Quantum dot based scintillators for charged particle detection

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Similar spirits (J. Metcalfe on thin film detectors)

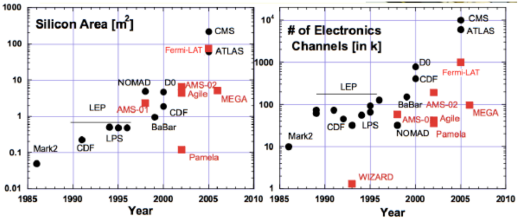
Motivation

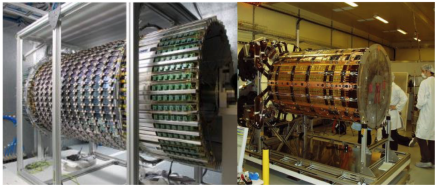
Silicon detectors are a cornerstone of High Energy Physics

Larger fractions of detectors are made with silicon

- More layers for precise tracking
- Limiting factor is often the cost
- Shift toward high precision silicon calorimeters

Can we come up with an alternative that might have an advantage?





Where our effort lies (from I. Shipsey yesterday)

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.*

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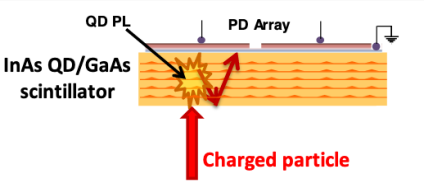
Beyond Si

Can we transition from a charge-drift paradigm to light collection for fast timing and/or tracking applications in HEP?

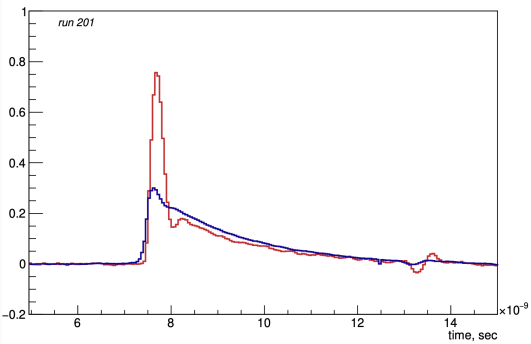
- Thin detector (small X_0)
- Fast light emmission (< 1 ns)
- High light yield
- Integrated photodetector
- Low power
- Radiation hard

Lab-grown InAs quantum dots (QDs) embedded in GaAs semiconductor



1. Quantum Dot Scintillator (QDS) — shown in orange
   - Thin layers of QDs sandwiched between thin layers of GaAs semiconductor
   - Total detector thickness of ∼20 μm
   - Ionizing particle produces e^-/h pairs in GaAs
   - Charges quickly absorbed by QDs (∼few ps)
   - Excited state QDs emmit photons as they transition to ground state
   - QD emission time of ∼ 1 ns
   - 1.1 eV emitted photons resulting in low photon self-absorption (∼ 1 cm^{-1})
2. Photosensor — physically integrated ∼1 μm thick InGaAs photodiodes

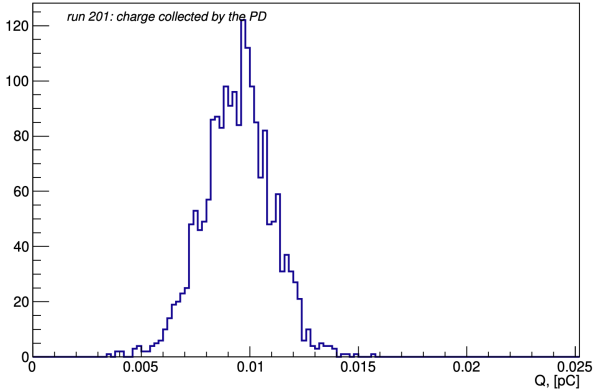
Phase α: QDS performance with α-particles (P. Murat—CPAD 2019)



- 5.5 MeV α-particles from Am-241
- two event types — likely signals produced via first hitting either PD or QDS
- $\sim$100 ps rise time with no PD bias voltage and only reading out with a scope

Energy spectra (P. Murat—CPAD 2019)

Energy resolution for 5.5 MeV α-particles

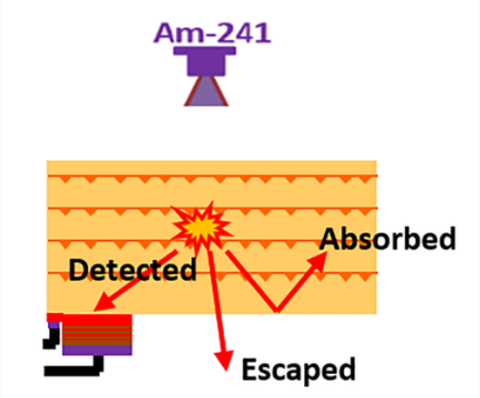


- charge on PD $\sim$ 1pC - corresponds to collection efficiency $\sim$ 8%
- observed energy resolution $\sim$ 10-15% ? - expected much better even for 8% efficiency

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

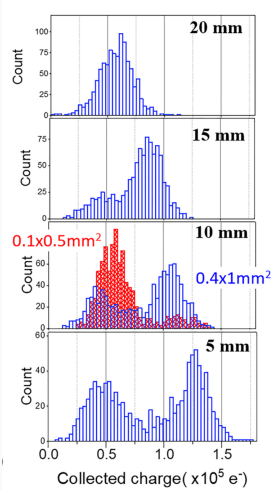
Same sensors, but QDS-impinging only

- Only take data with α source incident on QDS
- Expect ~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)

- Larger peak disappears as energy deposition is limited to QDS
- However, $\sim$10% observed energy resolution remains
- Still see $\sim$100 ps rise times (not shown)
- See light yield of $\sim 3 \times 10^4$ e^- / MeV incident energy
  - Impressive, but still only $\sim$10% of theoretical maximum



Phase $\alpha \rightarrow$ Phase β

Understand physics of uncommon sensor

- We need to understand our inefficiencies
  - Where does our $\sim$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 $\rightarrow$ 60 keV line from Am-241
- Will require 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

We need lab time to start working on any of this (tricky in modern times...)

Summary

- We have constructed detector technology based on quantum dots embedded in GaAs semiconductor
- We have measured 10^4 e^- / MeV with $\sim$100ps rise times 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
- We have a significant ways to go, including understanding the physics of our system