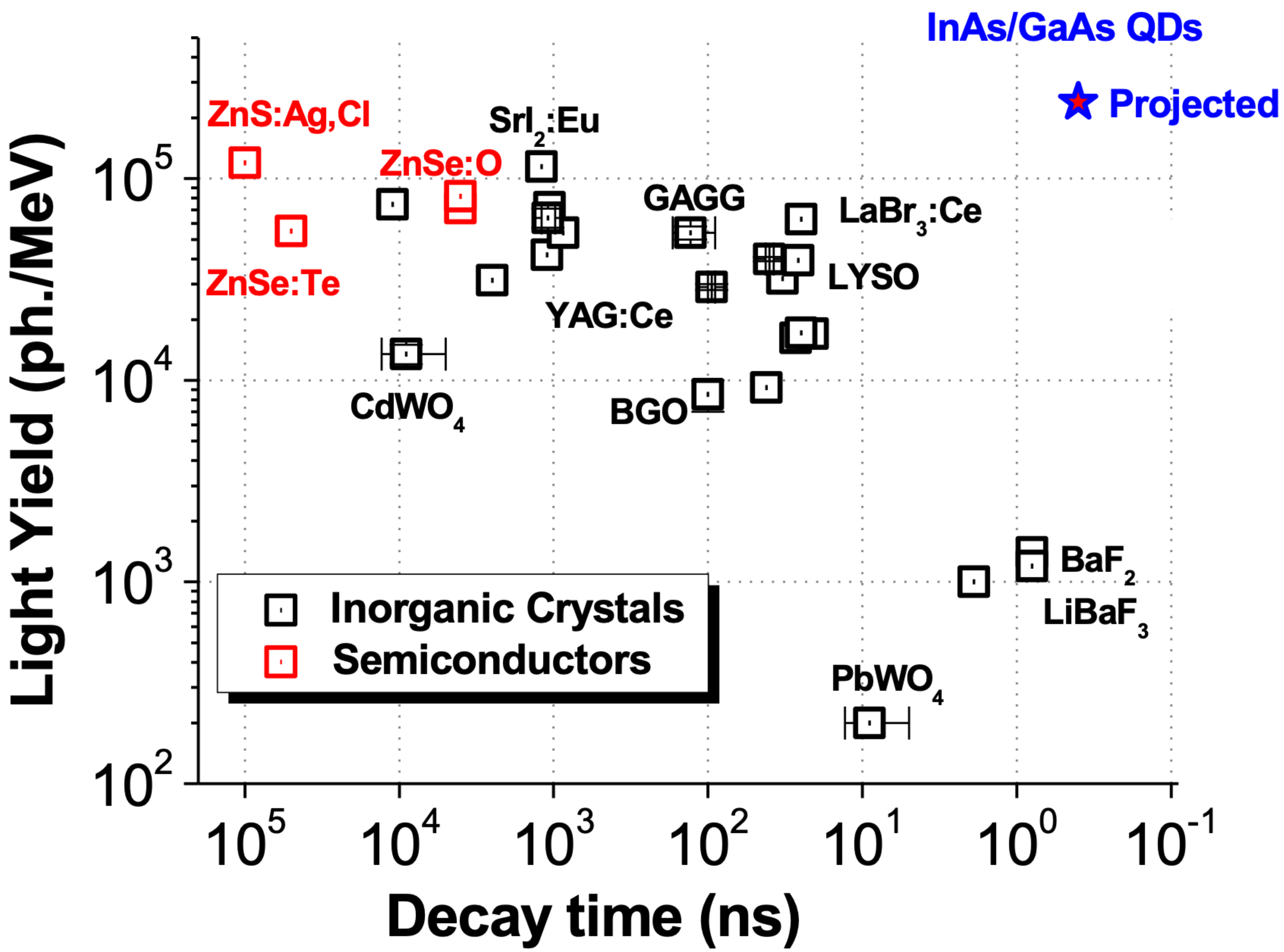



- As particle size decreases, they show different properties from the bulk
- Discreet energy in 0D material - Quantum Dots (~ few nm size)
- Quantum confinement occurs in all three directions

# InAs Quantum Dots - Novel Scintillator

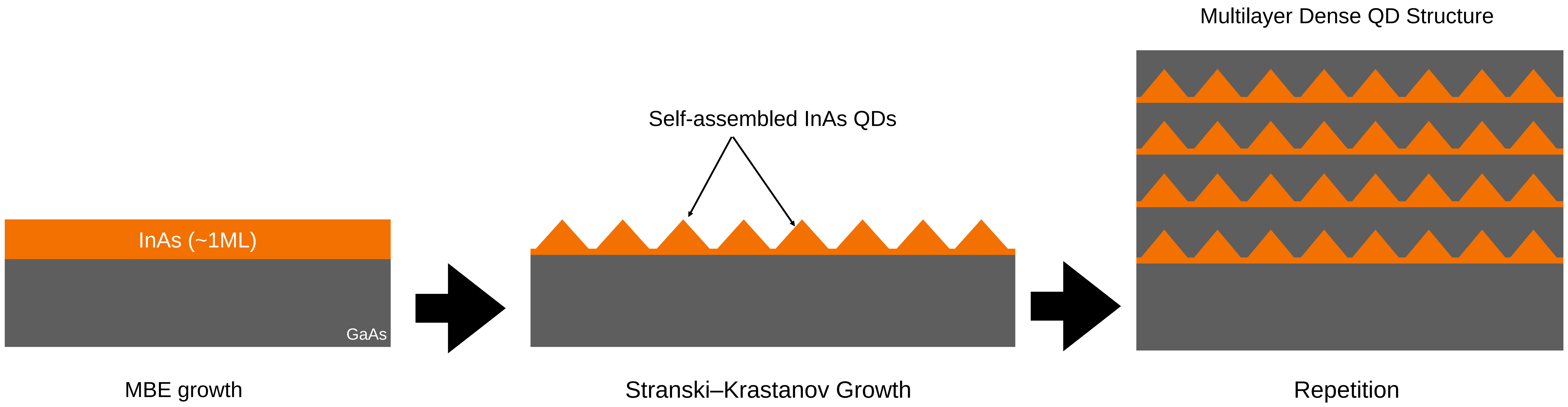
InAs QDs in GaAs - very high expectations

- Direct Gap - very high light yield (~240,000 photons/MeV)
- High electron mobility ( up to 8500 $cm^2/V$)
- Fast transport and capture of electrons in QDs ~ 2-5 ps
- Very short emission time ~ < 1ns - allows faster sampling rate
- Relatively high Z - radiation hard

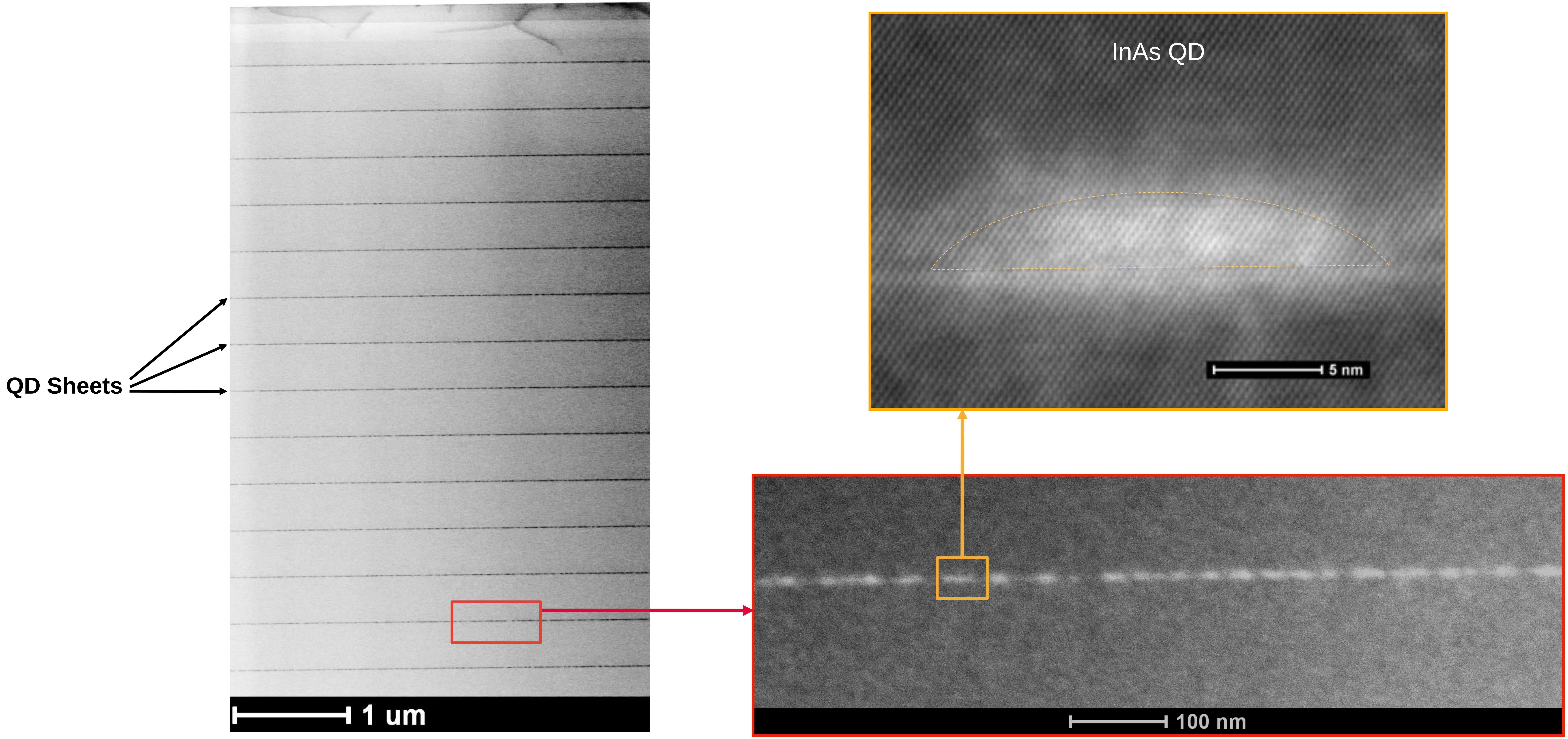


# Growth of InAs QDs in GaAs Matrix

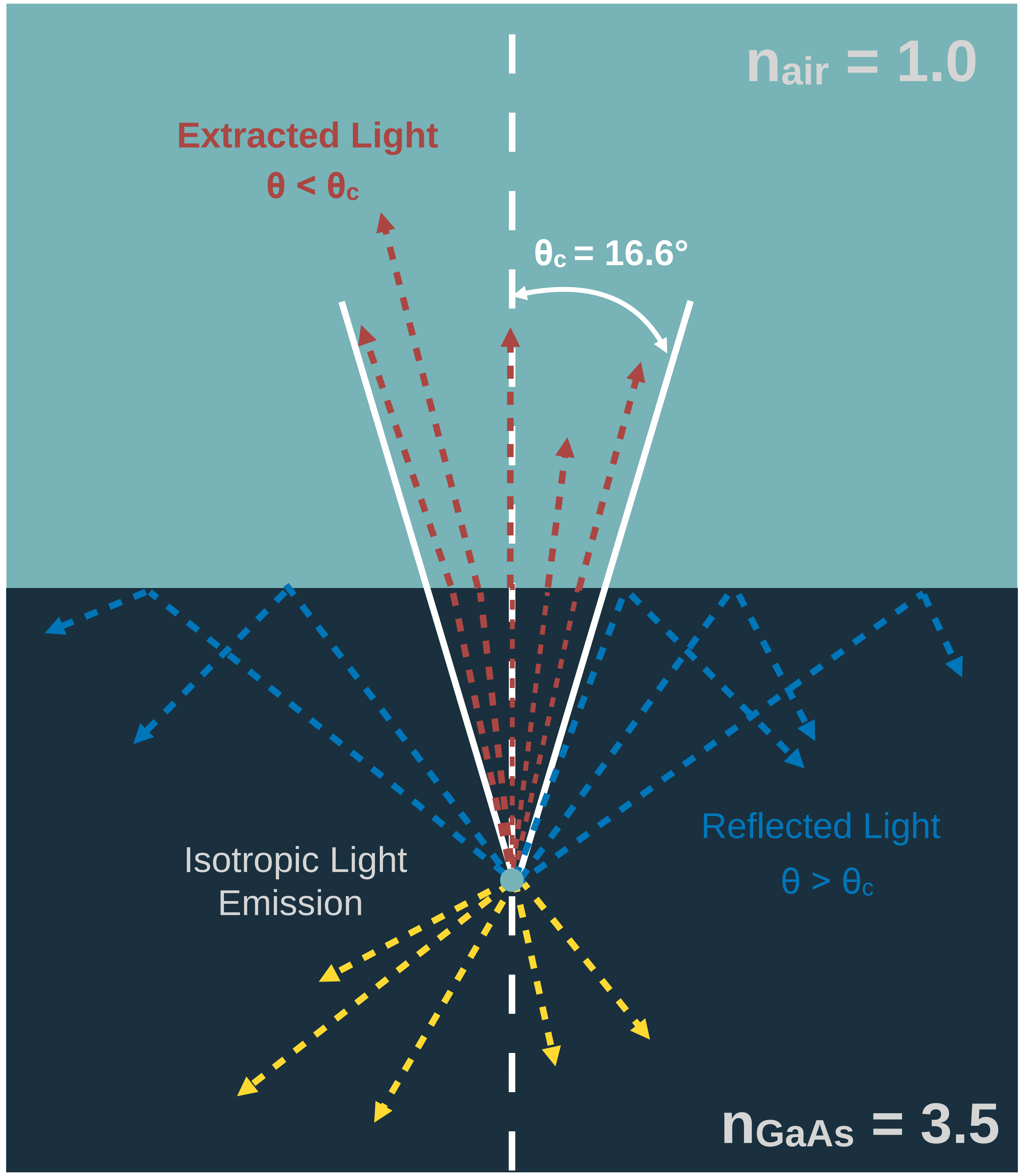
- Grown using Molecular Beam Epitaxy at ultra high vacuum.
- Minimization of the strain energy leads to stable nm-scale stable InAs islands - QDs.
- QDs are capped with ~ 2MLs of AlAs.
- Multilayer structure is grown by repetition.



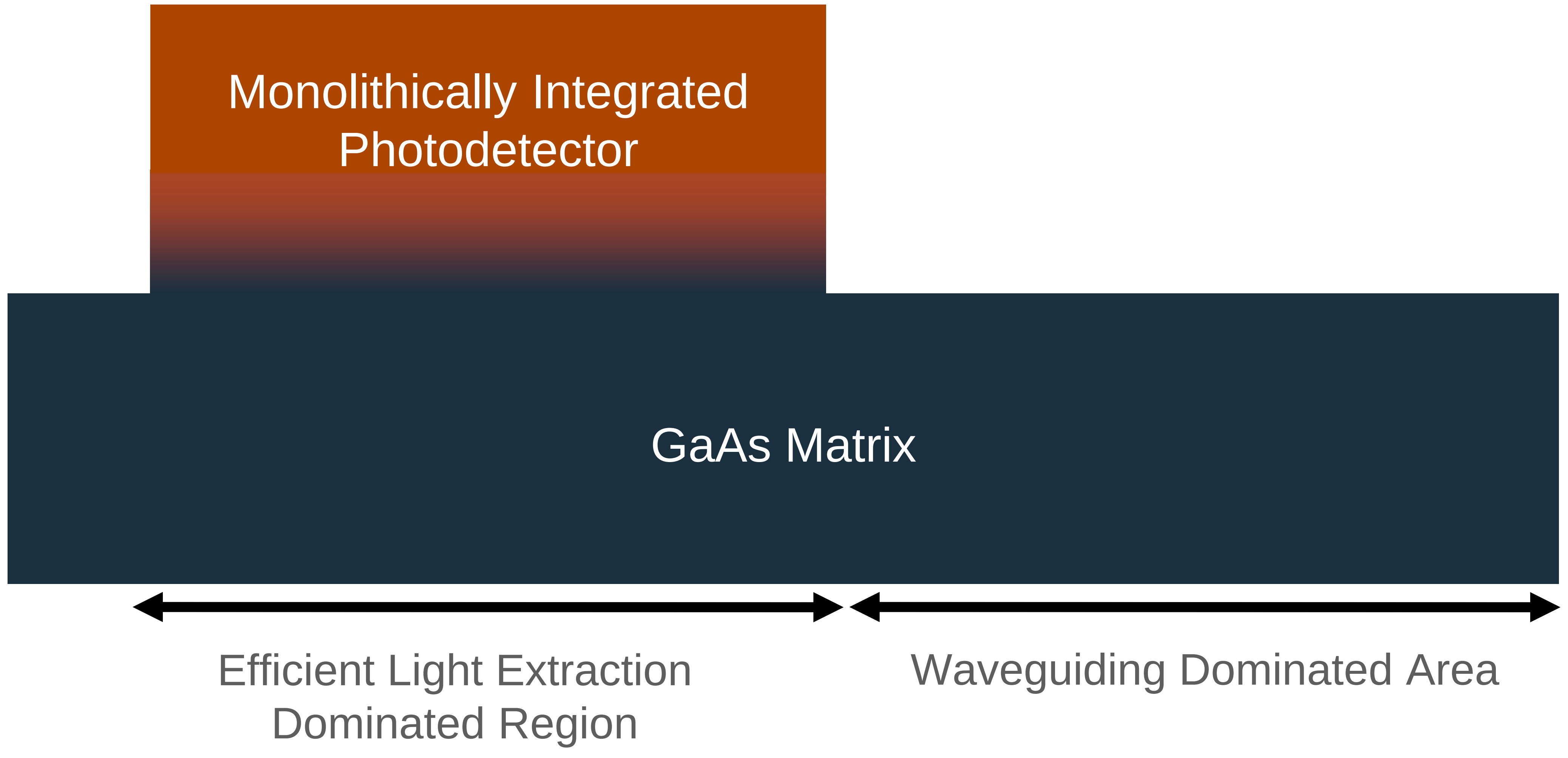
# InAs/GaAs Images



# Efficient Collection of light from high refractive index material



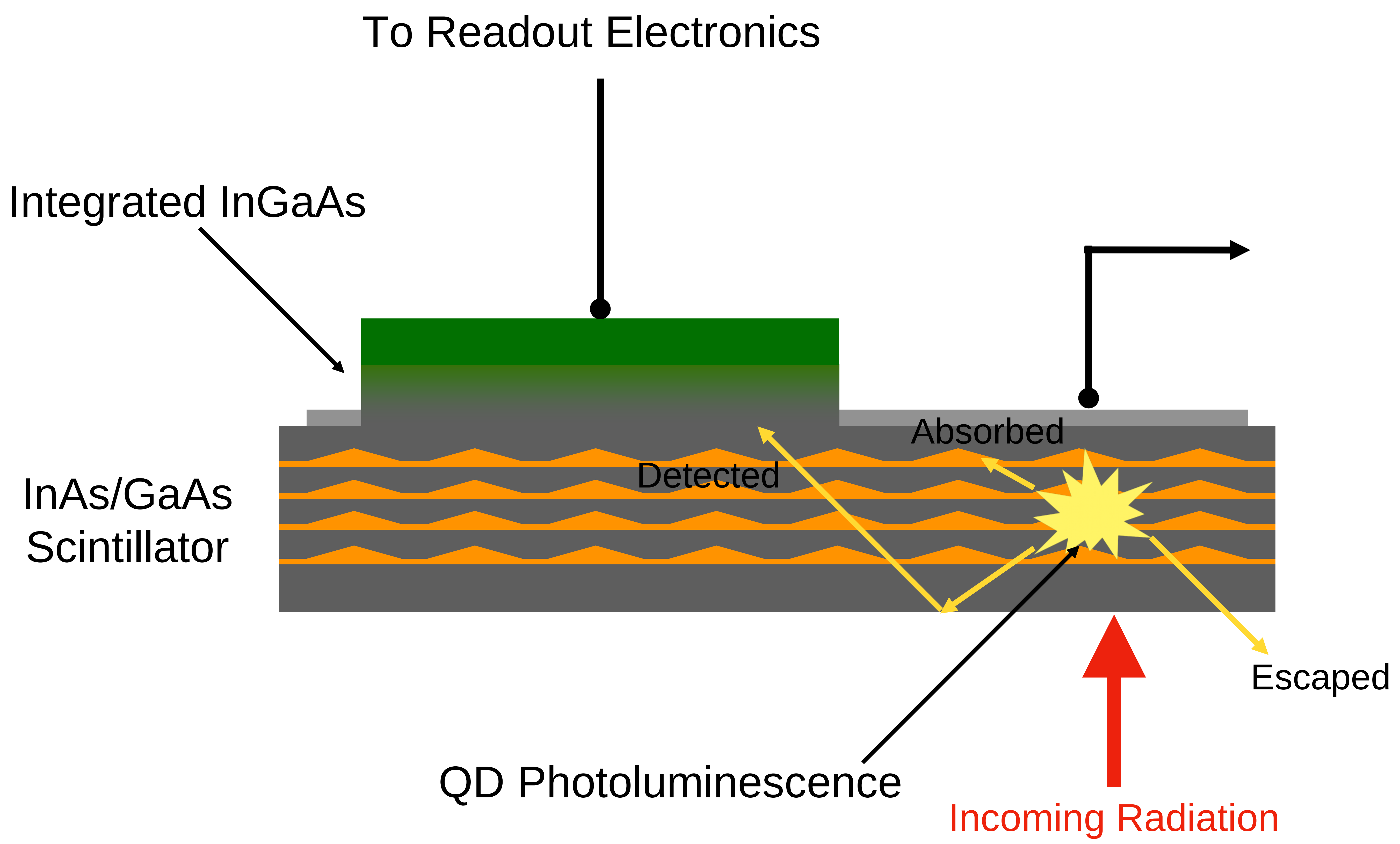

$LEE_{GaAs/Air} = \frac{1}{2n^2}$ ~2% per side

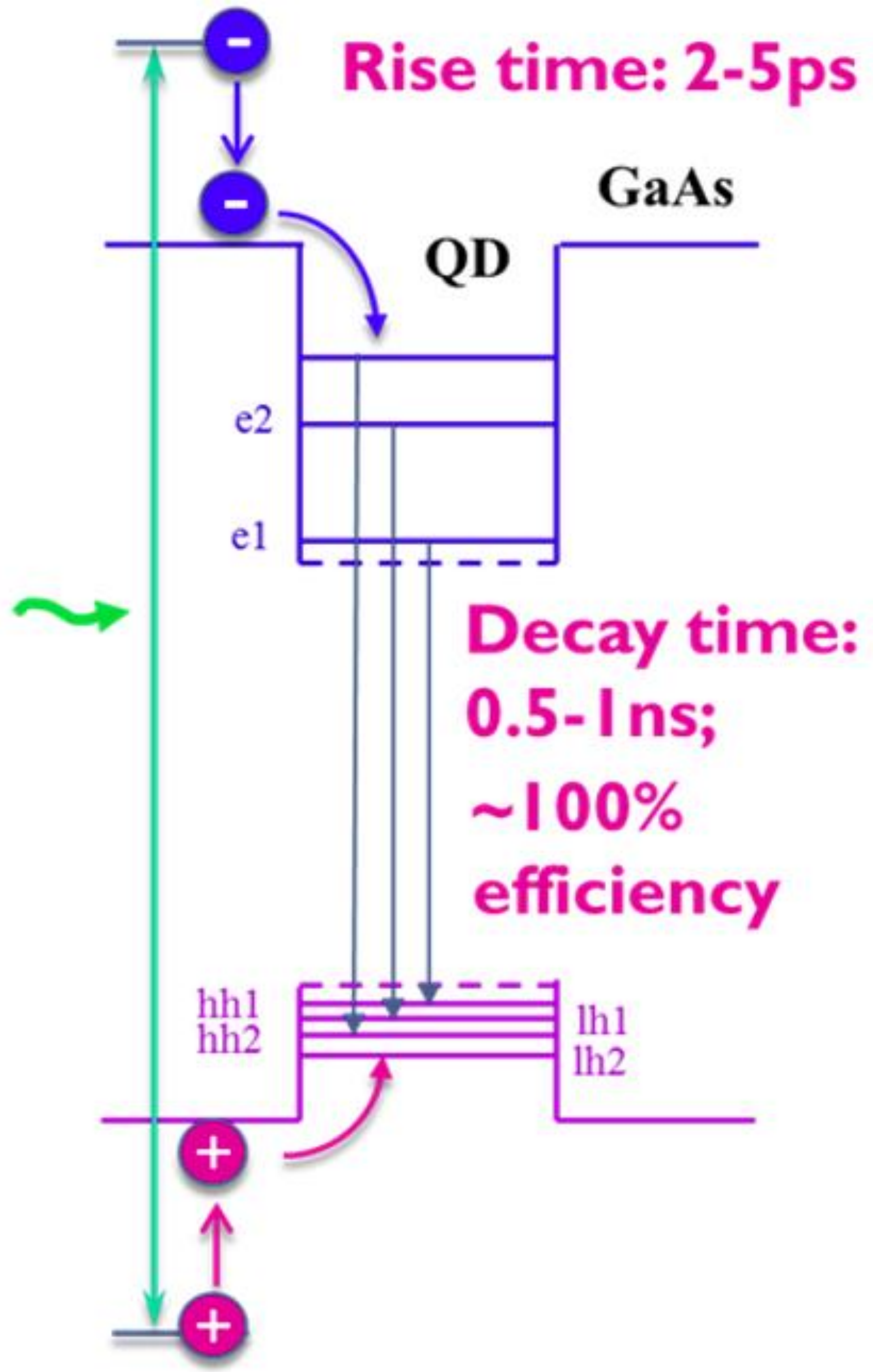



Why Monolithic Integration?

- More efficient light collection
- High refractive index medium can be used as waveguide
- Ability to design photodetector specifically tuned to QD's photoluminescence spectra

# Working Principle of Novel InAs/GaAs Based Detector

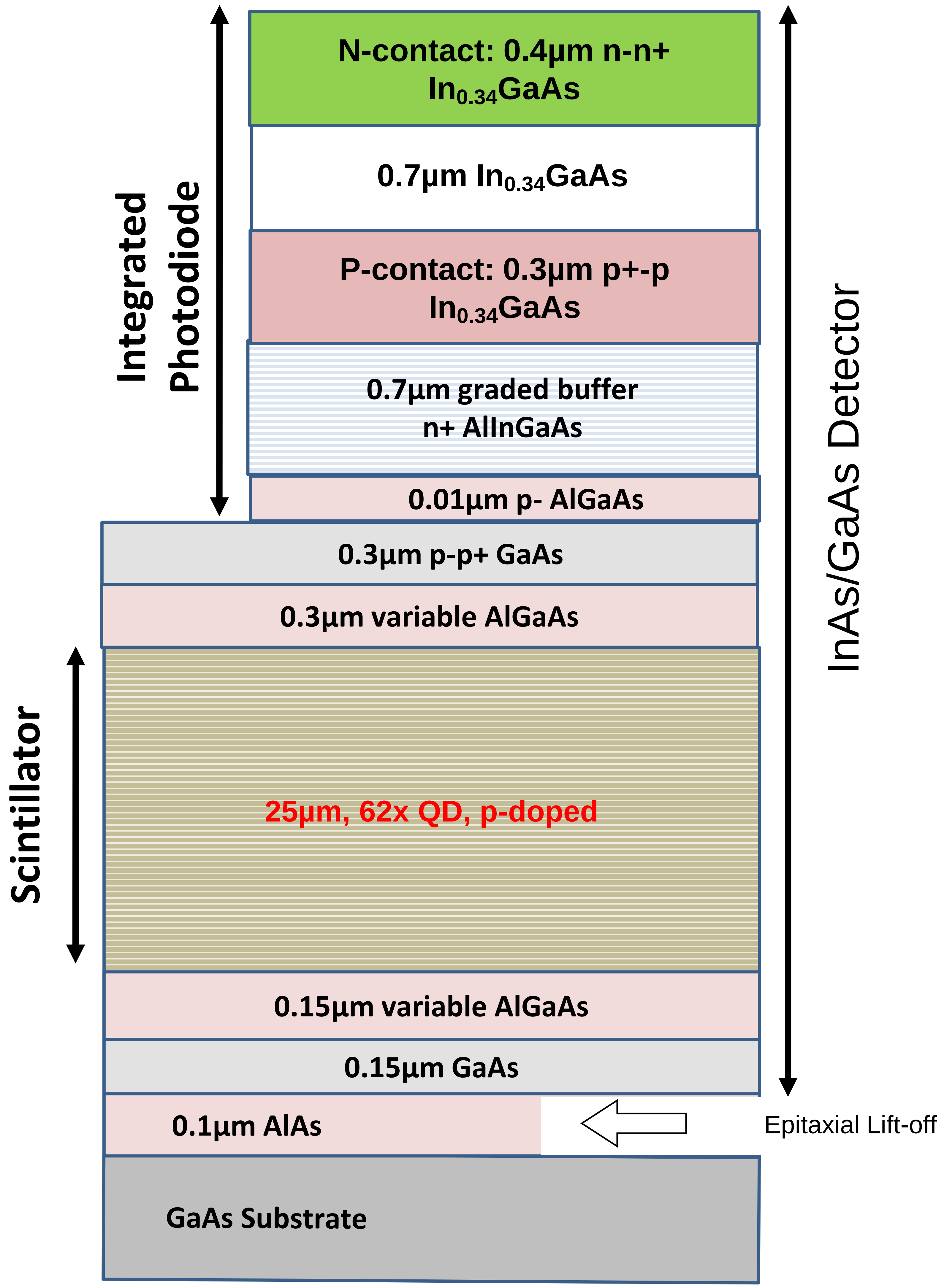



- Ionizing particle produces $e^-$/h pairs in GaAs
- Charges quickly captures by QDs (~few ps)
- Excited state QDs emit 1.1 eV photons with emission time of ~ 1 ns
- Monolithically integrated InGaAs photodetector captures photons

***Collects light not carriers!***

# InAs/GaAs with Monolithic InGaAs Detector



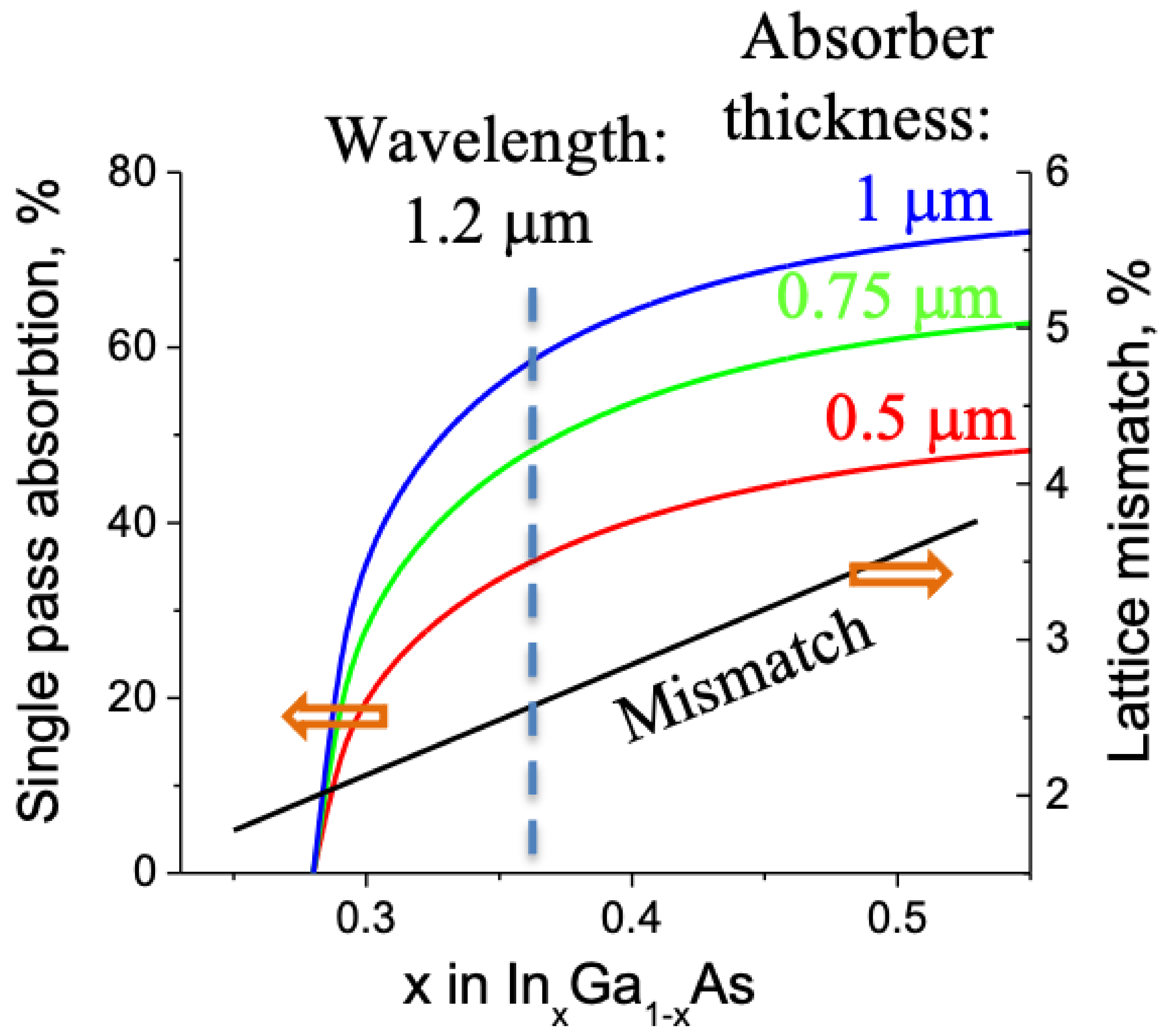

**The detector consists of three integrated systems:**

- QD/semiconductor as a radiation stopping material
- Waveguide for QD emission
- Photodiode for optoelectronic conversion

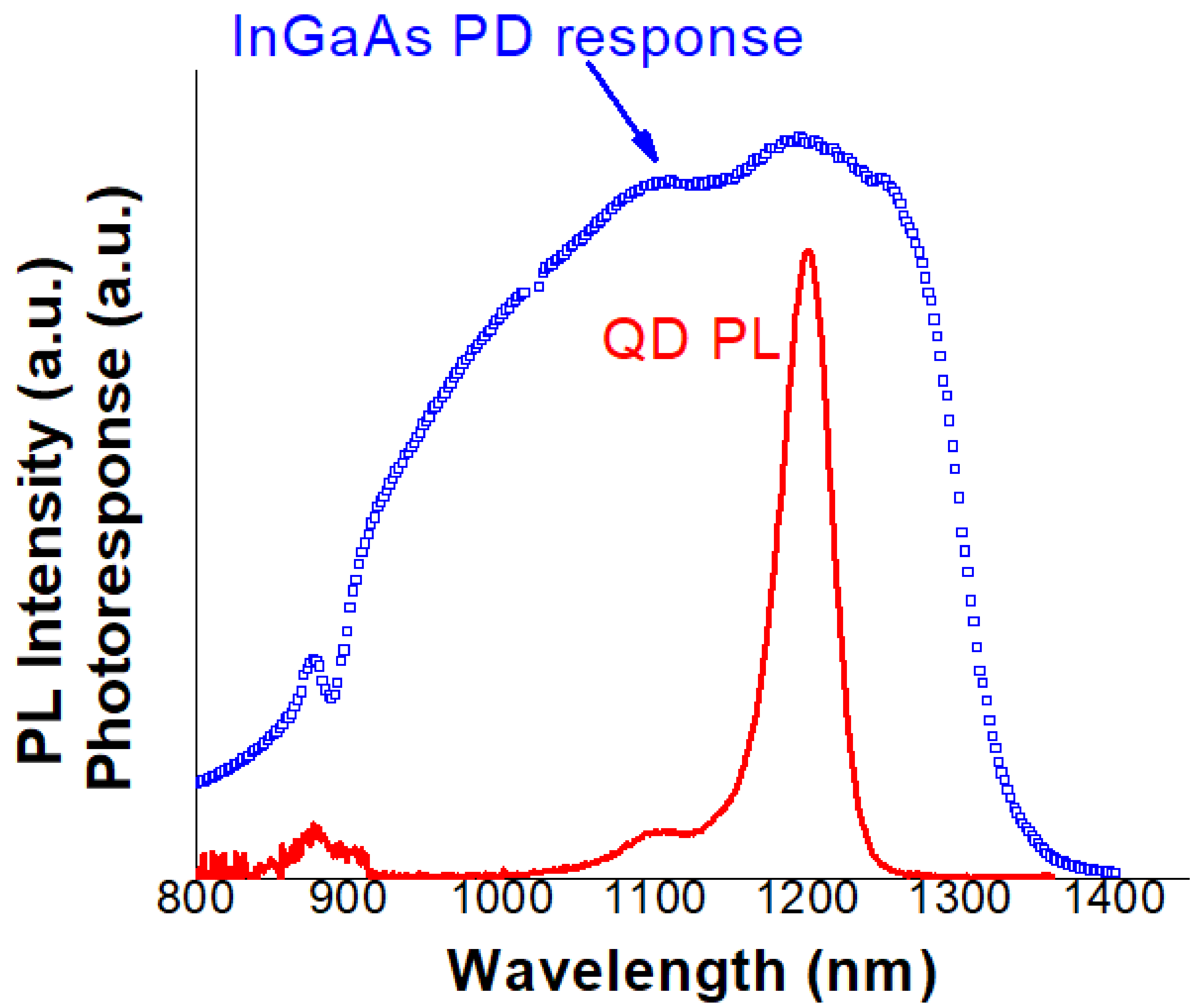
**InAs/GaAs with Integrated Photodetector:**

- Complete detector is grown in single Molecular Beam Epitaxy process
- Detector Mesa and contact metallization is formed with two mask lithography
- ~25 µm thick detector is released from the GaAs substrate by epitaxial lift-off

# Design of Monolithically Integrated InGaAs Photodetector




Single pass absorption of 1.2 μm light with variable composition of In with associated strain on GaAs substrate

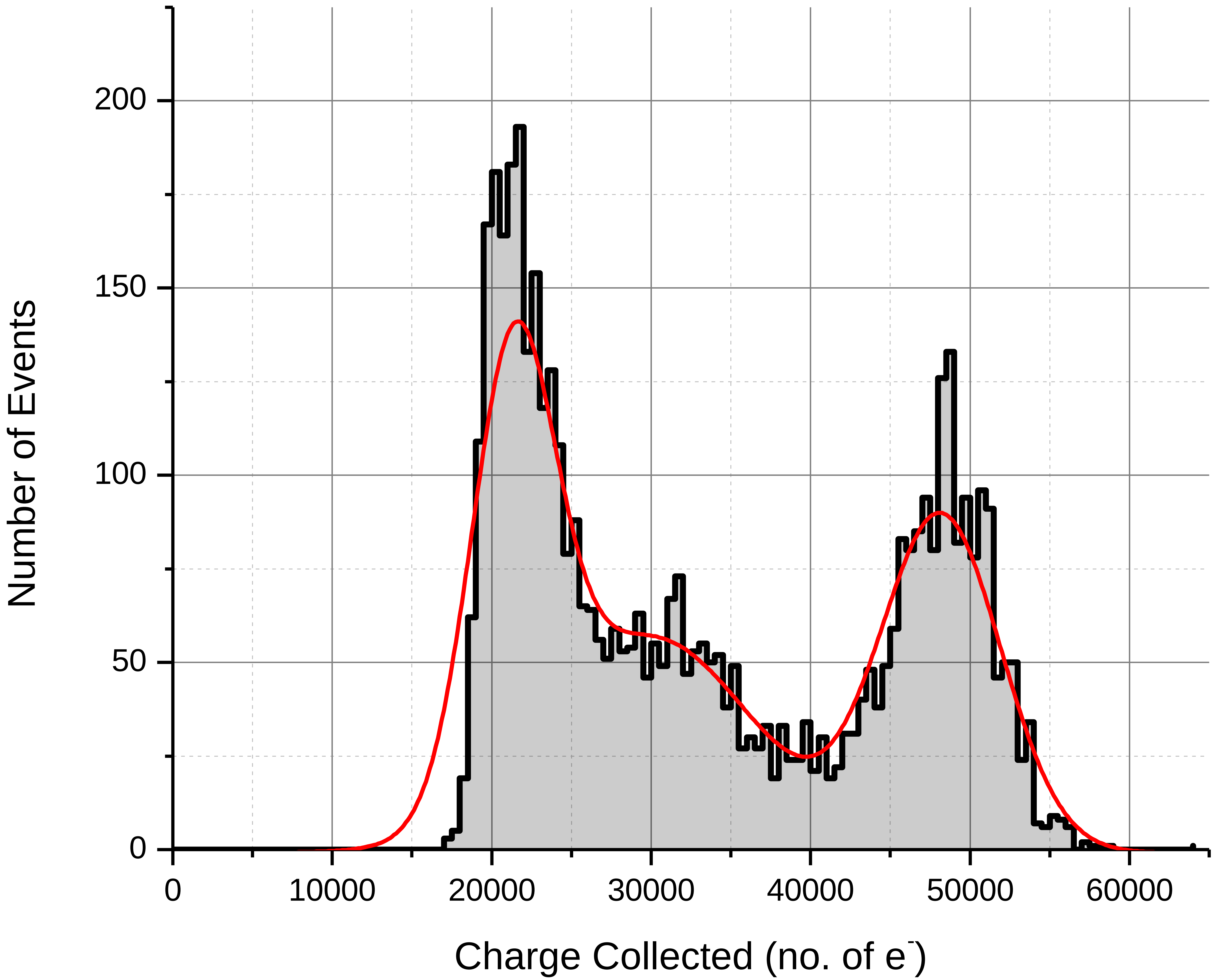



InAs QD photoluminescence and InGaAs photodetector photosensitivity

- QD luminescence at 1.2 μm wavelength detects use of photodetector (PD) with bandgap less than 1eV.
- InGaAs with In-content more than 34% provide practical PD efficiency.
- Metamorphic layer is needed to compensate lattice mismatch.

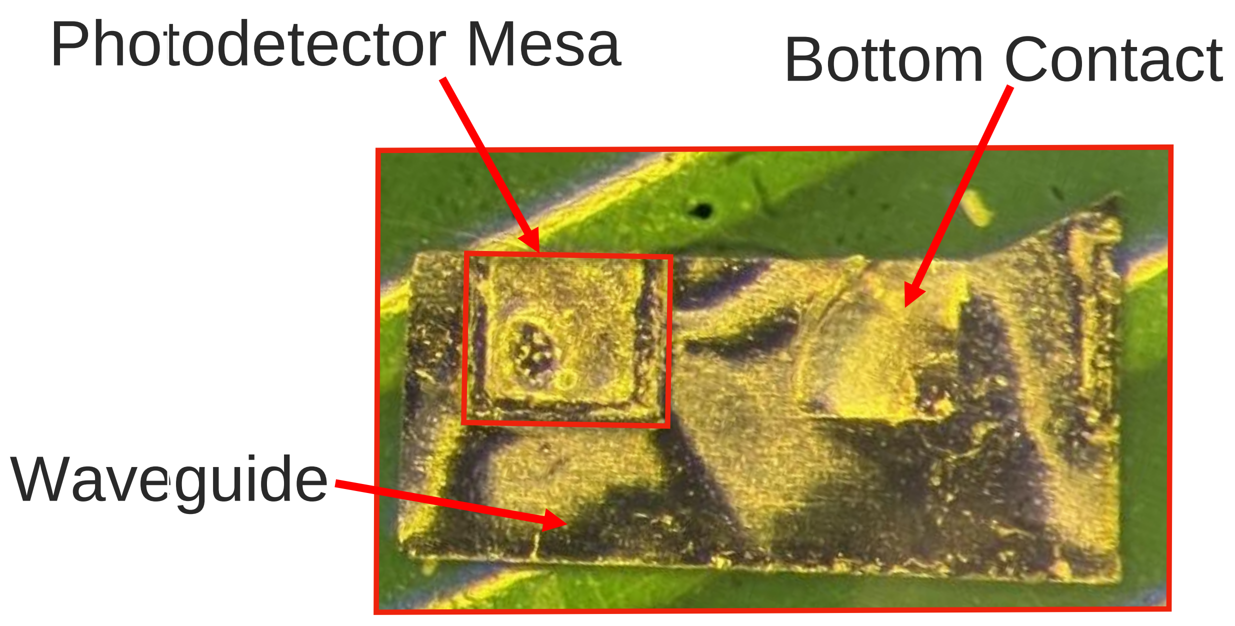
# Measurement with 5.5 MeV Alpha Particle

Histogram of 4.5 MeV Alpha particles

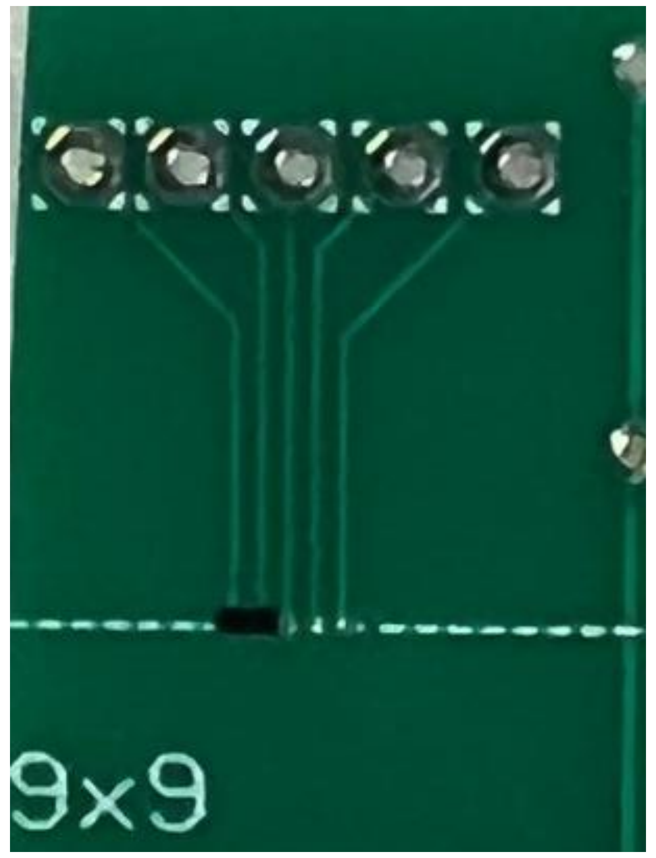



The presented data is collected with charge sensitive preamplifier followed by shaping amplifier

The Detector is bonded to PBC using flip chip method for easy readout



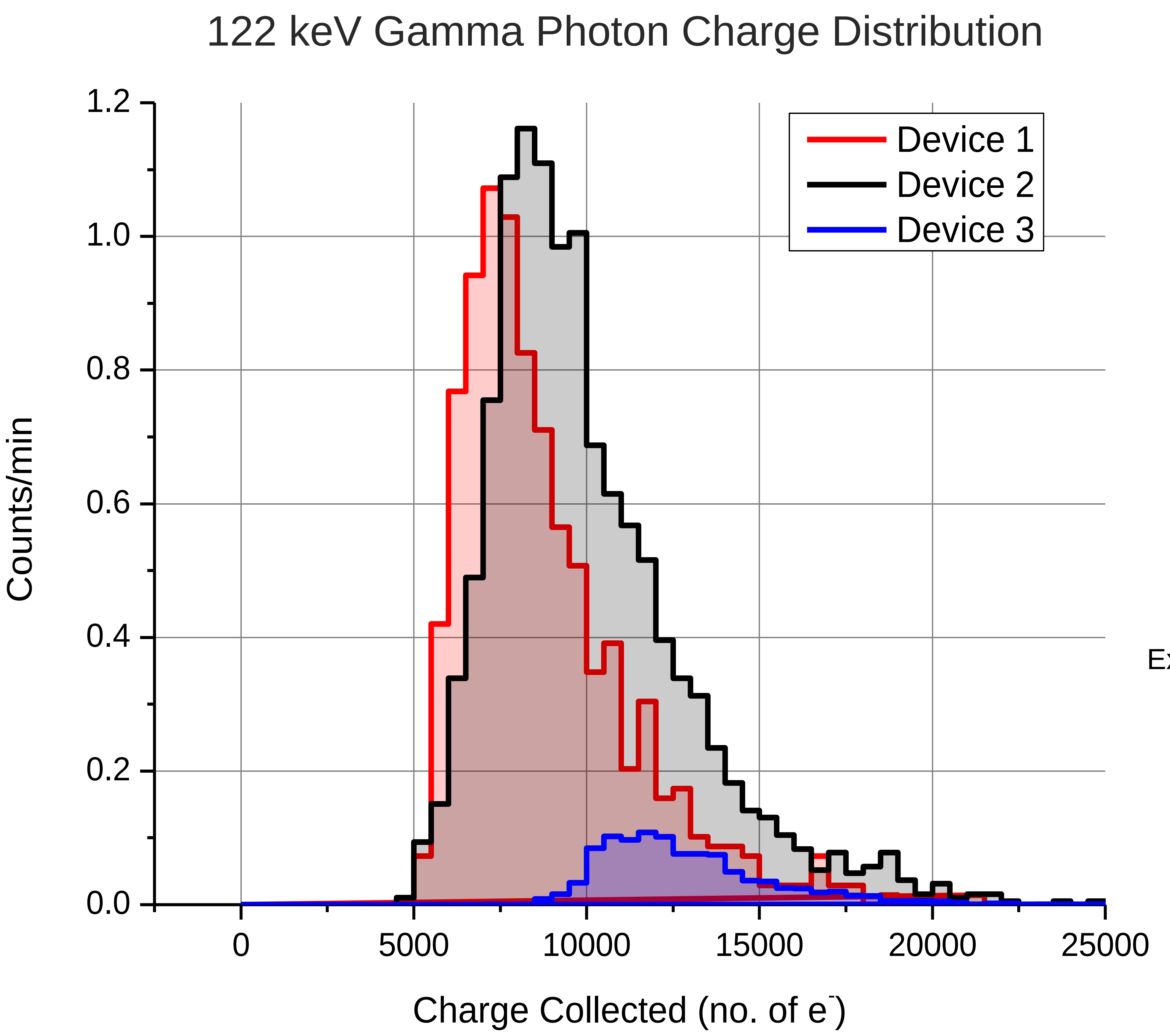

Top View of InAs/GaAs based detector



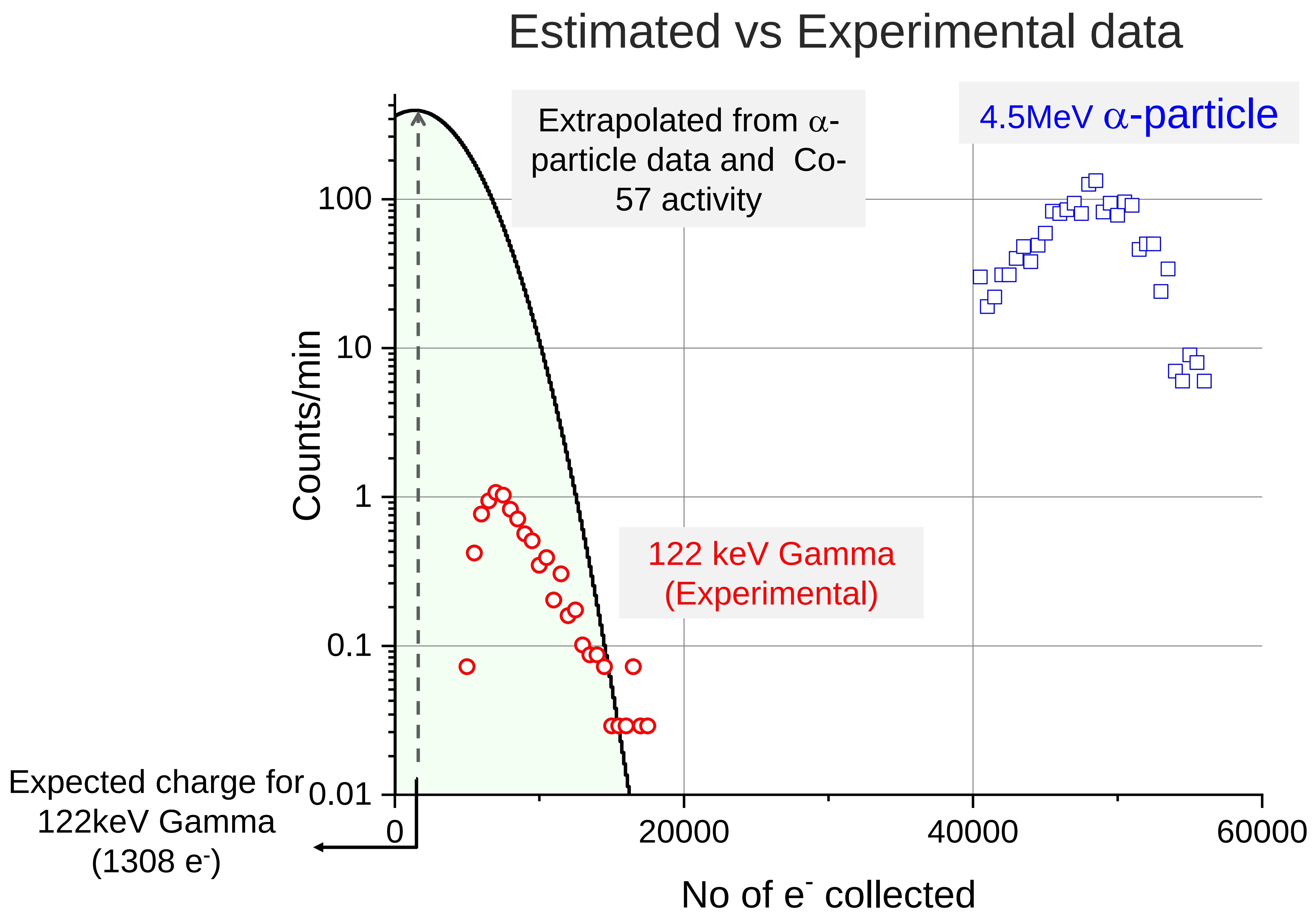

Flipchip Bonded Detector

- Bimodal charge distribution is observed
- Low charge peak corresponds to the alpha particle event in waveguiding region
- High charge peak corresponds to alpha particle events underneath the photodetector
- ~10,000 ph.e /MeV charge collected
- Lower charge threshold is still noise limited

# Measurement with Gamma Photons from Co-57



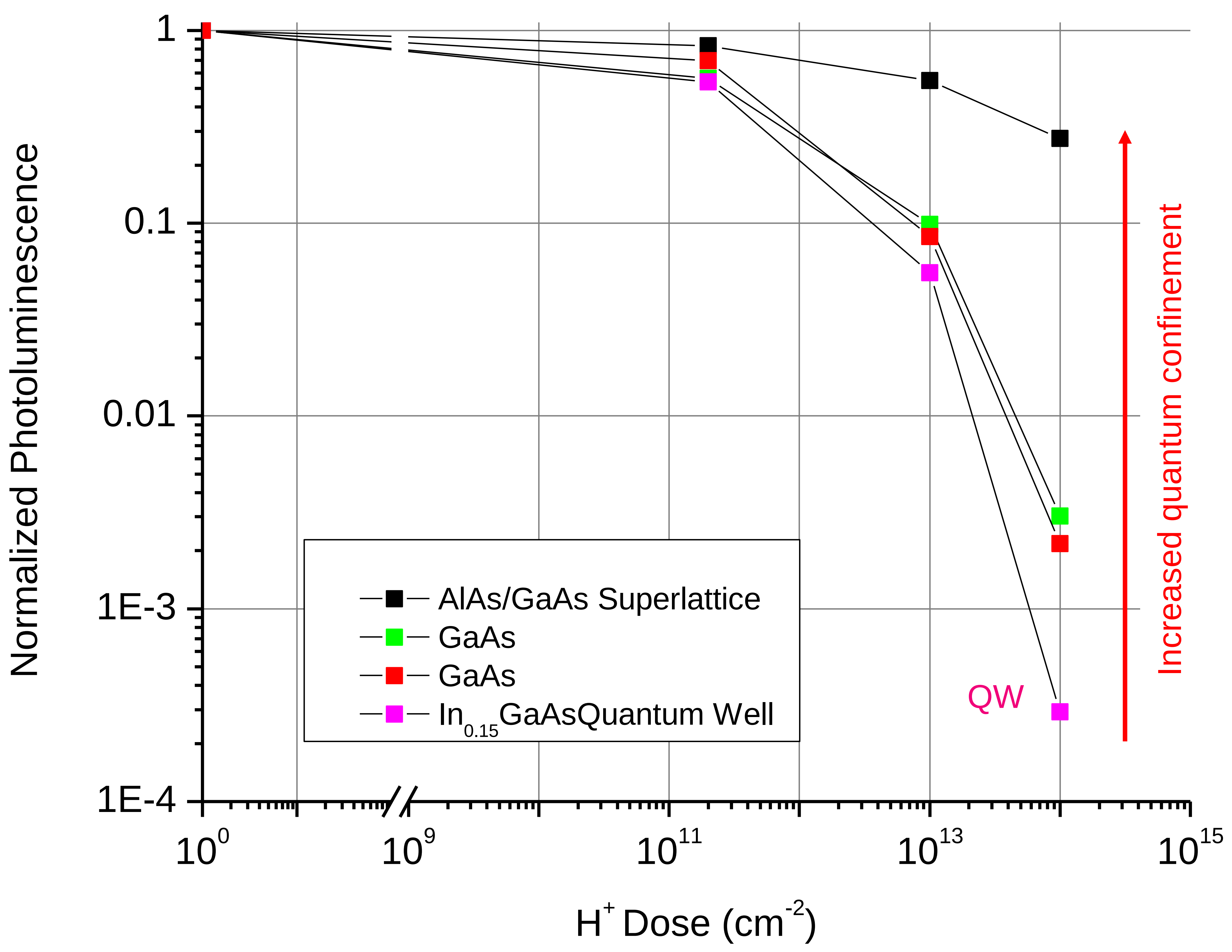

The presented data is collected with charge sensitive preamplifier followed by shaping amplifier




- The gamma responses are noise/threshold limited
- Majority interactions are screened by the noise level
- Tail of collected charge distribution is observed
- Charge collection is greater than 80,000 ph. e/MeV
- Possibility of Birk's suppression – need to study for this novel material

# Engineering of Radiation Hard InAs Quantum Dots

Effect of 1 MeV Proton Irradiation on Quantum dots photoluminescence



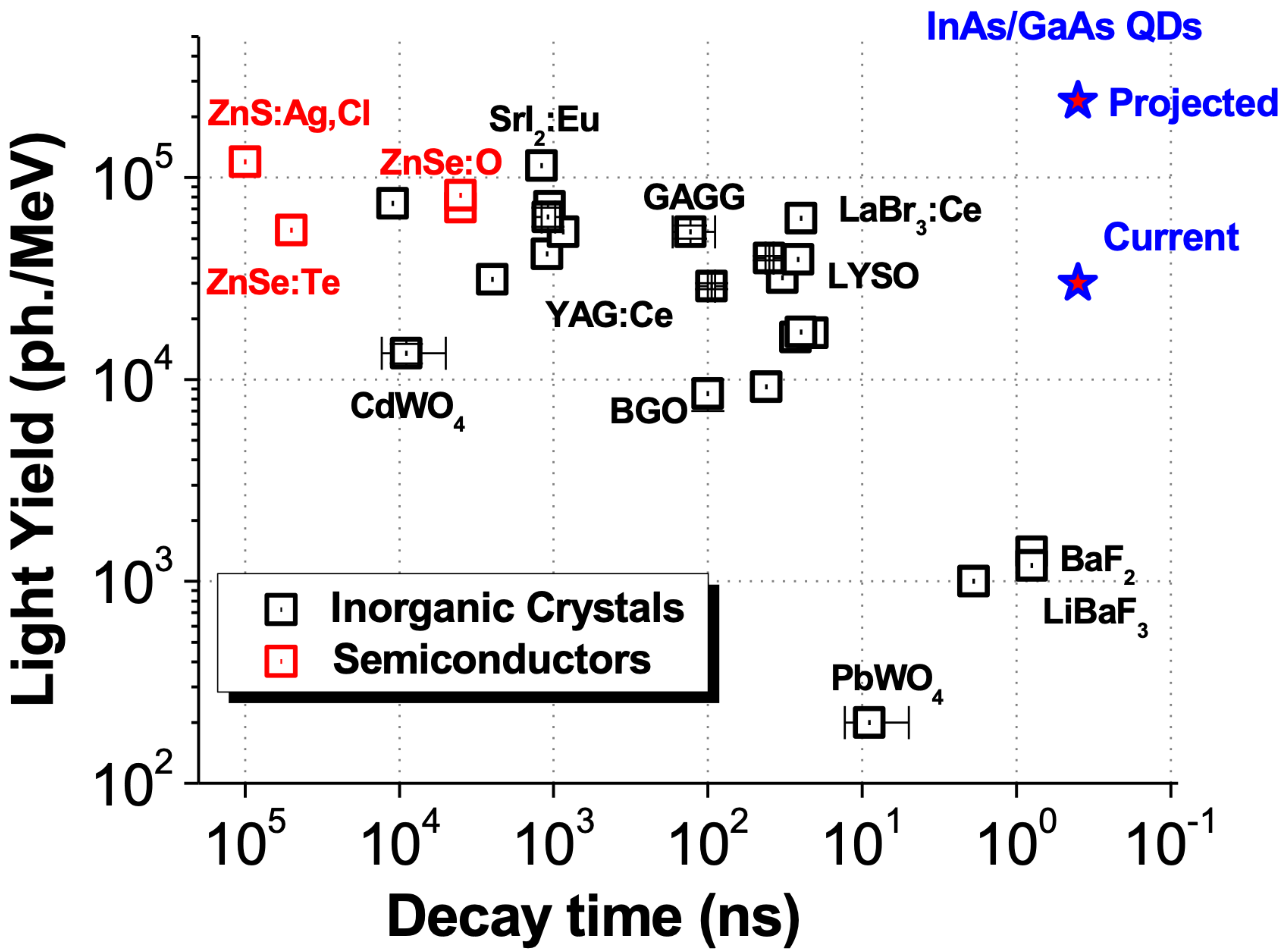

- Proton generates displacement defects along its path
- Degradation of the PL due to non-radiative recombination on these defects
- The highest radiation hardness is observed in QDs embedded in AlAs/GaAs superlattice structure, corresponding to $Al_{0.2}Ga_{0.8}As$ alloy
  - Highly localized states of carriers in QDs
  - Lower probability for carriers to escape the QDs and recombine non-radiatively

*InAs Quantum dots can be designed to be a radiation hard by hosting it in high barrier periodic structures*

# Summary

Demonstrated a novel semiconductor-based scintillator for charged particle detection

- Low self absorption (< 1 $cm^{-1}$)
- Very short scintillation time (< 1ns)
- Suitable for room temperature
- Can be operated without bias
- Designed and integrated monolithic photodetector
- Can be designed to be radiation hard
  - QDs hosted in high barrier like AlAs/GaAs superlattice
- High charge collected
  - 10,000 ph.e/MeV in case of Alpha particles
  - charge >80,000 ph.e/MeV is observed for gamma photons



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