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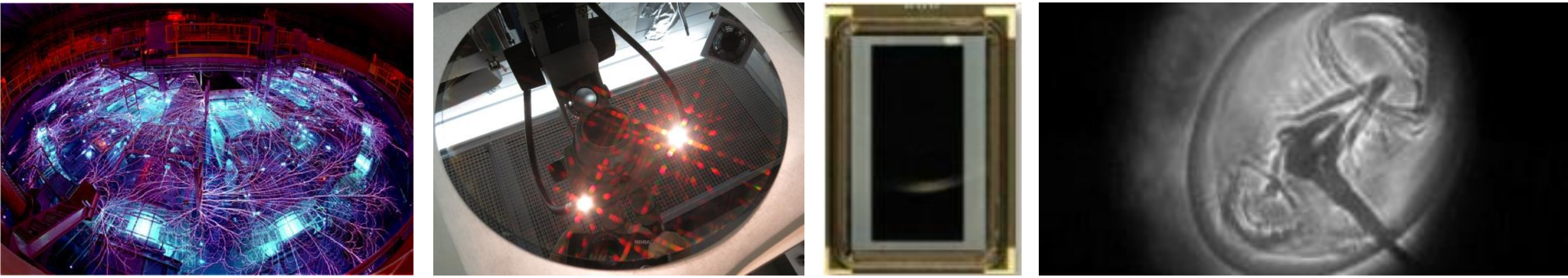


Low-Energy Sensitive Diodes for hCMOS Sensors

Q. Looker, R. Kay, J. Long, G. Robertson,
M. Sanchez, D. Trotter, J. Porter

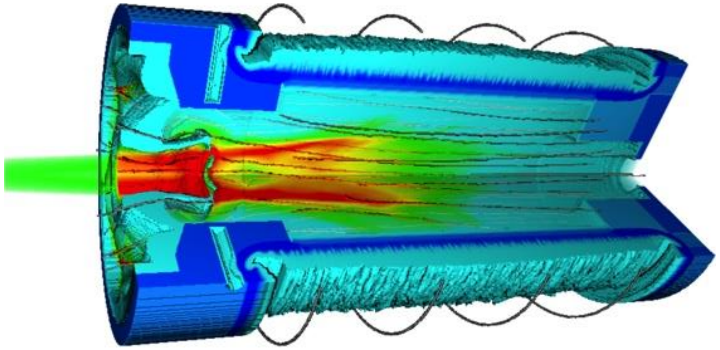
10/6/2015

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

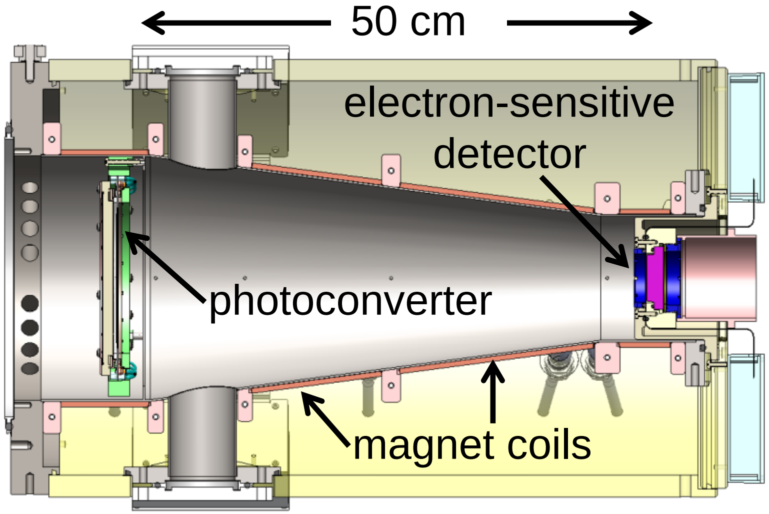
Pulsed Power Applications Exist for Soft X-Ray and Electron Detectors

- Potential Applications
  - Thermometry on Z shots: soft x-rays 100-600 eV
  - Pulse dilation camera: electrons 2-10 keV
- Si Diodes Advantageous
  - Time-resolved measurements
  - Easily integrated into hCMOS camera
- Current Challenges
  - Current diodes insensitive to photons below ~700 eV
  - Low detection efficiency for electrons below about 10 keV

MagLIF Pre-Heating

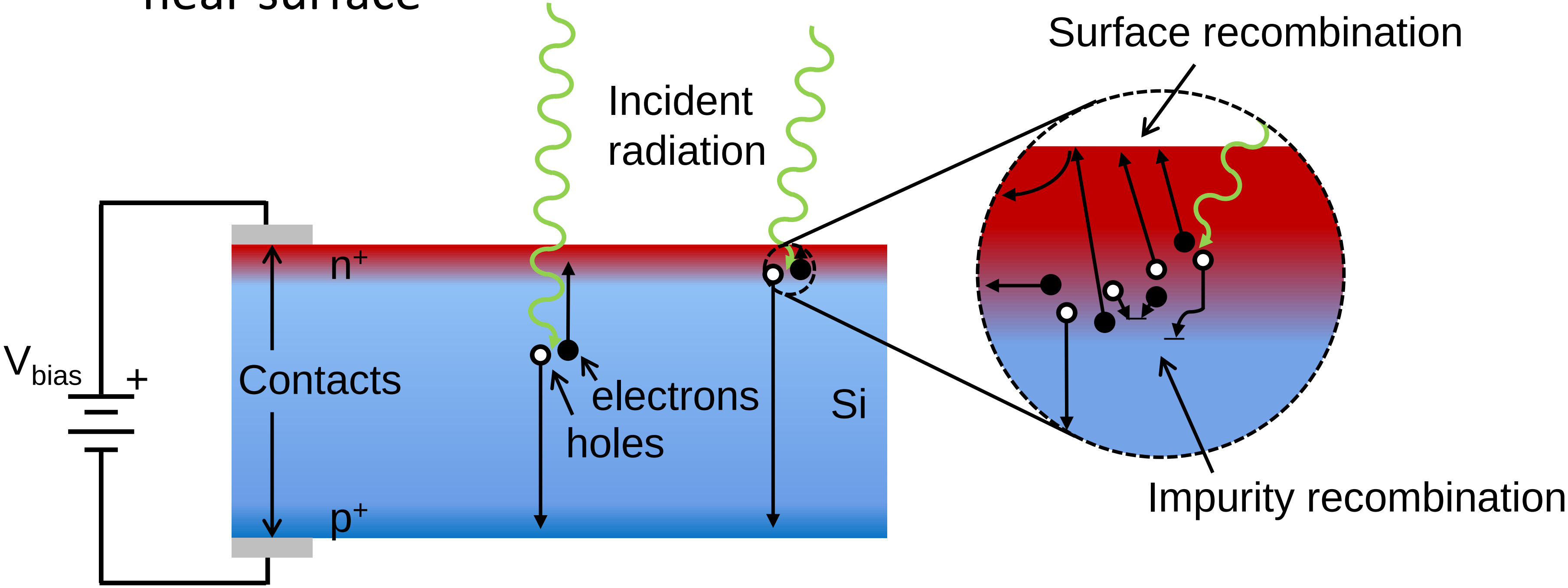


Pulse dilation camera



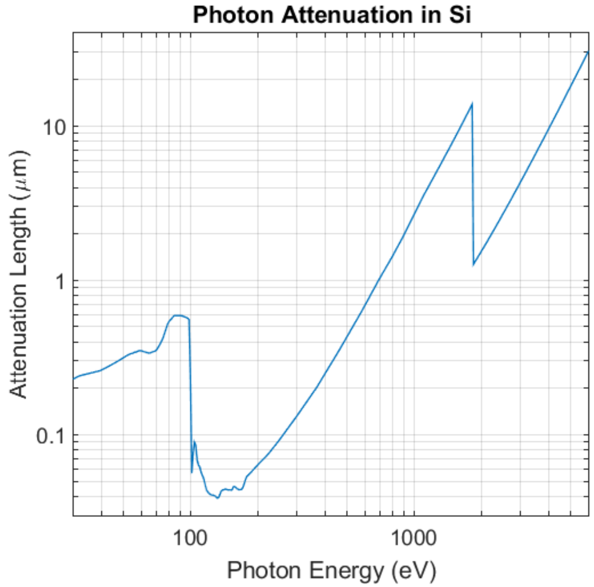
Silicon Detector Construction Matters

- Detector electrodes sense moving charge
- Maximum signal generally requires complete charge collection
- Reduced charge collection from interactions near surface



Soft X-Ray Detection is a Shallow Issue

- X-Rays 100-1000 eV
- Predominantly photoelectric absorption – energy too high for reflection, too low for Compton scatter
- Extremely short absorption length – detector surface properties dominate
- Dead layer approximation

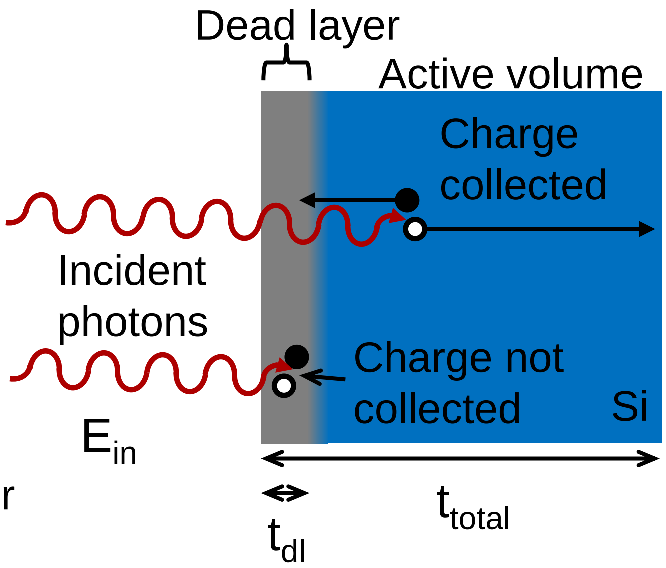


$$E_{abs} = E_{in}\left[1 - e^{-\frac{t_{total}}{l}}\right]$$

$$E_{dl} = E_{in}\left[1 - e^{-\frac{t_{dl}}{l}}\right]$$

$$\Delta_{dl} = \frac{E_{dl}}{E_{in}}$$

l: photon absorption length
E_{abs}: energy absorbed in diode
E_{dl}: energy absorbed in dead layer
Δ_{dl}: dead layer deficit

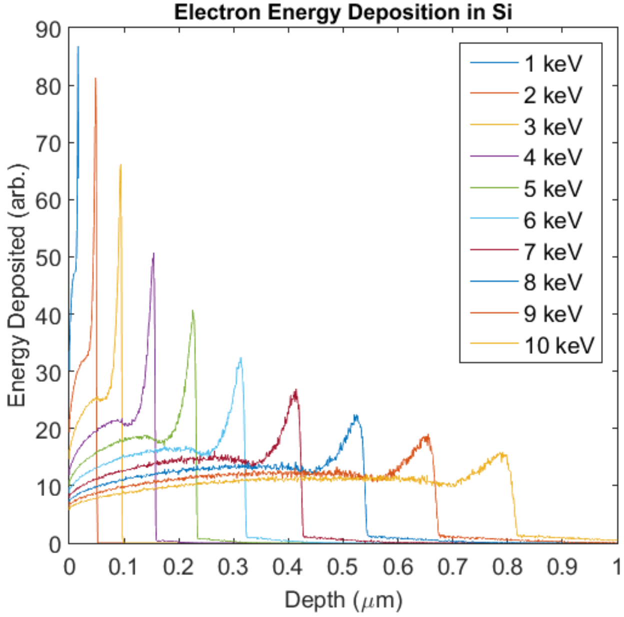


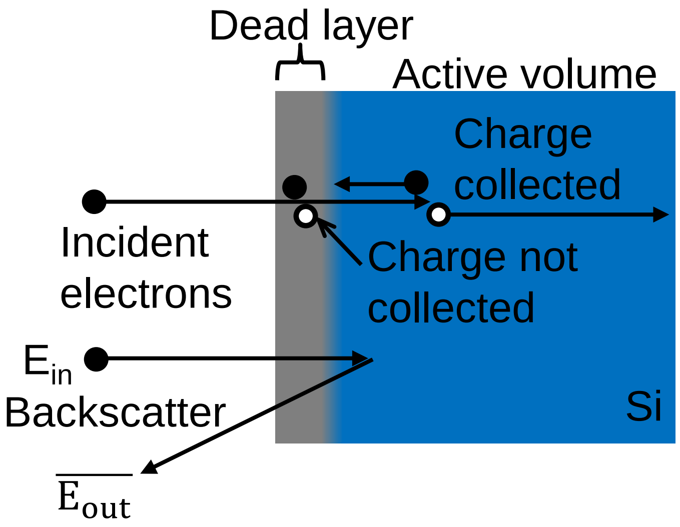
Electron Detection adds Backscatter to the Mix

- Electrons 1-10 keV
- Coulomb scattering – continuous energy deposition
- Extremely short absorption depth – dead layer requirements similar to soft X-Ray
- Backscatter also important

$$\Delta_{bs} = \eta \frac{\overline{E_{out}}}{E_{in}}$$

η: backscatter probability
E_{in}: incident electron energy
$\overline{E_{out}}$: average backscattered electron energy
Δ_{bs}: backscatter deficit





Dead layer

Active volume

Charge collected

Incident electrons

Charge not collected

E_{in}

Backscatter

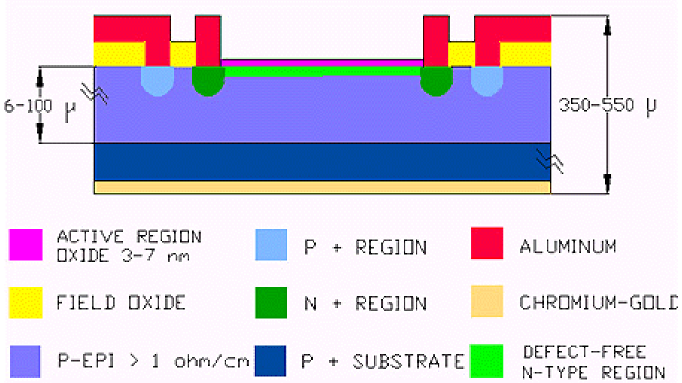
$\overline{E_{out}}$

Si

Existing Technology

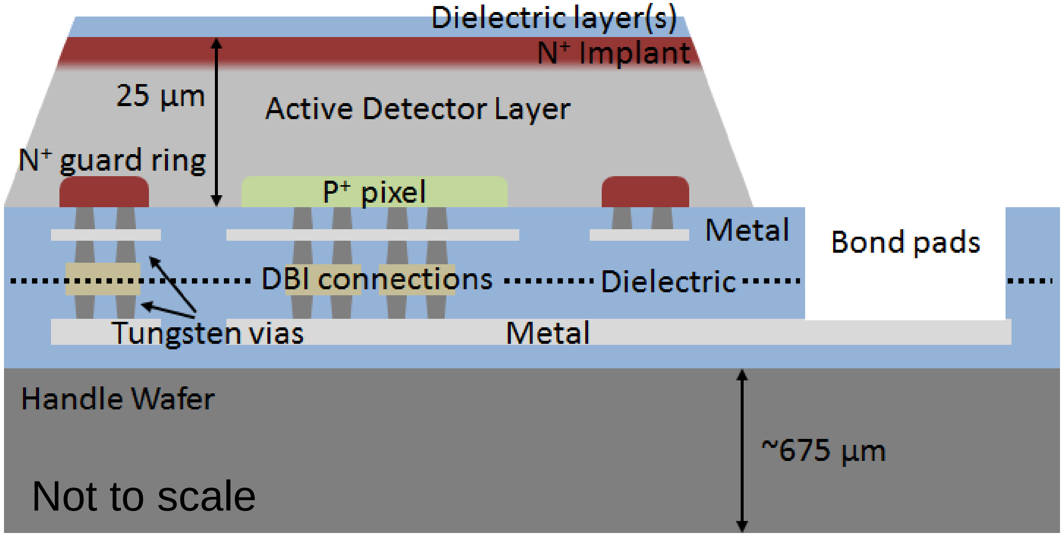
- OptoDiode AXUV models are a common standard
- Need for CMOS compatibility, high fill factor, and wafer real estate drove cameras to hybridization
- Sandia test photodiode utilizes similar technology to hCMOS cameras

OptoDiode AXUV Series



www.optodiode.com

Sandia Test Photodiode



Electron Sensitivity was Tested Using an SEM

- Responsivity is a general measure of diode sensitivity to a particular radiation type
- DC measurement is well-controlled

www.fei.com

$$R = \frac{I_{diode}}{P_{beam}}$$

R: diode responsivity
I_{diode}: diode photocurrent
P_{beam}: incident beam power
I_{beam}: incident beam current
E_{beam}: incident beam energy

$$P_{beam} = I_{beam} * E_{beam}$$

$$R_{ideal} = \frac{1}{w}$$

w: electron-hole pair creation energy
For Si, w=3.67±0.02 eV [1]

Following [2], three major loss mechanisms:

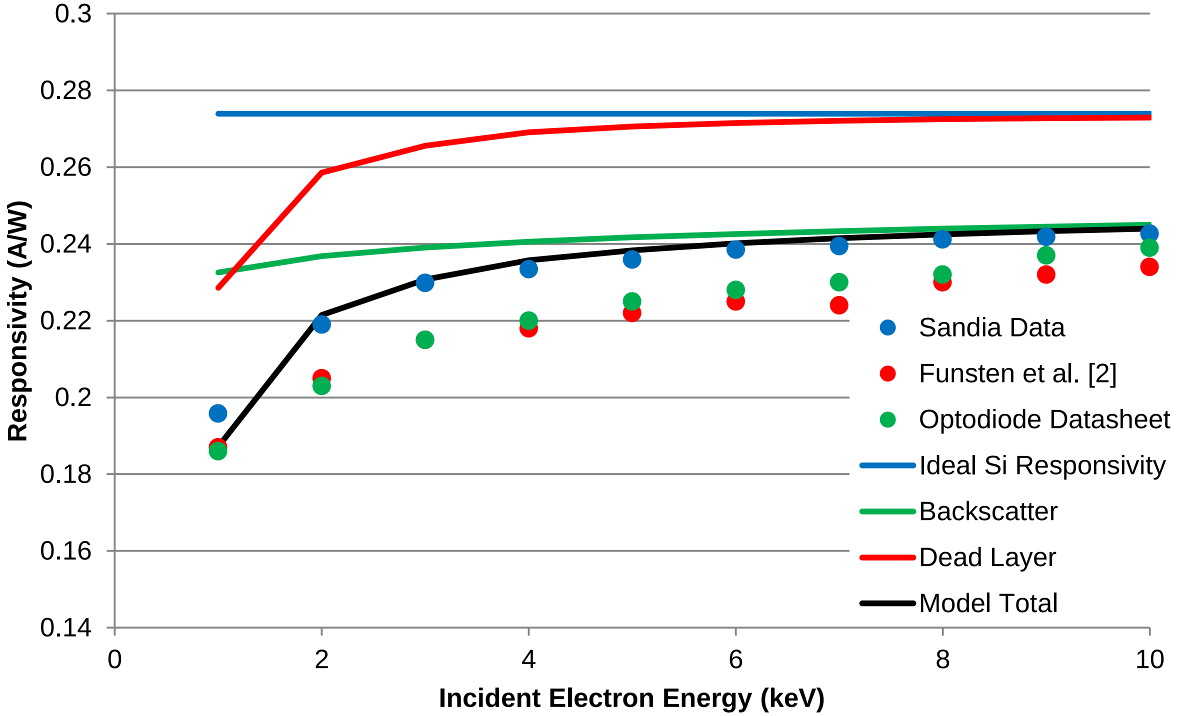
$$R = R_{ideal}[1 - \Delta_{dl} - \Delta_{bs} - \Delta_{res}]$$

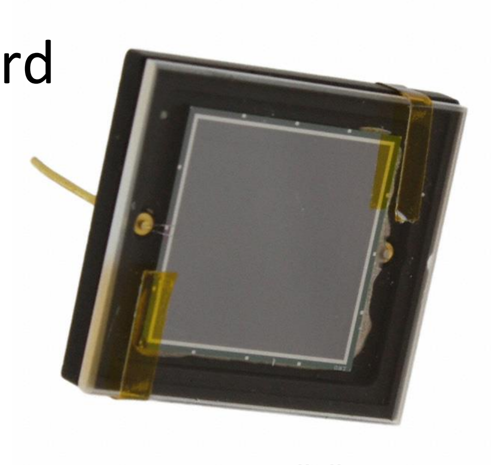
Δ_{dl}: dead layer absorption
Δ_{bs}: backscatter loss
Δ_{res}: residual loss

[1] R. Pehl et al., NIM Vol. 59, pp. 44-55 (1968)
[2] H. Funsten et al., IEEE TNS Vol. 44, No. 6, p. 2561 (1997)

Method was Benchmarked using Industry Standard

- OptoDiode's AXUV100G is a widely used standard
- Model predicts dead layer and backscatter loss





www.digikey.com

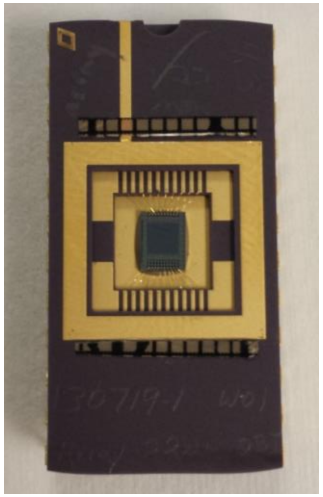
Backscatter based on average energy from [1], η values from [2]

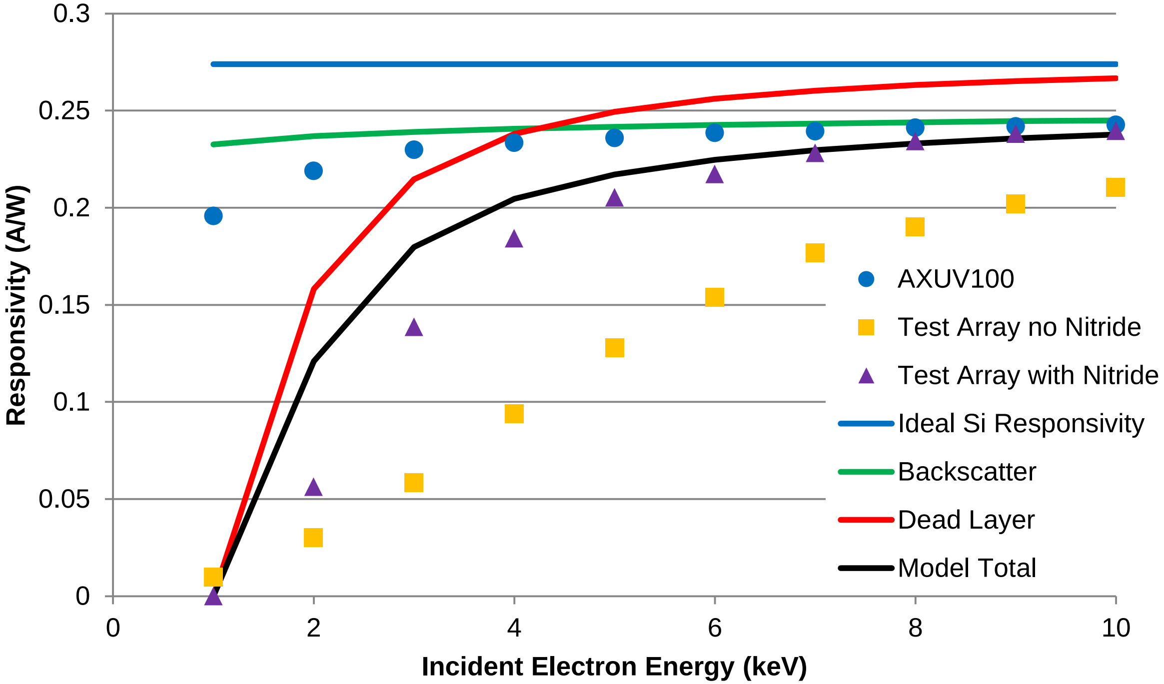
Dead Layer based on 8 nm SiO_2 with stopping power values from [3]

[1] H. Funsten et al., IEEE TNS Vol. 44, No. 6, p. 2561 (1997)
[2] H. Hunger & L. Kuchler, Phys. Stat. Sol. Vol. 56, pp. K45-K48 (1979)
[3] J. Ashley & V. Anderson, JES Vol. 24, pp. 127-148 (1981)

Current Generation Diode Array Sensitivity Tested

- Surface passivation adds more dead layer absorption, but apparently reduces surface recombination





Dead Layer based on Si_3N_4 stopping power from [1] and SiO_2 stopping power values from [2]

[1] NIST Estar, http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html
[2] J. Ashley & V. Anderson, JES Vol. 24, pp. 127-148 (1981)

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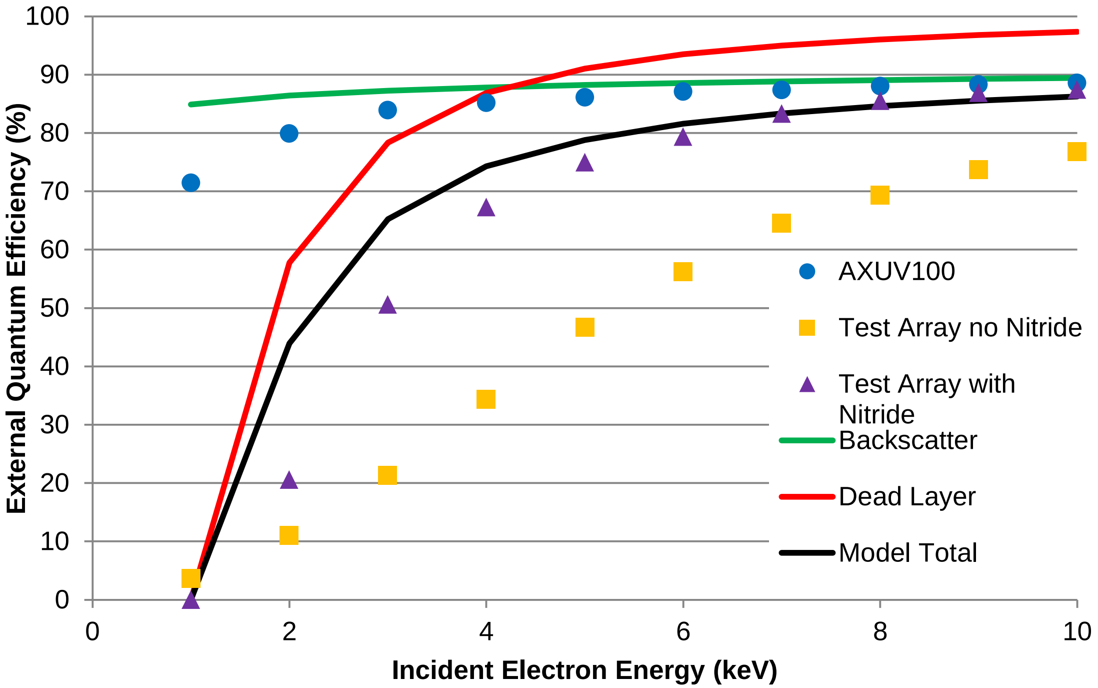

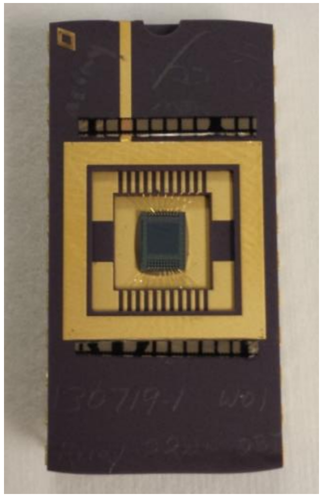

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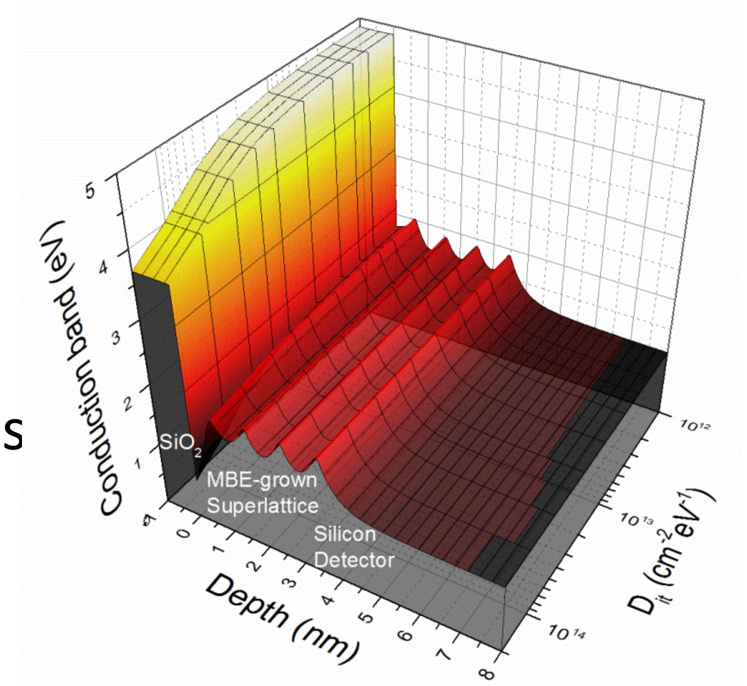
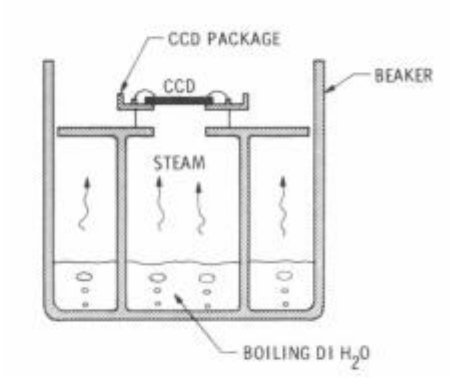
Path Forward

- hCMOS cameras will incorporate nitride passivation layer
- New discrete diodes will provide test bed for alternative technologies
  - JPL Delta Dope, successfully demonstrated to increase CCD UV sensitivity [1]
  - Univ. of Arizona flash oxide, also demonstrated for UV rays on CCDs [2]
- hCMOS diode arrays will incorporate new findings





[1] Hoenk et al., APL Vol. 61, pp. 1084-1086 (1992)
[2] Janesick et al., Opt. Eng. Vol. 26, pp. 852-863 (1987)