Semiconductor scintillators

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Why Semiconductor Scintillators

- the very first scintillator (ZnS phosphor used by Marsden) was a semiconductor
- keep looking for better scintillating materials
- better : faster, with higher light yield, more radiation hard, heavier
- Si : $\sim$ 3.5 eV/pair, $\sim$ 280,000 pairs/MeV
- NaJ : 25 eV/pair –> 40,000 pairs/MeV
- semiconductor scintillators : potentially, best light yield

How to make a semiconductor to emit the light: radiative recombination

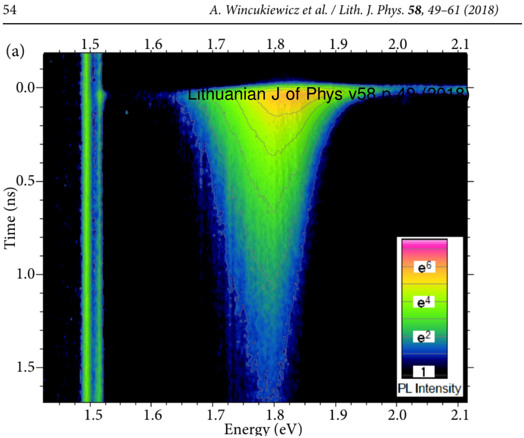
Yu,Cardona, Semiconductors, 3rd ed, 2010

Table 7.1. Minority carrier radiative lifetime in several tetrahedrally bonded semiconductors at room temperature. From [Ref. 7.15, p. 111]

	τ_{rad}	
Semiconductor	Intrinsic	10^{17} cm^{-3} majority carriers
Si	4.6 h	2.5 ms
Ge	0.61 s	0.15 ms
GaP		3.0 ms
GaAs	2.8 μs	0.04 μs
InAs	15 μs	0.24 μs
InSb	0.62 μs	0.12 μs

- radiative recombination time can be small, i.e. GaAs 40ns
- GaAs: efficiency of the radiative recombination > 95%, can use for cooling...

Fast emission: add quantum dots



- Time-resolved luminescence of $In_{0.4}(Al_{0.75}Ga_{0.25})_{0.6}As$ quantum dots immersed in $Al_{0.75}Ga_{0.25}As$, grown on GaAs
- characteristic scintillation time under the laser excitation < 1 ns

More on radiative recombination

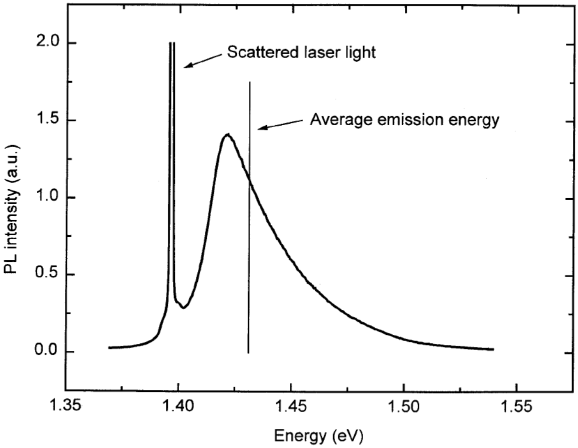
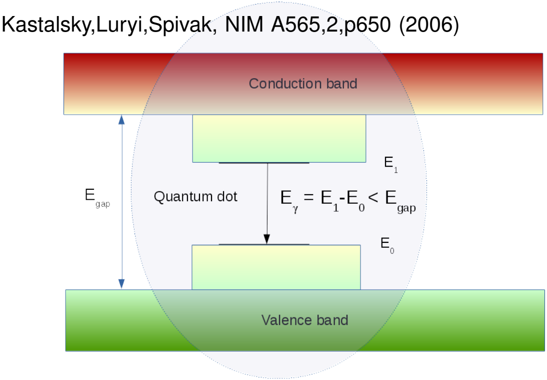


Fig. 4. Room temperature photoluminescence spectrum showing the blueshift of the emitted light relative to the energy of absorbed laser light

- light produced in a semiconductor gets reabsorbed, so, normally, semiconductors are not transparent to their own emission

2. Make quantum dots bigger !



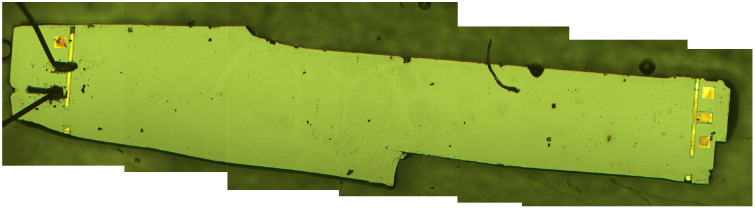
- embed bigger QDs into a semiconductor with the $E_{gap} > E_{\gamma}$
- most developed technology: InAs QD's ($E_{photon} \sim 1.08$eV) in GaAs bulk ($E_{gap} = 1.4$eV)
- other material choices possible, much less investigated

Collaboration with SUNY Poly Albany

- SUNY Poly: Serge Oktyabrsky, Mike Yakimov, Vadim Tokranov, Katie Dropiewski, Alan Minns
- FNAL: Christian Gingu (FNAL), Sergey Los, PM

The sensors: developed by our collaborators for SUNY Albany

N1801- PCD-E (MHC311 amp) “K8 D GR8”



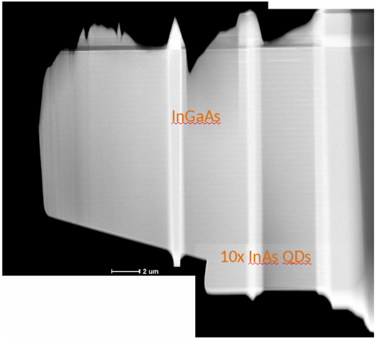
N1801- PCD-D (MHC311 amp) “Golden Boy”

- 2 sensors wire-bonded to preamps, rouphly speaking, 5mm x 1mm x 25um
- different photodiode configurations (step b/w contact pads - 150 um)

InAs QD / GaAs Sensors

N1801 20um Scintillator: low-mag. STEM

114012 HAADF



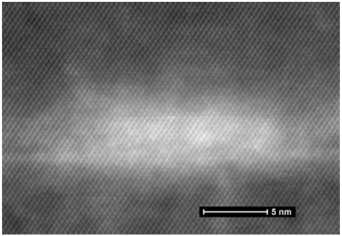
Layer	
200nm p+$In_{0.35}$GaAs	
200nm p-$In_{0.35}$GaAs	
700nm i-$In_{0.35}$GaAs 450C	
0.2µm n-$In_{0.35}$GaAs	
0.1µm n+$In_{0.35}$GaAs 450C	
0.8µm var-buf 350C n+$Al_{0.92\text{-}0.6}In_{0.03\text{-}0.35}Ga_{0.05}As$	
0.1µm i-$Al_{0.9}Ga_{0.06}In_{0.04}As$ 350C	
0.4µm n-n+GaAs 500C (var.)	
0.15µm vary-$Al_{0.3\text{-}0.1}$GaAs 565C	
10nm p(1e17cm^{-3})GaAs 595C	
195nm i-GaAs 595C (var.)	
2ML i-AlAs 515C	
2ML i-InAs QDs 515C	
100nm i-GaAs 595C (var.)	
95nm i-GaAs 595C	49x 19.6µm
10nm p(1e17cm^{-3})GaAs 595C	
195nm i-GaAs 595C (var.)	
2ML i-AlAs 515C	
2ML i-InAs QDs 515C	
100nm i-GaAs 595C (var.)	
0.15µm vary-$Al_{0.3\text{-}0.1}$GaAs 565C	
0.15µm i-GaAs 565C	
0.1µm i-AlAs 565C	
0.3µm i-GaAs buffer 615C	
i-GaAs, SI 3”	

- sensors produced 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

The QD TEM structure

N1801 20um Scintillator: QDs, TEM, DF

#120498HAADF



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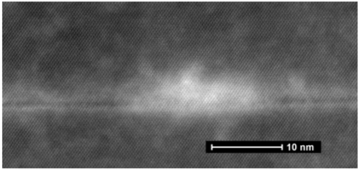

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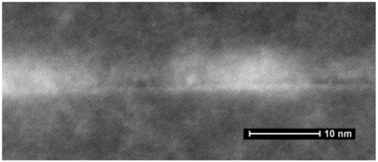
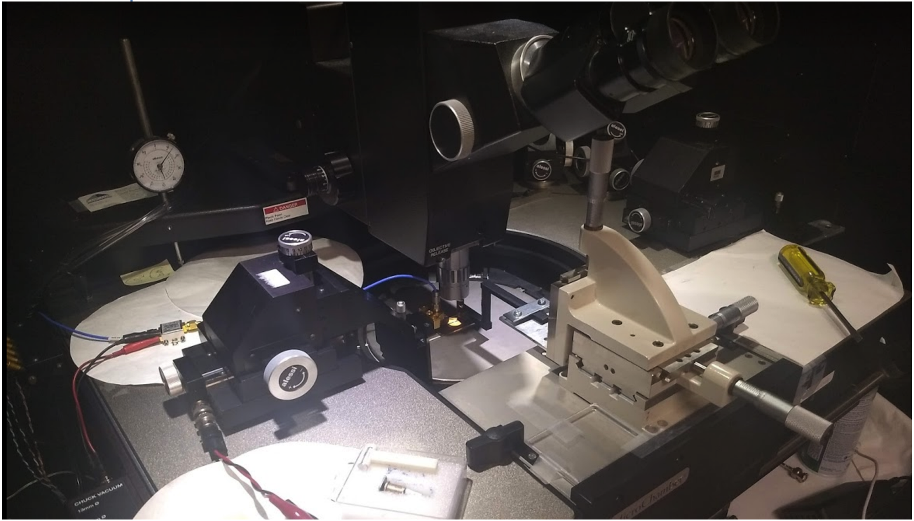


QD diam ~ 14nm

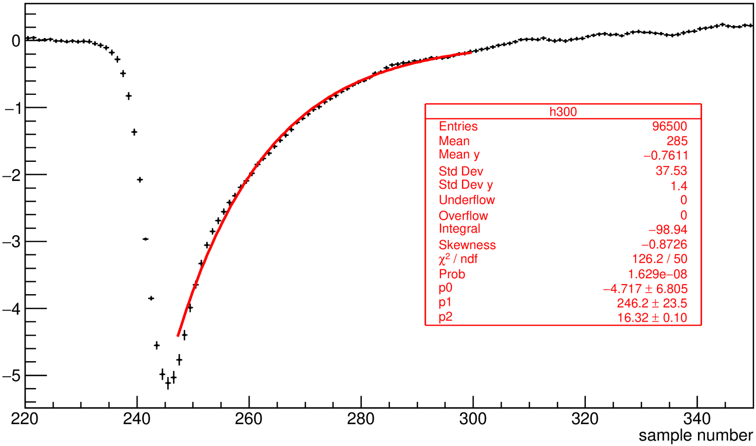
QD density (4-5) x 10^{10} cm^{-2}

Gen3 setup - 14th floor clean room



- a week of measurements made it clear that the experimental setup needed an upgrade
- Jim Freeman donated a 3D stage with micrometers - use to position the RA source in a reproducible way - big thanks!

Estimate of the scintillation time



- fit averaged 3 mV < |V| < 8 mV pulse with an exponential $f = p_0 \exp^{-(x-p_1)/p_2}$
- p_2 - in units of samples, 50 ps/sample
- leading edge: about 300 ps (10%-90%)
- fit done in units of channels, so $\tau = 50\ ps \cdot p_0 \sim 800$ ps

Summary

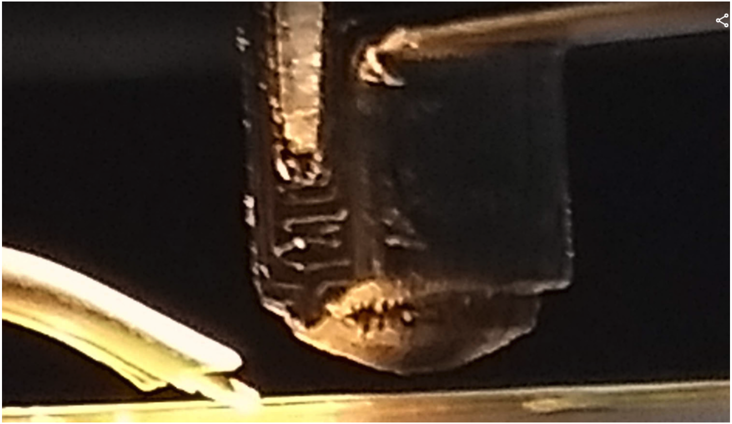
- observe very fast signals from the QD-semiconductor based sensors- $\tau \sim$ 0.8 ns, leading edge $\sim$ 500 ps, consistent with what expected from the QD scintillations
- a lot of questions to answer, but so far no showstoppers

next slides - backup

prototype positioning of the source with 3D stage

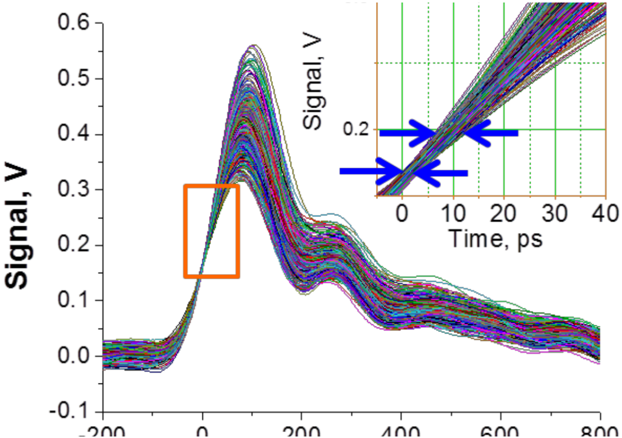
- with the 3D stage, control the uncollimated source positioning at heights less than 1 mm (the source inner bore depth $\sim$ 0.5 mm)
- need to move towards the sensors with contact pads wirebonded away

positioning of the collimated source



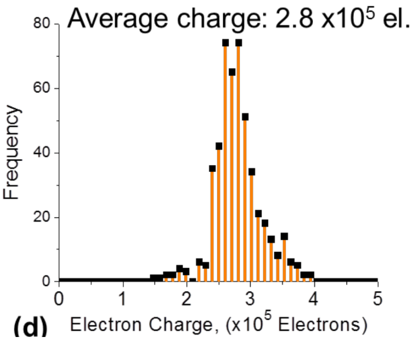
- can position the collimated source within 2mm from the probe tips, while staying within 1mm from the sensor vertically
- try to use (non-RF) probe manipulator to shield the photodiode

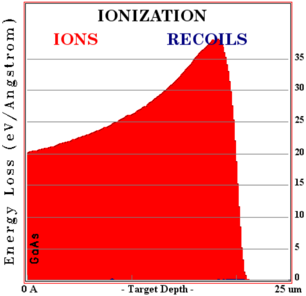
First measurements - timing



- 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

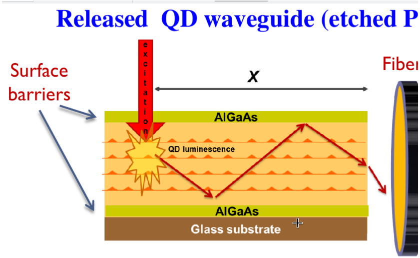
First measurements - energy resolution

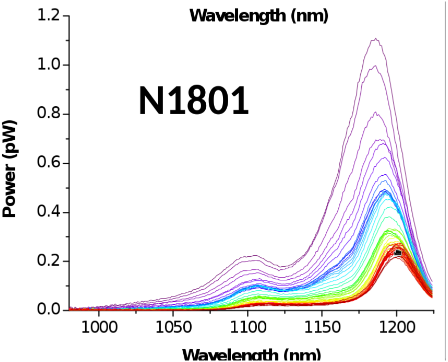




- 5.5 MeV α particle (^{241}Am) ranges out of 5 μ of GaAs, depositing there about 1.1 MeV
- resolution in the integrated charge limited by the fluctuations of the energy losses
- total collection efficiency > 90%

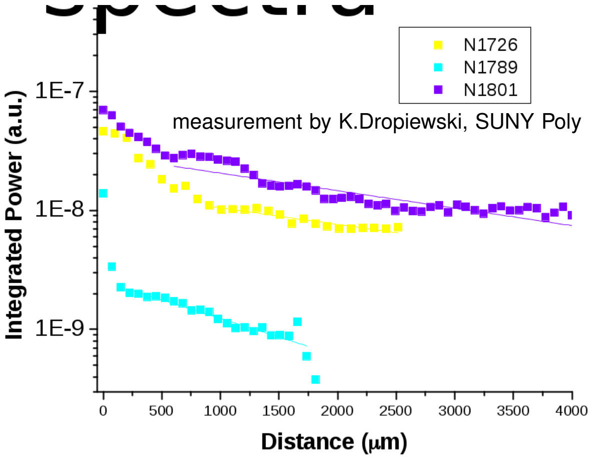
Emission spectrum measurements at SUNY Poly





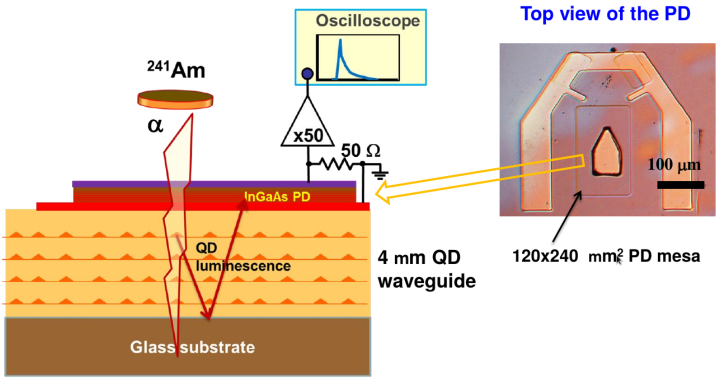
- GaAs refraction index n = 3.4, only 4% of the produced light exits the sensor
- maximum of the spectrum slightly moves to the right as the distance increases

measurements of attenuation length



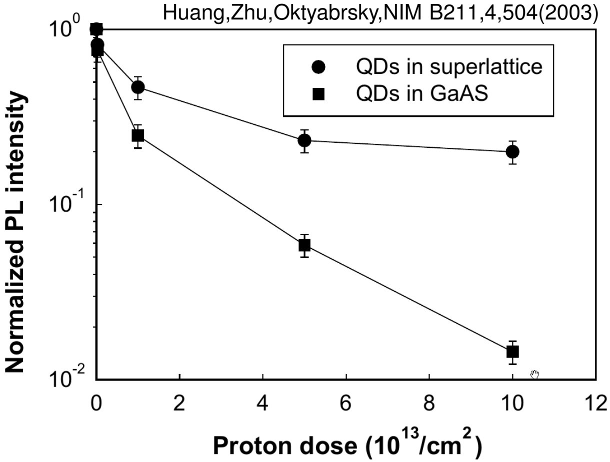
- most recent QD/GaAs sensor: 4mm x 0.8mm x 20 um
- attenuation length $\sim$ 4 mm

First source measurements: setup



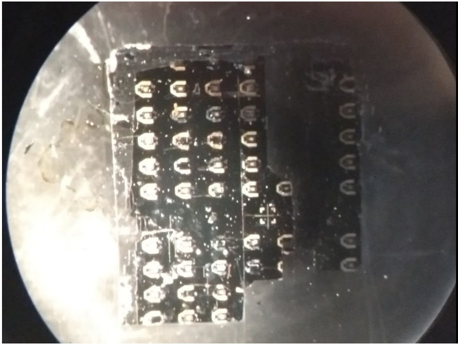
- to collect light, need an integrated photodetector
- InGaAs photodiode processed on the sensor, the photodiode can be thin - 1-2-3 microns
- biased by 10V (unit gain)
- total thickness of the integrated InAs/GaAs detector - about 5μ (4+1)
- reported measurements - very preliminary

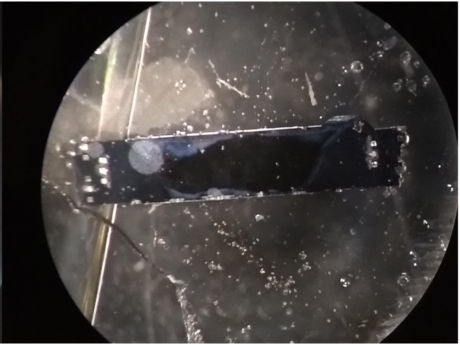
Radiation hardness



- 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

First QD/GaAs sensors at Fermilab





- first set of sensors arrived this week
- will use to learn how to handle them, to design the mechanical support structure, and prepare for the measurement