Time response of avalanche photodiodes based on GaAs/AlGaAs with separated absorption and multiplication region

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Outline

• Motivation
  – Why Avalanche PhotoDiodes (APDs)?
  – Why GaAs?
  – Why Molecular Beam Epitaxy?
• Results
  – Response of 3 different types of devices to a pulsed green laser
• Summary so far and what is next
Time-resolved single-photon X-ray detectors

Single photon detectors:

- medical imaging, hazard detection, (bio)-photonics, high energy and astrophysics …
- the best-known is Si avalanche photodiodes (APD's)
Why Avalanche Photodiodes?

- APD: electric field ($>10^5 \text{ V cm}^{-1}$) $\rightarrow$ impact ionization of electrons and holes (avalanche effect)
- High sensitivity, speed, gain and signal to noise ratio
- APDs for X-ray range traditionally based on silicon
- Next-generation of synchrotron light sources $\rightarrow$ GaAs/AlGaAs was proposed [1]

Why GaAs/AlGaAs?

<table>
<thead>
<tr>
<th></th>
<th>Band gap [eV]</th>
<th>Atomic number</th>
<th>Mobility of e- [cm²/(V⋅s)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.1</td>
<td>14</td>
<td>≤ 1400</td>
</tr>
<tr>
<td>AlₓGa₁₋ₓAs</td>
<td>&gt; 1.4</td>
<td>31(Ga),33(As)</td>
<td>≤ 8500</td>
</tr>
</tbody>
</table>

- Larger band gap → higher resistance to radiation damage, no cooling needed
- Band gap engineering: possibility to tailor material composition on nanoscale
- Higher atomic number → higher absorbance compared to silicon

Active absorption layer can be thinner → short pass time, faster devices

(for soft X-ray energies exceeding 11 keV absorption length is a factor of 22 shorter in GaAs than in silicon)
Stair case APD and noise

- Drawback of GaAs: same ionization ratio for holes and electrons → linear dependency of noise and multiplication factor [1]
+ This is the case for bulk! We can modify effective ionization ratios by band gap engineering

→ Stair case structure supports multiplication of electrons and suppresses multiplication of holes [2]


MBE

Molecular beam epitaxy (MBE)

- Atomic layer precision
- Not able to grow layer with gradual composition → digital alloy

![Graph showing Al concentration over thickness]

T (period) = 80 ± 1 nm
X (period) = 21.4% (nominal 19.3%)
Separated absorption and multiplication regions

- To increase sensitivity (fraction of photons counted by detector) and suppress the noise we decided to use APD with separated absorption and multiplication (SAM) regions
  
  - Majority of absorption occurs in absorption region
  
  - Multiplication just in multiplication region $\rightarrow$ lower noise


*Influence of $\delta$ p-doping on the behaviour of GaAs/AlGaAs SAM-APDs for synchrotron radiation, J. of Instr., 2017*
Device response to Synchrotron radiation

XRD2 beamline at Elettra Sincrotrone Trieste
(12.4 keV and 1.7x10^{13} ph/s over an area of 300x90 μm²)

Investigation of the Behaviour of GaAs/AlGaAs SAM-APDs for Synchrotron Radiation, AIP Conference Proceedings, 2019
Samples

- Different number of steps in multiplication region
- The time response to pulsed laser of wavelength 532nm, pulse duration 10ps and repetition rate 40 MHz on set of reverse biases from 0V to voltage close to brake down voltage
- From each set 2 devices are selected
- Mesa diameter 200 μm

<table>
<thead>
<tr>
<th></th>
<th>6 steps</th>
<th>12 steps</th>
<th>24 steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance [pF]</td>
<td>~ 6</td>
<td>~ 4</td>
<td>~ 2</td>
</tr>
<tr>
<td>$V_{bd}$ [V]</td>
<td>19</td>
<td>38</td>
<td>60</td>
</tr>
</tbody>
</table>
Experimental set up

- Table-top pulsed laser (532 nm wavelength, 10 ps pulse duration, 40MHz repetition rate)
- Oscilloscope with analogue bandwidth of 12.5GHz
Devices with 6 steps

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<tbody>
<tr>
<td>gain</td>
<td>~ 2.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rise time</td>
<td>~ 1ns</td>
<td></td>
<td></td>
</tr>
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Gain = \( \frac{\text{charge over time window (V)}}{\text{charge over time window (V)}} \)

\(V_0\) = voltage at which we do not observe multiplication

rise time = time from min + 0.1 of max to min + 0.9 of max
Devices with 12 steps

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<tbody>
<tr>
<td>gain</td>
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<td>~ 25</td>
<td></td>
</tr>
<tr>
<td>Rise time</td>
<td>~ 1 ns</td>
<td>~ 100 ps</td>
<td></td>
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- Rise time: ~1 ns for 6 steps, ~100 ps for 24 steps
- Gain: ~2.75 for 6 steps, ~25 for 24 steps
## Devices with 24 steps

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<td>~ 2.75</td>
<td>~ 25</td>
<td>~ 40</td>
</tr>
<tr>
<td><strong>Rise time</strong></td>
<td>~ 1 ns</td>
<td>~ 100 ps</td>
<td>~ 80 ps</td>
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- **Gain**: The gain values for the 6, 12, and 24 steps devices are approximately 2.75, 25, and 40, respectively.
- **Rise time**: The rise times are approximately 1 ns for 6 steps, 100 ps for 12 steps, and 80 ps for 24 steps.

The graphical data shows the APD signals and gain over reverse bias for devices labeled as `device_02` and `device_03`. The plots illustrate the change in signal with respect to time for different reverse bias voltages, highlighting the performance differences between the two devices.

- The `device_02` graph shows APD signals at various voltages from 55.4 V to 60 V, with a focus on the rise time and gain.
- The `device_03` graph similarly depicts APD signals at 55.6 V, with a comparison of rise time and gain characteristics.
## Summary

- **Further:**
  - More focus on the devices with 24 steps
  - Thinning down the back side of device (substrate)

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### Diagram

![Graph showing gain vs reverse bias for different step counts](image)

**Y-axis:** Gain

**X-axis:** Reverse bias [V]
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Dipartimento Politecnico di Ingegneria e Architettura - Università di Udine
Università di Trieste

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