Towards Solid State Photomultiplier
High Speed Avalanche Photodiodes
QD based Photodiodes

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Reader in Optoelectronic Sensors
Contents

Introduction

Basics of avalanche photodiodes

Electron-APD and nm scale avalanche regions

High speed avalanche photodiodes

Quantum dot based photodiodes.
Introduction
The Department of Electronic and Electrical Engineering
The University of Sheffield

- Origins date back to Firth College (1879) + Sheffield Technical School (1884) + Sheffield School of Medicine (1828)
- University College of Sheffield in 1897
- University of Sheffield – granted Charter in 1905
Overview of EEE department (Top 5)

- ~31 members academic staff
- ~50 research staff
- Student community comprises ~500 undergraduate and postgraduate taught and research students
- Research and teaching activities are spread across 3 research groups
  - Communications
  - Electrical Machines & Drives
  - Semiconductor Materials & Devices
EPSRC National Centre for III-V Technologies

Epitaxial Growth Capabilities

MOVPE Ga,In,Al,As,P
MOVPE Ga,In,Al,As,(P)
MOVPE Ga,In,Al,N

MBE 1
Ga,In,Al
As,P,N

MBE 2
Ga,In,Al
As,Sb, Bi

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Physics of avalanche photodiodes
PMT and MCP

PMT
• High gain
• Fast response
• Ø 3/8” to 20”
• Sensitive to vibration, magnetic field, temperature
• Higher cost

MCP
• High gain
• Fast response
• Immune to magnetic fields and vibration
• Lower power consumption
• Compact
• High cost

$D^* > 1 \times 10^{15}\text{cmHz}^{1/2}/\text{W}$ but not suitable for imaging arrays

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Impact ionisation

Holes and electrons (ii)
Significant gain fluctuation
Stochastic, Significant noise and limited bandwidth

Electrons (holes) only (ii)
Minimal gain fluctuation
Deterministic, Low noise and high bandwidth

Photocurrent and Dark current

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Gain and excess noise for $k=0$ and $k=1$

Gain vs. Reverse bias is a reasonable indicator of $k = \beta/\alpha$ value

Excess noise vs. Gain is a very good indicator of $k$ value

\[
F = \frac{\text{Measured noise}}{\text{Ideal shot noise}}
\]

\[
F = kM + (2 - 1/M)(1-k)
\]

\[
M = \exp(-\alpha w)
\]

\[
M = \frac{1}{1 - \alpha w}
\]

\[
F = 2 - 1/M
\]
To achieve a solid state PMT, k=0 is the most promising approach. CdHgTe (or CMT) APD is the leading technology. What next???????
Single photon detection

J. Beck et al., IEEE LEOS Newsletter, Oct. 2006

Figure 4 Log gain vs. bias at 80 K for 53 of 54 connected pixels on an 8x8, 4.3 μm cutoff array. The mean gain at 13.1 V was 1270.

Figure 5 Excess noise factor vs. gain data at 80 K on a 4.3 μm cutoff APD in an 8x8 array compared to McIntyre’s original theory.

3D imaging, SPAD with raster scan, Buller et al. Heriot-Watt
Research: Can InAs work as a Solid State PMT ??
InAs electron-APDs

<table>
<thead>
<tr>
<th></th>
<th>InAs (eV)</th>
<th>Cd$<em>{0.3}$Hg$</em>{0.7}$Te (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_g$ (eV)</td>
<td>0.35</td>
<td>0.29</td>
</tr>
<tr>
<td>$E_{\Gamma X}$ (eV)</td>
<td>1.39 (3.91E$g$)</td>
<td>3.18 (10.97E$g$)</td>
</tr>
<tr>
<td>$E_{\Gamma L}$ (eV)</td>
<td>0.98(2.8E$g$)</td>
<td>1.97(6.79E$g$)</td>
</tr>
</tbody>
</table>

TuP-7
10th Intern. Conf. on Indium Phosphide and Related Materials
11-15 May 1998   Tsukuba, Japan

Initial challenges in InAs

- Almost no prior work due to preconceptions
  - Unavoidable surface leakage
  - High tunnelling current

- High background doping

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Dark current

\[ I(T) = \pi r^2 J_{\text{bulk}}(T) + 2\pi r J_{\text{surf}}(T) \]

- **Bulk at high T**
- **Surface leakage at low T**

**Dark current for 110µm-diameter SU-8 passivated APD**
Responsivity / leakage current comparison in pin

- **Sheffield InAs**
- **Hamamatsu InAs**
- **Judson InAs**

**Wavelength (µm)**
- 1.4
- 1.6
- 1.8
- 2.0

**Responsivity (A/W)**
- 0.1
- 0.2
- 0.3
- 0.4
- 0.5
- 0.6
- 0.7
- 0.8
- 0.9

**Detectivity (cmHz\(^{1/2}\)/W)**
- 10\(^8\)
- 10\(^9\)
- 10\(^10\)
- 10\(^11\)
- 10\(^12\)
- 10\(^13\)

- **Calculated detectivity**
- **Judson InAs**
- **Hamamatsu InAs**

**1000/T (K\(^{-1}\))**
- 2
- 4
- 6
- 8
- 10
- 12
- 14

**Reverse voltage (V)**
- 0.0
- 0.5
- 1.0
- 1.5
- 2.0
- 2.5
- 3.0

**Current density (A/cm\(^2\))**
- 0.01
- 0.1
- 1
- 10

- **Sheffield InAs 300K**
- **Sheffield InAs 77K**
- **Judson InAs**
- **Hamamatsu InAs**

**High Detectivity InAs PD, Ready to move towards Solid State PMT**

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InAs electron-APDs

No measurable hole impact ionisation, confirming electron only avalanche process
Avalanche Noise

Excess Noise Factor, $F$

Multiplication, $M$

AlInAs data from Goh et al. Journal of Quantum Electronics

VISION: InAs single photon avalanche photodiode for visible to SWIR wavelengths up to 3 $\mu m$

F is independent of temperature
SWIR Geiger mode Arrays/FPAs

320x256 and a pixel pitch of 30 μm

Princeton Lightwave: 32x32 GmAPD camera

FLIR (Core by Indigo) but low bias < 5V but InGaAs/InP works at >20V

VISION: Work towards low voltage APD FPA (Solid State PMT FPA??)
InAs electron-APDs

Bandwidth limited by the transit time, not the avalanche process. This means unlimited gain-bandwidth product.

InAs low noise high APDs for free space communication (>40 Gb/s) and LIDAR at 1.55-3μm
InAs X-ray APDs

Fano limited energy resolution

Improved FWHM for X-ray detection
-42 meV/% Bi for InAsSb
-46 meV/% Bi for InAsSbBi
-55 meV/% Bi for InAsBi

Bi based IR e-APDs?
Exploring the nonlocal effects in nm scale avalanche region for Solid State PMT
Monte Carlo simulation in GaAs

Avalanche statistics at high field

600kV/cm

300kV/cm
Excess noise in thin avalanche regions

Excess noise corresponds to $k \sim 0.1-0.2$ when $w < 100$ nm. Even smaller $w$ is required to reduce excess noise towards unity. Is wide bandgap materials the answer?
Excess noise in wide bandgap materials

Noise comparable to Si when \( \nu = 25 \) nm in wide indirect bandgap materials (similar trends for \( x = 0.7 \) and \( 0.9 \))
Novel AlAsSb APDs

200nm AlAsSb has extremely low noise
Can we achieve even lower noise using thinner avalanche region?
Extremely low temperature coefficient of breakdown voltage

<table>
<thead>
<tr>
<th>Material</th>
<th>(w) (nm)</th>
<th>(C_{bd}) (mV/K)</th>
<th>(w) (nm)</th>
<th>(C_{bd}) (mV/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlAsSb</td>
<td>80</td>
<td>0.95</td>
<td>230</td>
<td>1.47</td>
</tr>
<tr>
<td>Si</td>
<td>70</td>
<td>1.53</td>
<td>290</td>
<td>4.38</td>
</tr>
<tr>
<td>GaAs</td>
<td>100</td>
<td>1.67</td>
<td>270</td>
<td>8.89</td>
</tr>
<tr>
<td>Al_{0.6}Ga_{0.4}As</td>
<td>89</td>
<td>3.18</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>GaInP</td>
<td>--</td>
<td>--</td>
<td>200</td>
<td>3.68</td>
</tr>
<tr>
<td>InP</td>
<td>80</td>
<td>3.9</td>
<td>200</td>
<td>6.0</td>
</tr>
<tr>
<td>InAlAs</td>
<td>80</td>
<td>2.2</td>
<td>200</td>
<td>4.1</td>
</tr>
</tbody>
</table>
High speed avalanche photodiodes
InAlAs and InP have reached their limits ???
InAs requires very small area and have some issues with surface leakage.
Waveguide APD with gain ~3 works at 40Gb/s.

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APD design

**Drift time**

**Avalanche multiplication**

**Absorption**

**Avalanche region thickness (nm)**

- GBP1_20nm
- GBP2_40nm
- GBP3_60nm
- GBP4_80nm
- GBP5_100nm
- GBP6_150nm
- GBP7_200nm
- GBP0_no absorption

**Bandwidth (GHz)**

- BW1_20nm
- BW2_40nm
- BW3_60nm
- BW4_80nm
- BW5_100nm
- BW6_150nm
- BW7_200nm
- BW0_no absorption

<table>
<thead>
<tr>
<th>Frequency</th>
<th>( W_m &lt; )</th>
<th>( W_a &lt; )</th>
</tr>
</thead>
<tbody>
<tr>
<td>200GHz</td>
<td>100nm</td>
<td>1000nm</td>
</tr>
<tr>
<td>500GHz</td>
<td>45nm</td>
<td>500nm</td>
</tr>
<tr>
<td>1THz</td>
<td>20nm</td>
<td>100nm</td>
</tr>
</tbody>
</table>

For bandwidth >100GHz \( w_a < 150 \) and \( w_m < 20 \) nm

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Wide band APDs

Bias = 17.0 V
Frequency (GHz)
Relative response (dB)

Absolute impedance
Frequency (GHz)
Impedance (Ω)

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Wide band APDs

Absorption = 1200nm

Absorption = 400nm
QD detectors for imaging: How to achieve low cost and multifunction?

www.kentoptronics.com

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QD on Si for low cost FPA

UoSHEFF
UCL

QDIP on Silicon is promising!
VISION: Reconfigurable IR sensors

Can be dynamically configured into

- **Multispectral: Full FPA**
- **Multispectral: Row-by-row**
- **Multispectral: Pixel-by-pixel**

High resolution multicolour FPA

Future Intelligent Sensors?

- No moving parts
- No cooled optical filters needed

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Algorithmic spectrometer

Quantum Dot Infrared Photodiodes (QDIPs)

Optimised Algorithm

MWIR  LWIR
Multispectral imaging without dispersive optics?

Multicolor using a single detector
Absorption feature as small as 300nm measured

Thank you
To Discover And Understand.
“ultralarge-format arrays; mosaic tiling technologies; pixel size reduction; smarter pixels and on-focal plane processing; improved three-dimensional (3-D) integration and hybridization; higher-operating-temperature devices; multicolor pixels; improved short-wavelength infrared (SWIR) arrays; photon counting technologies and lower readout noise; curved focal surfaces; lower-power operation; radiation hardening; cost reduction; and improved cooler technology.”
Novel Applications

http://www.sensorsinc.com/swirconops.html
Detectivity

**Bulk semiconductors**
InSb, InAs, HgCdTe

- Conduction band
- Valence band

**Impurity doped semiconductors**
Ge:Zn, Si:As

- Conduction band
- Impurity band
- Valence band

Detectivity = Responsivity x Area^{0.5}

Noise current

Bulk is the leading technology in terms of D*  What next????
<table>
<thead>
<tr>
<th>Parameter</th>
<th>HgCdTe</th>
<th>QWIP (n-type)</th>
<th>InAs/GaInSb SLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR absorption</td>
<td>Normal incidence</td>
<td>$E_{\text{optical}} \perp$ plane of well required</td>
<td>Normal incidence</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normal incidence: no absorption</td>
<td></td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>$\geq 70%$</td>
<td>$\leq 10%$</td>
<td>$\approx 30-40%$</td>
</tr>
<tr>
<td>Spectral sensitivity</td>
<td>Wide-band</td>
<td>Narrow-band ($\text{FWHM} \approx 1-2 \mu m$)</td>
<td>Wide-band</td>
</tr>
<tr>
<td>Optical gain</td>
<td>1</td>
<td>0.2-0.4 (30-50 wells)</td>
<td>1</td>
</tr>
<tr>
<td>Thermal generation lifetime</td>
<td>$\approx 1\mu s$</td>
<td>$\approx 10$ ps</td>
<td>$\approx 0.1\mu s$</td>
</tr>
<tr>
<td>$R_0A$ product ($\lambda_c=10$ μm, $T=77K$)</td>
<td>300 Ωcm²</td>
<td>$10^4$ Ωcm²</td>
<td>100 Ωcm²</td>
</tr>
<tr>
<td>Detectivity ($\lambda_c=10$ μm, FOV=0)</td>
<td>$2 \times 10^{12}$ cmHz$^{1/2}$/W$^{-1}$</td>
<td>$2 \times 10^{10}$ cmHz$^{1/2}$/W$^{-1}$</td>
<td>$5 \times 10^{11}$ cmHz$^{1/2}$/W$^{-1}$</td>
</tr>
</tbody>
</table>
Photonic Bandgap

![Diagram showing Photonic Bandgap with band structures and wavevectors.](image-url)
Photonic Bandgap

J. Rosenberg, physics.optics,16July2009

Posani et al., APL 88,151104,2006

VISION: Multispectral and polarimetric sensing
BULK N and Bi detectors

InAsN

InAsBi

D. Wang, S. P. Svensson, L. Shterengas, G. Belenky J. Cryst Gr. 312, 2705, 2010
Room temperature Type II FPA on GaAs

MWIR Type II InAs/GaSb

D* (cmHz^{1/2}/W)

GaSb substrate

GaAs substrate

EMRSDTC
InGaAs has large $\alpha/\beta$ at low fields.

What about InAs???