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: $\sim 3.5 \text{ eV/pair, } \sim 280,000 \text{ pairs/MeV}$
  - NaJ: 25 eV/pair $\rightarrow$ 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]

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>Intrinsic</th>
<th>$\tau_{rad}$</th>
<th>$10^{17}$ cm$^{-3}$ majority carriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>4.6 h</td>
<td>2.5 ms</td>
<td></td>
</tr>
<tr>
<td>Ge</td>
<td>0.61 s</td>
<td>0.15 ms</td>
<td></td>
</tr>
<tr>
<td>GaP</td>
<td></td>
<td>3.0 ms</td>
<td></td>
</tr>
<tr>
<td>GaAs</td>
<td>2.8 µs</td>
<td>0.04 µs</td>
<td></td>
</tr>
<tr>
<td>InAs</td>
<td>15 µs</td>
<td>0.24 µs</td>
<td></td>
</tr>
<tr>
<td>InSb</td>
<td>0.62 µs</td>
<td>0.12 µs</td>
<td></td>
</tr>
</tbody>
</table>

- 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 $\text{In}_{0.4}(\text{Al}_{0.75}\text{Ga}_{0.25})_{0.6}\text{As}$ quantum dots immersed in $\text{Al}_{0.75}\text{Ga}_{0.25}\text{As}$, 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 $E_{\text{gap}} > E_\gamma$
- Most developed technology: InAs QD’s ($E_{\text{photon}} \sim 1.08\text{eV}$) in GaAs bulk ($E_{\text{gap}} = 1.4\text{eV}$)
- 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, roughly 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**

- 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

QD diam ~ 14nm
QD density \((4-5) \times 10^{10} \text{ cm}^{-2}\)
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 \( f = p_0 \exp\left(-\frac{x-p_1}{p_2}\right) \)
- \( p_2 \) - in units of samples, 50 ps/sample
- Leading edge: about 300 ps (10%-90%)
- Fit done in units of channels, so \( \tau = 50 \text{ ps} \cdot p_0 \sim 800 \text{ ps} \)
observes 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
5.5 MeV α particle \(^{241}\)Am) ranges out of 5 \(\mu\) 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%
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
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

Huang, Zhu, Oktyabrsky, NIM B211, 4, 504 (2003)

- Emission of InAs QD's in a 5-layer superlattice reduced by 20% after $10^{13}$ protons/cm$^2$
- 99% recovery after $5 \cdot 10^{13} \text{ p/cm}^2$ 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