Scintillation detector based on InAs quantum dots in a GaAs semiconductor matrix for charged particle tracking
or
can one build a tracker out of scintillating wafers ?

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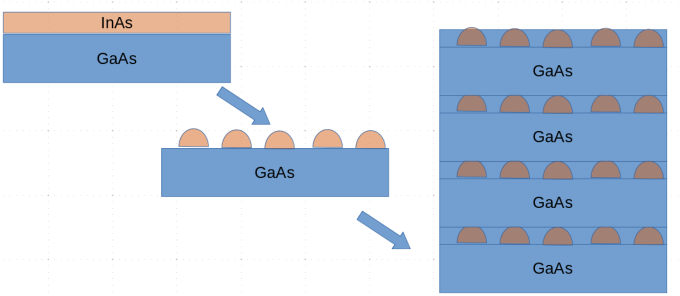
Why quantum dots?

if only Mu2e had a low-mass solid state tracker with the TOF resolution of 100 ps ...

- is it possible to build a tracker based on scintillating sensors?
  - collect photons, not drifting electrons - the detector could be much faster
  - not fibers - too long travel, too much material, - but planar ones ?
- the scintillator would need to have very high light yield, fast emission
- semiconductor-based scintillators ? $N_{ph}/MeV \sim 1e6/1.8 \cdot E_{gap} \sim (2-2.5)10^5$
- semiconductor quantum dots (QDs) are excellent and fast emitters with $\tau_{rad} \sim 1ns$
- have very limited use in HEP, mostly - wavelength shifting
  - making an efficient QD-based scintillator is a problem to solve
- how to make a scintillator out of QD's, how to read it out
- what happens when you start reading it out - first results
- a concept of tracking sensor with properties quite different from Si sensors

How to make a dense material with embedded QDs ?

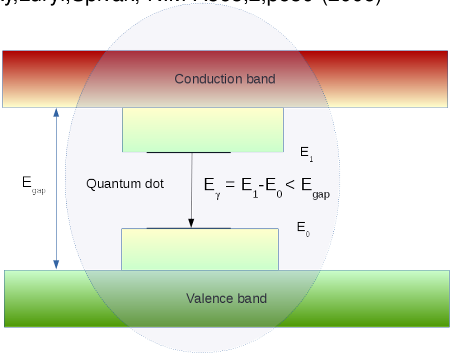
- the answer: InAs/GaAs self-assembling quantum dots
  - produced using molecular beam deposition in vacuum (MBE) at several hundred C
- lattice constants of GaAs and InAs are different
- minimization of the strain energy leads to stable nm-scale stable InAs islands - QD's
- repetitive procedure leads to a multi-layer structure



N.B. InAs/GaAs structures are grown as thin wafers (i.e, 3 inch)

How to make created material transparent to the QD emission?

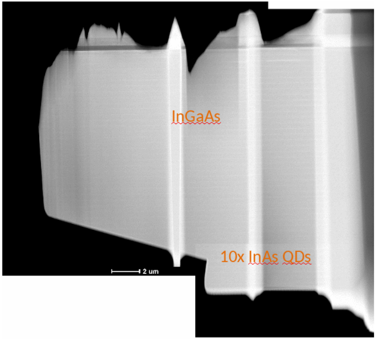
Kastalsky,Luryi,Spivak, NIM A565,2,p650 (2006)



- condition satisfied if QD's are embedded into a semiconductor bulk with $E_{gap} > E_\gamma$
  - InAs QD's: $E_\gamma \sim 1.08$ eV, $E_{gap}^{\mathrm{GaAs}} = 1.4$ eV
- other material choices possible, however much less investigated
- very high expectations: **light yield** $\sim$ **240,000 photons/MeV, emission time** $\tau \sim 1$ **ns**

N1801 20um Scintillator: low-mag. STEM

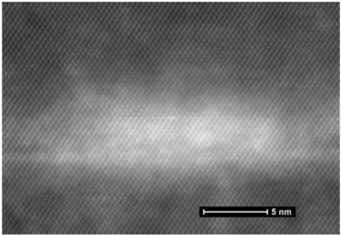
114012 HAADF



- sensors produced and characterized by our collaborators from SUNY Poly:
  - high-vacuum MBE, ∼ 3” wafers
- InGaAs photodiode - integrated, processed on a sensor
- N1801: 50 layers of InAs QD’s separated by 0.4 um of GaAs

N1801 20um Scintillator: QDs, TEM, DF

#120498HAADF



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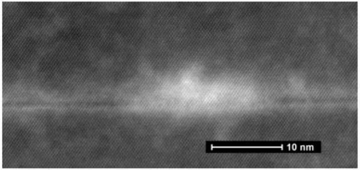

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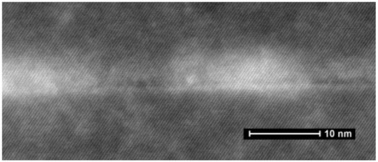
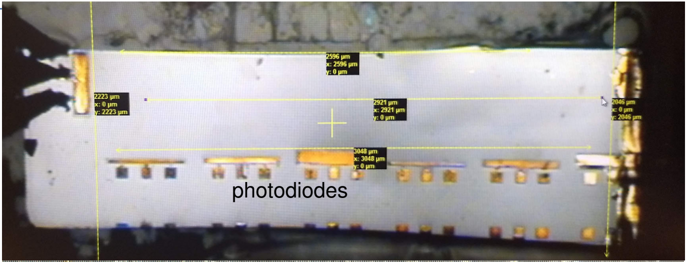
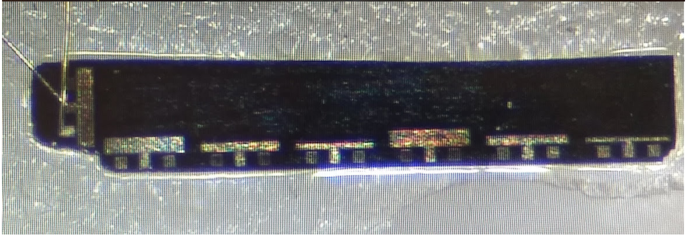


QD diam ~ 14nm
QD density (4-5) x 10^{10} cm^{-2}

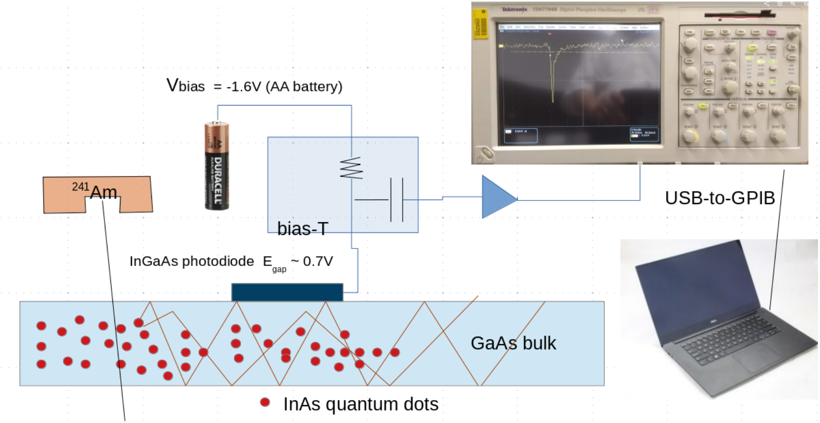
First generation sensors: 20 um thick





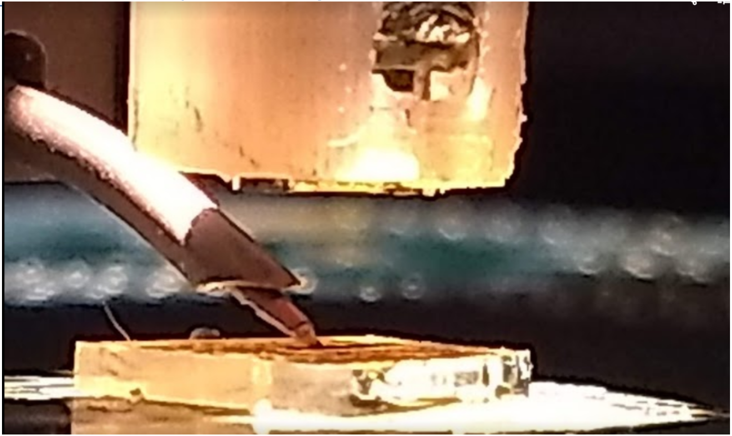
- gen1 sensors: 4-5 mm long , $\sim$ 1 mm wide, 20 um thick - to stop a 5.5 MeV α-particle
- GaAs index of refraction n = 3.4 => upon reflection from a plane only 2% of light exits
- expect $\sim$ 90% of the emitted light not to exit ==> **InGaAs photodiodes integrated**
- photodiodes - 500um x (35 -50 - 100) um x 0.7 um mesa

First characterization attempt at Fermilab



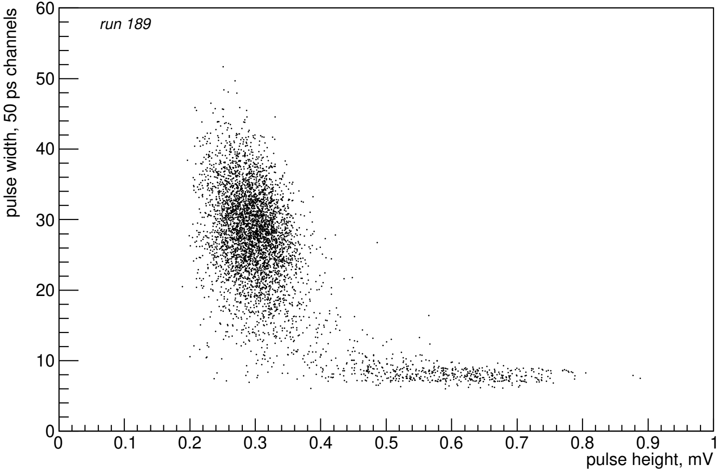
- amplifiers - 1-3 stages, the total gain up to 600
- use TDS7704B (7GHz, 20Gs) as a trigger+DAQ
- read the oscilloscope over GPIB (up to a few Hz), analyze data offline

schematics can be very misleading



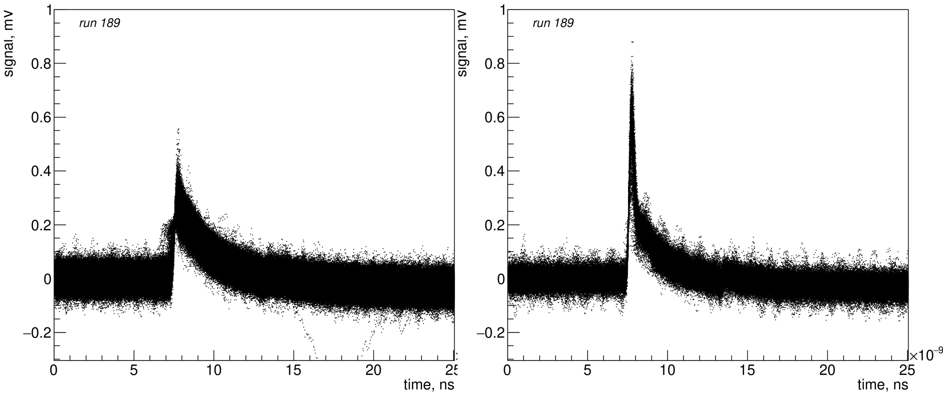
- for scintillators, goal number one - measure the energy resolution
- Am-241 5.5 MeV α-particle range in the air $\sim$ 4 cm
- want the r/a source as small as possible - a $14 smoke detector is the best bet
- the source energy resolution $\sim$ 3%, source-to-source variations at a level of 2%
- uncollimated source with the D=2.2 mm ^{241}Am foil

First data



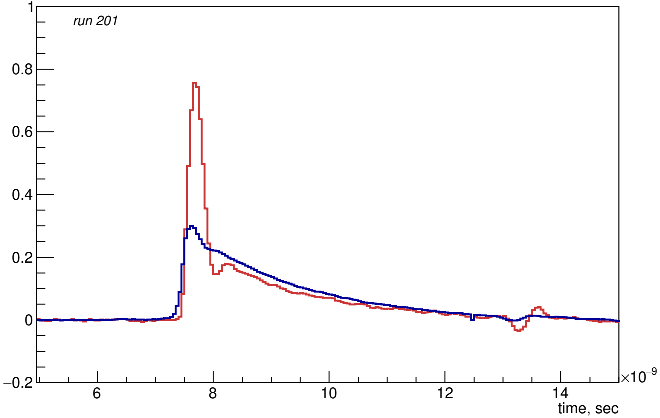
- observe two very distinct groups of pulses

waveforms from the two groups - strikingly different



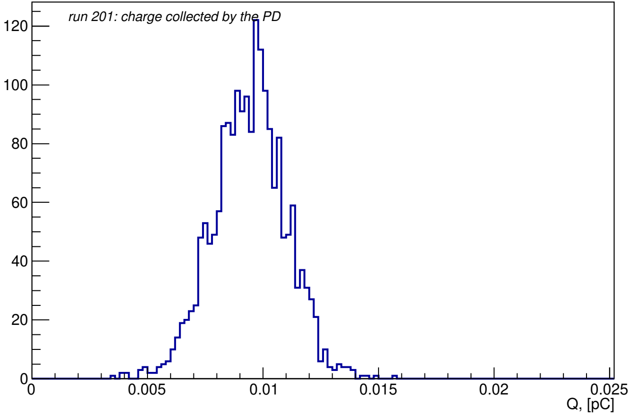
- full width of the spike (left) - about 500 ps
  - consistent with being limited by the amplifier bandwidth
- noise - 30 μV, a $\sim$ 1 GHz pick-up seen
  - the digital oscilloscope itself is an important contributor

Overlaying pulses of two types



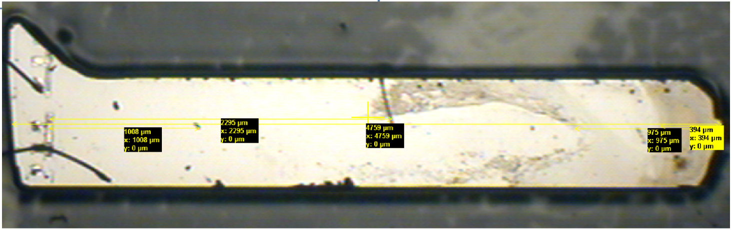
- charge in the spike consistent with the direct ionization in the 50x500x0.7 um PD
- pulses with spikes - α's going through the PD and stopping in the scintillator
- pulses without spikes - particles hitting the scintillator, but not the PD
- tail consistent with the QD radiative lifetime of $\sim$ 1-1.5 ns

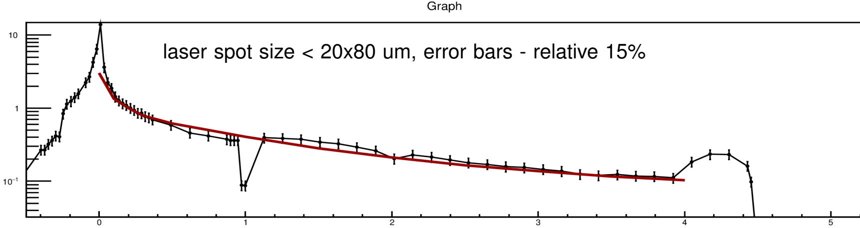
Energy resolution for 5.5 MeV α-particles



- charge on PD $\sim$ 1pC - corresponds to collection efficiency $\sim$ 8%
- observed energy resolution $\sim$ 10-15% ? - expected much better even for 8% efficiency
- the sensors are 20 um thin - could multiple reflections in the sensor play a role ?

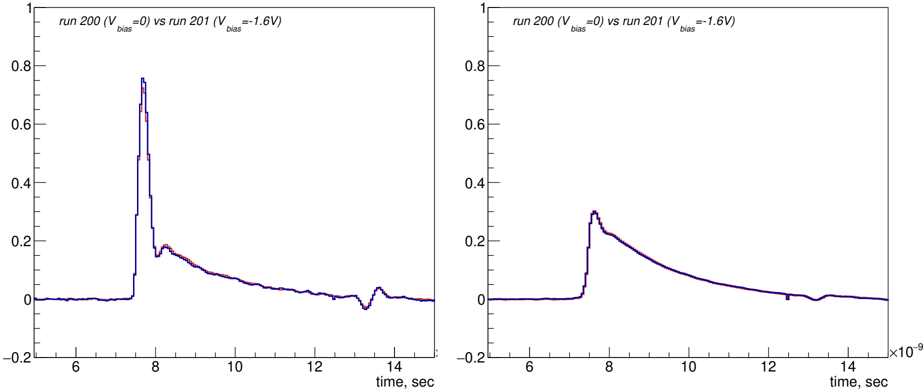
Laser scan of the sensor:measure the PD photocurrent





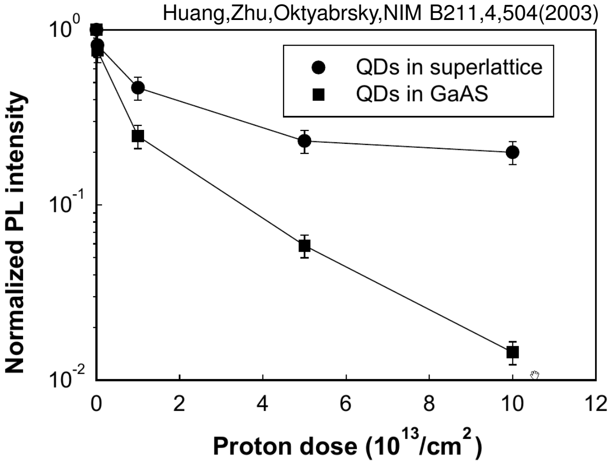
- laser scan captures the photodiode, defect, and epoxy in the end
- MC : $\lambda_{abs} \sim$ 2.2 mm, probability of diffuse reflection - 2.5% - good description
- geometry is important: **1 mm away from the PD the signal drops by $\sim$ x10**
- **photodiodes on gen1 detectors are too small for efficient detection**

Running with zero external bias on PDs



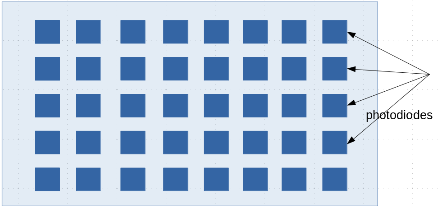
- a p-n junction has an internal bias of the order of 1V (0.7 for Si)
- external bias of $\sim$ 1V doesn't add much
- detector - sensor + PD - can operate in a photovoltaic mode, as a solar cell
- zero-bias mode minimizes the dark current, no shot noise

Radiation hardness - irradiation with 1 MeV protons



- emission of InAs QD's in a 5-layer superlattice reduced by 20% after 10^{13} protons/cm^2
- 99% recovery after $5 \cdot 10^{13} p/cm^2$ ($\sim$ 90 MRad) and 10 min annealing in N_2 at 600 deg C
- Mu2e-II: expect $\sim 10^{12}$ protons / cm^2

Concept of a tracking sensor: GaAs/QD sensor with PD's as pixels



- have technology producing rad-hard scintillating sensors
- sensors are produced as thin wafers with integrated photodetectors
- detect light, light propagates in all directions - could expect high "fill factor"
- coordinate resolution: 500 um pad ==> $\sigma \sim 150\mu$ - adequate for many trackers
- material budget: 20 um GaAs $\sim$ 40 um Si ==> 3800 $e^{-}h$ pairs
  - **need to read out signals corresponding to 1000 photons**
- measure signals with $\sim$ 200 ps leading edge
  - timing resolution expectations are high
  - detect photons traveling $|sim$ 1 mm, no $\sim$ 10-15 ps floor
- sensors and photodiodes may not need power

Summary

- detectors made of semiconductor-based scintillators may quite interesting applications in HEP
- QD/GaAs -based sensors are fast, rad-hard, have integrated photodiodes
- signals from α-particles have leading edge shorter than 1 ns
- photodiodes can operate without an external bias
- further R&D is needed to
  - improve light collection efficiency
  - develop low noise readout for MIP signals
- **one could think of a charged particle tracking sensors built based on this concept**