QD/semiconductor-based scintillators and their potential for Mu2e-II

Mu2e-II workshop, ANL

P.Murat, A.Ronzhin (Fermilab), S.Oktyabrsky, M.Yakimov, V.Tokranov (SUNY Polytechnic Institute, Albany, NY)

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Semiconductor-based scintillators and quantum dots

- the very first scintillator used in particle physics was semiconductor-based (Geiger-Marsden, ZnS)
- quantum dots (QDs): 3D nano-crystals, known from early 1980's
- confined quantum system - have discrete energy levels
- emission wavelength depends on the QD size
- two main production technologies: wet growth - in colloids, **epitaxial growth (CVD, MBE)**

Self-assembling QDs

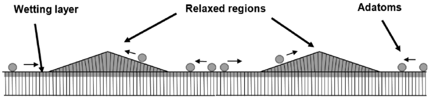

Fig. 5 Schematic drawing illustrating QD self-assembly. Two main driving forces for self-assembled growth: (i) strain energy is lower in 3D structure then in the uniform 2D strained layer, and (ii) stress term in surface chemical potential drives adatoms toward the tops of the islands.

- the self-assembling process controlled by thermodynamics (like water on the glass)
- deposited material has to have lattice parameter significantly different from the substrate
- InAs lattice parameter (6.06 A): 7.2% larger than GaAs lattice parameter (5.65 A)
- islands grow as a function of time
- multiple handles to control size and concentration

InAs QD emission

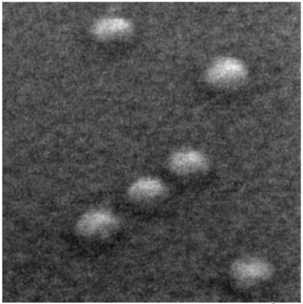

Fig. 5. Plan view scanning electron microscopy image of a small group of uncapped InAs quantum dots grown on GaAs. The field of view is 150 $\times$ 150 nm^2. Image courtesy of J. Fraser, Institute for Microstructural Sciences, National Research Council Canada.

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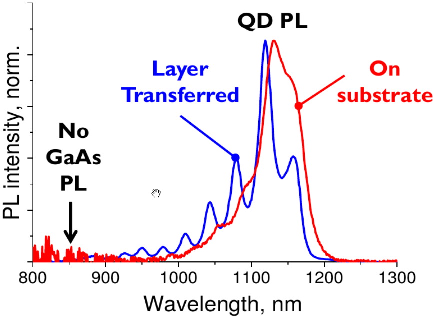
RT PL spectra from the surface before and after layer transfer

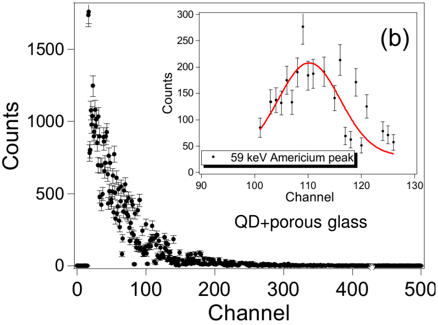


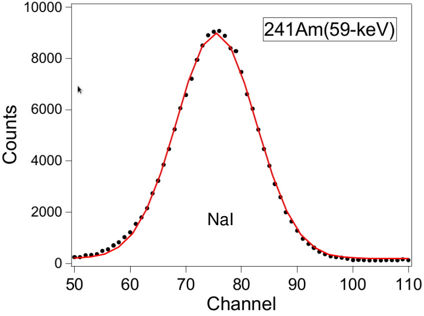
- InAs / GaAs system is the best studied system
- InAs QDs emit in infrared region

QDs and photon detection

Channel

Letant, Wang, Nano Lett.,2006,6(12) pp 2877-2880

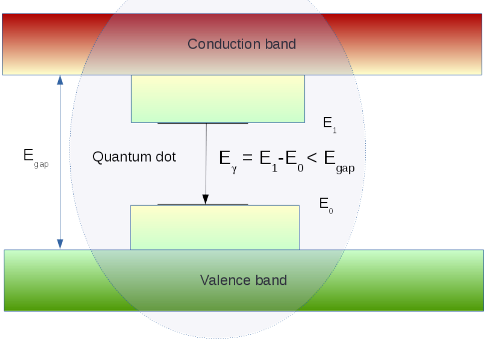




- issue: how to create medium transparent to the QD emission ?
- Letant,Wang'2006: use porous glass substrate and CdSe/ZnS QDs
- resolution @59 keV x2 better than NaI ($\delta E/E = 15\%$ vs 30%) at a room temperature
- use of QD's as wavelength shifters (Steve Magill discussed that for BaF2, also - in neutrino physics, for 2β decay)

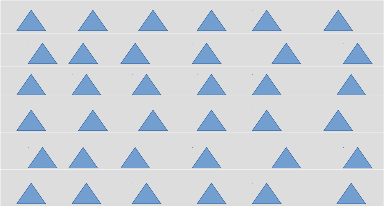
QD/semiconductor based scintillator - the idea

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



- embed QDs into a semiconductor with the $E_{gap} > E_{photon}$
- technology available: InAs QD's in GaAs bulk
- other material choices possible, however much less investigated

What to expect from a QD/semiconductor based scintillator



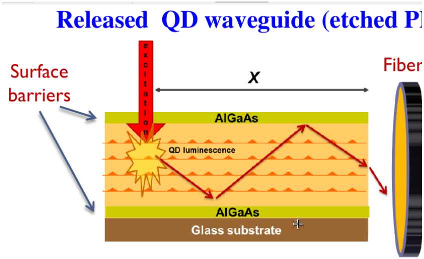
- 3D QD/semiconductor structure can be created by growing multiple capped QD layers
- band gap 1.4 eV => $E_{pair} \sim$ 4.2 eV => $\sim$ 240,000 pairs/MeV
- QD concentration of $10^{15}/cm^3$: effects of re-absorption/re-emission small
- typical distance to the closest QD: $\sim 10^{-5}$ cm = 0.1μ « free electron path length
- saturation electron drift velocity in GaAs $\sim 10^7 cm/sec$
- typical time for an electron to reach a QD $\sim$ 1ps
- QD emission time : $\sim$ 1 ns
- comparison to Si detectors: **electron drift path 0.1 um vs 100 um**

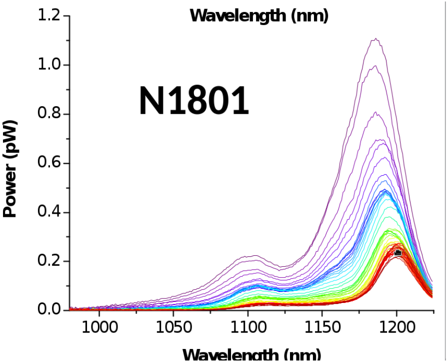
Comparison to inorganic scintillators

scintillator	density, g/cm3	X0, cm	Photon Yield, N/MeV	Decay Time, ns	Peak Emission, nm	time between first photons, tau/yield, ps
NaI(Tl)	3.67	2.6	45000	250	415	5.6
BaF2	4.88	2.03	1800	0.8	190/220	0.44
LYSO	7.4	1.14	33000	40	420	1.2
PbWo4	8.2	0.9	300	2.5/11/98	490	33
InAs QD in GaAs	5.3	2.3	240000 *)	0.5	1100-1200	0.002

- can expect quite outstanding timing resolution
- energy resolution of the same order as Ge detectors
- all at the same time
- sensors produced as thin films, the relevant unit cm^2, not cm^3

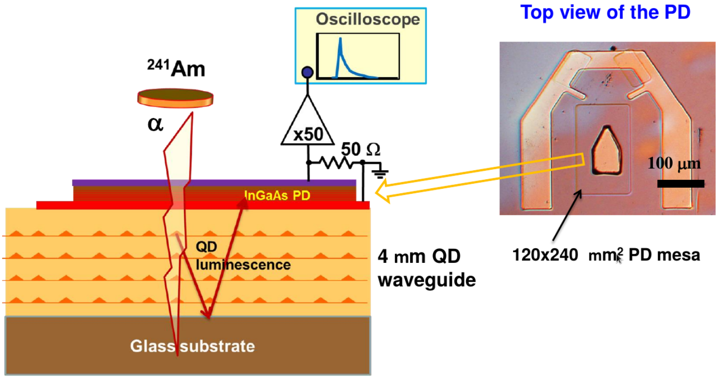
First measurements at SUNY Polytechnic institute with the laser





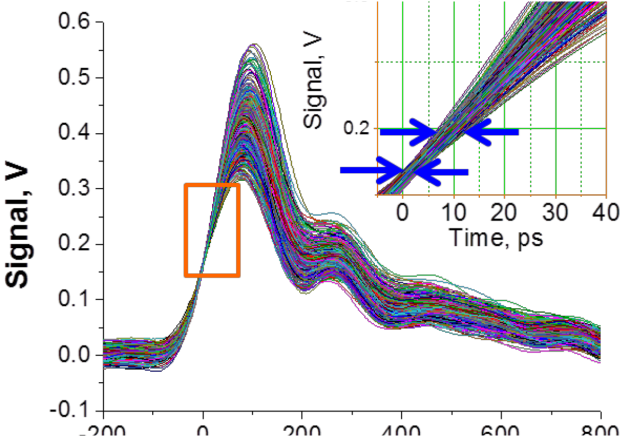
- GaAs refraction index n = 3.4, only 4% of the produced light exits the sensor
- maximum of the spectrum slightly moves to the right as the distance increases

First source measurements: setup



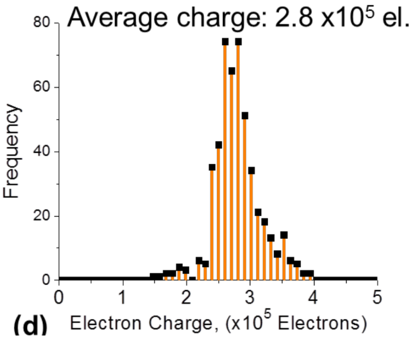
- to collect light, need an integrated photodetector
- InGaAs photodiode processed on the sensor, detector can be thin - 1-2-3 microns
- biased by 10V (unit gain)
- total thickness of the integrated InAs/GaAs detector - about 5μ (4+1)
- reported measurements - very preliminary

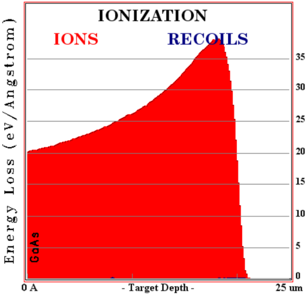
First measurements - timing



- 500 pulses detected with 40 Gsample scope, full scale - 1ns
- estimated emission time $\sim$ 300 ps
- pulse rise time $\sim$ 140 ps
- timing resolution - much better than that

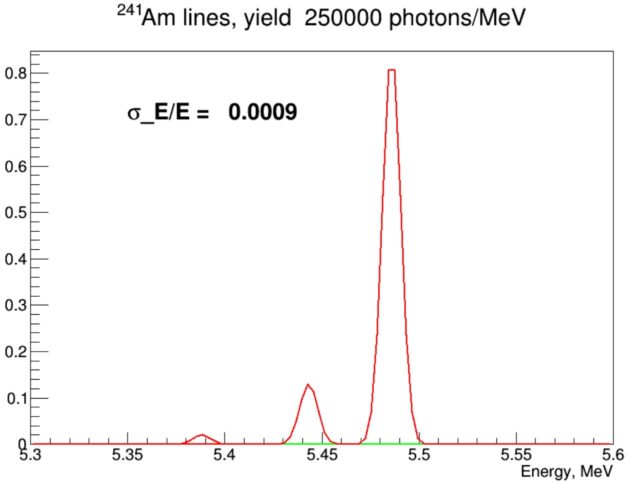
First measurements - energy resolution





- 5.5 MeV α particle (^{241}Am) ranges out of 5 μ of GaAs, depositing there about 1.1 MeV
- resolution in the integrated charge limited by the fluctuations of the energy losses
- total collection efficiency > 90%

Expectatations for 20μ thick sensor



- assume 100% efficiency of energy conversion
- with fully stopped 5.5 MeV alpha particles can expect to resolve individual ^{241}Am lines

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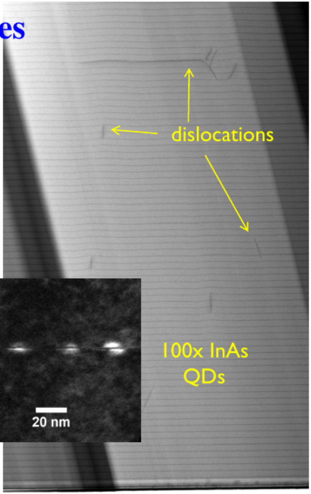
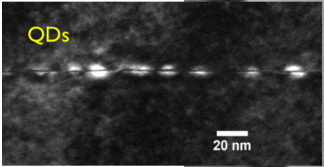
20 µm Scintillator: Structure

TEM images





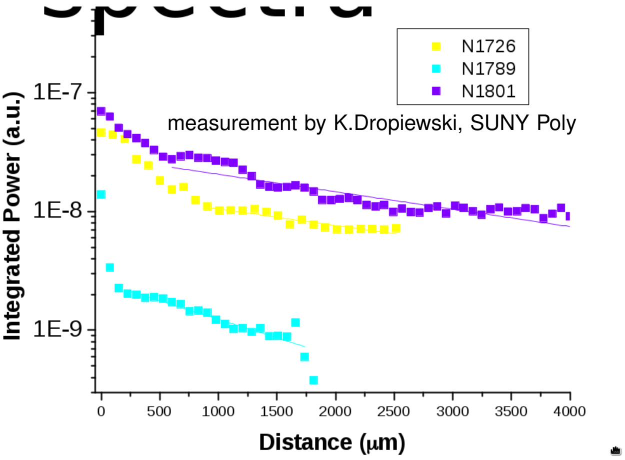
Glass

2 um

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

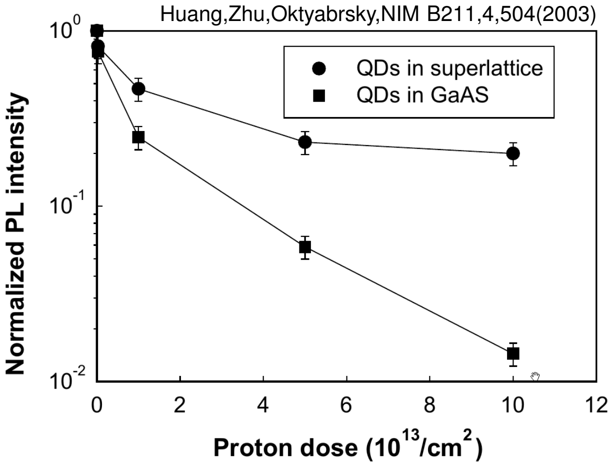
Layer	
200nm p+$In_{0.35}$GaAs	
200nm p-$In_{0.35}$GaAs	
700nm i-$In_{0.35}$GaAs 450C	
0.15µm n-$In_{0.35}$GaAs	
0.15µm n+$In_{0.35}$GaAs 450C	
0.7µm var-buffer 350C n+$Al_{0.92-0.6}In_{0.03-0.35}Ga_{0.05}As$	
0.3µm n-n+GaAs 500C (var.)	
0.1µm i-$Al_{0.28}Ga_{0.72}As$ 565C	
30nm i-GaAs 590C	
10nm p(1e17cm^{-3})GaAs 590C	
10nm i-GaAs 590C (var.)	
2ML i-InAs QDs 510C	
50nm i-GaAs 590C (var.)	
130nm i-GaAs 590C	99x =19.8µm
10nm p(1e17cm^{-3})GaAs 590C	
10nm i-GaAs 590C (var.)	
2ML i-InAs QDs 510C	
50nm i-GaAs 590C (var.)	
0.1µm i-$Al_{0.28}Ga_{0.72}As$ 565C	
0.1µm i-GaAs 565C	
0.1µm i-AlAs 565C	
0.3µm i-GaAs buffer 615C	
i-GaAs, SI 2”	

First measurements - attenuation length



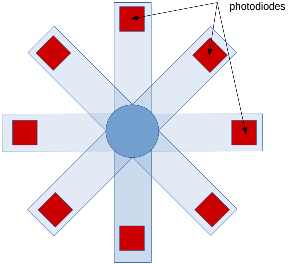
- most recent QD/GaAs sensor: 4mm x 0.8mm x 20 um
- attenuation length $\sim$ 4 mm

Radiation hardness



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

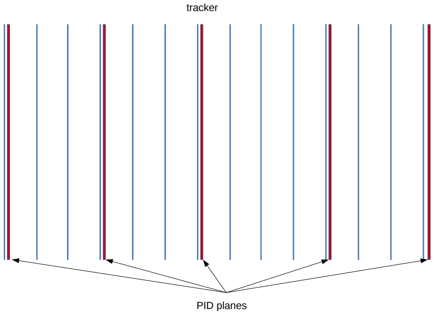
QD/semiconductor-based scintillators and Mu2e-II: count stopped muons



STM cartoon

- muon capture in Al: several distinct emission lines, 350 - 1800 keV photons
- HP-Ge detectors may have issues with the the counting rates already for Mu2e-I
- QD/GaAs-based scintillator - orders of magnitude faster
- stopping range of a 350 keV electron in GaAs $\sim$ 300 um
- stack of 16 20μ-thick sensors with integrated photodiodes would be sufficient
- detector small, runs at a room temp, can be mounted on the tracker support structure

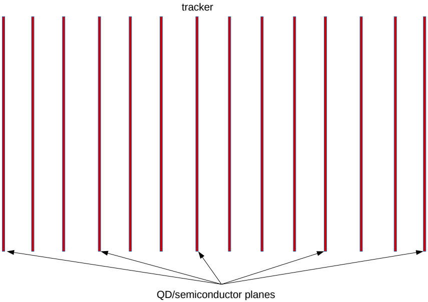
Low mass tracker with PID capabilities



- 100 MeV/c **e** crossing 10um of GaAs at 45° produces $\sim$ 3000 e-h pairs
- 10% collection efficiency => 300 photons, dE/dX resolution about 6% per layer
- a 100 MeV/c muon would produce x2 photons , $\sim$ 600
- timing: 0.5 ns / layer would be great, intrinsic resolution orders of magnitude better
- 10 um of GaAs are close to material budget of one Mu2e straw tracker panel

several planes of QD/GaAs scintillator positioned inside the tracker could improve robustness of tracking and, compared to current Mu2e projections, provide better PID

QD/semiconductor scintillator-based tracker with PID capabilities?



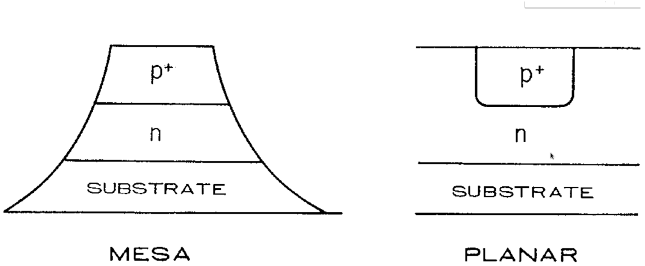
- for beam intensities x10 the current Mu2e rate (3.9 10^7 protons/pulse) or higher, any drift-based gas detector would suffer from high occupancies
- 5μ (?) thick QD/GaAs scintillators could provide a sensor technology for building a tracker with momentum resolution $\delta p/p \sim 2 \cdot 10^{-3}$ and built-in PID capabilities
- 500 μ pitch => $\sigma \sim 144\ \mu$
- precision timing - efficient triggering
- how thin could the readout electronics layer be made?
- 4μ-thick InGaAs APD's with G>10^3 have been reported

Summary

- QD/semiconductor-based scintillators could have time and energy resolutions significantly surpassing best inorganic scintillators
- QDs are radiation hard : 75% of original emission intensity after 10^{13} p/cm^2
- ultra-low mass tracking combined with time-of-flight and dE/dX could find multiple applications in HEP
- thin film detectors based on QD/semiconductor scintillators could allow high-resolution, ultra high-rate calorimetery at low energies (below 1 MeV)
- next generation $\mu \to e$ conversion experiments could use QD/semiconductor scintillators in several subsystems: stopping target monitor, PID system, tracking
- LDRD proposal submitted to Fermilab, expect decision in early 2018

Backup

Mesa vs Planar Photodiodes



Scintillator table