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

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In collaboration with
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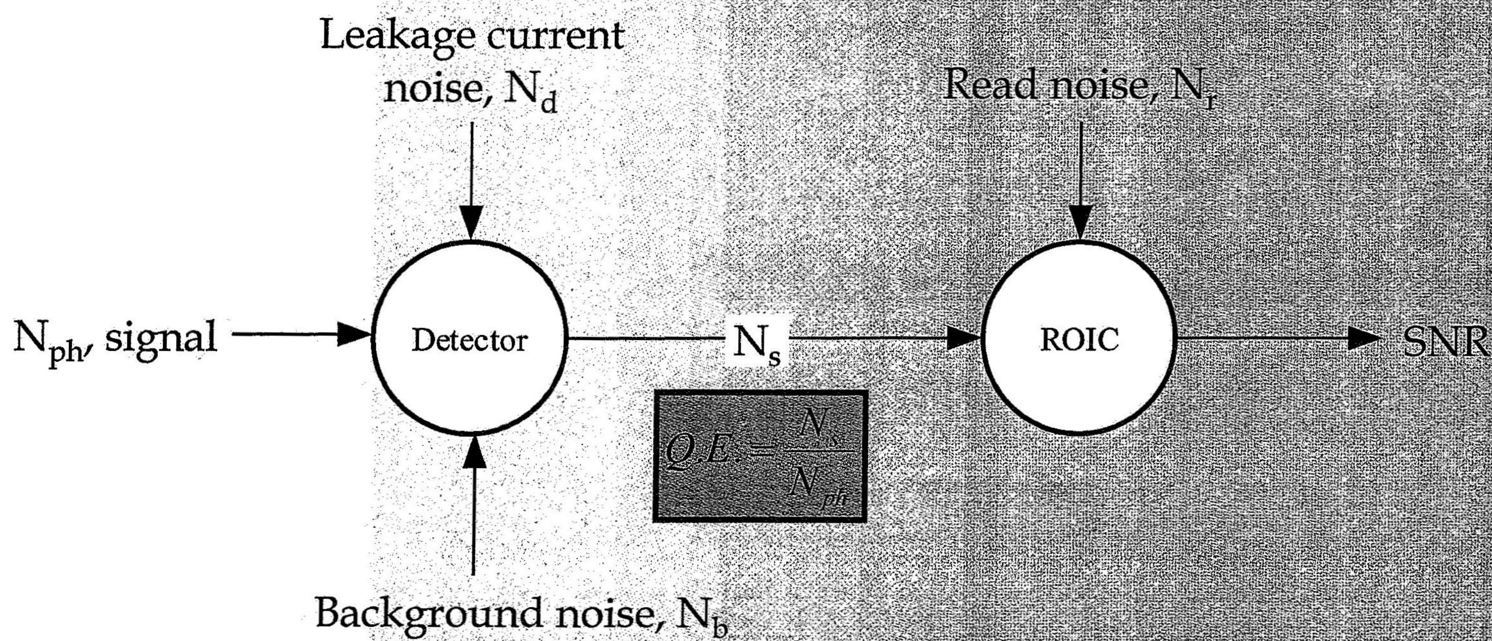
- Maurice Weiner at United Silicon Carbide, Inc.

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 & N_b: the number of electrons generated by signal, leakage current, read noise and background during the observing period

An ideal photo-detector

$$SNR = \frac{Q.E.*N_{ph}}{\sqrt{Q.E.*N_{ph} + N_b + N_d + N_r^2}}$$

An ideal detector

- Q.E. = 1 for low energy photons or E_{ph}/E_{pair} for high energy photons
- N_d negligible (detector related)
- N_b negligible (instrument related)
- N_r negligible (ROIC related)

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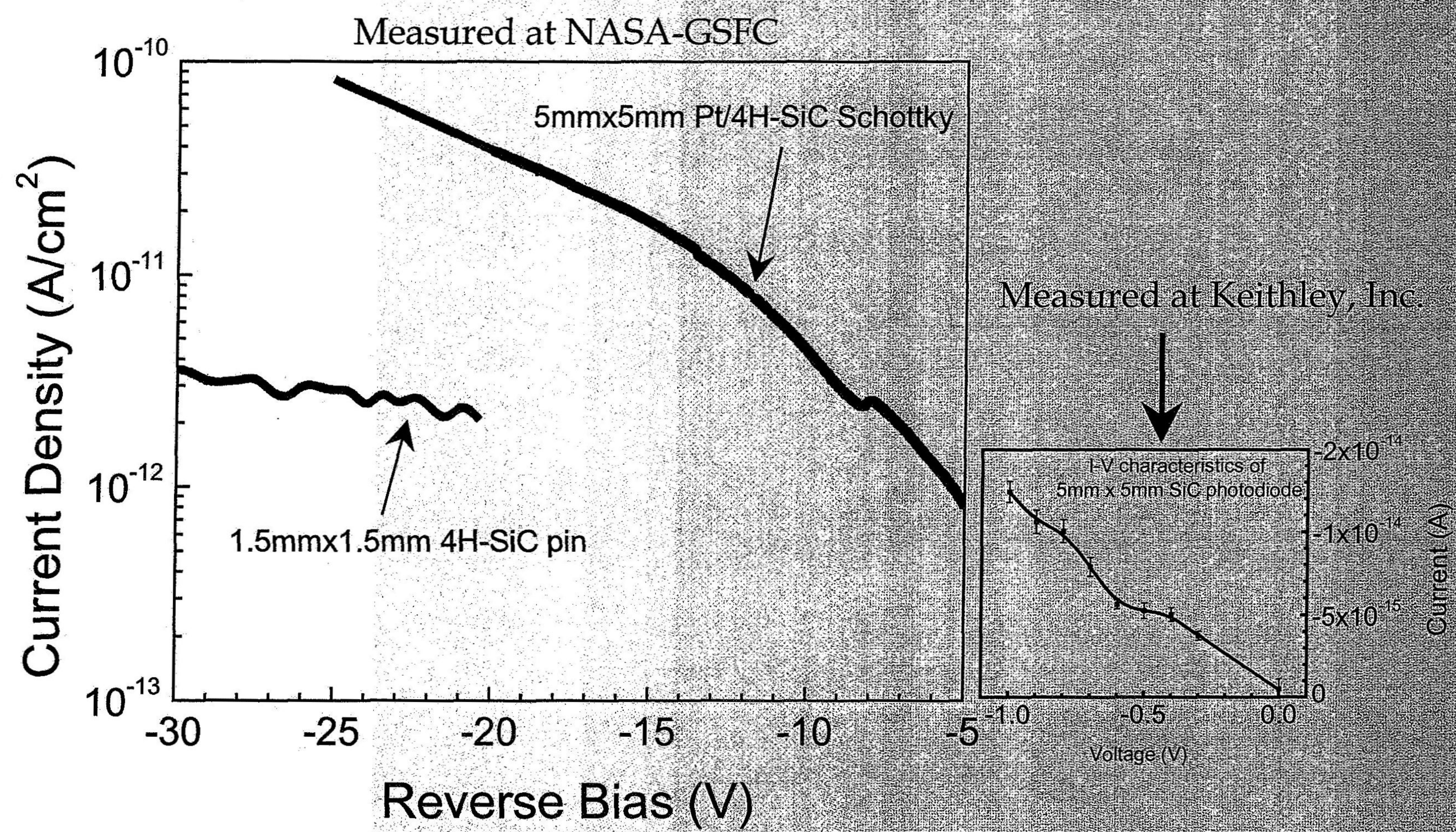
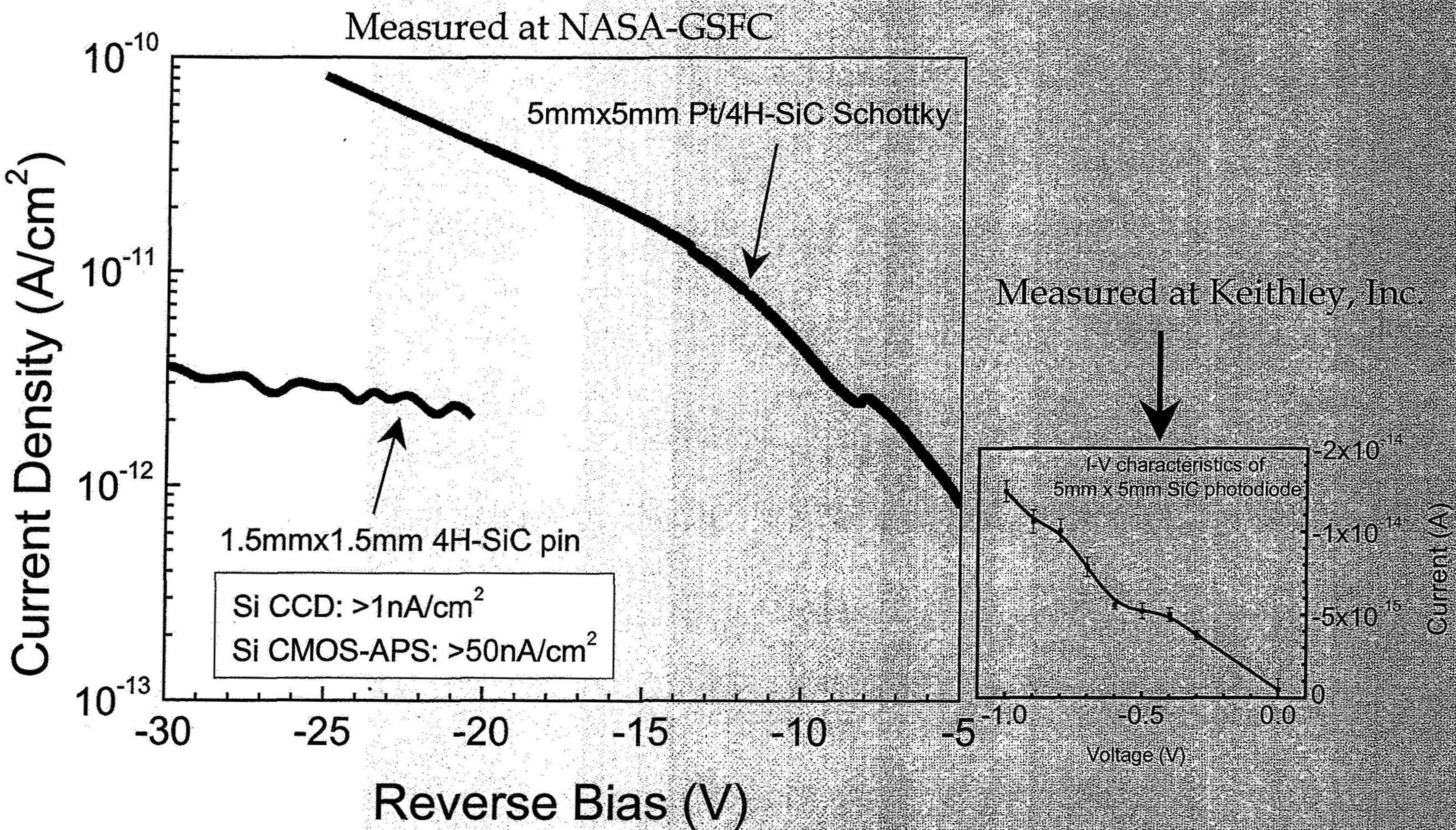
Ultimate limit: $QE*N_{ph}=1$ → $SNR=1$

Dark current

Dark current density of SiC photodiodes



Dark current density of SiC photodiodes at room temperature



Dark current in SiC detectors

	I_d^{SiC}/I_d^{Si} *(present experimental)*	I_d^{SiC}/I_d^{Si} *(theoretical)*
Schottky	**10^{-6}** **(surface defects)**	**10^{-17}** †
PIN	**$\sim 10^{-7\text{-}8}$** **(bulk defects)**	**10^{-18}** ‡

$$^{\dagger}\, I_d = A \cdot A^{**} \cdot T \cdot exp\left(-\frac{q\Phi_b}{kT}\right) \cdot exp\left(\frac{q\sqrt{qE/4\pi\varepsilon_s}}{kT}\right)$$

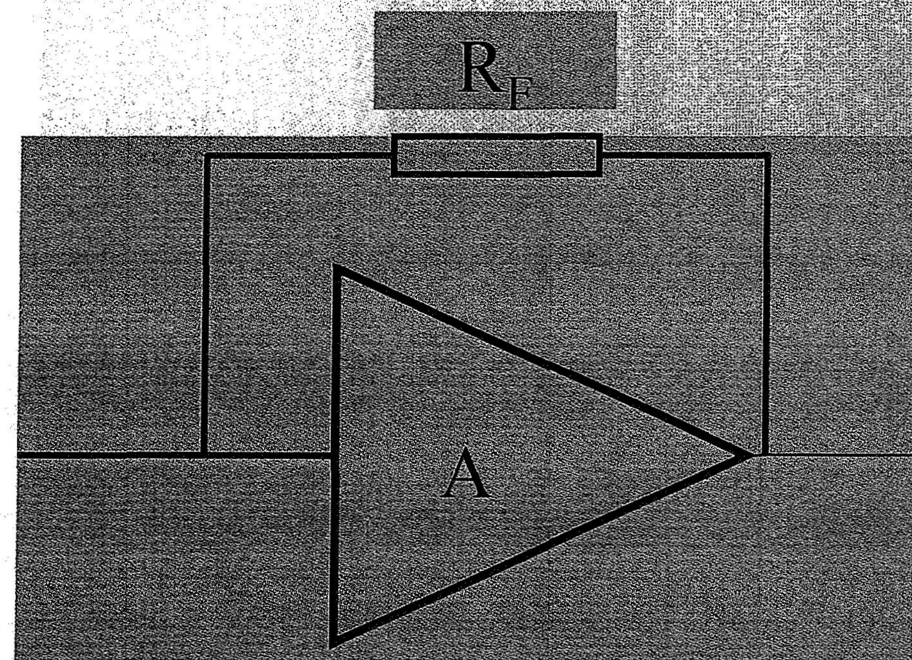
$$^{\ddagger}\, I_d \sim q\sqrt{\frac{D_p}{\tau_p}} \cdot \frac{n_i^2}{N_D} + \frac{qn_iW}{\tau_e}$$

- $N_{Si} > 10^{10}$ /cm²·sec
- $N_{SiC} \sim 10^{4}$ /cm²·sec (can be lower)

- $dN_{Si}/dT \sim 0.2/K$
- N_{SiC} at RT < N_{Si} at 77K

Read noise

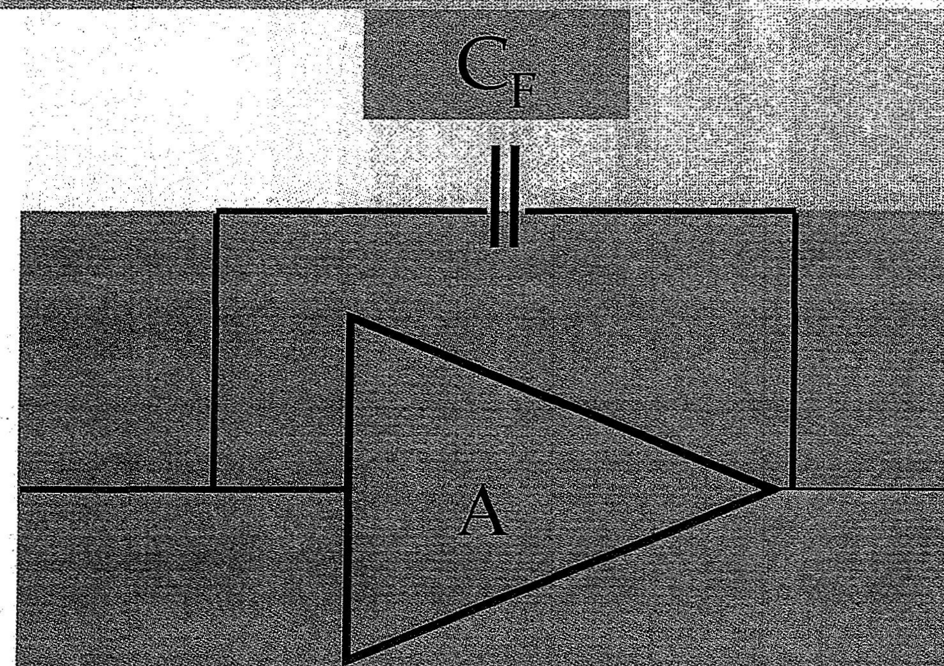
Resistive feedback trans-impedance amplifier



Noise $\longleftrightarrow$ Bandwidth

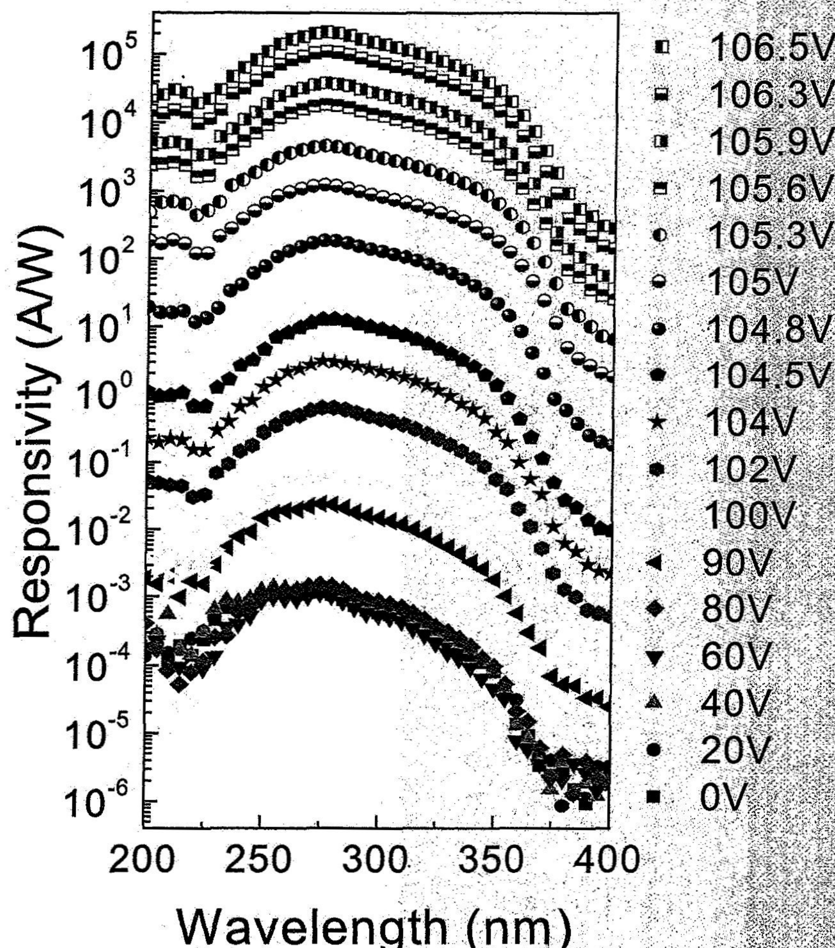
$(4kTB/R_F)^{1/2}$ $\quad$ R_FC

Capacitive feedback trans-impedance amplifier



Noise~$(kTC_FB)^{1/2}$

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= 10^3
  - Linear gain of InGaAs/InP$<10^2$
  - Best APD
- k=0.1

Excess noise

$$SNR = \frac{Q.E. * N_{ph} * M}{\sqrt{(Q.E. * N_{ph} + N_b + N_d) * M^2 * (kM) + N_r^2}}$$

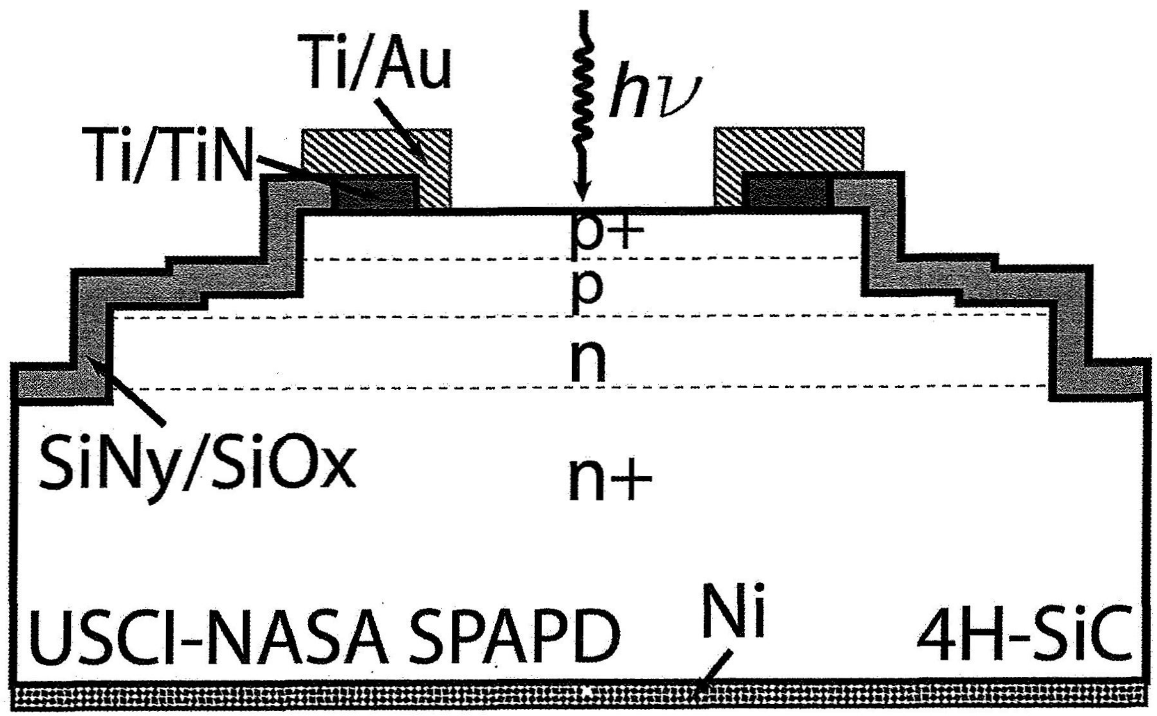
Excess noise

$$SNR = \frac{Q.E. * N_{ph} * \cancel{M}}{\sqrt{(Q.E. * N_{ph} + N_b + N_d) * \cancel{M}^2 * (kM) + \cancel{N}^2}}$$

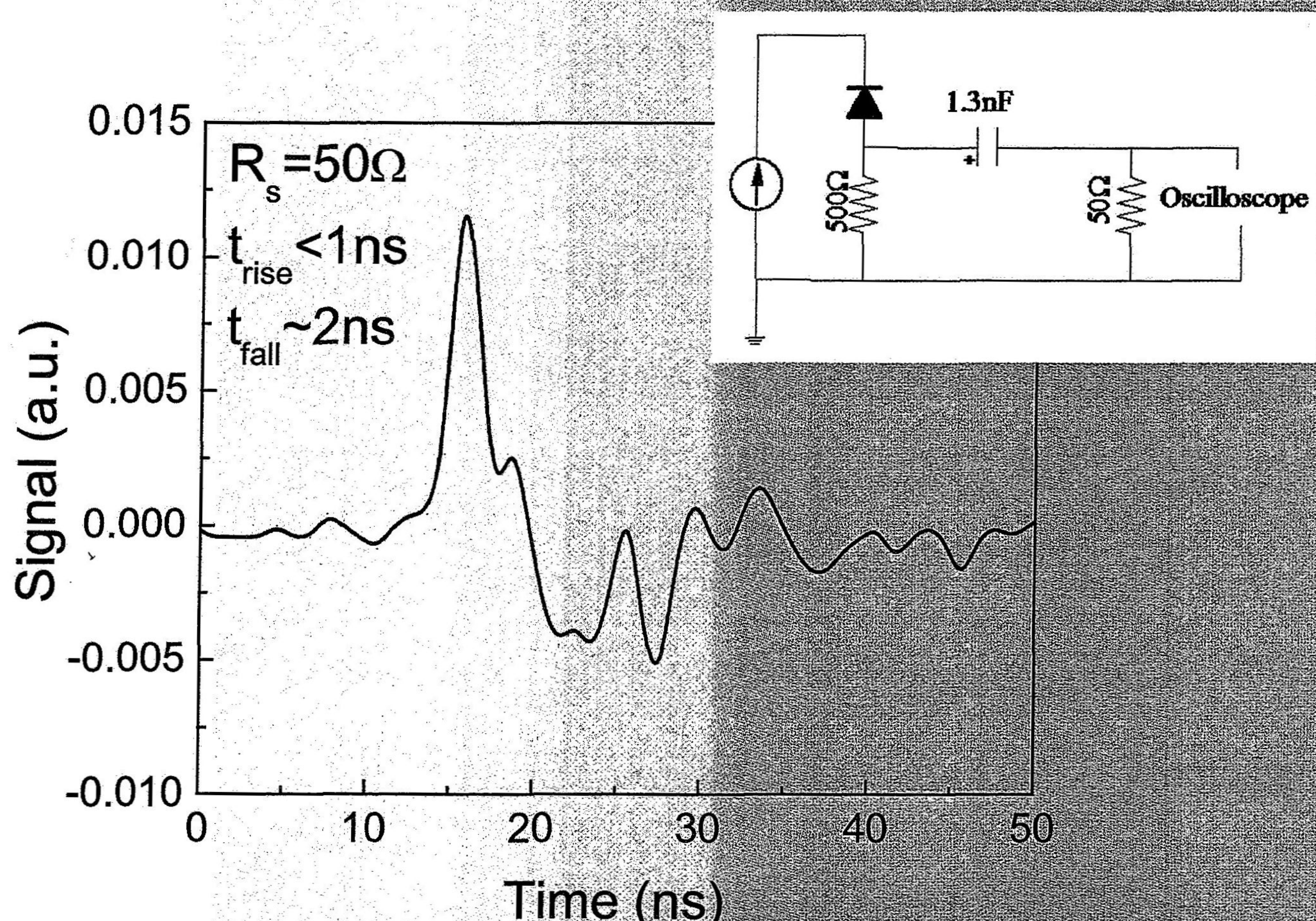
SNR in single photon counting mode

$$SNR = \frac{Q.E.*N_{ph}}{\sqrt{Q.E.*N_{ph} + N_b + \cancel{N_d} + \cancel{N_r^2}}}$$

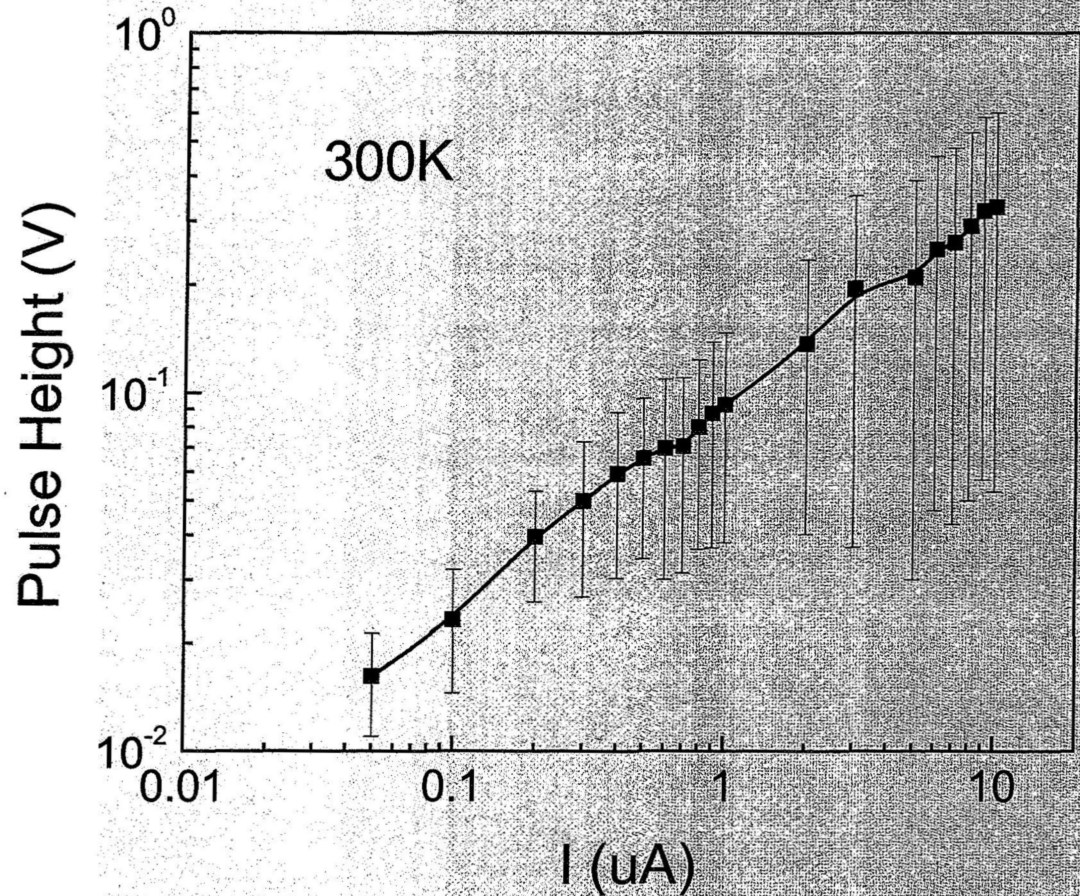
Structure of SiC single photon counting APD and testing structure



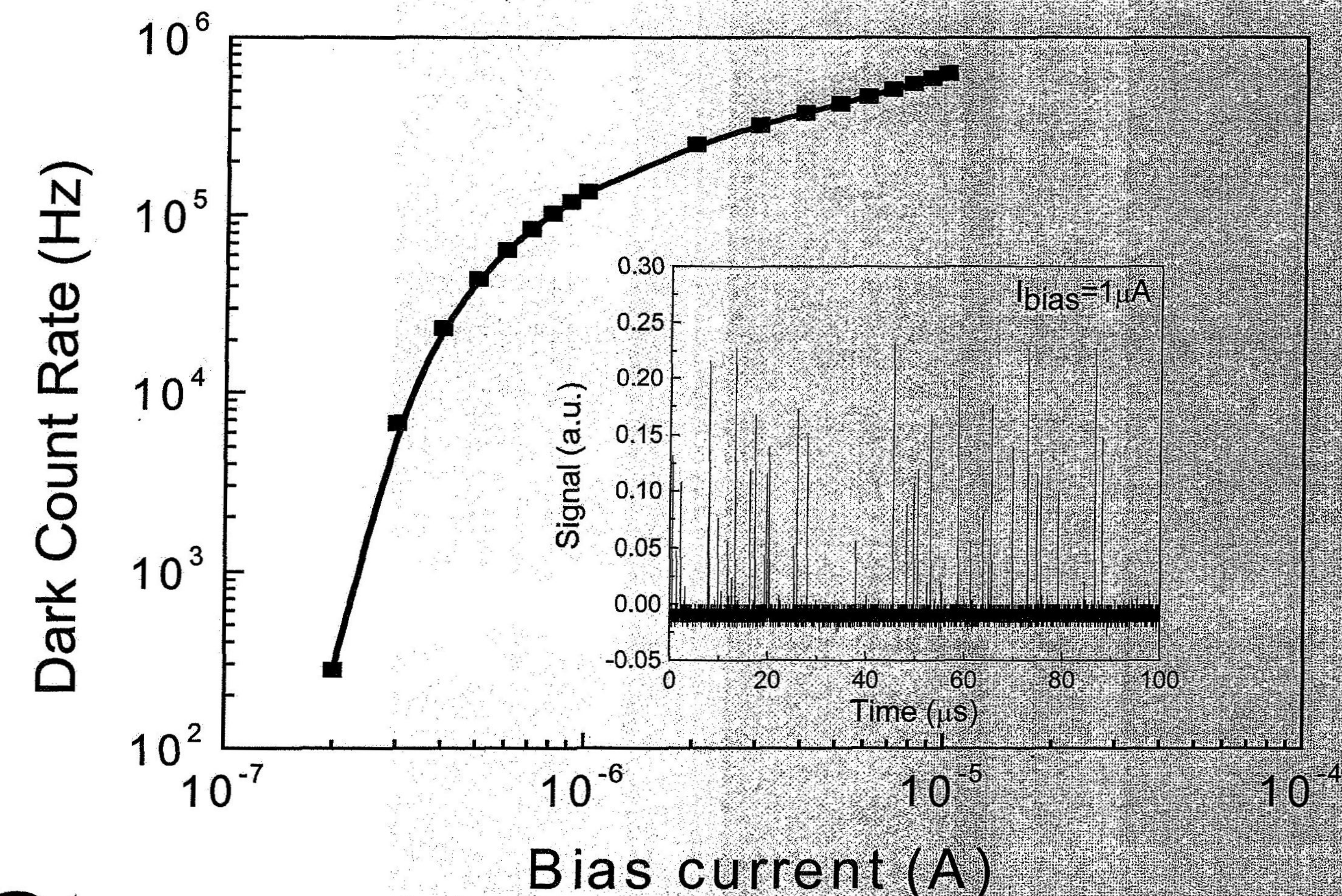
Single photon counting waveform and testing circuit



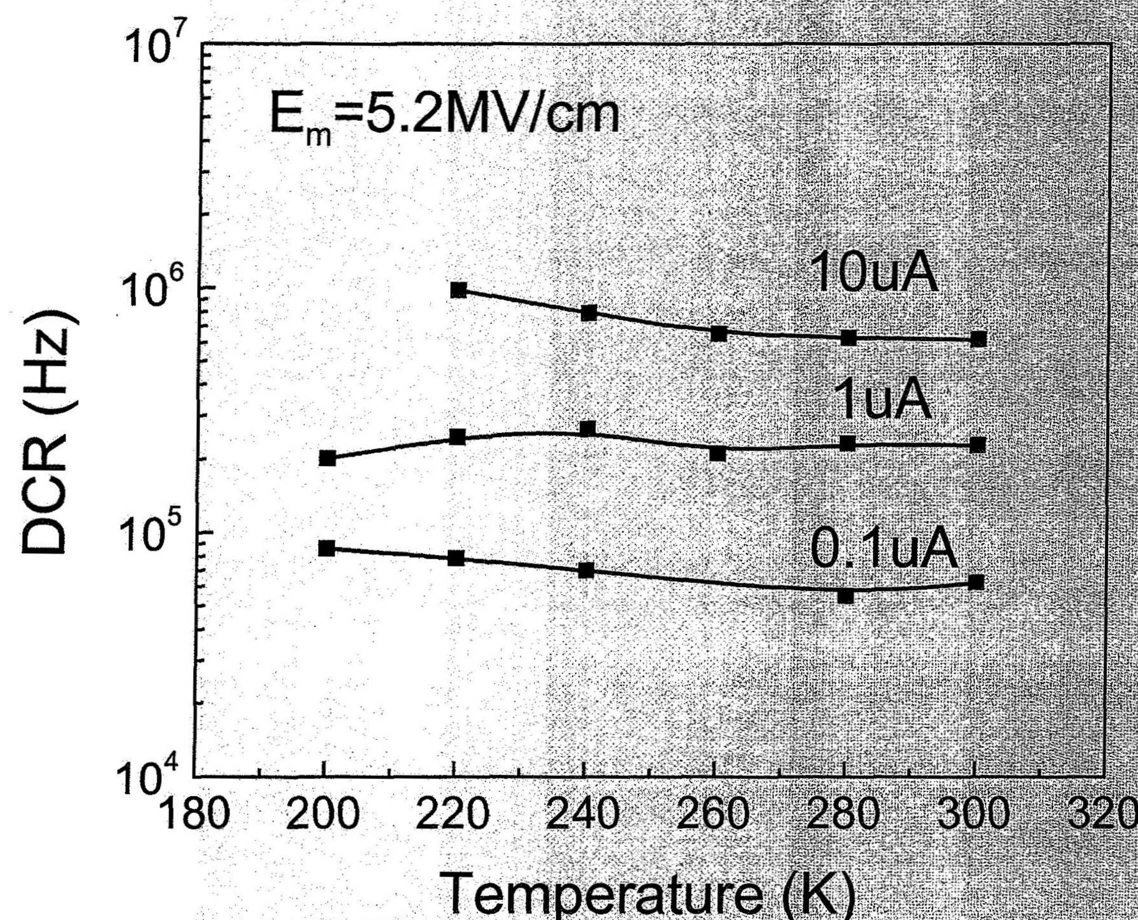
Amplitude of SiC single photon counter



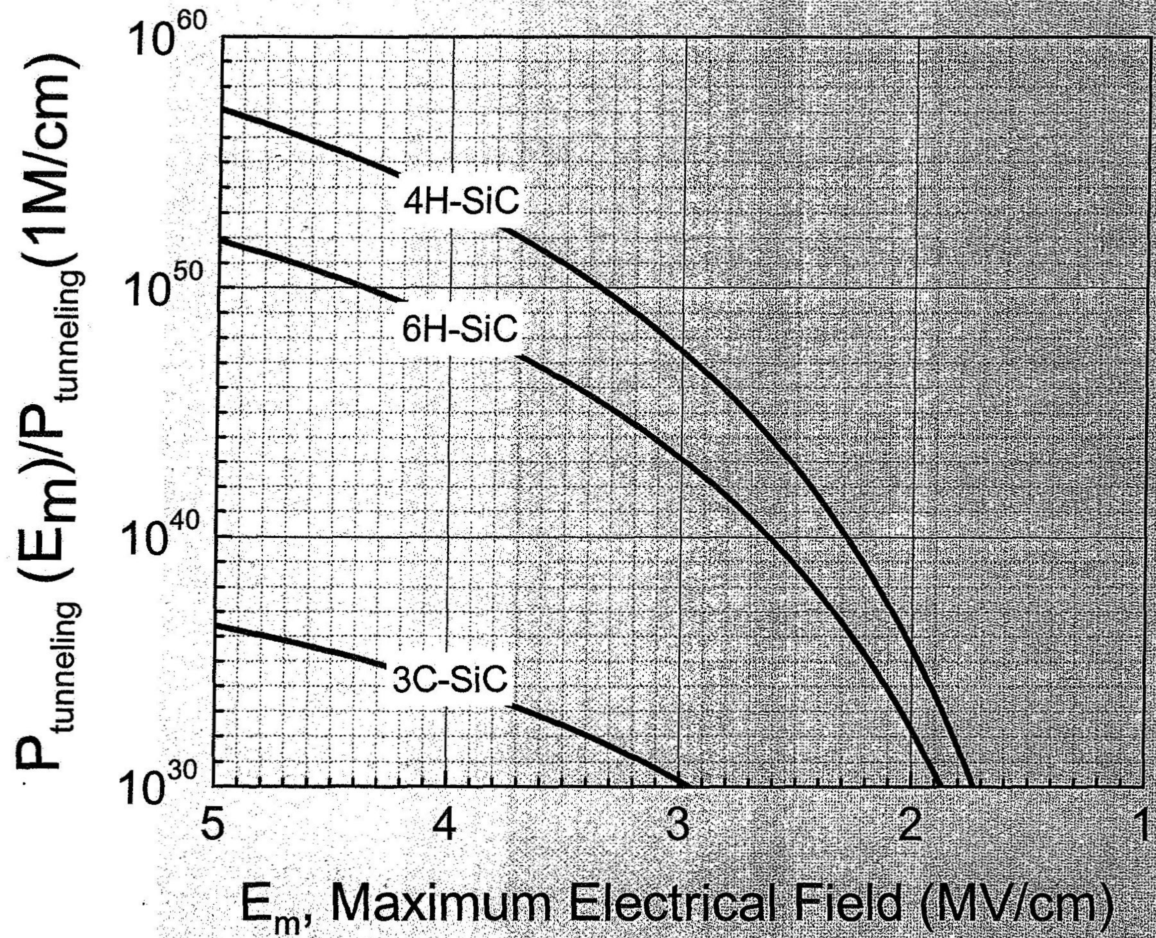
Dark count of SiC APD photon-counters



Temperature-dependence of dark count rate

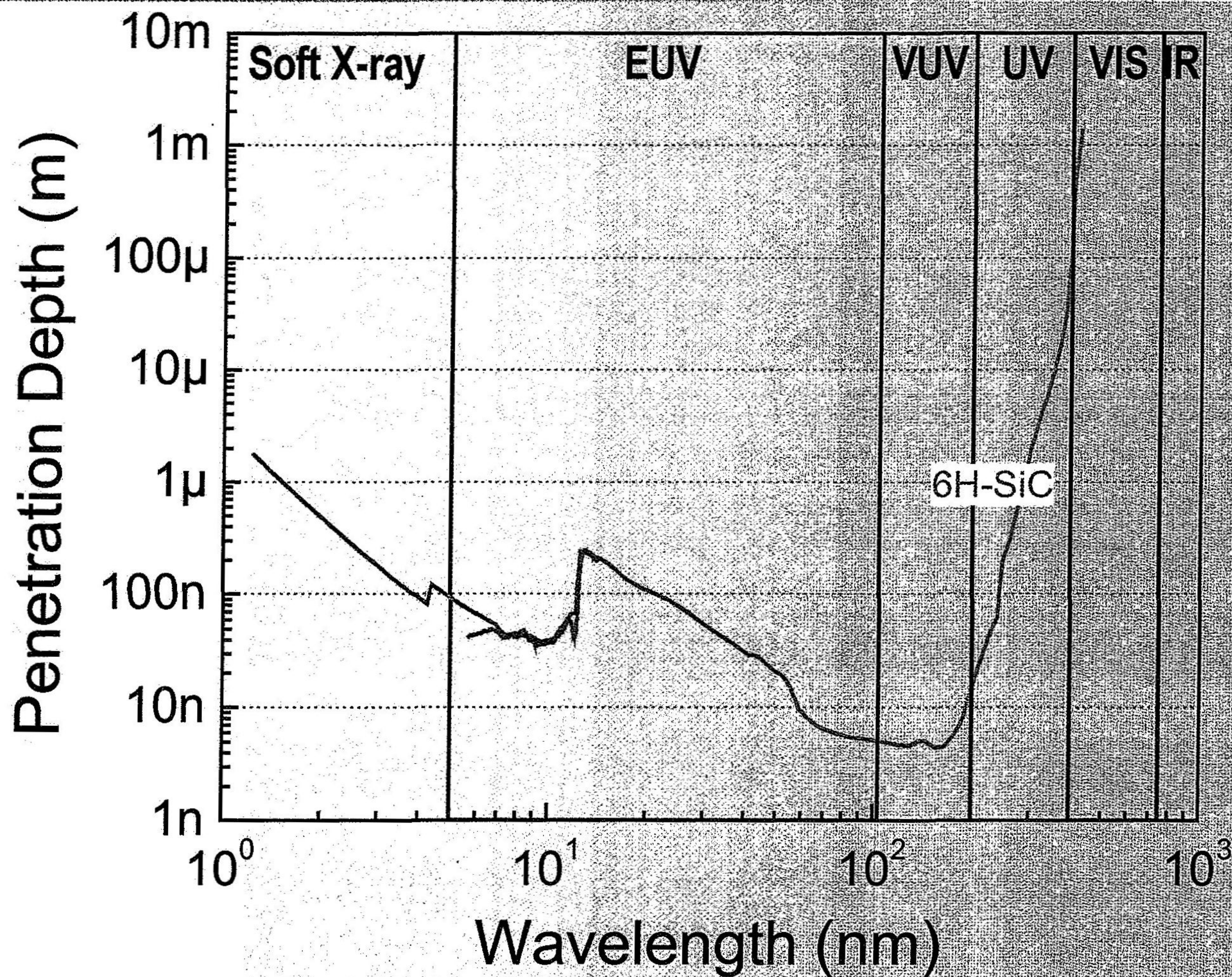


Reduce the dark count rate by reducing the breakdown electric field



Quantum Efficiency

Spectrum range for SiC detectors



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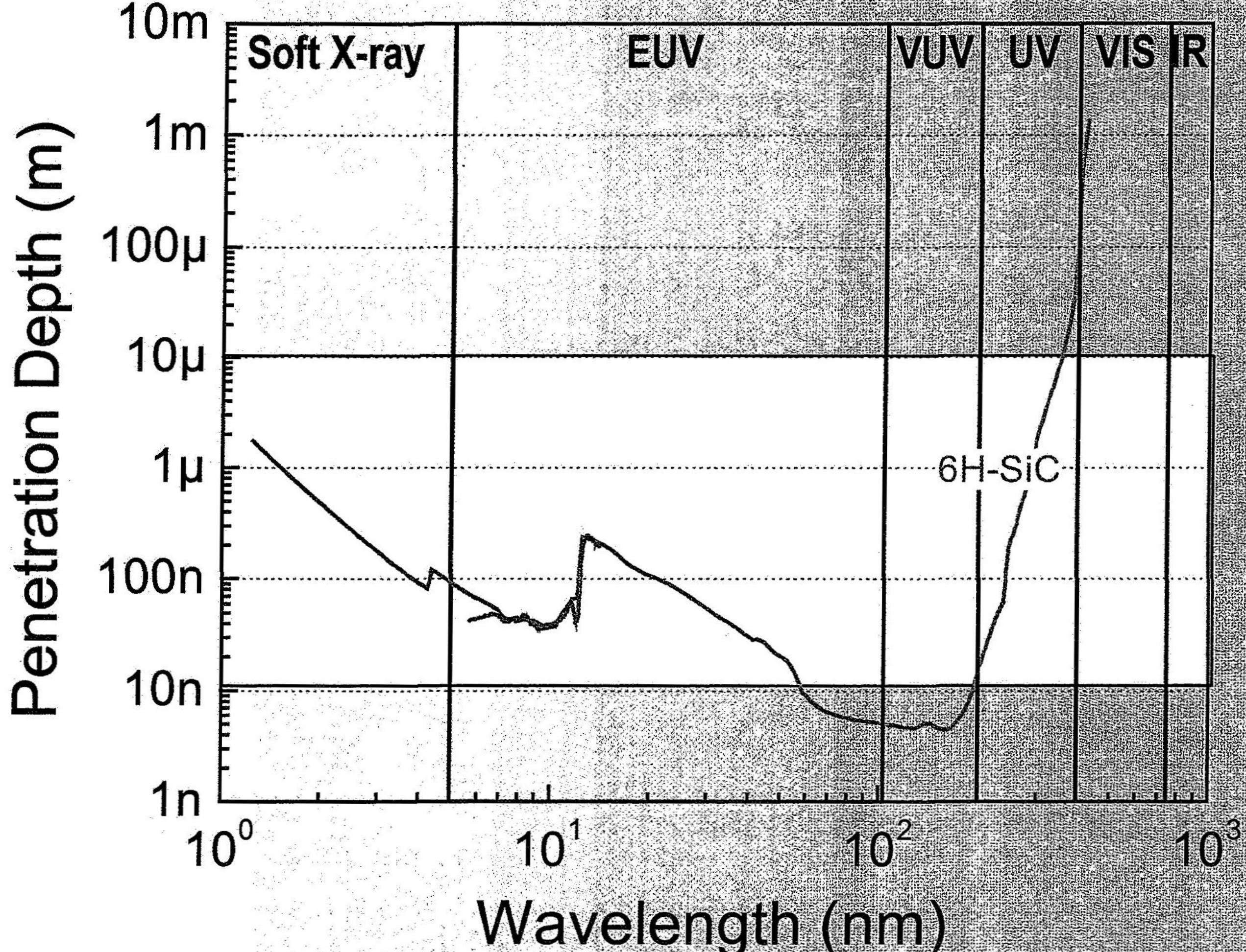
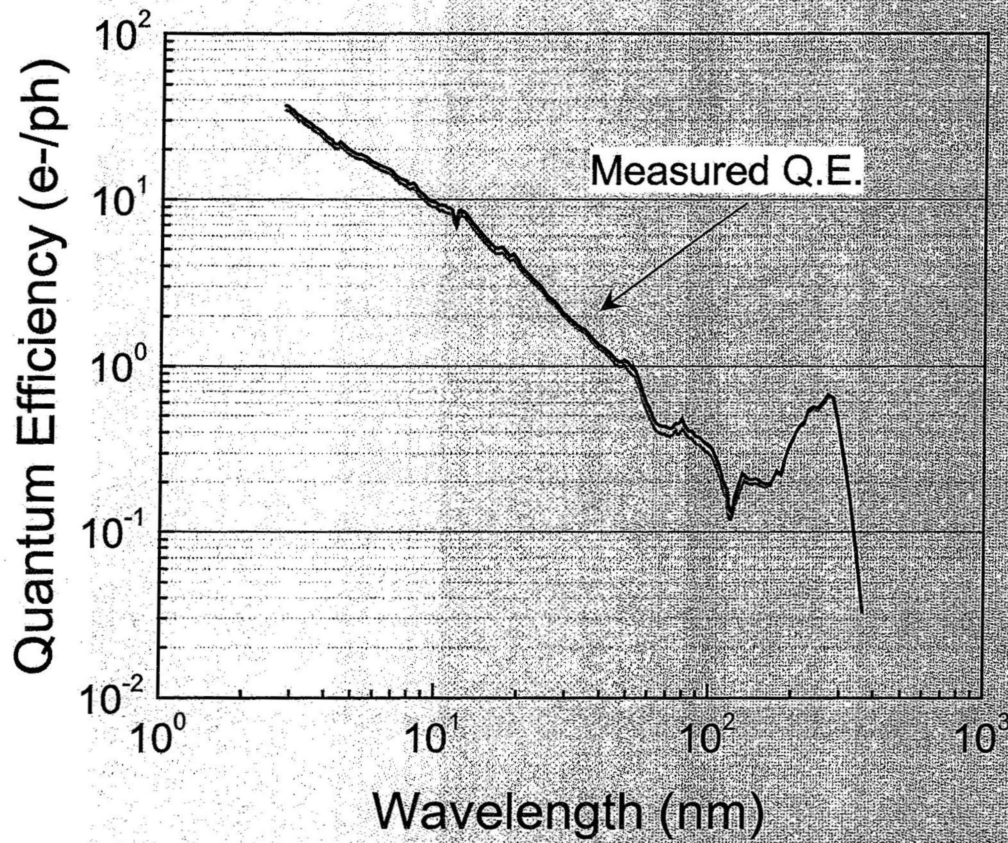
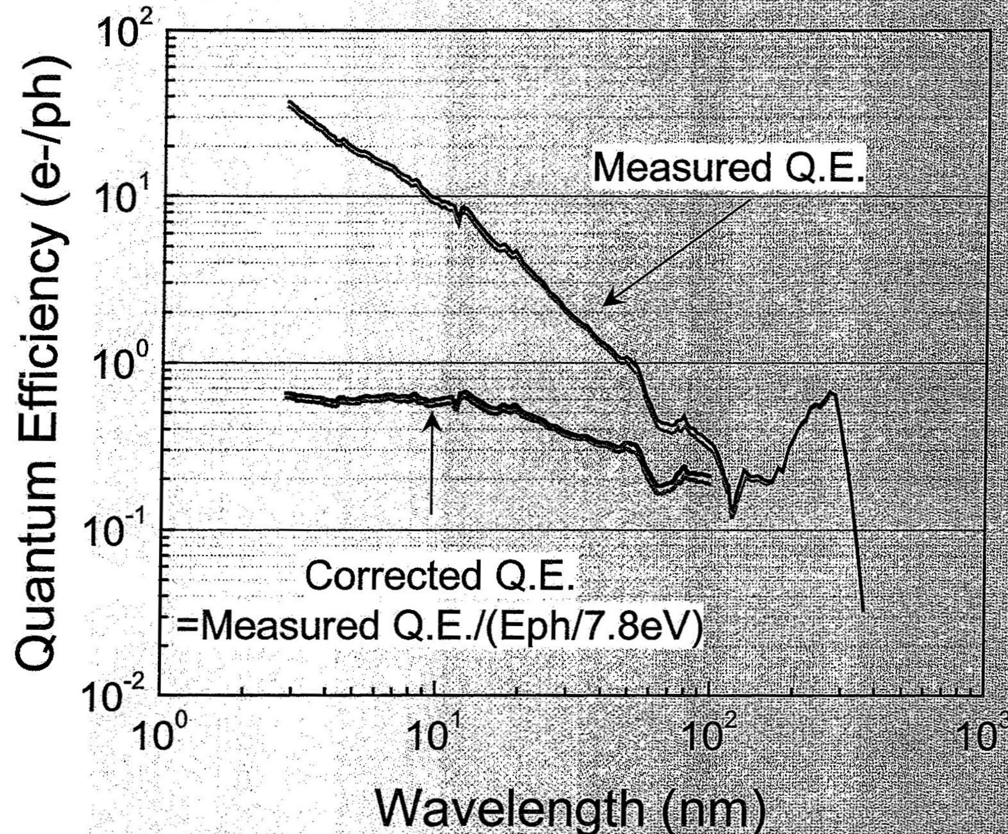


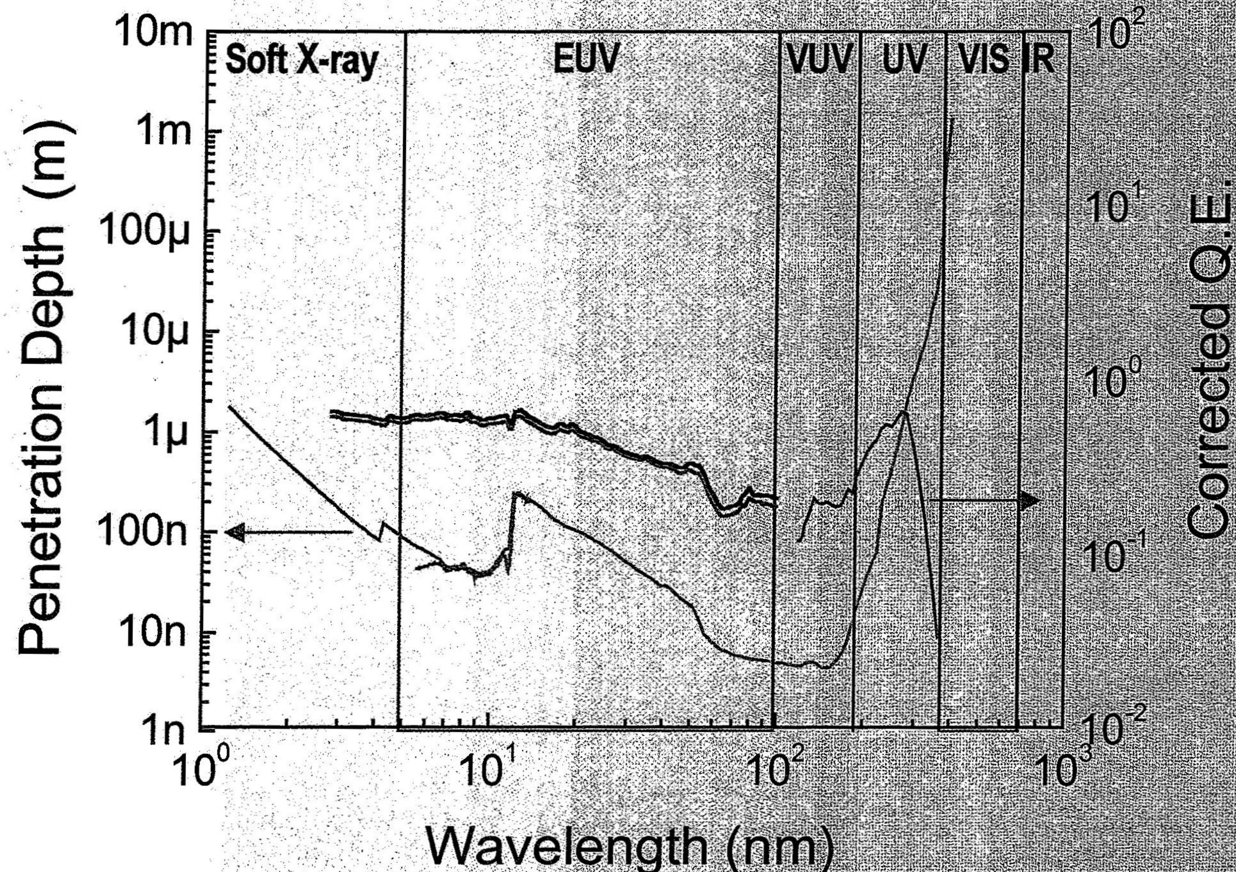
QE curves of Pt/4H-SiC photodiodes



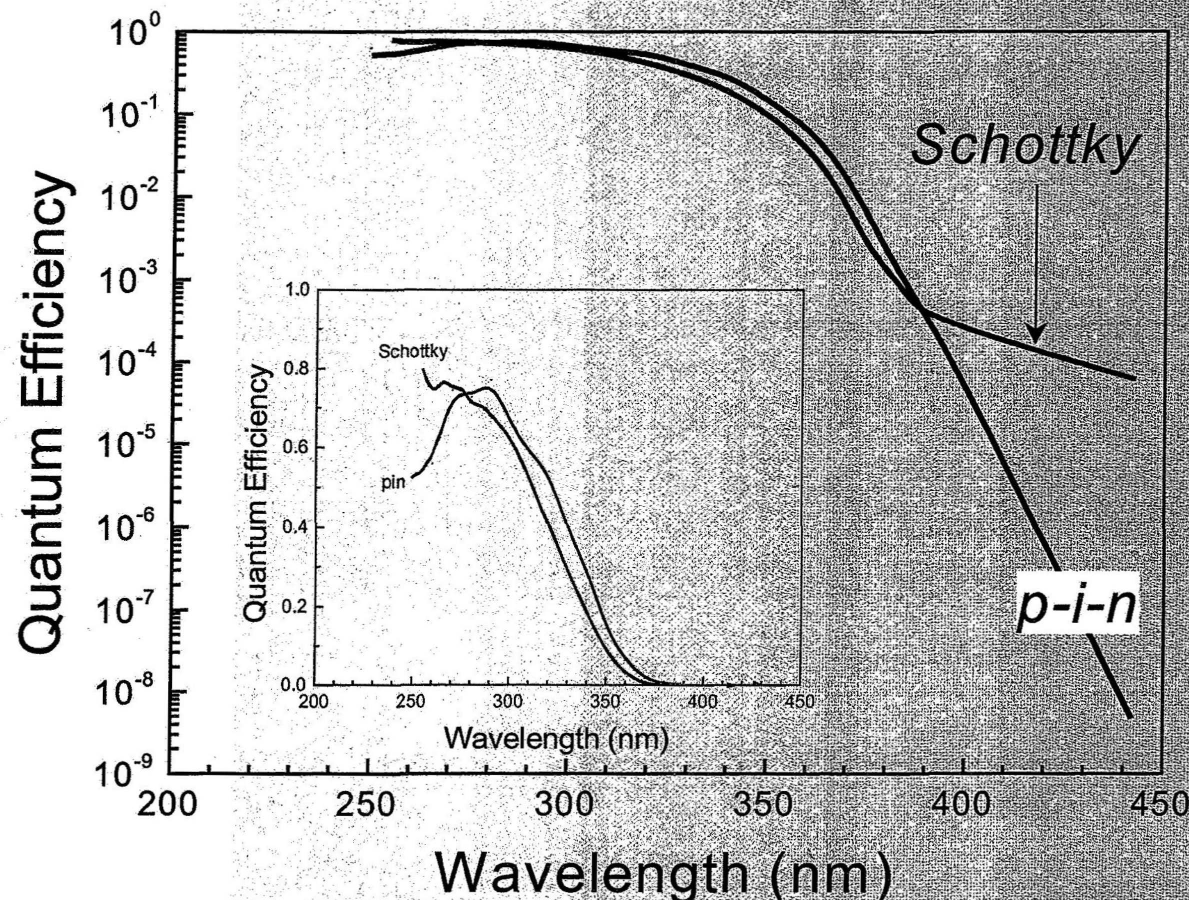
QE curve of SiC



QE curves of SiC photodiode vs. penetration depth



Visible rejection of SiC photodiodes

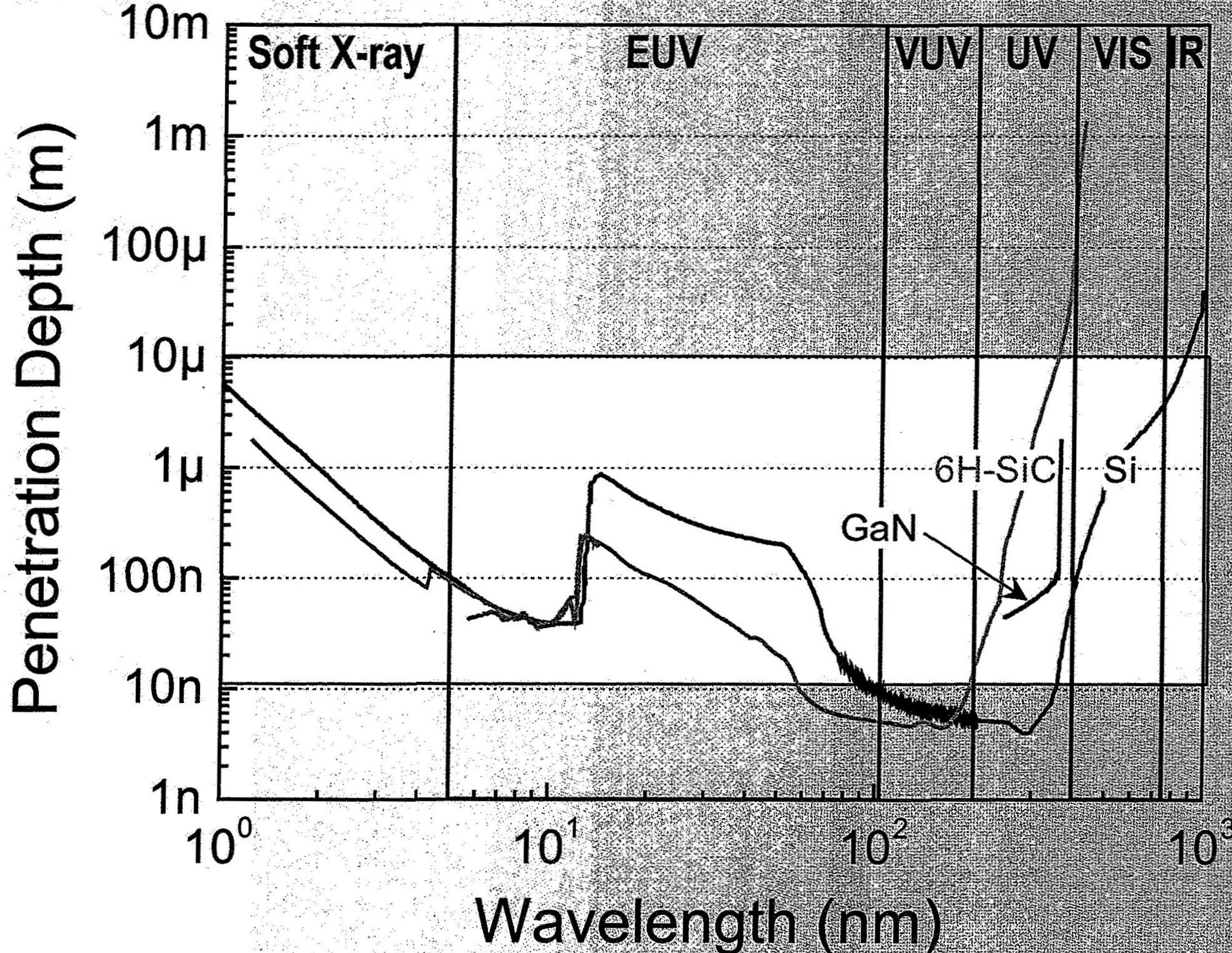


Advantages of SiC photodiodes

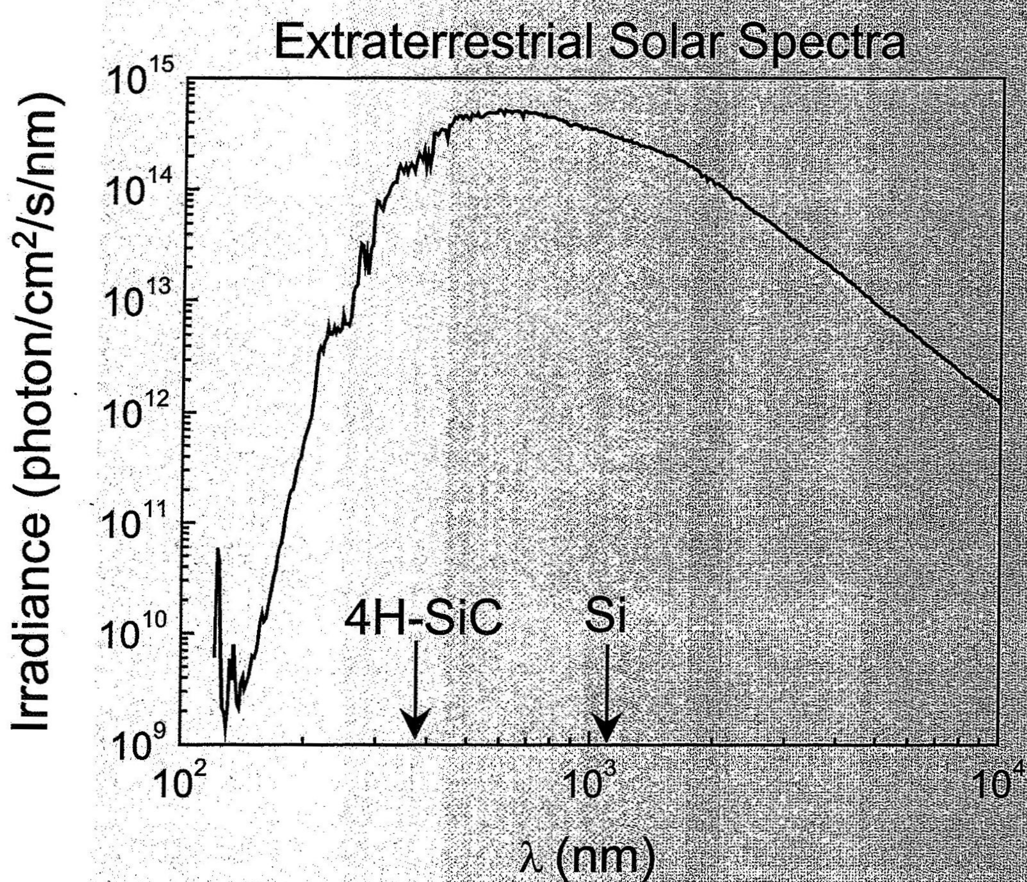
- Ideal for detector fabrication
  - Negligible dark current
  - Negligible read noise (SPADs)
  - Good Q.E. for 1nm~300nm
  - Blind to visible photons
- Additionally,
  - Good MOS interface, which allows to fabricate *monolithic (!!!)*
    - SiC CCD (SiC EMCCD?)
    - SiC CMOS-APS (active pixel sensor)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

Applications

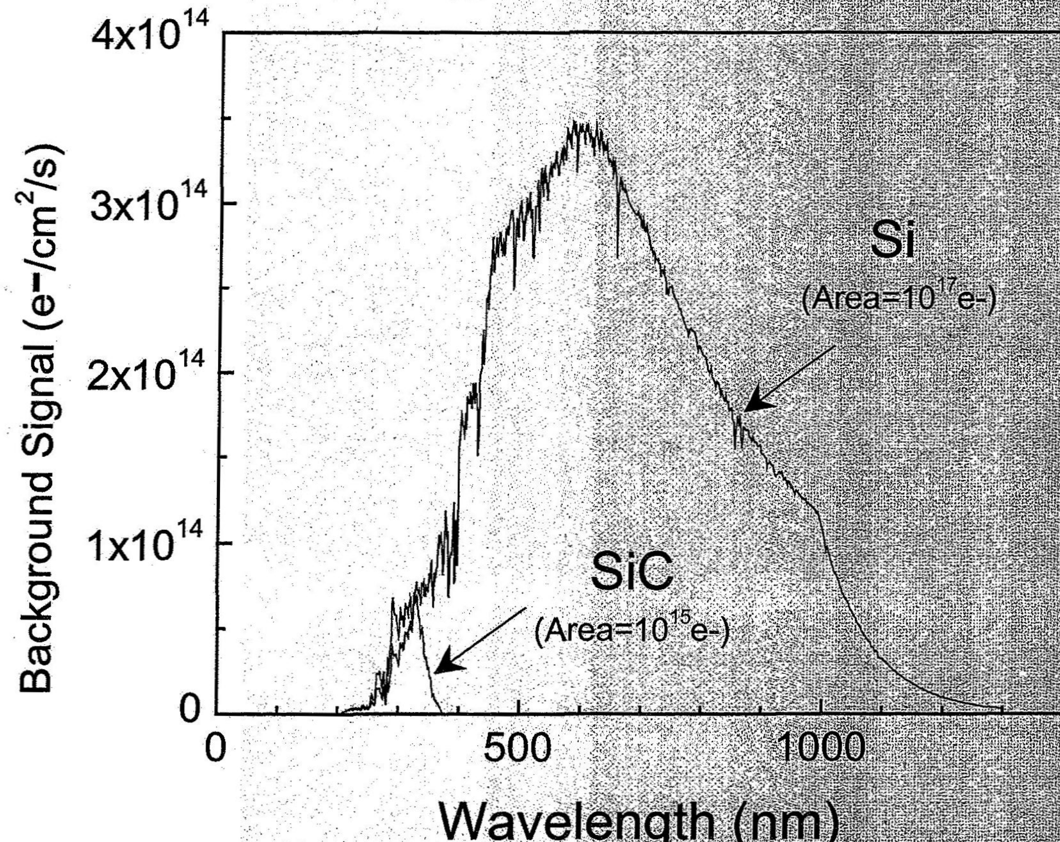
Competitors of SiC detectors

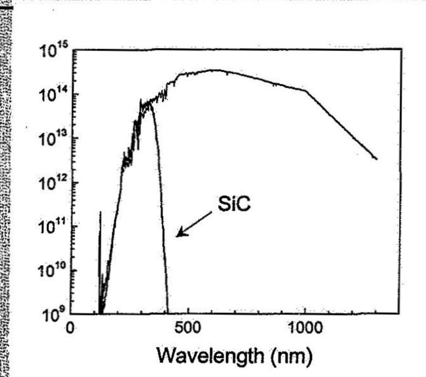


Extraterrestrial solar spectra

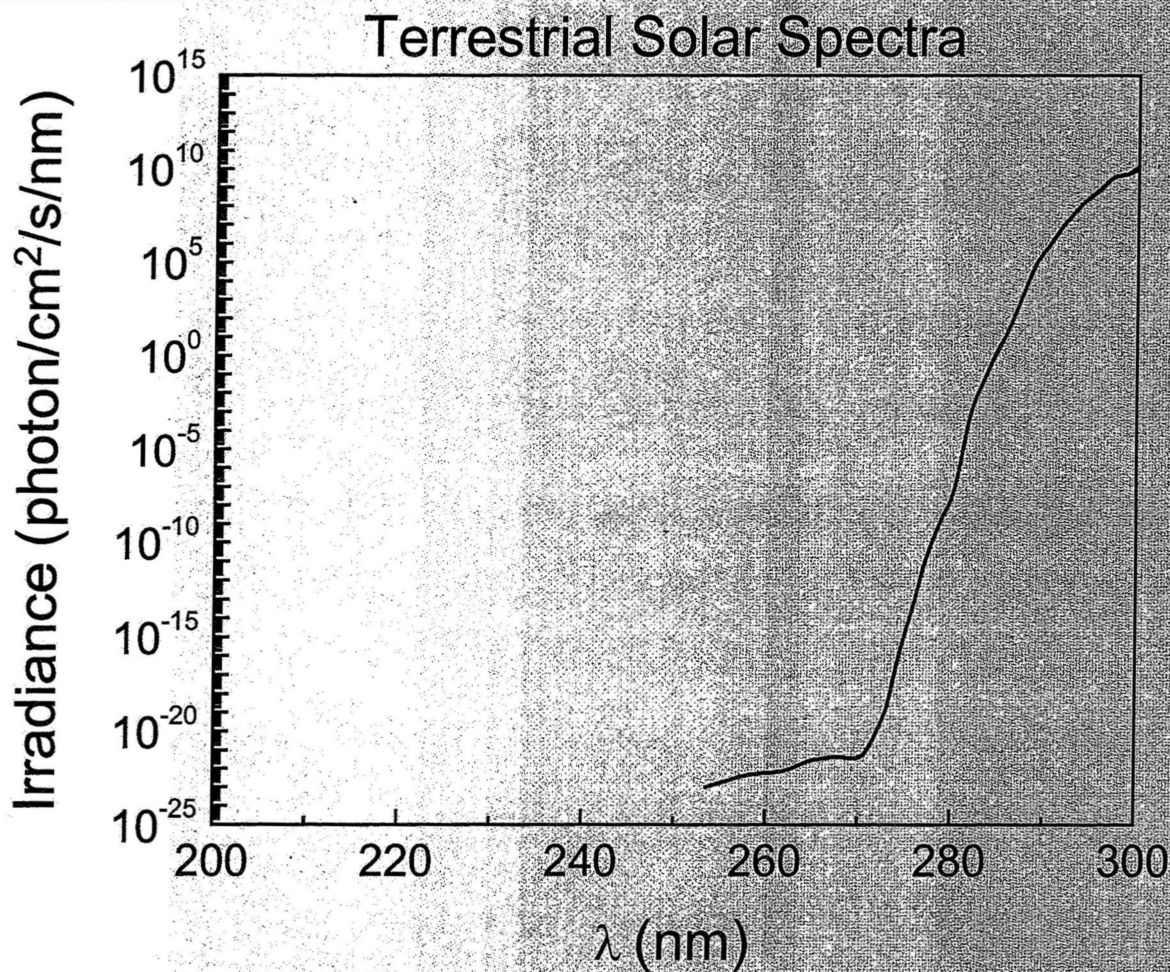


Visible-blind EUV detection





Terrestrial solar spectra



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

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  - 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