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Three-Dimensional Simulation of Signal Generation in Wide-Bandgap Semiconductor Radiation Detectors

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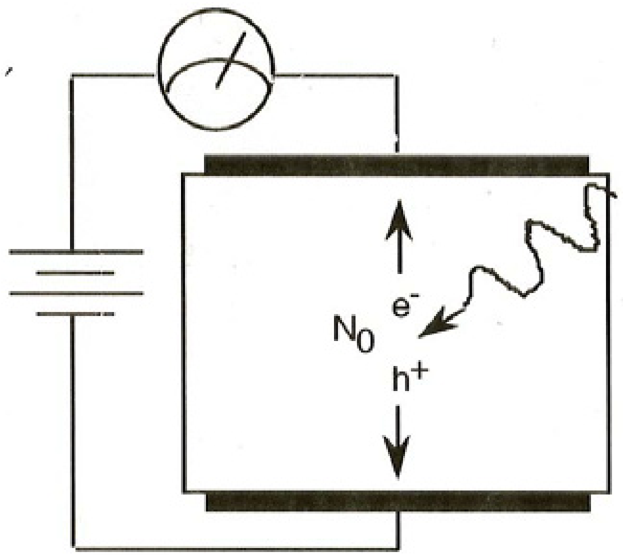
Outline

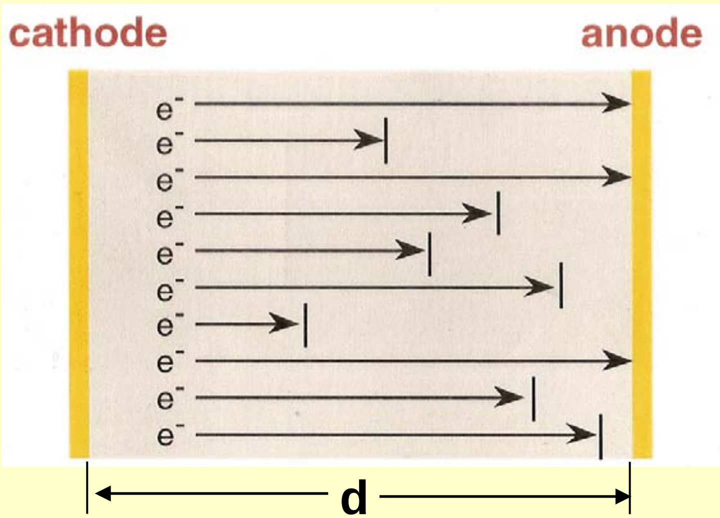
- Operation of a semiconductor radiation detector
- Hole tailing and the need for special electrode configurations
- Comsol-Matlab model
- Planar vs. Quasi-hemispherical detectors

Semiconductor Radiation Detector Geometry



- A bias voltage is applied to the detector.
- Interaction creates N_0 electron-hole pairs, proportional to the energy deposited by the photon.
- The charge carriers move to the electrodes, inducing a current.
- The integrated current should be qN_0.

Signal Generation in a Semiconductor Detector



$$N(t)=N_0 e^{-t/\tau_e}$$ ← trapping

$$I_e(t) = e\mu_0 E N(t)/d$$ ← Application of Ramo's theorem

$$Q_e = \int_0^{t_{ce}} I_e(t)\, dt$$

Putting these 3 equations together and adding the hole contribution gives the Hecht relation:

$$Q = \frac{qN_0E}{d}\left[(\mu\tau)_e\left(1 - e^{-(d-x_0)/(\mu\tau)_e E}\right) + (\mu\tau)_h\left(1 - e^{-x_0/(\mu\tau)_h E}\right)\right]$$

“Hole Tailing” in Wide-Bandgap Semiconductors

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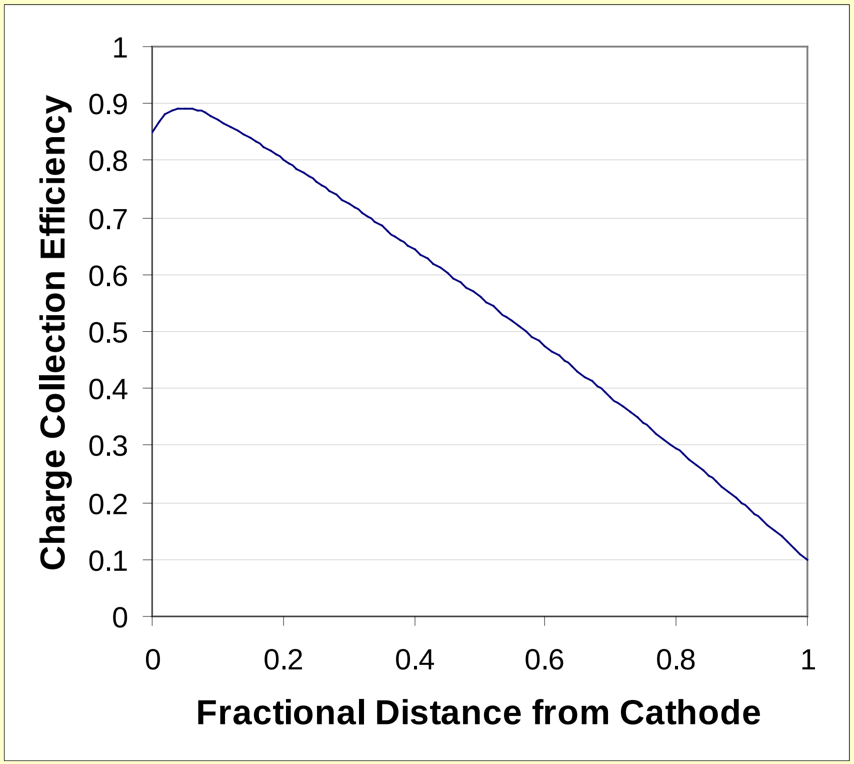
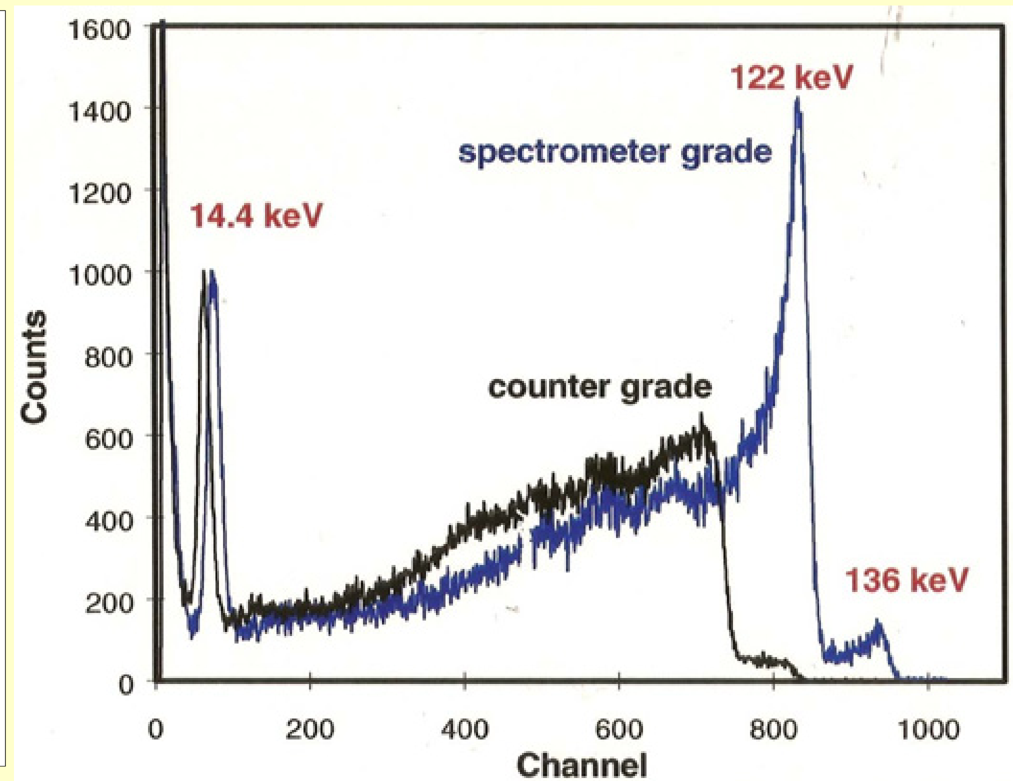
Typical charge collection profile from Hecht relation



^{57}Co spectra for two CdZnTe detectors $10x10x3\ mm^3$



Electrode Designs to Correct for Hole Tailing

Various ways to weight signal induction towards the anode:

- Coplanar Grid
  - Subtract signals from two interdigitated electrodes
  - Need two preamplifiers plus differencing amp
- Segmented
  - "Small-pixel effect"
  - Need a separate amplifier for each pixel or strip
- Guard Ring Structures
  - "Frisch grid" to shield the anode
- Coaxial
  - Machine crystal into cylindrical shape and drill a hole through the center
- Quasi-hemispherical

Signal Generation for Arbitrary Electrode Configurations

General Form of Ramo's Theorem

$i\,(t) = q\,\mathbf{v}.\mathbf{E_1}$ ($\mathbf{E_1}$=“weighting field”)

Constant Mobility Approximation

$\mathbf{v} = \mu_{e(h)}\mathbf{E}$

Constant Trapping Lifetime, No De-trapping

$q(t) = q_0\, e^{-t/t_{e(h)}}$

Put it all together

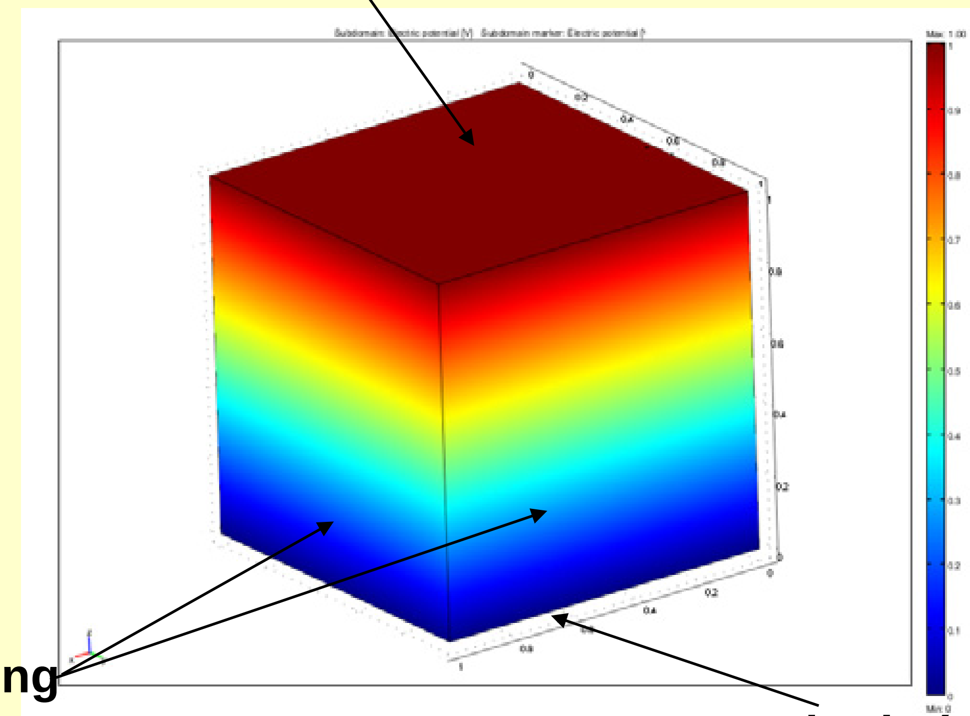
$$\frac{Q_{e(h)}}{eN_0} = \int_0^{t_{c,e(h)}} \mu_{e(h)} e^{-t/\tau_{e(h)}} \vec{E} \cdot \vec{E}_1 dt$$

Comsol Radiation Detector Model

- Electrostatics with Conductive Media application mode to compute electric fields
- Export FEM structure to Matlab
- Integrate induced current in Matlab to compute charge collection efficiency as a function of interaction point
- Repeat for numerous interaction points to get a charge collection profile

FEM Model for Planar Detector

Anode (applied bias)



Insulating surfaces

Cathode (grounded)

For the case of two electrodes, one grounded, the physical and weighting fields are the same except for a factor of the bias voltage.

Integration of Electron/Hole Currents

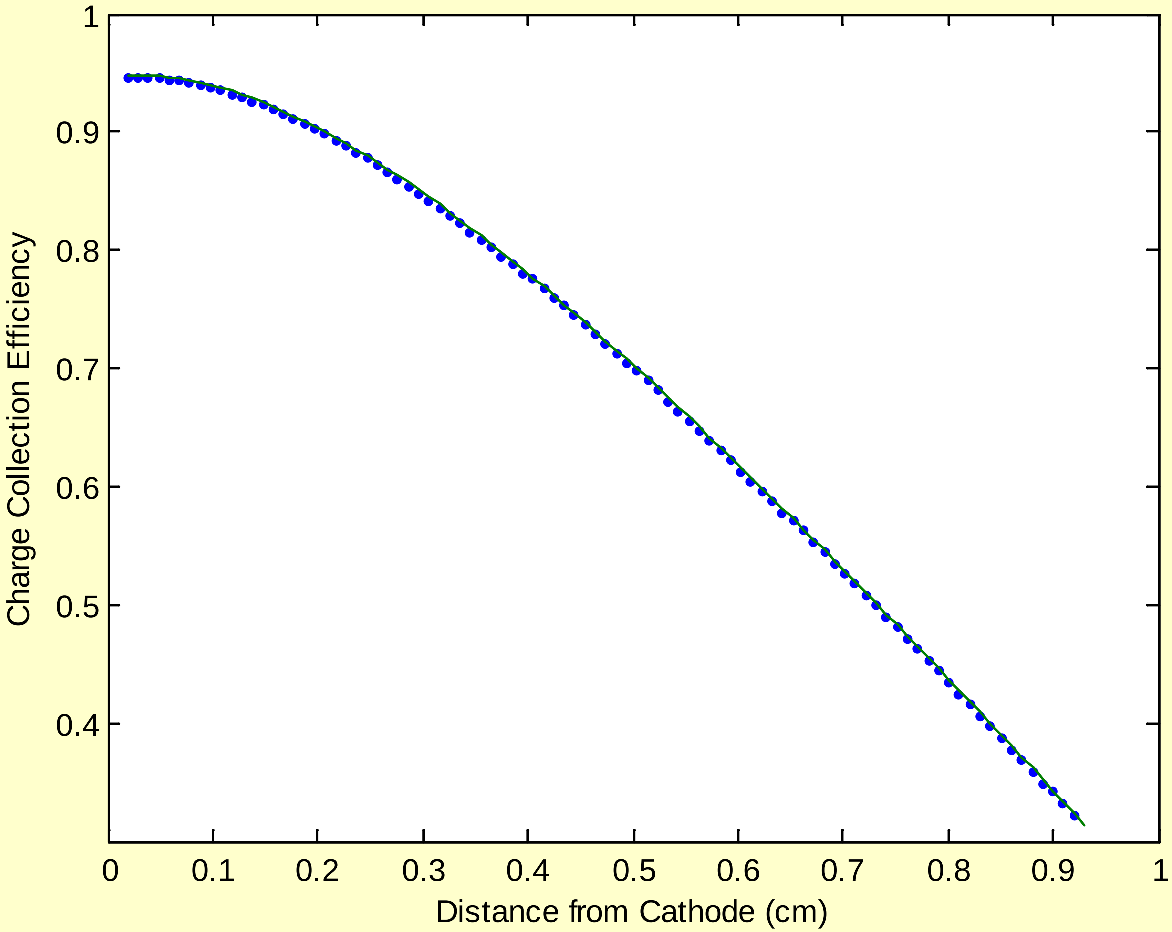
- Discretize the integral
- Take constant-distance jumps for better efficiency
- Repeat until a boundary is reached
- Compute electron and hole contributions separately and add

$$\frac{Q_{e(h)}}{eN_0} = \sum \mu_{e(h)} e^{-t_i/\tau_{e(h)}} \vec{E}(\vec{r}_i) \cdot \vec{E}_1(\vec{r}_i) \Delta t_i$$

$$\Delta t_i = \frac{\Delta r}{\mu_{e(h)} \left| \vec{E}(\vec{r}_i) \right|}$$

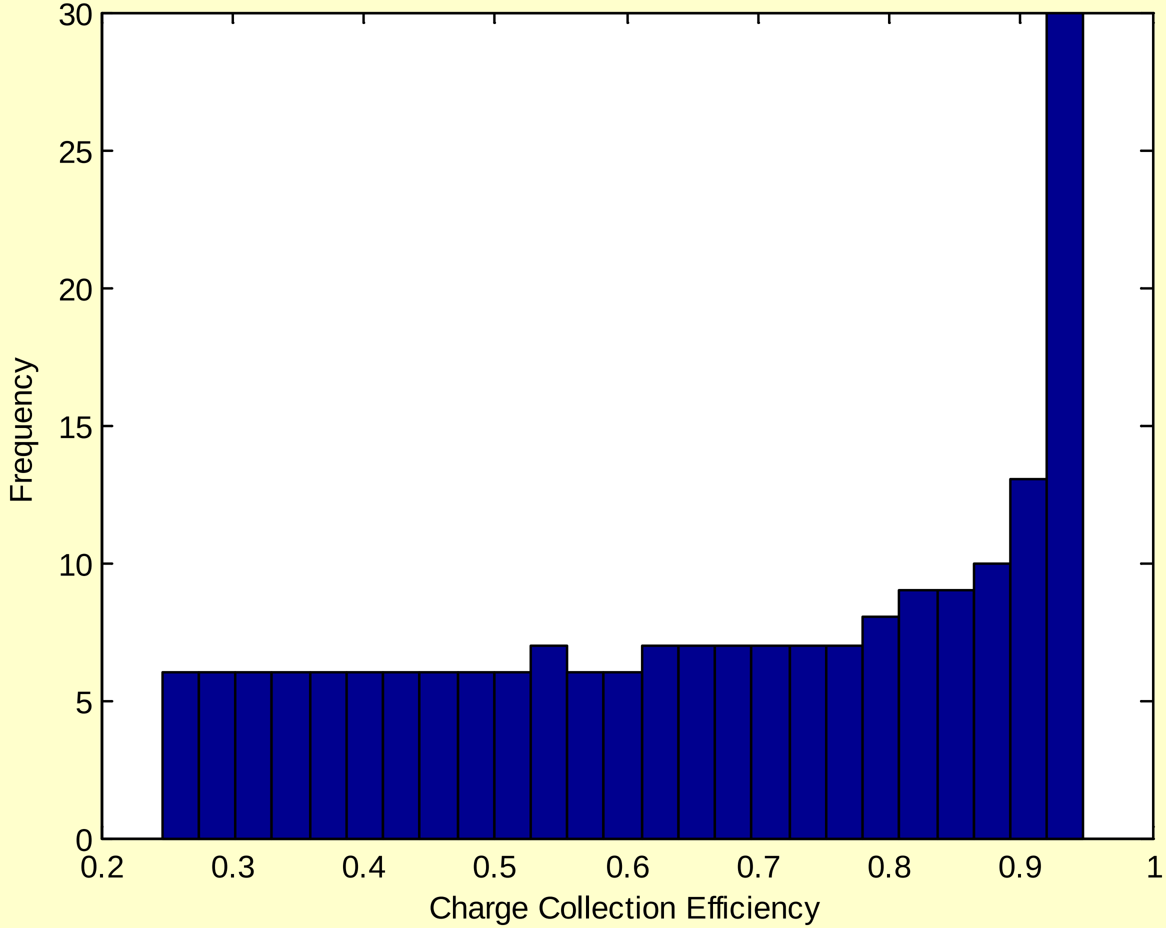
$$\Delta \vec{r}_i = \mu_{e(h)} \vec{E}(\vec{r}_i) \Delta t_i$$

Charge Collection Profile for Planar Detector



- Comsol-Matlab model
- Hecht equation

Charge Collection Histogram for Planar Case

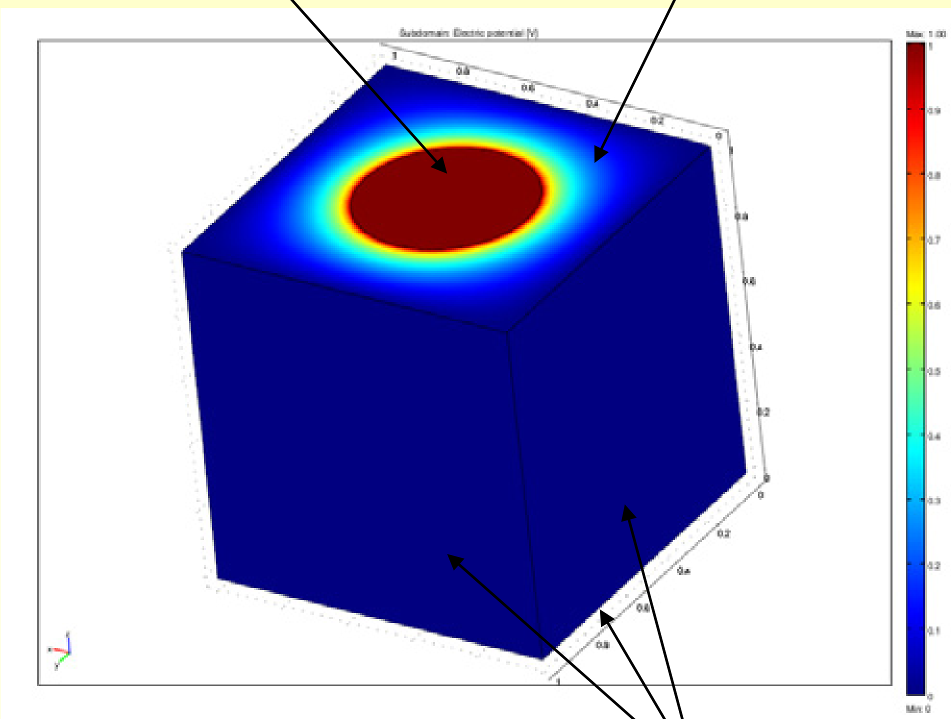


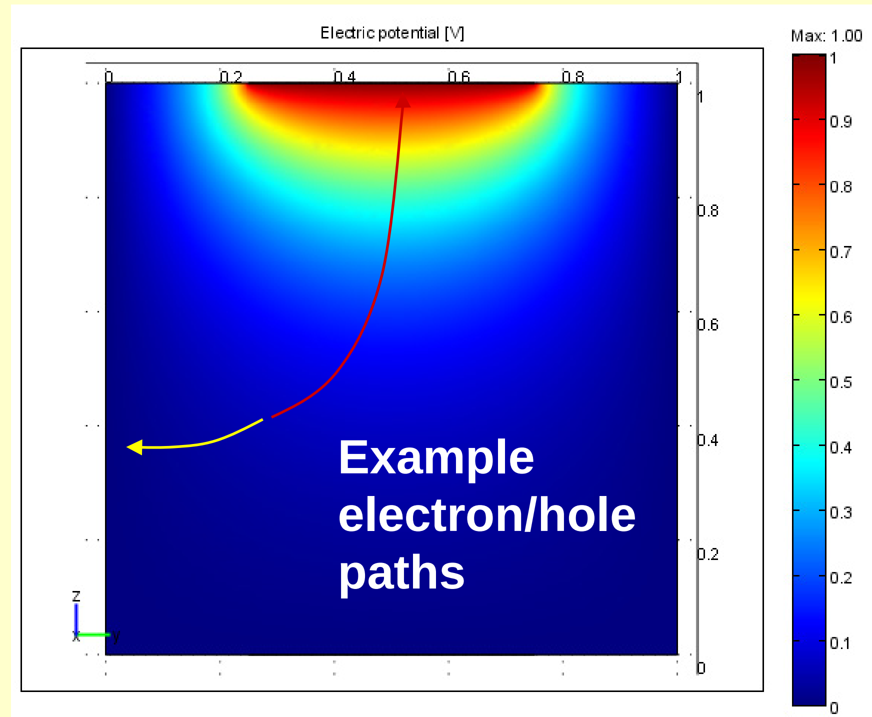
FEM Model for Quasi-Hemispherical Detector

Anode (applied bias)

Insulating surface

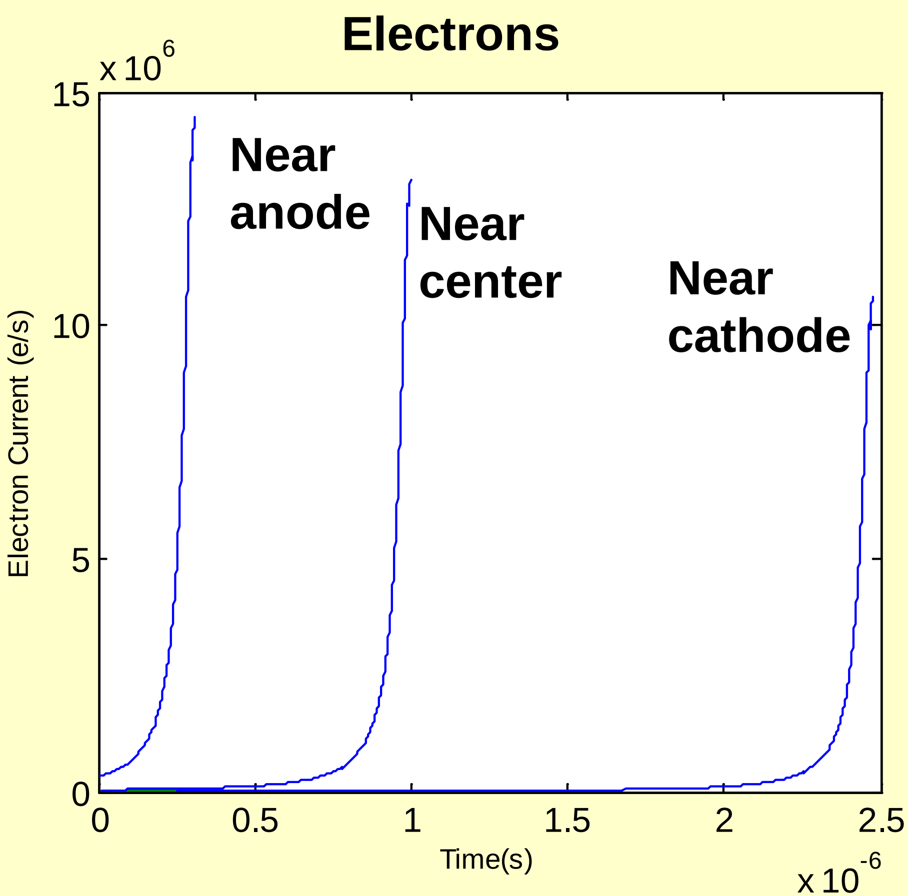
X-Z Section of Equipotential Map

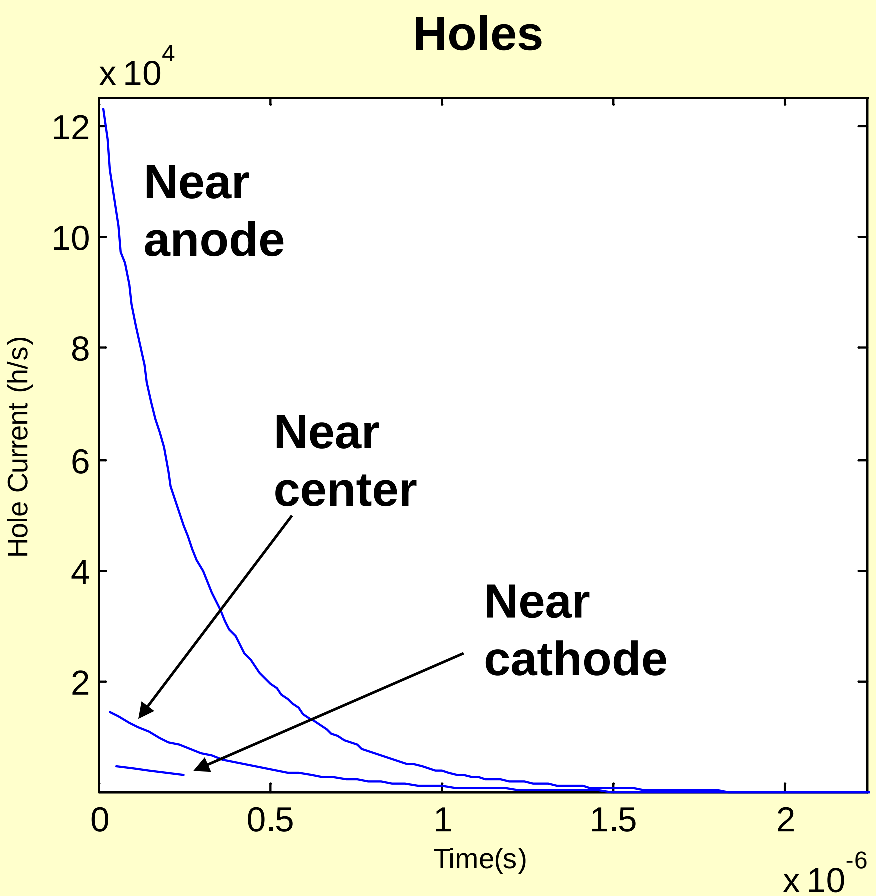




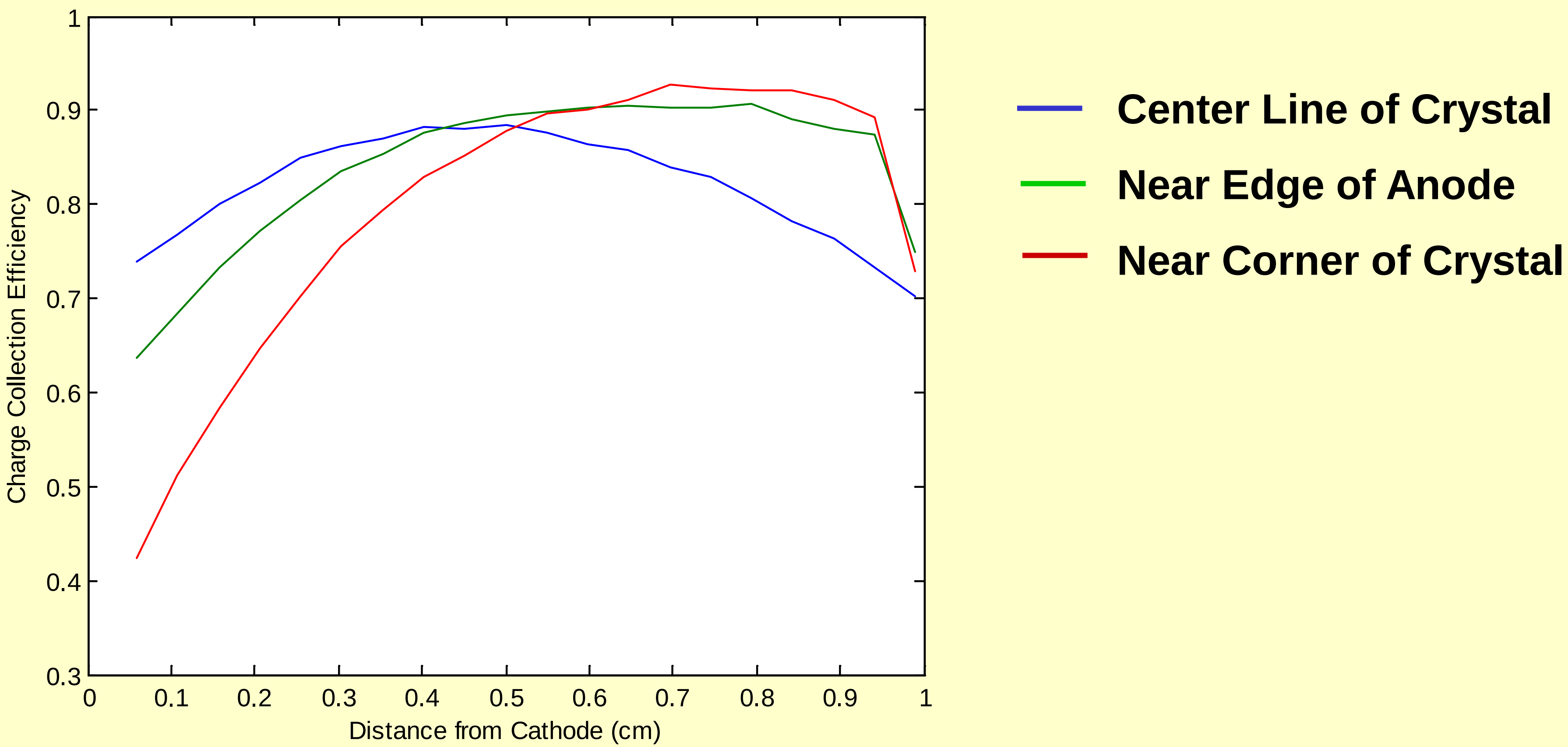
Cathode (grounded)

Electron and Hole Current Waveforms

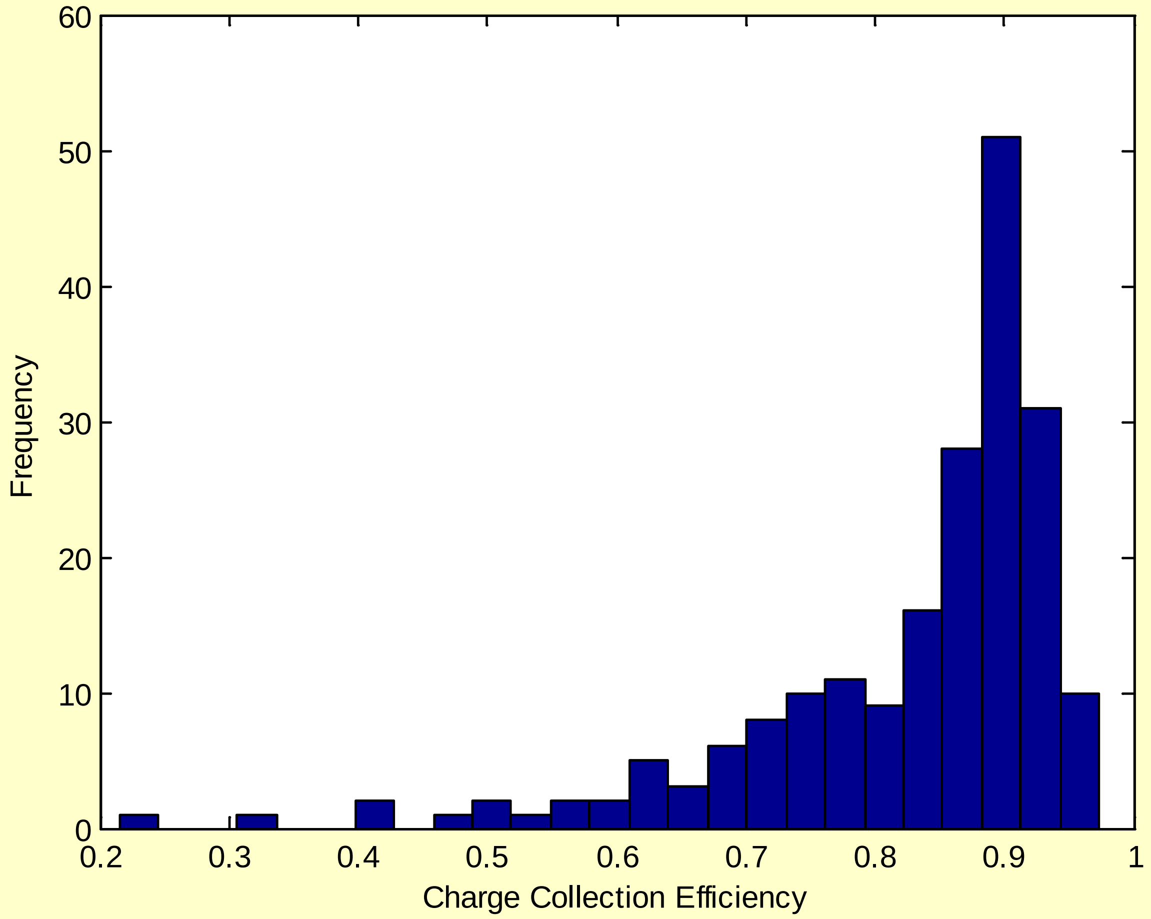




Charge Collection Profiles Quasi-Hemispherical Case



Charge Collection Histogram Quasi-Hemispherical



Conclusions

- Comsol Multiphysics with Matlab can easily compute signal generation in semiconductor detectors with arbitrary electrode configurations.
- Quasi-hemispherical detector can improve energy resolution and photopeak efficiency in compound semiconductor detectors without grid bias or multiple readout amplifiers.

Thank You!

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