SiC-based photo-d Detectors for UV, VUV, EUV and soft X-ray detection

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Outline

- An idea detector
  - SNR discussion
  - Features for an ideal detector

- SiC detectors
  - Dark current
  - Read noise
  - Quantum efficiency

- Applications

- Conclusion
$N_s$, $N_d$, $N_r$, and $N_b$: the number of electrons generated by signal, leakage current, read noise and background during the observing period.
An ideal photo-detector

\[
\text{SNR} = \frac{Q.E. \cdot N_{ph}}{\sqrt{Q.E. \cdot N_{ph} + N_b + N_d + N_f}}
\]

- Q.E. = Efficiency (energy photons or E - in for high energy photons)
- N_d = negligible (detector-related)
- N_f = negligible (ROIC-related)
An ideal photo-detector

\[ SNR = \frac{Q.E. \cdot N_{ph}}{\sqrt{Q.E. \cdot N_{ph} + N_b + N_d + N_r^2}} \]

An ideal detector

- Q.E. \(\approx 1\) for low energy photons or \(E_{ph}/E_{par}\) for high energy photons (detector related)
- Nd negligible (detector related)
- Ni negligible (instrument related)
- Nr negligible (ROIC related)

Ultimate limit: \(QE \cdot N_{ph} = 1\) \(\rightarrow\) \(SNR = 1\)
Dark current
Dark current density of SiC photodiodes

Measured at NASA-GSFC

5mmx5mm Pt/4H-SiC Schottky

1.5mmx1.5mm 4H-SiC pin

Measured at Keithley, Inc.

LV characteristics of 5mm x 5mm SiC photodiode

Current (A) vs. Voltage (V)
Dark current density of SiC photodiodes at room temperature

Measured at NASA-GSFC

Current Density (A/cm²)

1.5mmx1.5mm 4H-SiC pin

Si CCD: >1nA/cm²
Si CMOS-APS: >50nA/cm²

5mmx5mm Pt/4H-SiC Schottky

Measured at Keithley, Inc.

Current (A)

Voltage (V)

1-V characteristics of 5mm x 5mm SiC photodiode
### Dark current in SiC detectors

<table>
<thead>
<tr>
<th></th>
<th>$I_d^{\text{SiC}} / I_d^{\text{Si}}$ (present experimental)</th>
<th>$I_d^{\text{SiC}} / I_d^{\text{Si}}$ (theoretical)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Schottky</strong></td>
<td>$10^{-6}$</td>
<td>$10^{-17}$‡</td>
</tr>
<tr>
<td></td>
<td>(surface defects)</td>
<td></td>
</tr>
<tr>
<td><strong>PIN</strong></td>
<td>$\sim 10^{-7.8}$</td>
<td>$10^{-18}$‡</td>
</tr>
<tr>
<td></td>
<td>(bulk defects)</td>
<td></td>
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\[ I_d = A^* A^{**} T \exp \left( -\frac{q \Phi_b}{kT} \right) \exp \left( \frac{q \sqrt{qE / 4\pi \varepsilon_s}}{kT} \right) \]

\[ I_d \sim q \sqrt{\frac{D_p}{\tau_p} \cdot \frac{n_i^2}{N_D}} + \frac{q n_i W}{\tau_e} \]

‡ This is a theoretical value for the dark current in SiC detectors.
- $N_{Si} > 10^{10} / \text{cm}^2 \cdot \text{sec}$
- $N_{SiC} \sim 10^4 / \text{cm}^2 \cdot \text{sec}$ (can be lower)
- $dN_s / dT \sim 0.2 / K$
- $N_{SiC}$ at RT < $N_{Si}$ at 77K
Read noise
Resistive feedback trans-impedance amplifier

\[
\text{Noise} = \left( \frac{4kTB}{R_F} \right)^{1/2}
\]

\[
\text{Bandwidth} = R_F C
\]
Capacitive feedback trans-impedance amplifier

\[ \text{Noise} \sim (kT C_F B)^{1/2} \]
Avalanche gain

- Very large gain possible
- The functional form of the responsivity does not change over several orders of magnitude
- Linear gain $>10^6$
  - Linear gain of SiC = $10^6$
  - Linear gain of Si = $10^2$
  - Linear gain of InGaAs/InP < $10^2$
  - Best APD
- $k = 0.1$
Excess noise

\[ SNR = \frac{Q.E. \cdot N_{ph} \cdot M}{\sqrt{(Q.E. \cdot N_{ph} + N_b + N_d) \cdot M^2 \cdot (kM) + N_r^2}} \]
Excess noise

\[
\text{SNR} = \sqrt{\frac{Q.E. \cdot N_{ph} \cdot X}{N_b + N_d}} \cdot \frac{X}{(kM) + X^2}
\]
SNR in single photon counting mode

\[
SNR = \frac{Q.E. \cdot N_{ph}}{\sqrt{Q.E. \cdot N_{ph}^2 + N_b + N_d + N_n^2}}
\]
Structure of SiC single photon counting APD and testing structure
Single photon counting waveform and testing circuit

- $R_s = 50\Omega$
- $t_{\text{rise}} < 1\text{ns}$
- $t_{\text{fall}} \sim 2\text{ns}$

Diagram:
- Oscilloscope
- 1.3 nF capacitor
- Resistance $R_s = 50\Omega$
Amplitude of SiC single photon counter

![Graph showing the amplitude of SiC single photon counter at 300K. The x-axis represents current (I) in microamperes (uA), ranging from 0.01 to 10. The y-axis represents pulse height (V) on a logarithmic scale, ranging from 10^-2 to 10^0. The graph includes error bars representing data variability at different current levels.]
Dark count of SiC APD photon-counters

![Graph showing dark count rate vs. bias current.](image)

- Dark Count Rate (Hz)
- Bias current (A)

Inset: Signal (a.u.) vs. Time (µs) for $I_{bias} = 1\mu A$
Temperature-dependence of dark count rate

\[ E_m = 5.2 \text{MV/cm} \]

- 10\(\mu\)A
- 1\(\mu\)A
- 0.1\(\mu\)A

DCR (Hz)

Temperature (K)
Reduce the dark count rate by reducing the breakdown electric field

\[ P_{\text{tunneling}} \left( \frac{E_m}{P_{\text{tunneling}}} \right) = 10^{30} \text{ to } 10^{60} \]

- 4H-SiC
- 6H-SiC
- 3C-SiC

\[ E_m, \text{ Maximum Electrical Field (MV/cm)} \]
Quantum Efficiency
Spectrum range for SiC detectors
Spectrum range for SiC detectors
QE curves of Pt/4H-SiC photodiodes
QE curve of SiC

Quantum Efficiency (e-/ph) vs. Wavelength (nm)

Measured Q.E.

Corrected Q.E. = Measured Q.E. / (Eph/7.8eV)
QE curves of SiC photodiode vs. penetration depth

![Graph showing penetration depth vs. wavelength for different regions of the spectrum, including Soft X-ray, EUV, VUV, UV, VIS, and IR.]
Visible rejection of SiC photodiodes

- Quantum Efficiency vs Wavelength (nm)
- Schottky
- p-i-n
Advantages of SiC photodiodes

- Ideal for detector fabrication
  - Negligible dark current
  - Negligible read noise (SPADs)
  - Good Q.E. for 1nm~300nm
  - Blind to visible photons
- Additionally,
  - Good MOS interface, which allows to fabricate monolithic (!!!)
    - SiC CCD (SiC EMCCD?)
    - SiC CMOS-APS (active pixel sensor)
    - Radiation sensors (for x-ray and particles)
  - Wider operating temperature
  - Excellent radiation hardness
Applications
Competitors of SiC detectors
Extraterrestrial solar spectra

Extraterrestrial Solar Spectra

Irradiance (photon/cm²/s/nm)

\[ \lambda \text{ (nm)} \]

4H-SiC
Si
Visible-blind EUV detection

![Graph showing background signal against wavelength with peaks for Si and SiC](image-url)
Terrestrial solar spectra

Irradiance (photon/cm²/s/m²)

λ (nm)

10⁻¹⁵ 10⁻¹⁰ 10⁻⁵ 10⁻¹⁰ 10⁻⁵ 10⁻¹⁰ 10⁻²⁰ 10⁻²⁵

100 200 220 240 260 280 300
Less than 1keV soft x-ray detection

- Critical emission lines
  - Carbon Kα1 (277 eV) → ~35 e⁻
  - Nitrogen Kα1 (392.4 eV) → ~50 e⁻
  - Oxygen Kα1 (524.9 eV) → ~67 e⁻

- No radiation detector module can cover this spectrum
  - Radiation detector module: providing energy spectrum
Less than 1keV soft x-ray detection

- Critical emission lines
  - Carbon (277 eV) → \( \approx 35 \text{ e}^- \)
  - Nitrogen (392.4 eV) → \( \approx 50 \text{ e}^- \)
  - Oxygen (524.9 eV) → \( \approx 67 \text{ e}^- \)

- No radiation detector module can cover this spectrum
  - Radiation detector module: providing energy spectrum

Could SiC detectors or detector modules help?
- single photon-counting or
- avalanche gain
Conclusion

- SiC has the elements to build nearly "ideal" detectors
  - Ultra low dark current
  - High avalanche gain with low k value
  - Single photon-counting at room temperature

- SiC is suitable for the visible blind detection of
  - UV
  - VUV and EUV
  - Soft X-ray for less than 1keV

- SiC can be a good candidate for solar blind UV, EUV and Soft X-ray (<1keV) detection