Near-infrared (NIR) Single Photon Counting Detectors (SPADs)

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Outline

✓ Introduction to Single Photon Counting Detectors (SPADs)

✓ Current States of near-infrared SPADs

✓ Summary and Future Goals
**PMT**
- High gain
- Low dark current
- Low noise
- Low quantum efficiency
- Large, bulky
- Expensive
- High voltage
- Fragile
- Ambient light catastrophic

**APD**
- Electron & Hole avalanche multiplication
- Good efficiency
- Acceptable dark counts
- Afterpulsing

**Superconductors**
- Hotspot Generation and Resistive Barrier
- High efficiency
- Low dark counts
- No afterpulsing
- $T < 1K!!$
Geiger mode - APD functions as a switch

Analog
- Responsivity
- Dark current

Digital
- Single photon detection efficiency
- Probability of dark count

Concept of excess noise does not apply!

Geiger-mode operation

Single photon input

APD output

Digital comparator output

Successful single photon detection

Photon absorbed but insufficient gain – missed count

Dark count – from dark current
Performance Parameters

✓ Photon detection efficiency (PDE)
  ➢ The probability that a single incident photon initiates a current pulse that registers in a digital counter

✓ Dark count Rate (DCR)/Probability (DCP)
  ➢ The probability that a count is triggered by dark current instead of incident photons

Diagram:
- Single photon input
- APD output
- Digital comparator output
  - Successful single photon detection
  - Photon absorbed but insufficient gain – missed count
  - Dark count – from dark current
Photon Detection Efficiency

$$\eta_{PDE} = \eta_{\text{external}} \times \eta_{\text{collection}} \times P_{\text{avalanche}}$$

**Graph:**
- Breakdown Probability vs. $\Delta V/V_{br}$
- InP: 1110 nm
- Breakdown Probability values: 0.0, 0.1, 0.2, 0.3

**Diagram:**
- p-contact metallization
- SiN$_x$ passivation
- $p^+$-InP diffused region
- i-InP cap
- multiplication region
- n-InP charge
- n-InGaAsP grading
- i-InGaAs or i-InGaAsP absorption
- n$^+$-InP buffer
- n$^+$-InP substrate
- anti-reflection coating
- n-contact metallization
- Optical input

**Materials and Wavelengths:**
- InGaAsP: 1.06, 1.3 $\mu$m
- InGaAs: 1.55 $\mu$m
40µm-diameter In$_{0.53}$Ga$_{0.47}$As/InP

- **0.18nA** at 95% of $V_{br}$ at 297K
- **0.15pA** at 95% of $V_{br}$ at 200K

Good enough?
1.06 μm SPADs: DCR vs. PDE

✓ InGaAsP absorber lower generation-recombination dark current
✓ DCR approaching Si SPAD DCR with greatly increased PDE
   ➢ Si SPADs have PDE < 2% at 1.06 μm
Dark Count Probability versus Photon Detection Efficiency

InGaAs/InP, 300K 1550 nm (2007)
Quenching Techniques

Quenching circuit
- Quench avalanche current
- Reset the device

• Passive Quenching
  - Quenched by discharging capacitance
  - Slow recharge

• Active Quenching
  - Raise the anode voltage
  - Quick recharge

• Gated Quenching
Afterpulsing

Number of trapped carriers

Initial avalanche

Released carriers from traps

![Graph showing dark count rate over hold-off time with different bias temperatures (220K, 200K, 175K, 150K) and 6 V overbias. The graph illustrates the decrease in dark count rate with increasing hold-off time.]
Reduction of Afterpulsing: Decreasing Charge Flow

The total charges flowing through device:
\[ Q = (C_s + C_d)V_{ex} \]

- \( C_d \): device capacitance
- \( C_s \): stray capacitance
Passive Quenching with Active Reset (PQAR)

$V_b + V_{ex}$

$R_s = 50 \, \Omega$

10nF

10M$\Omega$

Transistor

Amplifier

Counter

Pulse Generator

Trigger in

Output

Released carriers from traps

Conventional passive quench 100k$\Omega$

PQAR active reset

PQAR passive quench 10M$\Omega$

Excess voltage (V)

Carrier emission rate (a.u.)

Time (ns)
PQAR at 230K

**Measured counts x 1000 (/s)**

![Graph showing measured counts vs. CW laser power](image-url)

**CW laser power (fW)**

**Photon flux (#/s)**

**Photon count rate (#/s)**

**Dark count probability (/ns)**

**NEP ~ 10^{-16} W/Hz^{1/2}**

**Voltage on device**

\( V_{b} \)

\( \text{Hold-off} = 15 \mu s \)

\( \text{Compare with gated mode results} \)

\[ DCR = \frac{N_{d}}{1 - N_{d} \cdot \tau_{\text{hold-off}}} = R_{d} \cdot P_{b} \]

\[ \text{TotalCR} = \frac{N_{t}}{1 - N_{t} \cdot \tau_{\text{hold-off}}} = (R_{d} + \Psi \cdot QE) \cdot P_{b} \]

\[ PCR = \text{TotalCR} - DCR = \Psi \cdot PDE \]
Gated Quenching of a SPAD

Total bias on APD

AC pulse width

Excess bias ($V_{ex}$)

V_{br}

V_{dc}

Laser pulse

Avalanche pulse due to incident photon

Avalanche pulse due to dark carriers (false positive)

Missed photon (false negative)

Photon Detection Efficiency

Dark Count Rate
Gated-PQAR

Compared to PQAR

• Suppressed dark counts by gated bias
• Reduced complexity
• Array operation: recharge together, quench separately

The transistor can be HBT monolithically integrated on the SPAD, and the its gate/base input can be shared over the whole array.
Gated Quenching and Gated PQAR
Gated Quenching and Gated PQAR

![Graph showing the relationship between dark count probability and repetition rate for different temperatures and Vex values.](image)

- Dark Count Probability
- Repetition Rate (MHz)
- 220K, Vex = 5.6%
- 200K, Vex = 6.0%
- 180K, Vex = 6.2%

**Gated-quenching**

**Gated-PQAR**
Conclusions

✔ Performance of Geiger-mode APDs is improving rapidly
  ➢ Acceptable detection efficiencies and dark count probability levels
  ➢ Getting a better control over the afterpulsing problem
Future Goals

✓ Move closer to quantum limited detection
  ➢ Dark Current $\rightarrow 0$
  ➢ Quantum Efficiency $\rightarrow 100$
  ➢ Read Noise $\rightarrow 0$

✓ Move to longer wavelengths

✓ Do photon number resolving
High QE Structure

GaAsSb resonant-cavity enhanced avalanche photodiode operating at 1.06 μm

R. Sidhu, H. Chen, N. Duan, G.V. Karve, J.C. Campbell and A.L. Holmes, Jr.

A resonant-cavity enhanced, separate absorption, charge, and multiplication avalanche photodiode using GaAs$_{0.8}$Sb$_{0.2}$ quantum wells on GaAs has been demonstrated. The device exhibited high gain and <1 nA dark current at 90% of breakdown. Peak quantum efficiency of 93% and full-width at half-maximum of 7 nm were observed at 1.064 μm.

Fig. 2 Photo-current, dark-current and DC avalanche gain against reverse bias, for 160 μm diameter mesa device

Fig. 3 Measured responsivity against wavelength for device with no top mirrors (circles), one pair of top dielectric mirrors (triangles) and two pairs of top dielectric mirrors (squares)
Type-II Quantum Wells (QWs)

Formed between materials with staggered band line-ups

- Electrons and holes are confined in adjoining layers
- Spatially indirect absorption and emission
  - Smaller effective bandgap for long-wavelength operation

\[ \text{GaAs}_{0.5}\text{Sb}_{0.5} \]

\[ \text{Ga}_0.47\text{In}_{0.53}\text{As} \]

\[ \Delta E_c = 0.236 \text{eV} \]

\[ \Delta E_v = 0.247 \text{eV} \]

\[ 0.49 \text{eV} \approx 2.5 \mu\text{m} \]
Where we are now (pin devices)


-2 V bias (200K)

-2 V bias (RT)
Gated-PQAR for Synchronized Detection

Gated Quench

Compared to gated quench
- Comparable circuit complexity
- Wider AC pulses: easier to generate and synchronize
- Uniform output pulse shape, good for photon-number-resolution with multiplexing

AC

output

Gated-PQAR

Transistor on: low resistance for fast reset
Transistor off: high resistance for fast passive quench

\[ V_{\text{bias}} \]

\[ V_{\text{gate}} \]

\[ V_{\text{diode}} \]

output
Questions??
Simulated Breakdown Probabilities

J. P. R. David, University of Sheffield

Breakdown Probability

$\Delta V/V_{br}$

Decreasing thickness:
0.2 $\mu$m, 0.5 $\mu$m, 1.0 $\mu$m
• 20 x 20 Array – 98% yield

• 4 x 4 Subarray – uniform single-photon response
Afterpulsing Probability vs. Total Charge

AC pulse

Laser pulse

Delay 1µs

Period

Afterpulsing probability vs. Total charge (pC)

- Duration
- Magnitude

0 20 40 60 80 100

0 0.2 0.4 0.6 0.8 1

Total charge (pC)
Total Charge Flow

- **Gated-Quench with 2 ns Gates**
- **PQAR with 0.23 pF of total capacitance**

**36x reduction**

- **Total Charge (pC)**
- **Excess Bias (V)**
- **Normalized Afterpulsing Probability**
Effective excess noise factor $\equiv 1 + \frac{\sigma^2(\text{peak signal})}{<\text{peak signal}>^2}$

$= 1 + \left(\frac{11.6mV}{572mV}\right)^2 = 1.0004$
Pixel Level Monolithic Integration of Active Switching Elements

- Reduced parasitics
- Faster quenching
- Reduced afterpulsing
- Increased transmission and sampling rates
- Packaging advantages