Quantum dot based scintillators for charged particle detection

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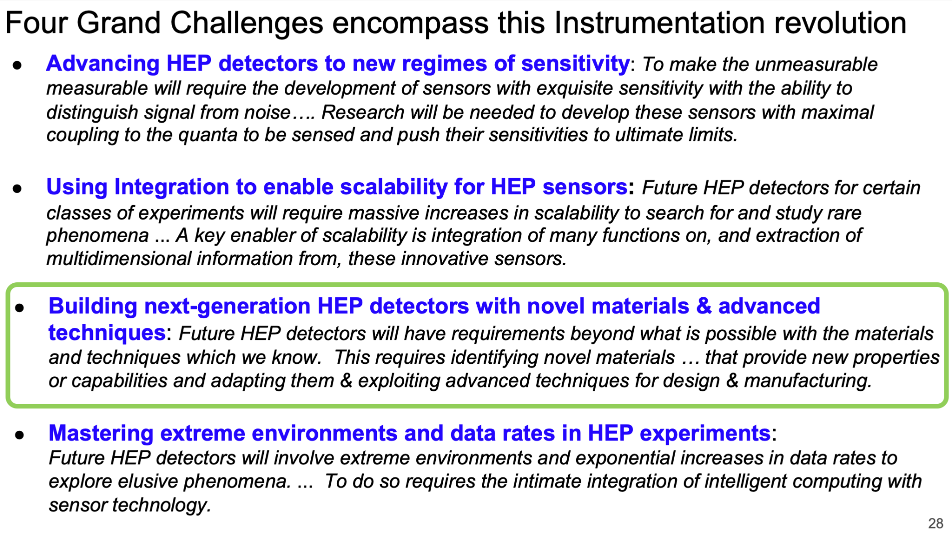
M. T. Hedges[1], P. Murat[2], T. Mahajan[3], A. Minns[3], V. Tokranov[3], M. Yakimov[3], S.Oktyabrsky[3]

[1]*Purdue University*, [2]*Fermi National Accelerator Laboratory*, [3]*SUNY Polytechnic Institute Albany*

Where our effort lies (from I. Shipsey, CPAD 2021 on BRN)



Four Grand Challenges encompass this Instrumentation revolution

- **Advancing HEP detectors to new regimes of sensitivity**: *To make the unmeasurable measurable will require the development of sensors with exquisite sensitivity with the ability to distinguish signal from noise…. Research will be needed to develop these sensors with maximal coupling to the quanta to be sensed and push their sensitivities to ultimate limits.*
- **Using Integration to enable scalability for HEP sensors**: *Future HEP detectors for certain classes of experiments will require massive increases in scalability to search for and study rare phenomena ... A key enabler of scalability is integration of many functions on, and extraction of multidimensional information from, these innovative sensors.*
- **Building next-generation HEP detectors with novel materials & advanced techniques**: *Future HEP detectors will have requirements beyond what is possible with the materials and techniques which we know. This requires identifying novel materials … that provide new properties or capabilities and adapting them & exploiting advanced techniques for design & manufacturing.*
- **Mastering extreme environments and data rates in HEP experiments**: *Future HEP detectors will involve extreme environments and exponential increases in data rates to explore elusive phenomena. ... To do so requires the intimate integration of intelligent computing with sensor technology.*

Beyond Si

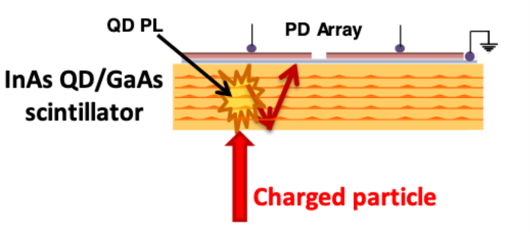
Can we change the paradigm from charge-drift to light collection for fast timing, tracking applications in HEP?

- Light travels faster than electrons can drift
- Bias voltages of 100s of V (Si) vs internal bias

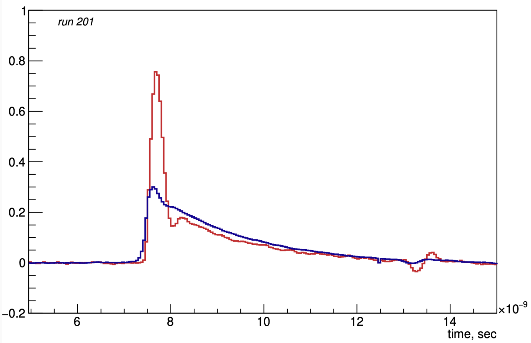
- Thin detector (small X_0)
- Fast light emmission (< 1 ns)
- High light yield
- Integrated photodetector
- Low power
- Radiation hard

Self-assembled InAs QDs embedded in GaAs semiconductor

1. Quantum Dot Scintillator (QDS) — shown in orange
    - ~20 μm thick
    - Ionizing particle produces e^-/h pairs in GaAs
    - Charges quickly captures by QDs (~few ps)
    - Excited state QDs emmit 1.1 eV photons with emission time of $\sim$ 1 ns
    - Low photon self-absorption ($\sim$ 1 cm^{-1})
2. Photosensor — monolithically integrated 1–2 μm thick InGaAs photodiodes

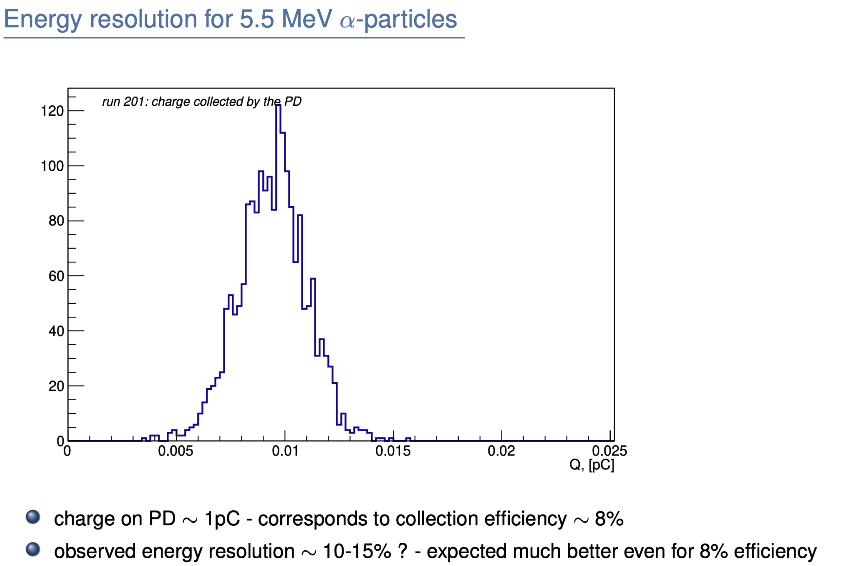


Phase α: QDS performance with α-particles (P. Murat—CPAD 2019)



- 5.5 MeV α-particles from Am-241
- two event types — likely signals produced via first hitting either PD or QDS
- ~100 ps rise time with no PD bias voltage

Energy spectra (P. Murat—CPAD 2019)



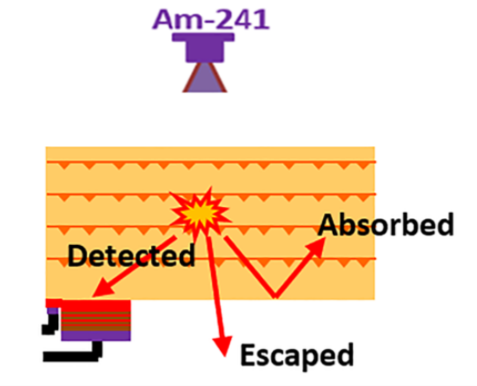
Energy resolution for 5.5 MeV α-particles

- charge on PD $\sim$ 1pC - corresponds to collection efficiency $\sim$ 8%
- observed energy resolution $\sim$ 10-15% ? - expected much better even for 8% efficiency

Backside illumination only (A. Minns et. al. MRS 2021)

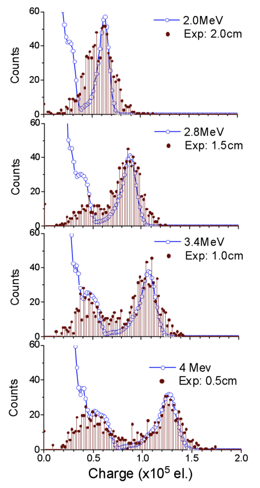
Same sensors, but QDS-impinging only

- Only take data with α source incident on QDS
- Expect $\sim$20μm range of 5.5 MeV α
- Expect fewer events with energy deposition in PD
- Make measurements at increasing distance between Am-241 and QDS

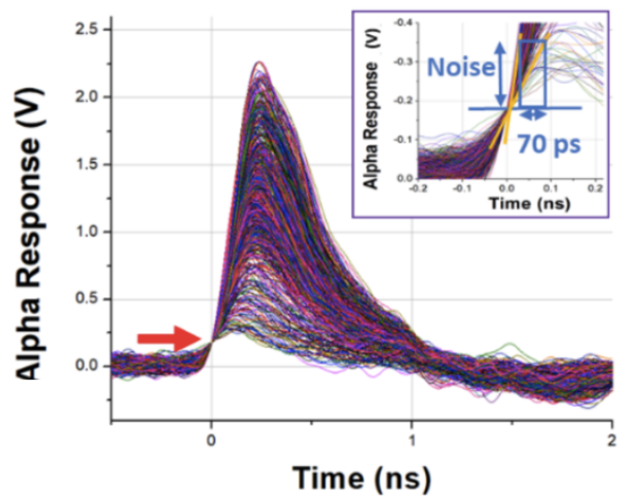


α-energy spectra vs distance (A. Minns et. al. MRS 2021)

- High charge peak corresponds to energy deposited directly under the PD
- However, ~10% observed energy resolution remains
- See light yield of ~3 × 10^4 e^- / MeV incident energy
    - Impressive, but still only ~10% of theoretical maximum



Timing performance (K. Dropiewski et. al, J. Lumin. 2020)



Phase $\alpha \rightarrow$ Phase β

Understand physics of uncommon sensor

- We need to understand our inefficiencies
  - Where does our ~10% energy resolution come from?
    - Perhaps nonuniformities in MBE growth?
    - Other ideas not yet thought of?
  - How can we improve our light collection efficiency?
    - Design new sensors with larger PD coverage

Feasibility for HEP applications

- We need to demonstrate effectiveness in MIP detection
- Start with transition from 5 MeV → 60 keV line from Am-241
- To reduce noise, will use longer integration times for short term measurements
- Sophisticated electronics and readout required for fast MIP detection
  - Expect signals of thousands of e^- in 100s ps

New sensor design completed, further tests starting at SUNY and FNAL

Summary

- We have constructed detector technology based on quantum dots embedded in GaAs semiconductor
    - Primary focus has been charged particle detection, but possibilities also exist for applications for X-ray imaging
- We have measured 10^4 e^- / MeV, $\sim$100ps rise times, and $\sim$70 ps resolution in α-particles in photovoltaic mode (no bias voltage on PD)
    - Fastest and highest light-yield of any known scintillator
    - Still 10% of expected performance
- Significant work and challenges remain, but performance prospects are encouraging
- Very much "blue skies" research, supported by DOE with SUNY Albany receiving grant to continue research in this direction

Early comparisons (T. Mahajan et. al. IEEE SORMA 2021)