Scintillating sensors based on InAs quantum dots in a GaAs semiconductor matrix

Snowmass'2021 white paper planning

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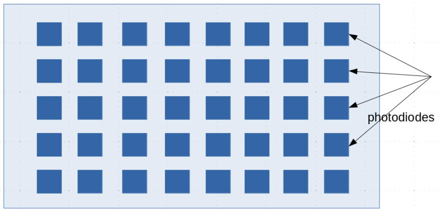
Motivation

- Next generation trackers will require timing resolution ~ 5 ps
- solid state detectors based on collecting drifting electrons may have a “floor” above that. For example, LGAD’s seem to have a floor at a level of 15 ps
- scintillating sensors:
  - collect photons, not drifting electrons - the detector could be much faster
  - SciFi trackers are know, but fibers have too long travel time, too much material
  - **focus on planar sensors**
- the scintillator would need to have very high light yield, fast emission
- semiconductor-based scintillators ? $N_{ph}/MeV \sim 1e6/1.8 \cdot E_{gap} \sim (2-2.5)10^5$
- people:
  - Fermilab: C.Gingu, S.Los, P.Murat
  - SUNY Poly : S.Oktyabrsky, M.Yakimov, V.Tokranov, K.Dropiewsky, A.Minns

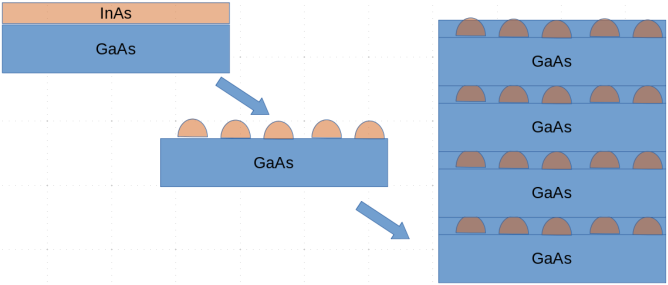
Concept of a tracking sensor: GaAs/QD sensor with PD's as pixels



- sensors : thin wafers with integrated photodetectors
- detect light, light propagates in all directions - could expect high "fill factor"
- not a sensor for vertex detectors
  - 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**
- currently, measure signals with the leading edge of $\sim$ 150-200 ps
  - detected photons travel distances $\sim$ 1 mm, no $\sim$ 10-15 ps theoretical floor

How to make a sensor with embedded QDs ?

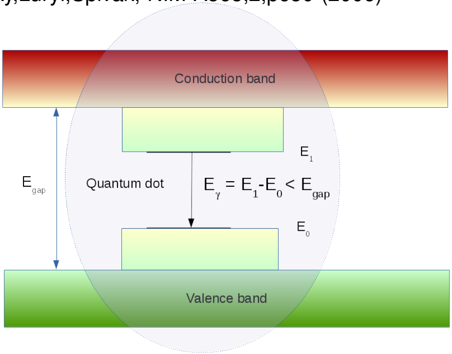
- the answer: InAs/GaAs self-assembling quantum dots
  - produced using molecular beam deposition in vacuum (MBE) at several hundred C
- lattice constants of GaAs and InAs are different
- minimization of the strain energy leads to stable nm-scale stable InAs islands - QD's
- repetitive procedure leads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



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

How to make sensor transparent to the QD emission

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

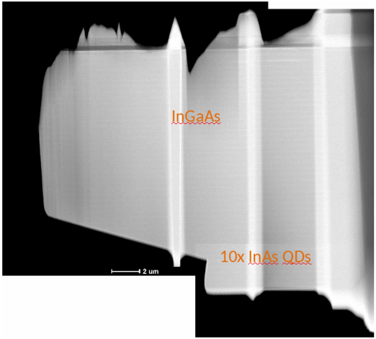


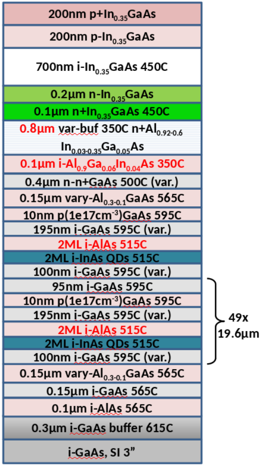
- condition satisfied if QD's are embedded into a semiconductor bulk with $E_{gap} > E_\gamma$
  - InAs QD's: $E_\gamma \sim 1.08$ eV, $E_{gap}^{\mathrm{GaAs}} = 1.4$ eV
- other material choices possible, however much less investigated
- **light yield $\sim$ 240,000 photons/MeV, emission time $\tau \sim$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

InAs QD / GaAs Sensors

N1801 20um Scintillator: low-mag. STEM

114012 HAADF

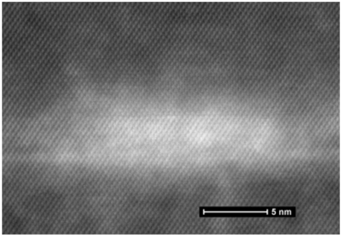




- sensors production, optical and electrical characterization at SUNY Poly
  - high-vacuum MBE, ∼ 3” wafers
- InGaAs photodiode - integrated, processed on a sensor
- wafer with codename N1801 : 50 layers of InAs QD’s separated by 0.4 um of GaAs

N1801 20um Scintillator: QDs, TEM, DF

#120498HAADF



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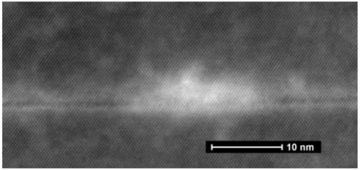

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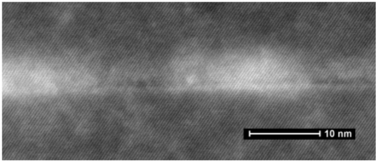
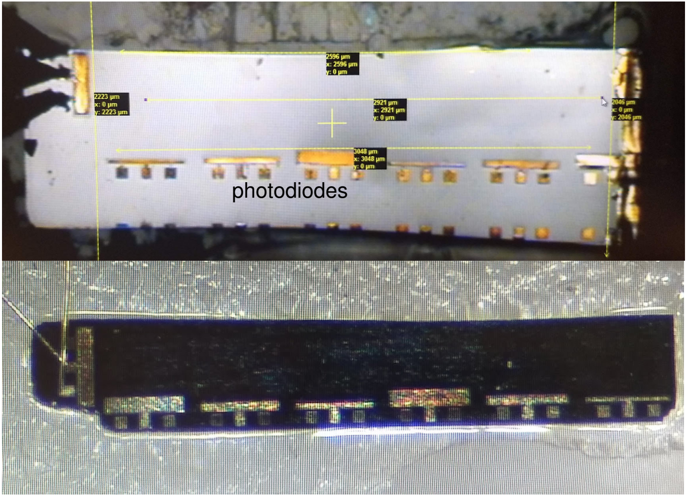


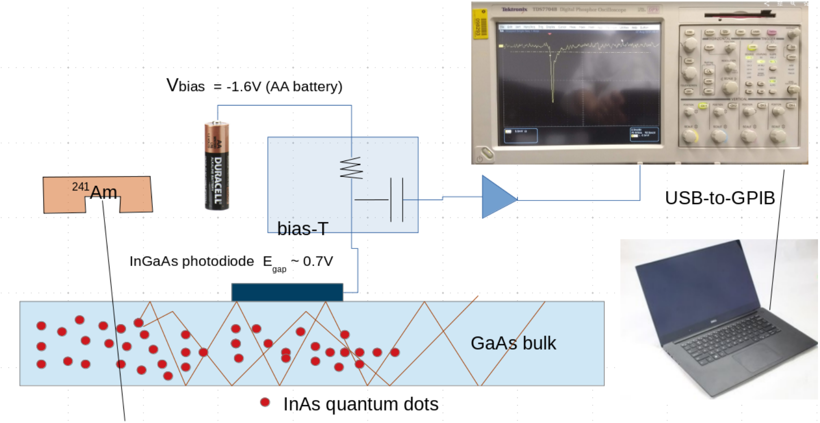
QD diam ~ 14nm
QD density (4-5) x 10^{10} cm^{-2}

First generation detectors: 20 um thick scintillators



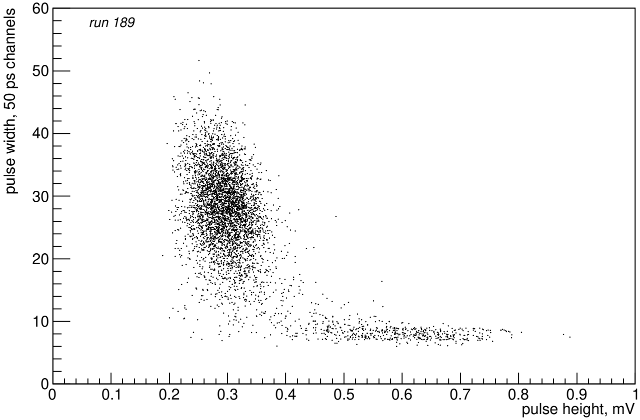
- gen1 sensors: 4-5 mm long , $\sim$ 1 mm wide, 20 um thick - to stop a 5.5 MeV α-particle
- photodiodes of 3 different sizes : 500um x (35-50-100) um x 0.7 um mesa

Measurements at Fermilab



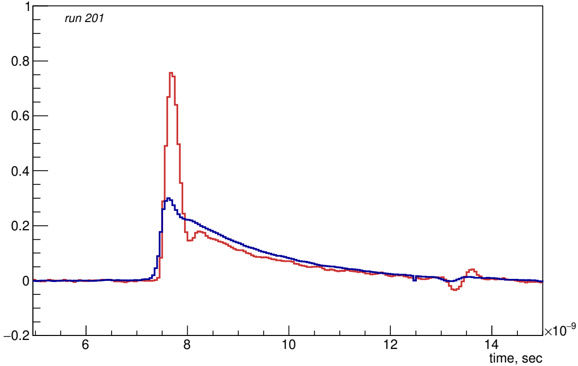
- measurements : use a probe station in WH14 clean room
- amplifiers - 1-3 stages, the total gain up to 600
- use TDS7704B (7GHz, 20Gs) as a trigger+DAQ
- read the oscilloscope over GPIB (readout rate up to a few Hz), analyze data offline

First data : waveform analysis



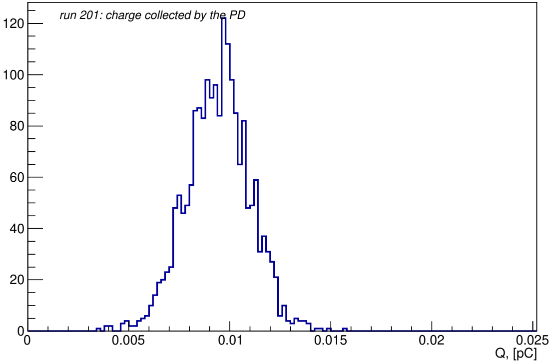
- for each waveform, reconstruct the pulse height and the pulse width (FWHM)
- observe two distinct groups of signals
- the effect is robust, observed with different sensors, different photodiodes, and different amplifiers

Comparison of the averaged waveforms



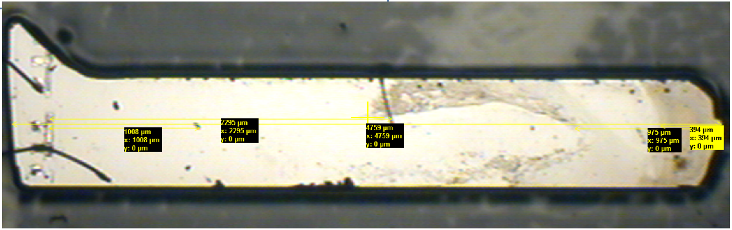
- charge in the spike consistent with the direct ionization in the 50x500x0.7 um PD
- current interpretation:
  - pulses with spikes - α's going through the PD and stopping in the scintillator
  - pulses without spikes - particles hitting the scintillator, but not the PD
- tail consistent with the QD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

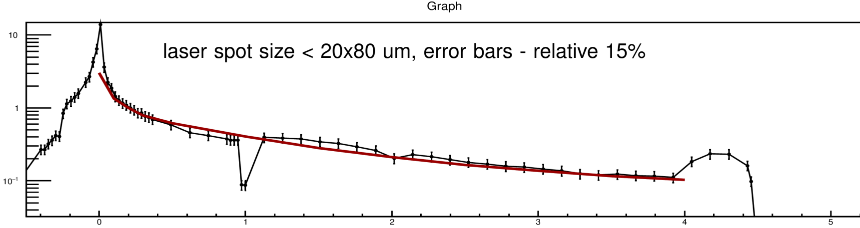
Energy resolution for Am-241 5.5 MeV α-particles



- energy of the particle entering the detector $\sim$ 4.6-4.7 MeV (losses in the source)
- charge on PD $\sim$ 0.01 pC - corresponds to the light collection efficiency of $\sim$ 6%
- observed energy resolution $\sim$ 10-15%, expected much better even for 6% efficiency
- tested sensors are long and thin - light is waveguided to the PD, reflects multiple times
- multiple reflections in the sensor?

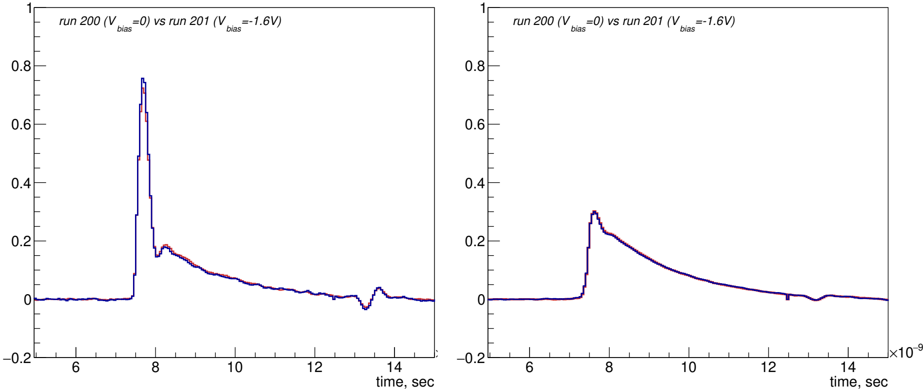
Laser scan of the sensor: measure the PD photocurrent





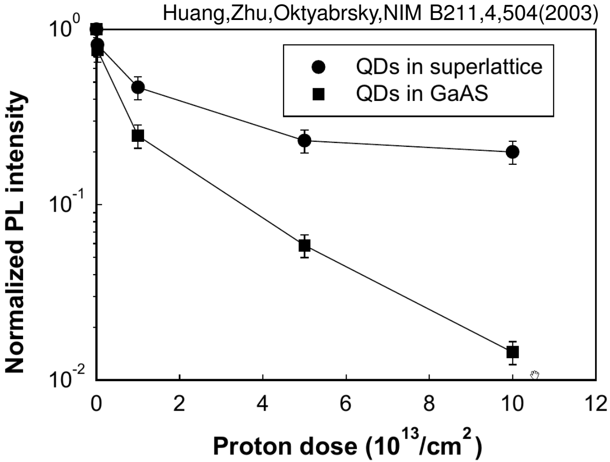
- laser scan (beam size 70x20 um^2) captures the structure of the photodiode, defects, epoxy at the end
- MC with $\lambda_{abs} \sim$ 2.2 mm and probability of diffuse reflection of 2.5% gives good description
- geometry is important: **1 mm away from the PD the signal drops by $\sim$ x10**
- **photodiodes on Gen1 detectors are too small for efficient light detection**

PD's can operate with zero external bias



- plotted: overlayed average waveforms for two runs - with Vbias = -1.6V and with Vbias = 0
- detector can operate without an external bias voltage (photovoltaic mode, as a solar cell)
- 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
- 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

Publications and Reports

- Optical Properties of InAs Quantum Dots/GaAs Waveguides for Ultra-fast Scintillators, K.Dropiewski et al, Journal of Luminiscence, 220 (2020) 116952

- Scintillation detector based on InAs quantum dots in a GaAs semiconductor matrix for charged particle tracking, P.Murat et al, CPAD'2019, Madison

Summary and next steps

Summary

- first set of measurements with the QD/GaAs-based scintillating detectors completed
- observed that detectors can operate in a photovoltaic mode

Next steps

- study of the sensor response as a function of deposited energy
- optimization of the detector geometry (larger PD's)
- study of detectors with multiple PD's
- development of the readout electronics
- temperature dependence of sensor response