The silicon photomultiplier

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SPAD: Principles of operation

- p-n diode
- 3 regimes:
  1. simple e-h creation through impact ionization
  2. secondary ionization by e
  3. secondary ionization by e and h (quenching needed)
- e ionization is more sensitive
- n-on-p for red
- p-on-n for blue

electrical equivalent circuit of the SPAD

Breakdown voltage and multiplication gain

- breakdown voltage

$$\int_0^W \alpha_n e^{-\int_0^x (\alpha_n - \alpha_p) dx'} dx = 1$$

- V_{bd} is more advantageous for thin depletion regions
- $$Gain = \frac{avalanche\_charge}{q} = \frac{V_{ov}(C_q + C_d)}{q}$$
- gain gives signal well above noise for $q = e$

V_{bd}

- measuring the gain as a function of V_{bias}.
- find the derivative

temperature dependence of parameters

- V_{bd} increases with T
- gain increases with lower T
- DCR increases with T

PDE

- $$PDE(V_{ov}, \lambda) = QE(\lambda)P_T(V_{ov}, \lambda)FF_{eff}(V_{ov}, \lambda)$$

SPTR

- $$\sigma_{timing} = \frac{\sigma_{v_{voise}}}{dv/dt_{@threshhold}}$$

error sources

- DCR
  - $\propto \frac{1}{T}$
  - residue at cryo. temperature: trap assisted tunneling
- after pulse:
  - release of trapped charges in high field regions
  - mitigation: slow recharge rate
  - secondary photons
  - mitigation: low life time substrate

Crosstalk

- photons arising from one cell triggering a signal in an other cell
- Mitigation: optical trenches
- delay cross talk
- Mitigation: reduce undepleted region thickness
- external crosstalk: emission of secondary photons producing reflection on "the window"
- Delayed vs. prompt cross talk.

Excess noise factor

- Expectation: $N_{phe} \pm \sqrt{N_{phe}}$
- we define

$$ENF = \frac{(\sigma_Q / < Q >)^2}{(\sigma_{Q_N} / < Q_N >)^2}$$

Saturation

- trade of between saturation and dead space

$$N_{fired} = N_{total}\left(1 - e^{-\frac{N_{photon} PDE \cdot ENF}{N_{total}}}\right)$$

digital SiPM

- each cell has it's own read out
- high data production
- compromise: small SiPM arrays

Applications

- TOF-PET
- PET-MR
- SPECT/MR
- HEP
  - Problem: High radiation environment
- LIDAR
- Scintillation detection
  - Cherenkov in scintillator

Prospect

- Digital will become more prevalent

Abbreviations

- SiPM: Silicon photomultiplier
- SSPM: solid state photmultiplier
- MPPC: multi pixel photon counter
- SPAD: single photon avalanche diode
- SPTR: single photon time resolution
- PDE: photon detector efficiency
- PMT: photo multiplier tube
- TCAD: technology computer aided design
- DCR: dark count rate
- LTE: light transfer efficiency
- PTS: photon transfer time spread

Abstract

- What is SiPM and what is it use for
- What are relevant qualitative parameters for best application specific performance

introduction

- Analog vs. Digital SiPM
- $10 - 100\mu m$ wide
- single photon sensitivity
- ps timing resolution
- applications:
  - TOF-PET
  - LIDAR
  - dark matter
  - double β
  - HEP
  - much more

electronic read out

- high gain
- high power consumption
- strong and fast amplifier

Analog SiPM

- large array of SPADS in parallel
- Counting photons via integration over charge
- individual SPADS interact via capacitance