Development of (V)UV-Sensitive GaN Geiger-Mode Photodiodes

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The Silicon Photomultiplier or G-APD

Can the SiPM concept be transferred to GaN?

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**Why GaN?**

- Large bandgap
  - Tunable bandgap -> tunable spectral response
  - Potential for high UV-VUV sensitivity with little to no red sensitivity
- Sufficiently clean substrates are available
  - Geiger-mode is possible
- Increasing use of GaN in high-power electronics, LEDs, Lasers
  - Increasing supply of GaN-substrates
  - Cleaner substrates
  - Lower cost
The GaN Technical and Intellectual Challenge

- **Geiger-mode in GaN is unexplored**
  - Breakdown probability?
  - Temperature dependencies?
  - Electric field dependencies?
  - Quenching?

- **Device Fabrication**
  - Uniform breakdown characteristics
  - Low dark-count rates
  - Scalability
  - Arrays
  - ...

Spectral response of a 82 um-dia. Georgia Tech GaN APD
Georgia Tech GaN Structures

https://doi.org/10.1117/12.2576888

- epitaxial growth

surface roughness:

Growth on: u-GaN/sapphire  n-GaN bulk substrate
IV-Curves

36 diode array of 60 um cells

- Uniform dark current characteristics
- Uniform light response

https://doi.org/10.1117/12.2576888
Breakdown Voltage Uniformity

● Uniform breakdown characteristics (<1% variations)
Geiger Mode Measurements

- New territory
  - Develop setups from scratch

Bias pulse

Dark-count breakdown

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Count Rate Measurements

Determine count rate from $\Delta t$ distribution

$$\alpha \propto \exp\left(-2R \cdot \Delta t\right)$$

Number of $\Delta t$

$\Delta t$

$0 \quad 200 \quad 400 \quad 600 \quad 800 \quad 1000$

$1 \quad 10 \quad 100 \quad 1000$

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Dark-Count Rates

- Temperature range -10°C – 10°C
- Overvoltages 0.5 V and 1 V
- Dark count rates (DCR) > 1MHz
- Activation energies ~0.2 eV -> DCR dominated by trap-assisted tunneling (Poole-Frenkel)
- Breakdown voltage shifts 0.02%/K (SiPMs 0.1%/K)

High dark-count rate prevents operation at higher overvoltages (cf. early SiPMs)
Photon Detection Efficiency: Setup

- **Photon Detection Efficiency**
- **Setup Diagram**

**Components:**
- **UV LED (375nm)**
- **Bifurcated Fiber**
- **Attenuator**
- **Si Photon counter**
- **Noninverting amplifier**
- **100nF capacitor**
- **Transimpedance amplifier**
- **GaN APD**
- **Thermoelectric cooler**
- **47kΩ resistor**
- **Water cooling system**
- **UV light illumination system**
- **Measurement circuit system**
- **Low-temperature control system**
- **DC Supply**
- **Pulse Generator**
- **N₂ box**
- **Dark box**
- **Si Photon counter**
- **Oscilloscope + computer**

**Additional:**
- **Water tube**
- **N₂ box**
Photon Detection Efficiency

~0.1% breakdown probability at 0.4V overvoltage (~0.5% above breakdown voltage)

Operation at higher overvoltages will result in higher breakdown probabilities
Next Steps

- Reduce DCR -> Get rid of Poole-Frenkel tunneling
  - Impurity states in “intrinsic layer”
  - Residual crystalline defects
- Growth studies have shown we can reduce “unintentional impurities” in the avalanche region
  - Employ low-defect III-N substrates
  - Further studies of ion-implantation
- AlGaN “window” for better UV sensitivity
- Back-side illumination designs
- Selective etching for substrate removal
- Provides for “flip-chip” mounting to Si bias/readout circuit
Summary

- GaN G-APDs have the potential for high (V)UV sensitivity.
- We succeeded in operating GaN diodes in Geiger mode.
  - All things considered the results are very encouraging.
- High DCR prevents operation at high breakdown probability.
  - Device can only operate <1% above breakdown -> latest SiPMs operate 10%-20% above breakdown -> lots of room for improvement.
  - Identified trap assisted tunneling as dominant DCR mechanism.
- The situation is very similar to early silicon SPADs and SiPMs.
  - No fundamental limitations identified.
  - The same methodology that improved SiPM characteristics can also improve GaN.

Look forward to our next generation of GaN SPADs.