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? \( N_{\text{ph}}/\text{MeV} \sim 1 \times 10^6/1.8 \cdot E_{\text{gap}} \sim (2 - 2.5) \times 10^5 \)

- semiconductor quantum dots (QDs) are excellent and fast emitters with \( \tau_{\text{rad}} \sim 1 \text{ns} \)

- 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

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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?


- Condition satisfied if QD’s are embedded into a semiconductor bulk with $E_{\text{gap}} > E_\gamma$
  - InAs QD’s: $E_\gamma \sim 1.08$ eV, $E_{\text{GaAs}}^{\text{gap}} = 1.4$ 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
**InAs QD / GaAs Sensors**

**N1801 20um Scintillator: low-mag. STEM**

- 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

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 \(\alpha\)-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 - 500\(\mu\)m x (35 -50 - 100) \(\mu\)m x 0.7 \(\mu\)m 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 $\alpha$-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

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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 ~ 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 - $\alpha$'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
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 ~ 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 $\implies \sigma \sim 150 \mu$ - adequate for many trackers
- material budget: 20 um GaAs $\sim$ 40 um Si $\implies$ 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 $|\sim 1 \text{ mm}, no \sim 10-15 \text{ ps floor}$
- sensors and photodiodes may not need power
Summary

- Detectors made of semiconductor-based scintillators may have quite interesting applications in HEP.

- QD/GaAs-based sensors are fast, rad-hard, and 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.