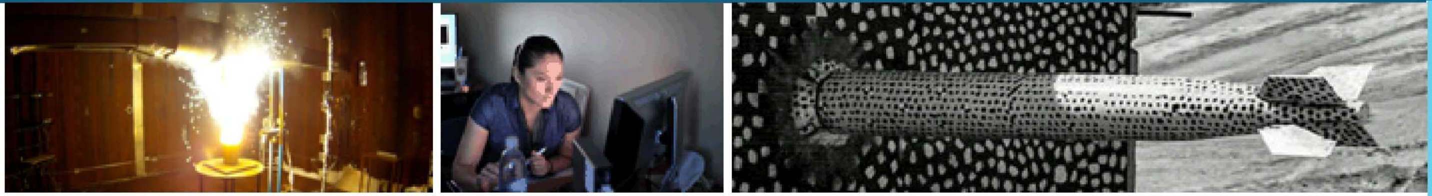
SAND2019-0260PE

Outlook for Si Detectors



PRESENTED BY

Quinn Looker

hCMOS Workshop

Sandia NM 1/17/19

SAND

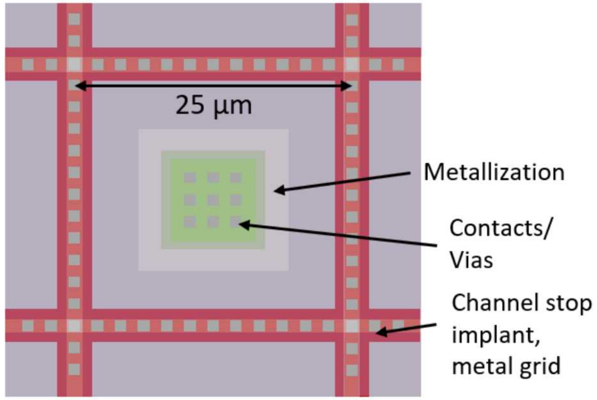
Base Diode Design Complexity Reduction

Diode Array Fabrication Changes

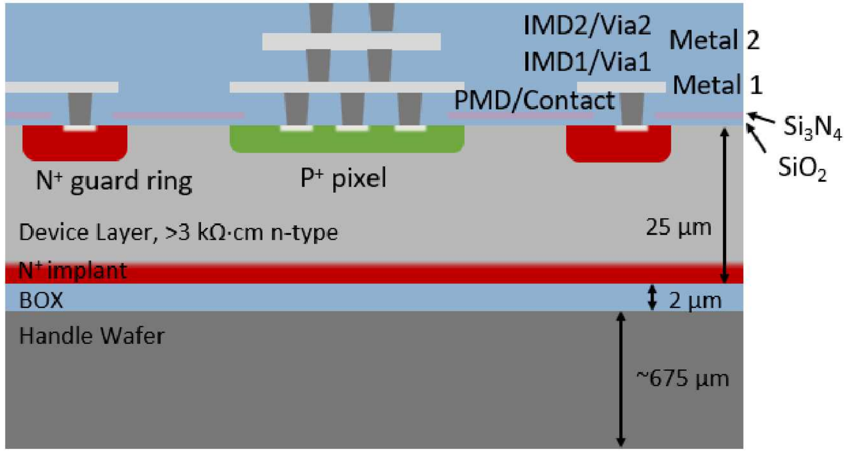
Detector Wafer, Single-pixel

Today's Pixel Design

Pixel Plan View

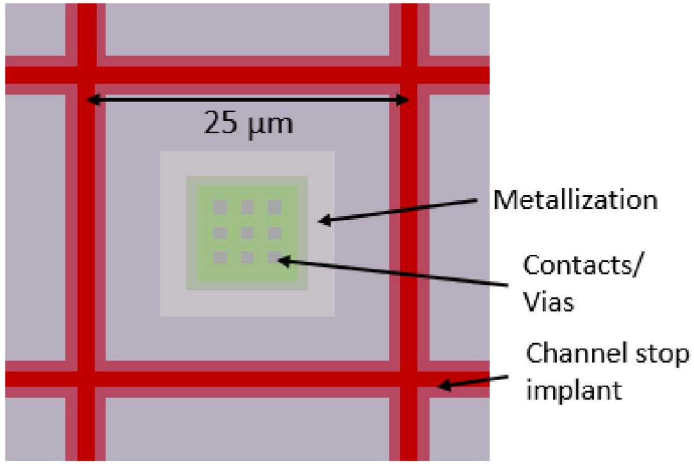


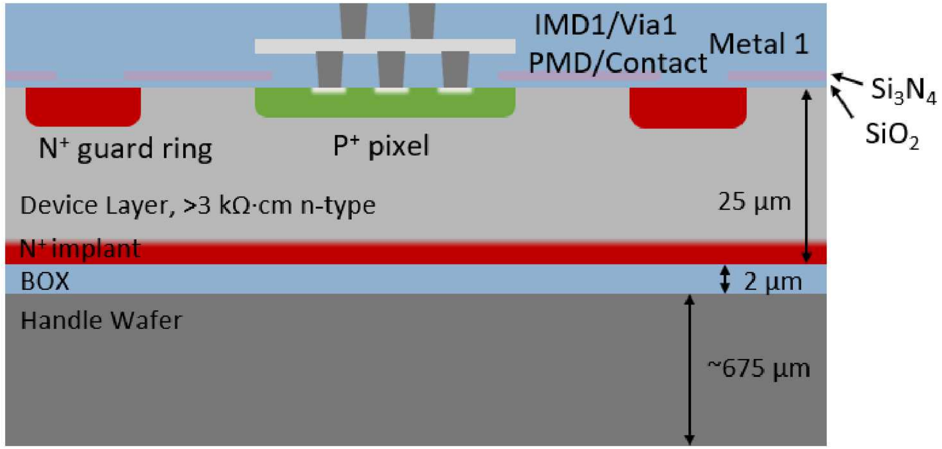
Cross Section View



Simplified Pixel Design

Pixel Plan View





Simpler Pixel Design

- -Eliminate contacts and metal grid to channel stop
  - -Lose ability to ROIC-side bias
  - -Reduces mask complexity, potential short paths
- -Eliminate M2/V2 stack
  - -Fewer routing options available (not needed if ch stop metal not present)
  - -Eliminates 45 steps, 2 mask layers

Base plan: 233 steps

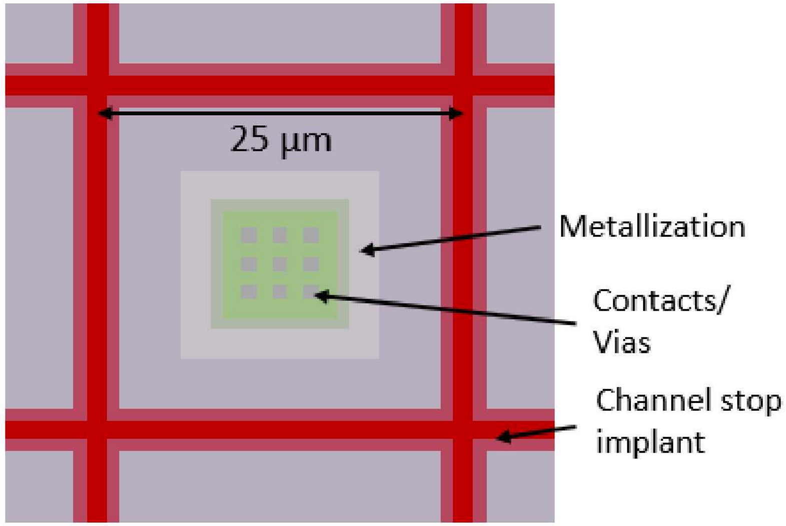
Modified plan: 188 steps
20% cost reduction?

External Fab Option

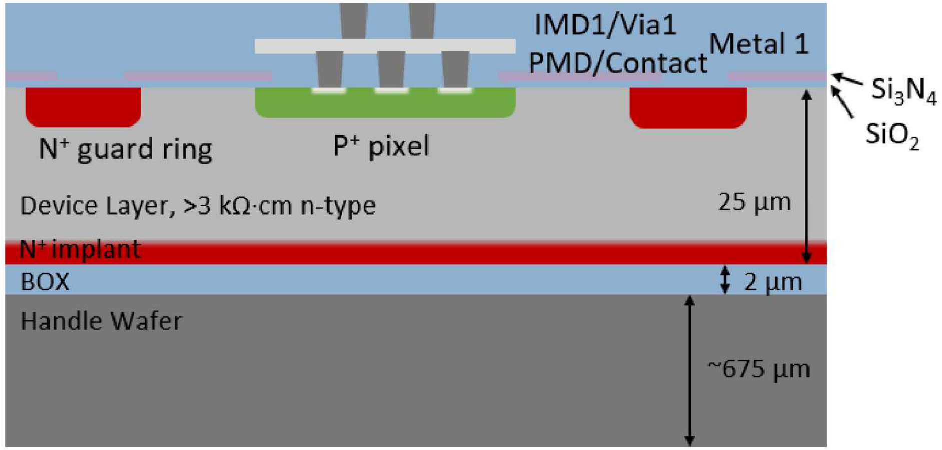
-Processing capability requirements: cleans, implant, thermal oxide, CVD nitride, silicide, dry etch, via fill, CMP, metal dep

Single-pixel

Pixel Plan View



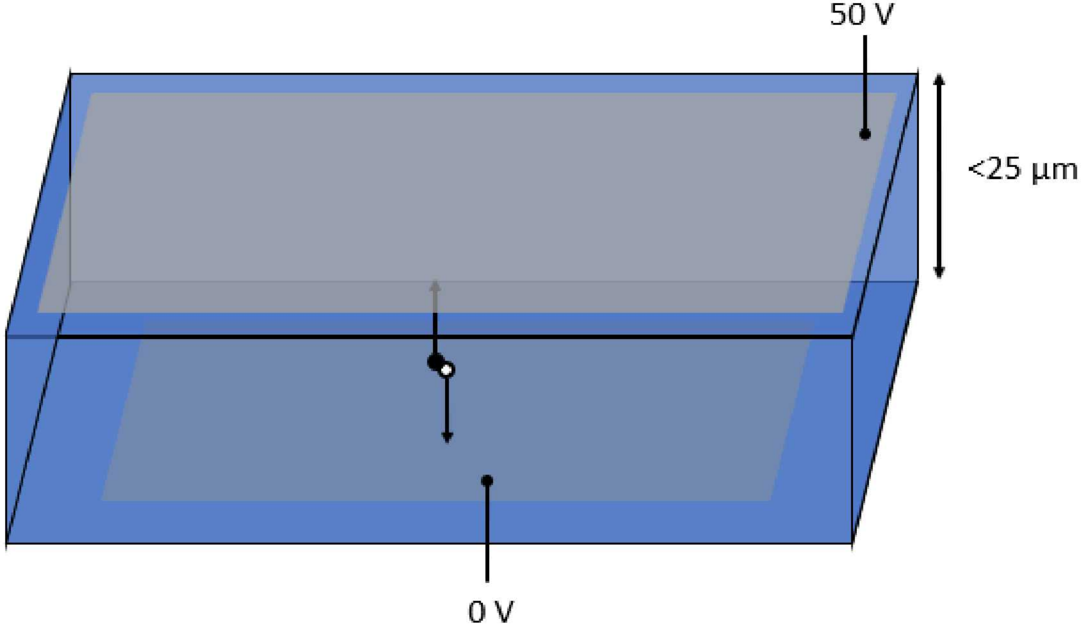
Cross Section View

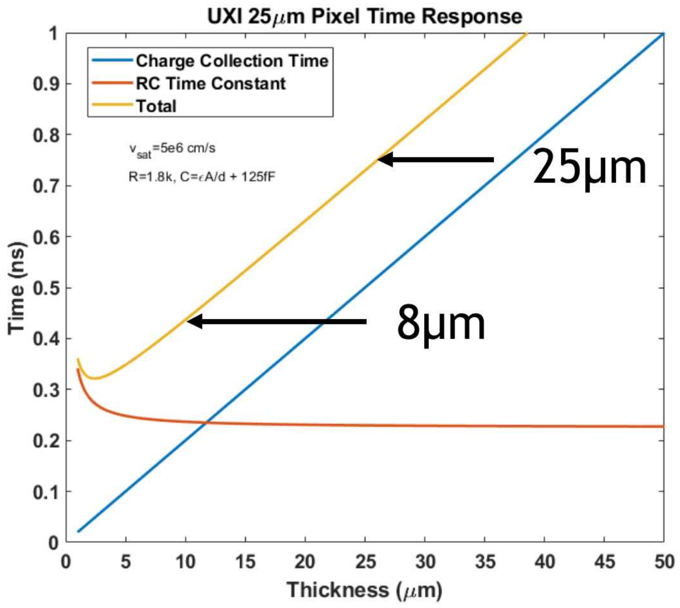


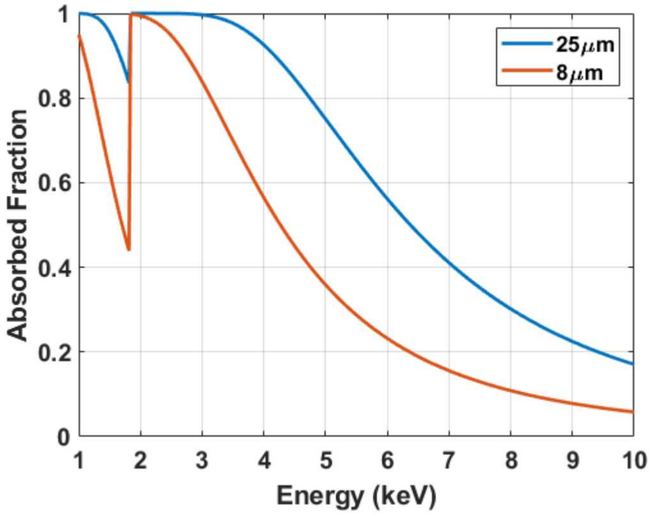
Potential Paths for Speed Improvements

Thinner Absorber Layer

8µm thick diodes ~2x faster than standard 25µm







Key Features

-Proportional decrease in charge collection time with decreasing detector thickness

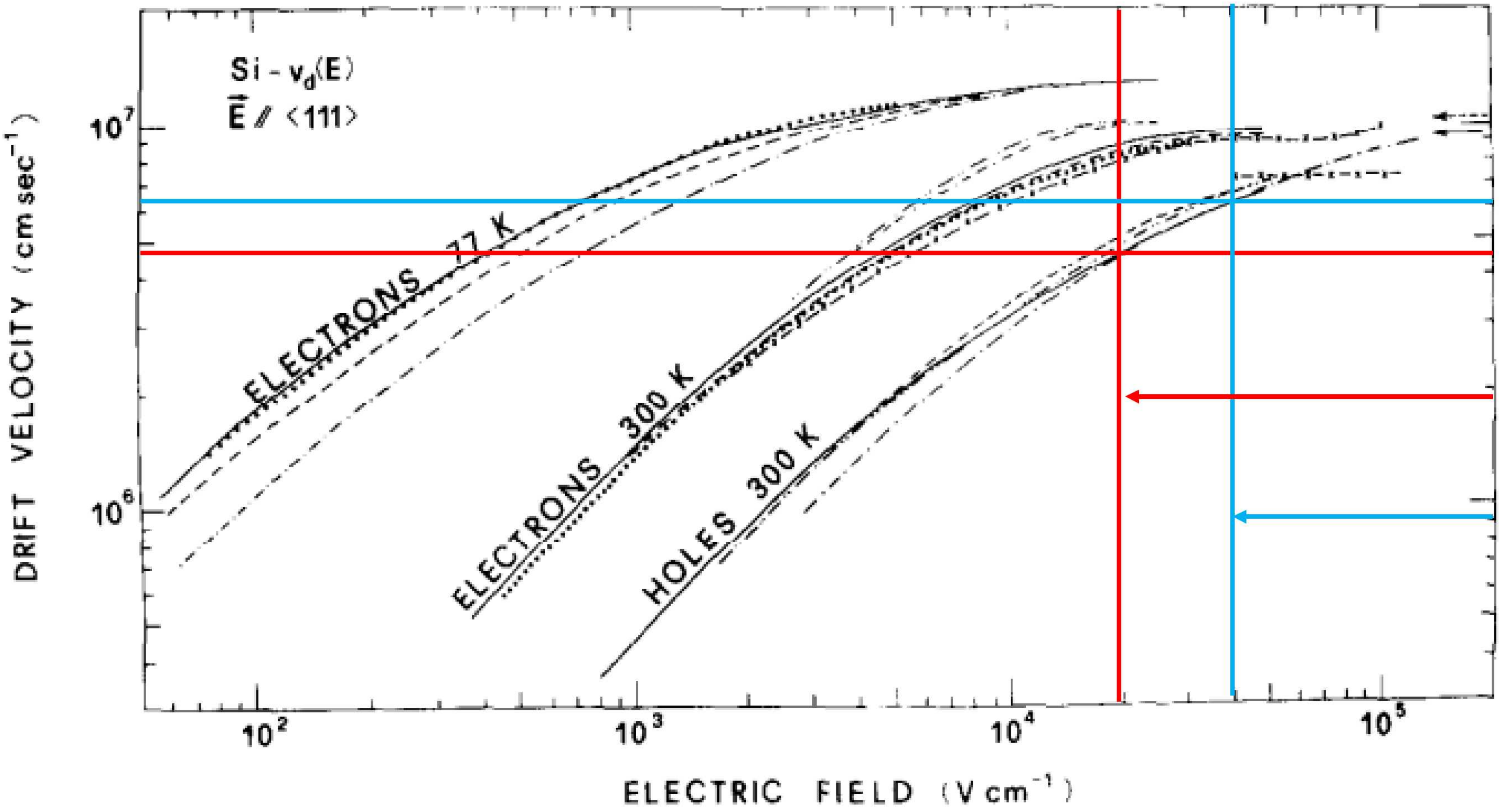
-Lower QE for all radiation types; may need thickness 10 µm or less

-Limit ~2 µm, where capacitance begins to take over

Feasibility: already done

Increasing Electric Field

Jacoboni et al., Solid-State Electronics Vol. 20, pp. 77-89 (1977)



We are probably here
~5e6 cm/s

Maybe double E field?
~6e6 cm/s

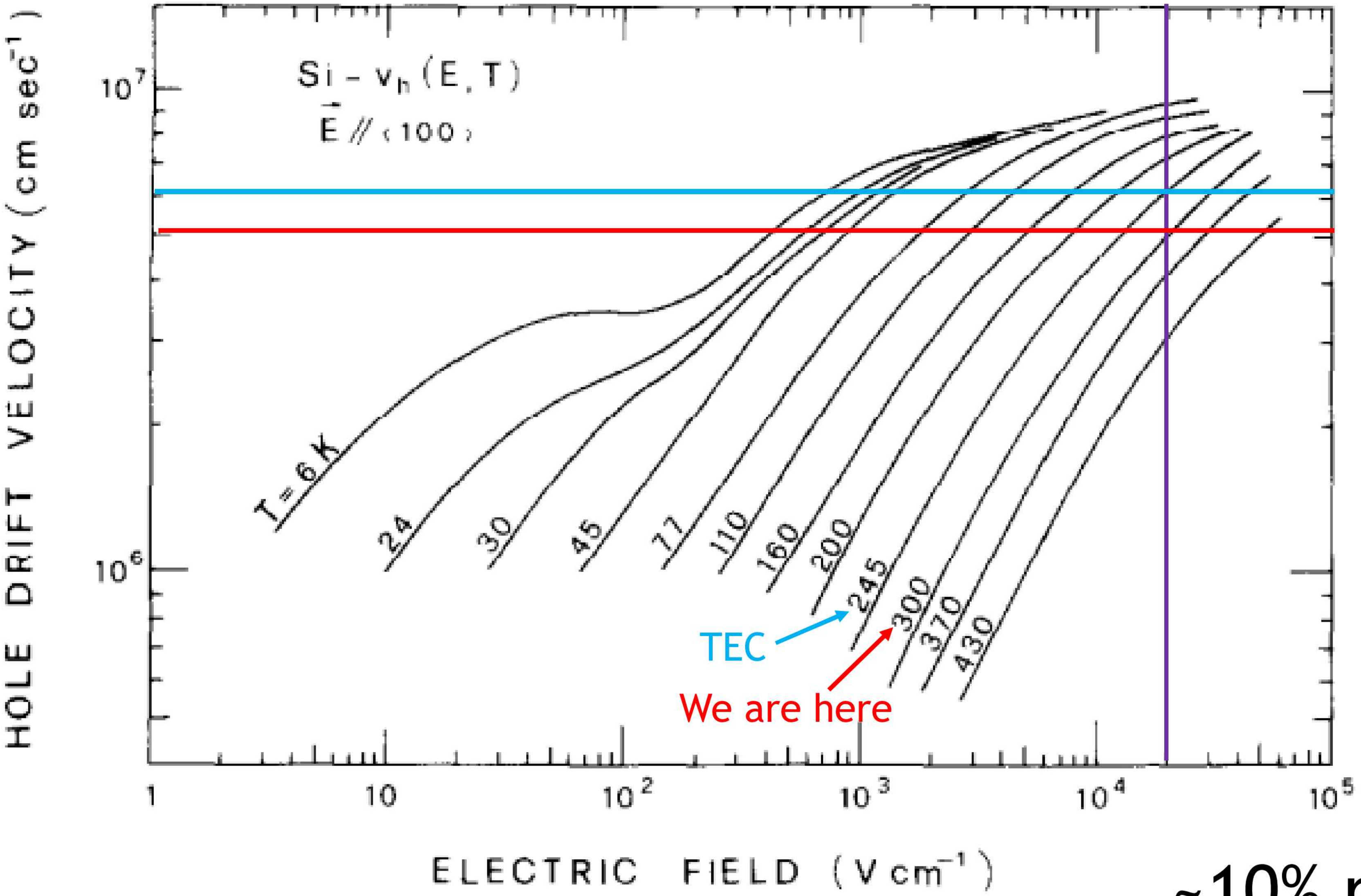
Key Features
-Likely minor design changes will allow the option of higher bias
-May reduce yield
-During operation, no inherent disadvantage

10-20% reduction

Feasibility: new diode lot

Cooling

Jacoboni et al., Solid-State Electronics Vol. 20, pp. 77-89 (1977)



TEC

We are here

~6e6 cm/s

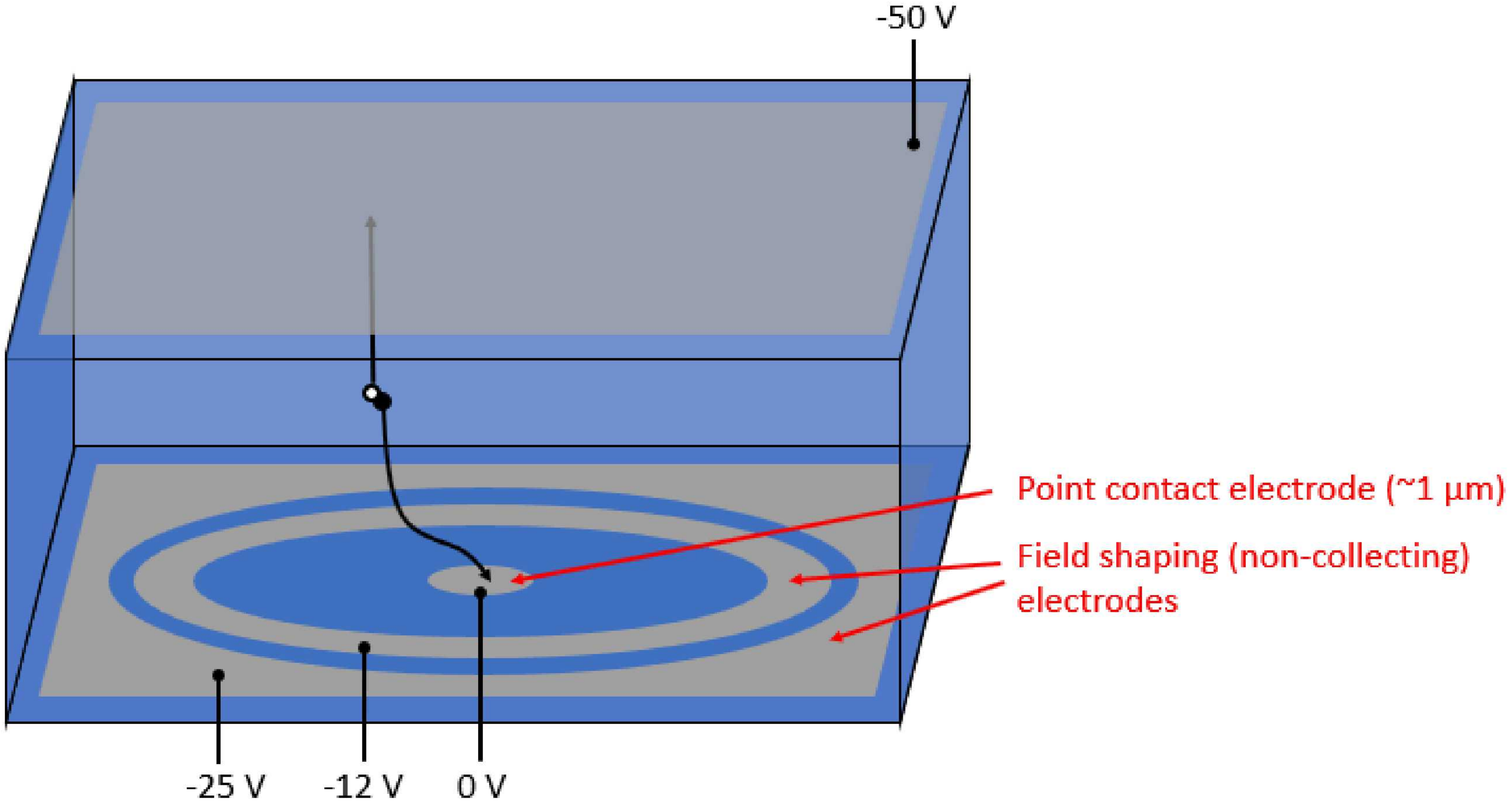
~5e6 cm/s

Key Features
-Complementary to other efforts
-Use is optional; no risk to baseline use case
-More complex camera operation

~10% reduction

Feasibility: working on it now
Hippo only

Other Electrode Configurations: Point Contact



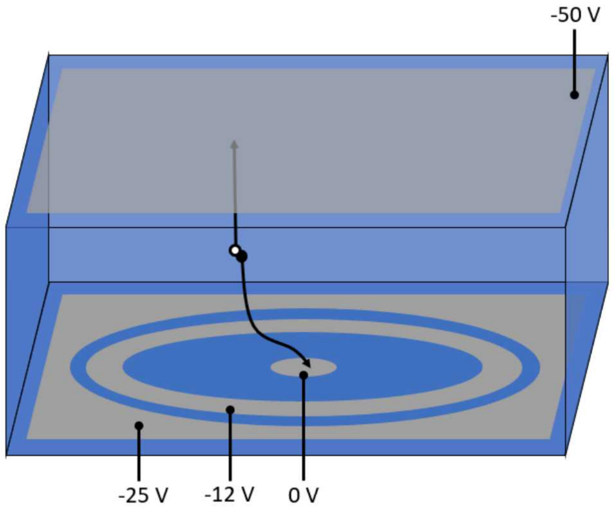
Key Features
-Small collecting electrode senses moving charge only in small volume nearby
-Field shaping electrodes needed to funnel charge to collecting electrode
-Secondary benefit of lower junction capacitance

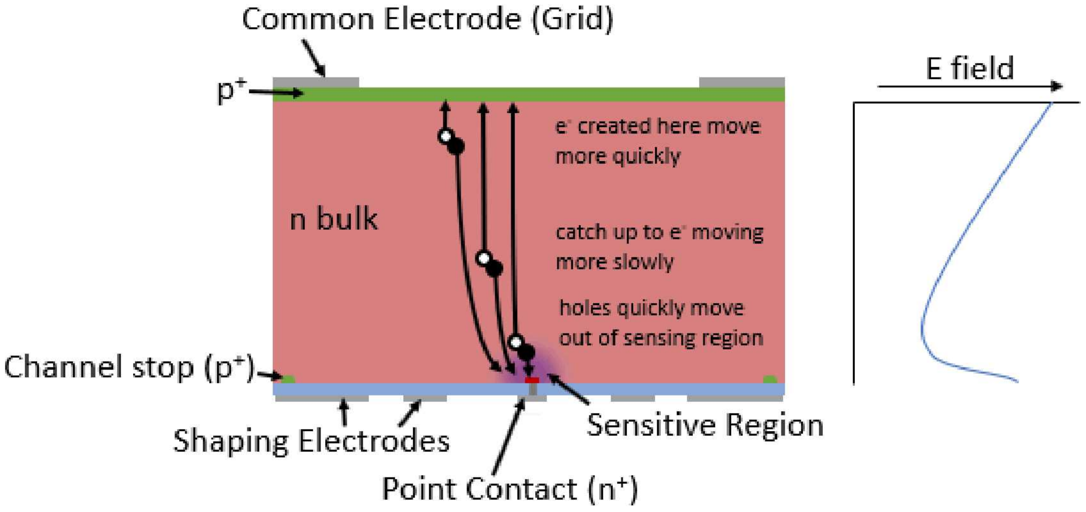
~40% reduction?

Feasibility: we can make it, but high risk

Other Electrode Configurations: Point Contact Part 2

This on its own may not offer much improvement. To fully take advantage of this electrode structure, we would need to move the junction to the illuminated side and collect electrons.



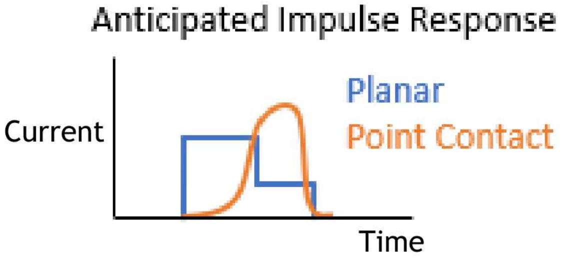


Key Features

-Small collecting electrode senses moving charge only in small volume nearby

-Field shaping electrodes needed to funnel charge to collecting electrode

-Secondary benefit of lower capacitance

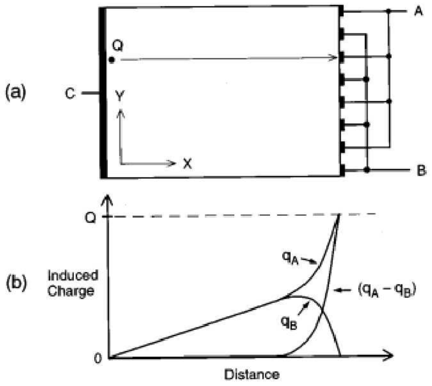


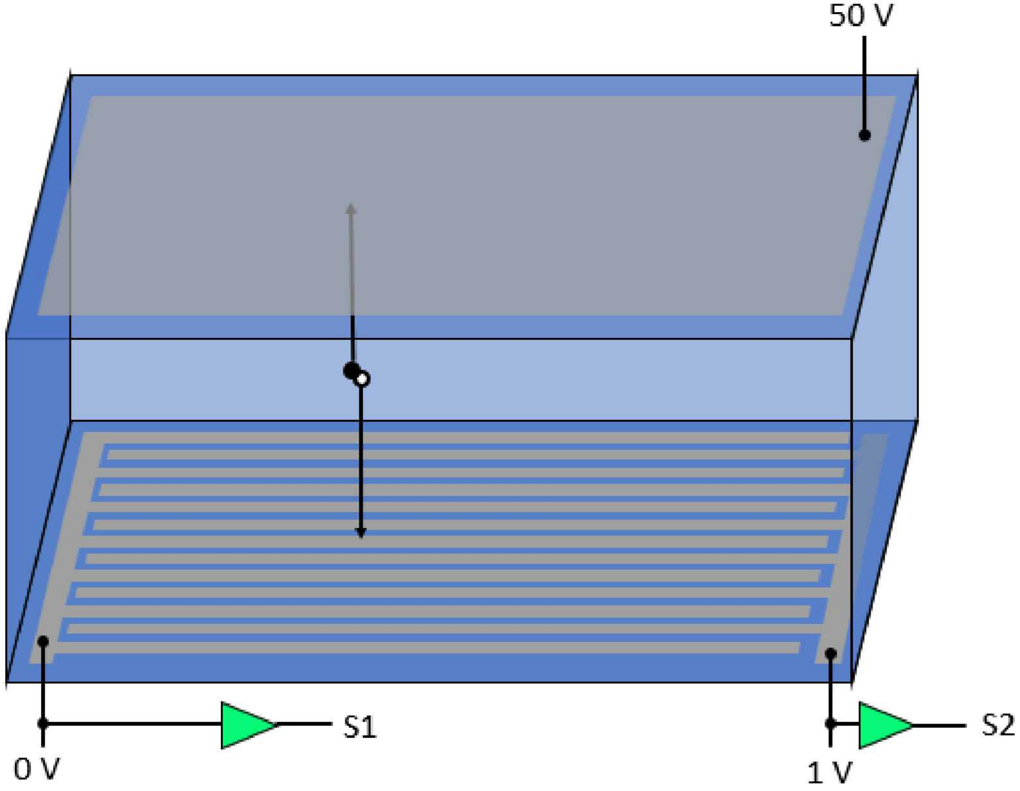
~40% reduction?

Feasibility: we can make it, but high risk

Other Electrode Configurations: Coplanar Grid

P. Luke, APL 65, p.2884 (1994)





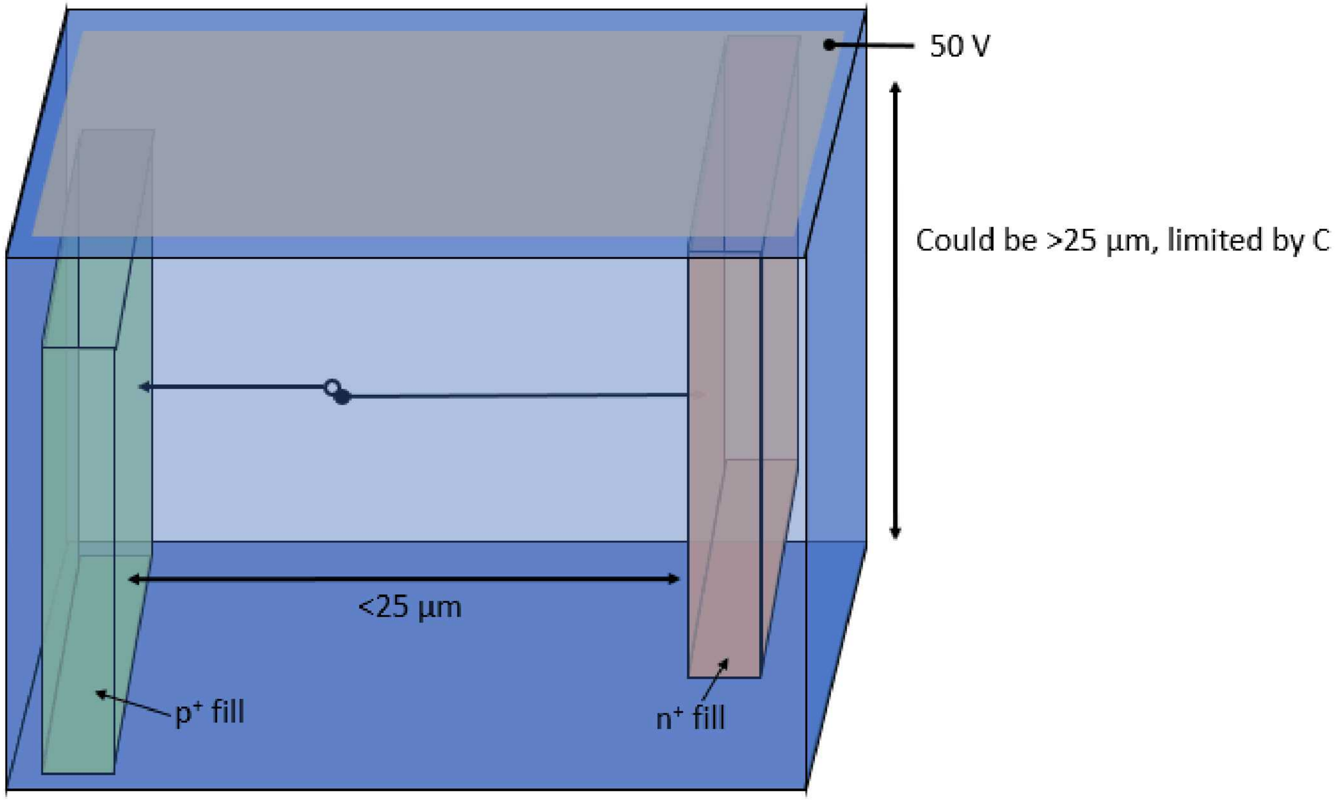
Key Features
-Requires more in-pixel structure
-Can operate as typical pixel when PV=S1+S2
-Can increase dynamic range when PV=S1 . S2 shunted to VRST.
-Can reduce sensitive volume when PV=S1-S2 , similar to point contact
-Unlike point contact, capacitance is higher

~40% reduction?

Feasibility: we can make it, but high risk

Other Electrode Configurations: 3D Diode (Trench)

Doped polyfill column structures described in Parker 1997, Kenney 1999, Kok 2006, etc.



Key Features

-Can select width based on desired timing; may be connected to pixel size

-Thickness can be increased to keep high QE

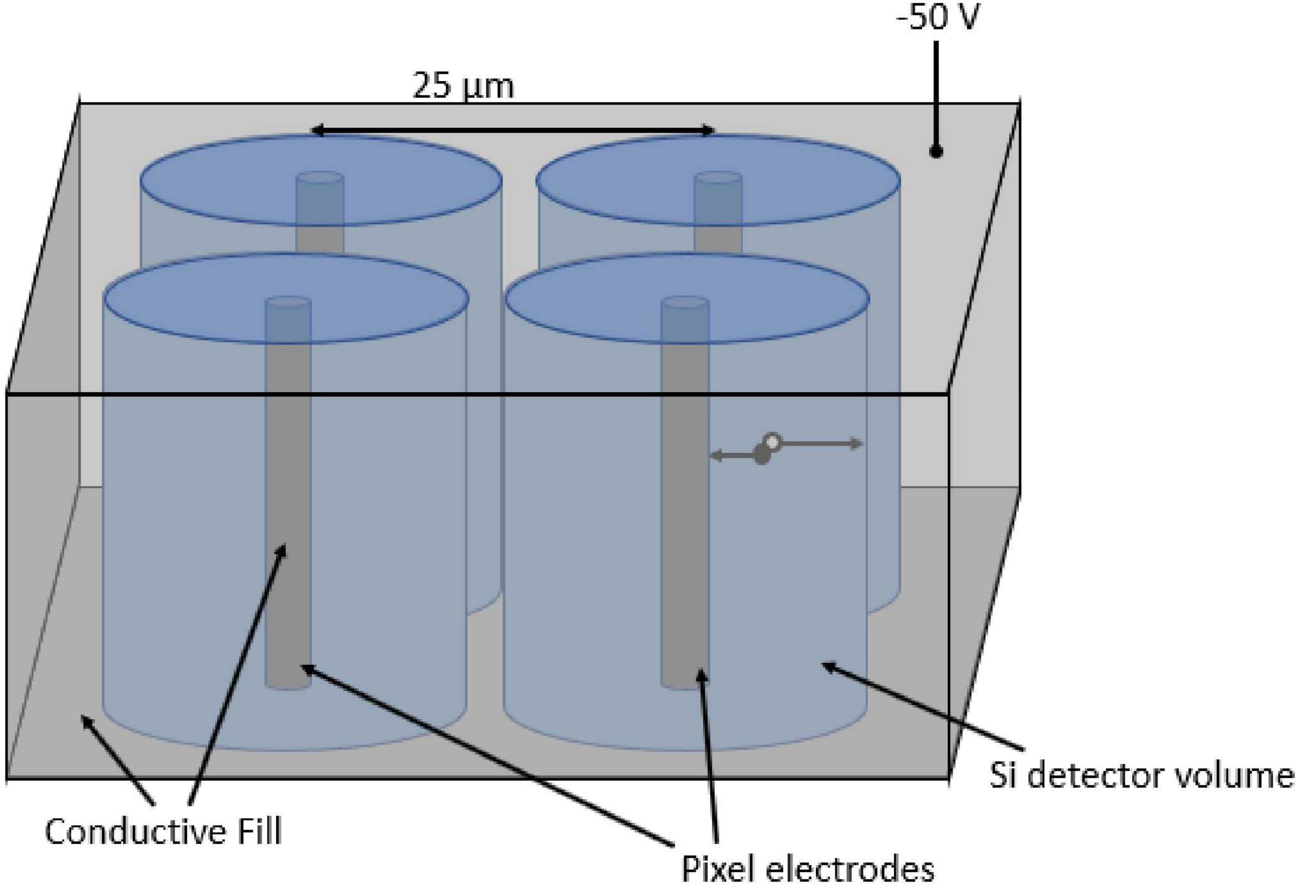
-Need to develop dry etch and conductive fill process for thick device layers

-2nd electrode would need to be created after hybridization (need low T process)

~50% reduction?

Feasibility: significant process development

Other Electrode Configurations: 3D Diode (Cylinder)



~60% reduction?

Feasibility: significant process development

Key Features
-Need mature dry etch and conductive fill process
-Better takes advantage of geometry to reduce hole contribution to signal

Potential Speed Improvements Summary

Method	Potential Reduction	Feasibility
Thinner Absorber Layer	50%	Done
Higher Electric Field	10-20%	New Diode Lot
Cooling	10%	No major technical hurdles
Point Contact Electrode	40%?	Easy to fab, need to understand behavior
Coplanar Grid Electrode	40%?	Can fabricate, need ASIC changes
Trench 3D Diode	50%?	Some process development work done; more needed
Cylindrical 3D Diode	60%?	Major process development work needed

Undesirable QE reduction

Universal – stacks with other methods

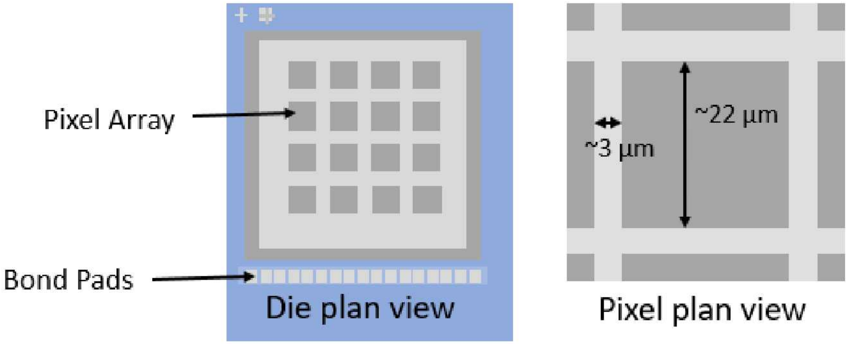
Some uncertainty as to how these will behave

Requires process development ($$$)

Extra Slides

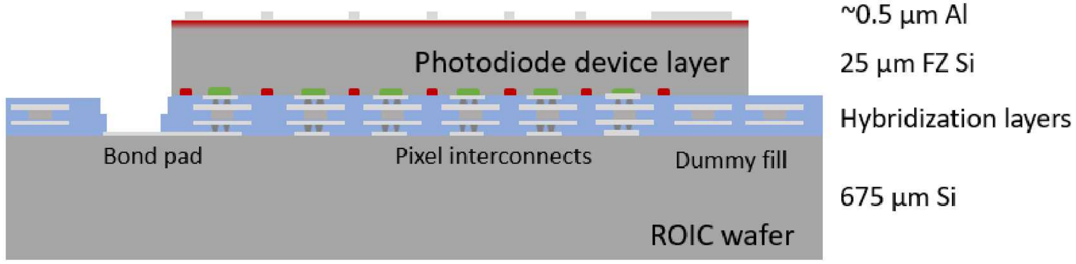
Today’s Pixel Design

Hybrid Device, Die-level



Die plan view

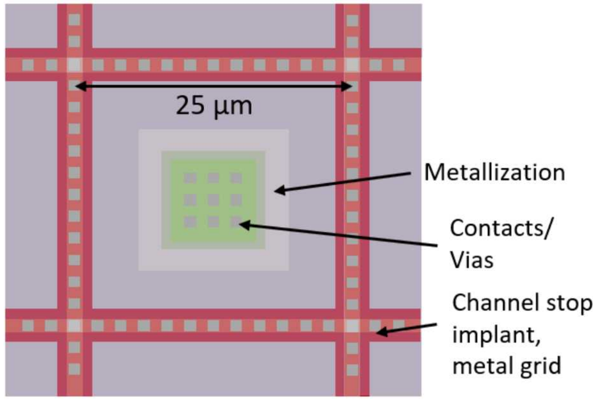
Pixel plan view



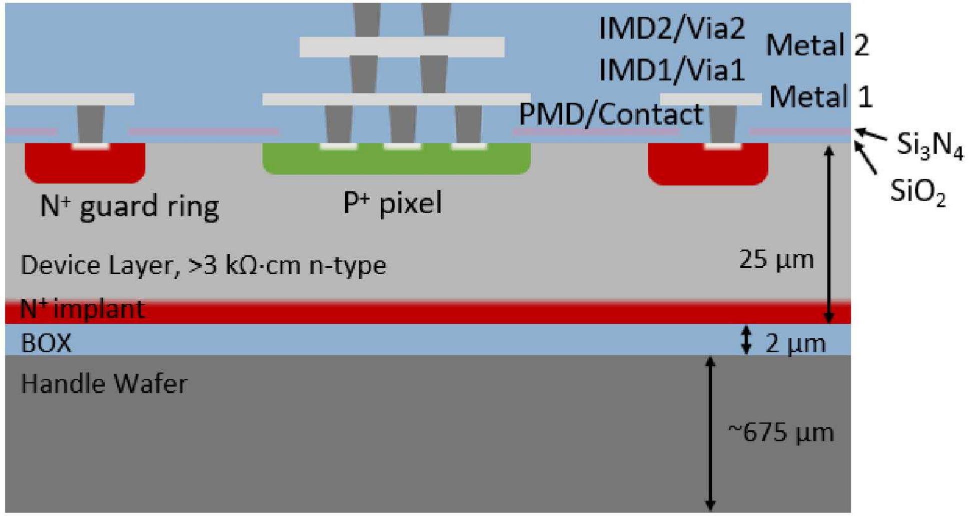
Cross-section view

Detector Wafer, Single-pixel

Pixel Plan View



Cross Section View



Simpler Pixel Design v2

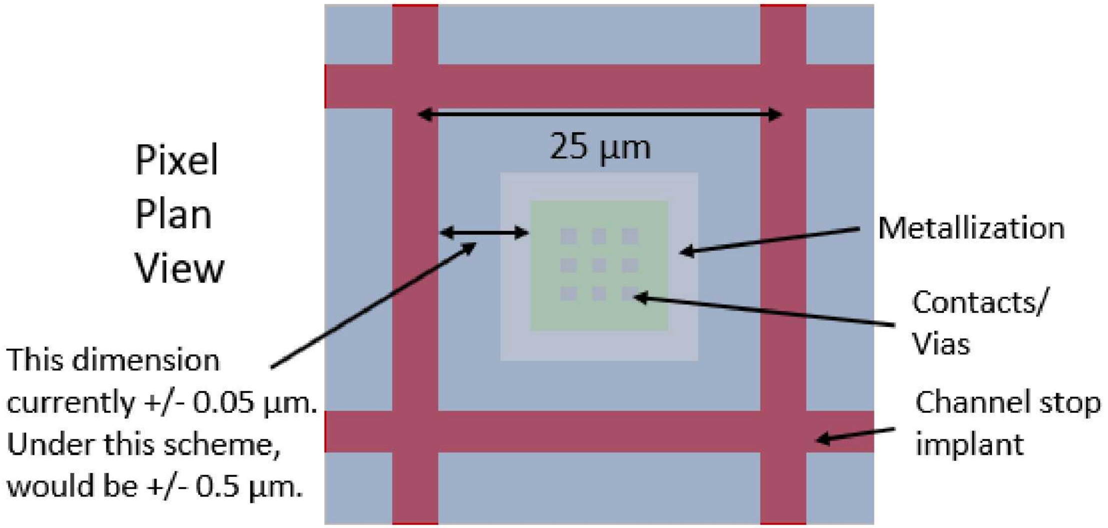
Base plan: 233 steps

- Eliminate nitride layer and etch
    - Eliminate 17 steps, 1 mask layer
    - Coarser implant-implant alignment
- Eliminate contacts and metal grid to channel stop
    - Lose ability to ROIC-side bias
    - Reduces mask complexity, potential short paths
- Eliminate M2/V2 stack
    - Fewer routing options available (not needed if ch stop metal not present)
    - Eliminates 45 steps, 2 mask layers

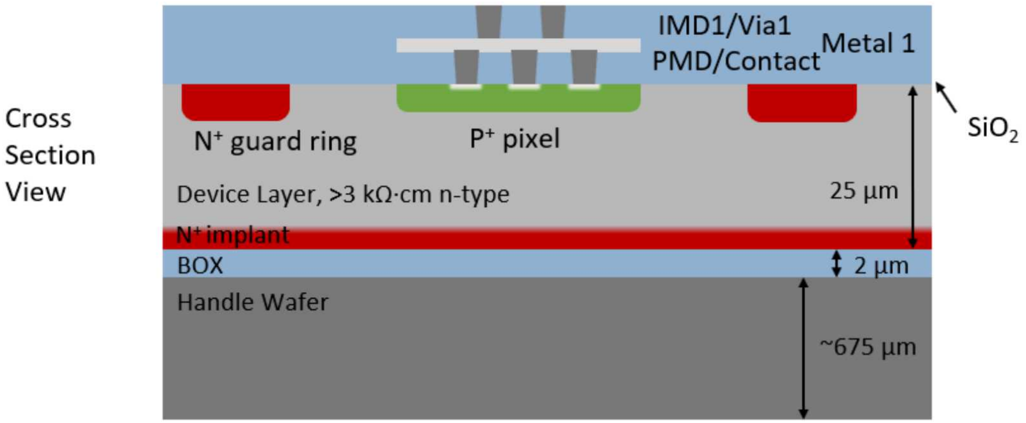
Modified plan: 171 steps
26% cost reduction?

I don’t believe the additional cost savings of eliminating the nitride layer are warranted. If we want to pursue this, detailed simulations should be conducted to determine the effect of implant-to-implant spacing.

Single-pixel



This dimension currently +/- 0.05 μm. Under this scheme, would be +/- 0.5 μm.



Shockley-Ramo Theorem

Key Principle: charge induction efficiency of electrodes can be calculated as a function of volume, independent of real electrostatic conditions

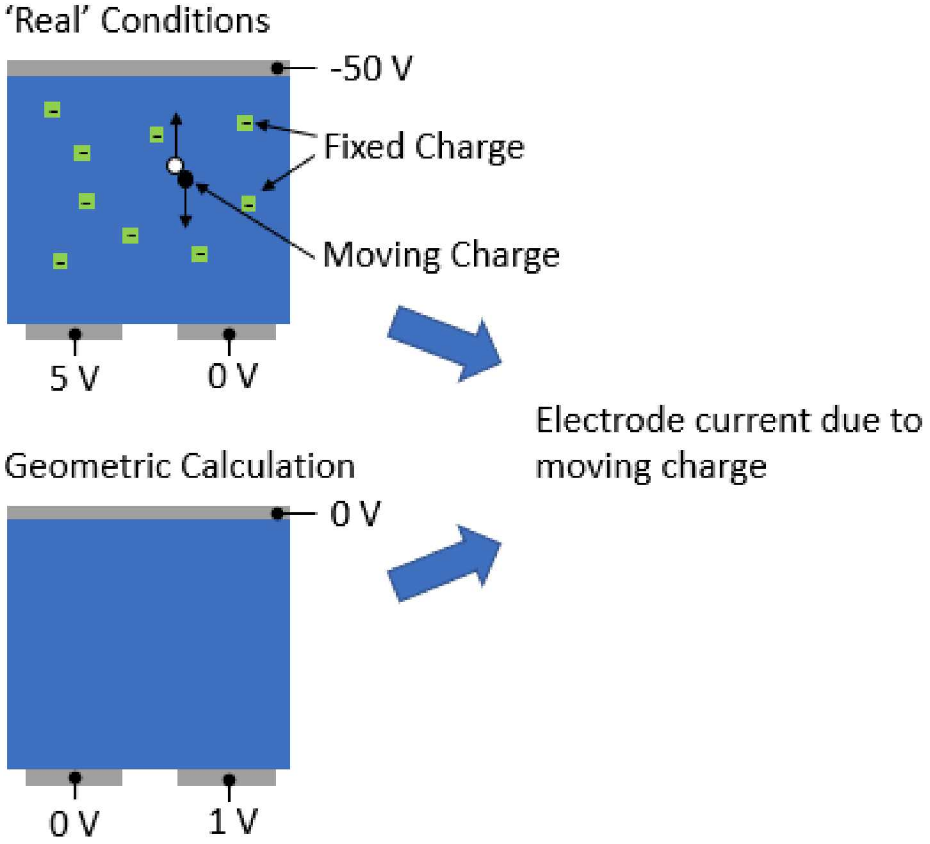
1. Remove all fixed charge
2. Set all electrodes to 0 V
3. Set electrode of interest to 1 V
4. Calculate potential => 'weighting potential' φ_0
5. Calculate E field => 'weighting field' $\overrightarrow{E_0}$
6. The following are true for given geometry:

Charge induced on an electrode $Q = -q\varphi_0$

Current induced on an electrode $i = q\vec{v} \cdot \overrightarrow{E_0}$

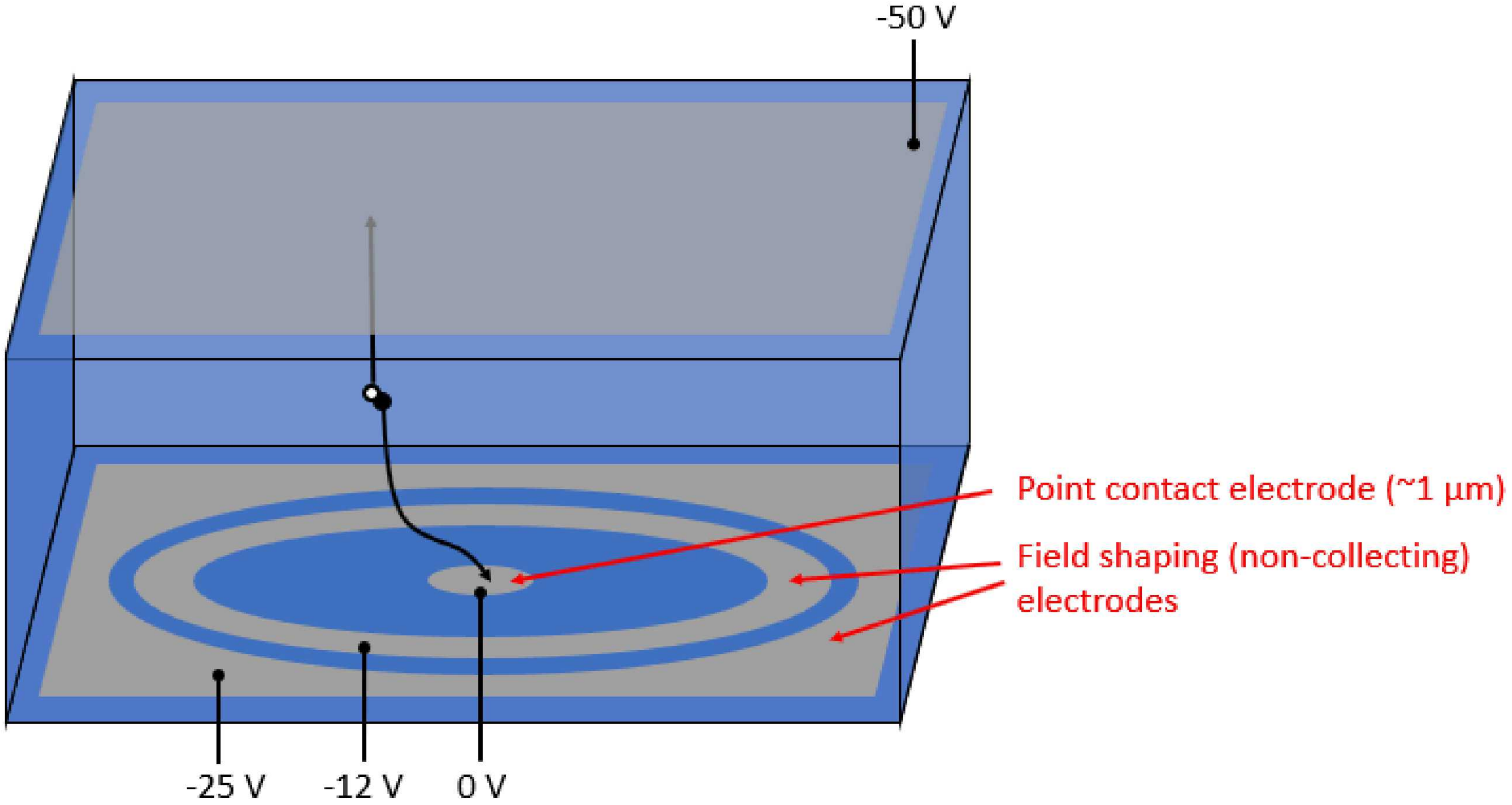
From real electric field, we have $\vec{v} = v(|\vec{E}|)\vec{E}$

Combination gives $i = qv(|\vec{E}|)\vec{E} \cdot \overrightarrow{E_0}$



For more information, see Helmuth Spieler's "Semiconductor Detector Systems" Ch. 2 or Zhong He NIMA 463 p. 250 (2001)

Point Contact



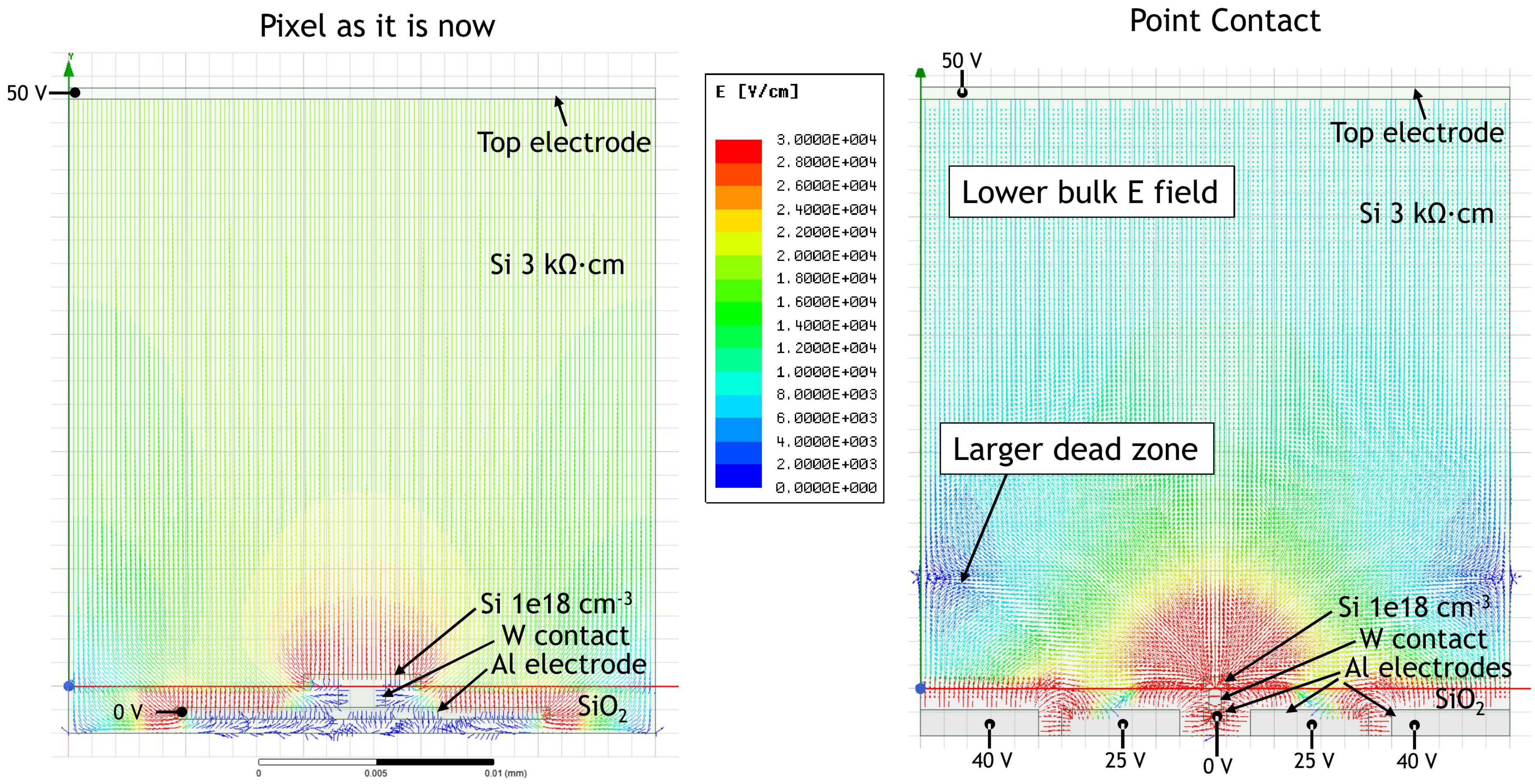
Key Features
-Small collecting electrode senses moving charge only in small volume nearby
-Field shaping electrodes needed to funnel charge to collecting electrode
-Secondary benefit of lower junction capacitance

~40% reduction?

Feasibility: we can make it, but high risk

Point Contact

‘Real’ Electric Field



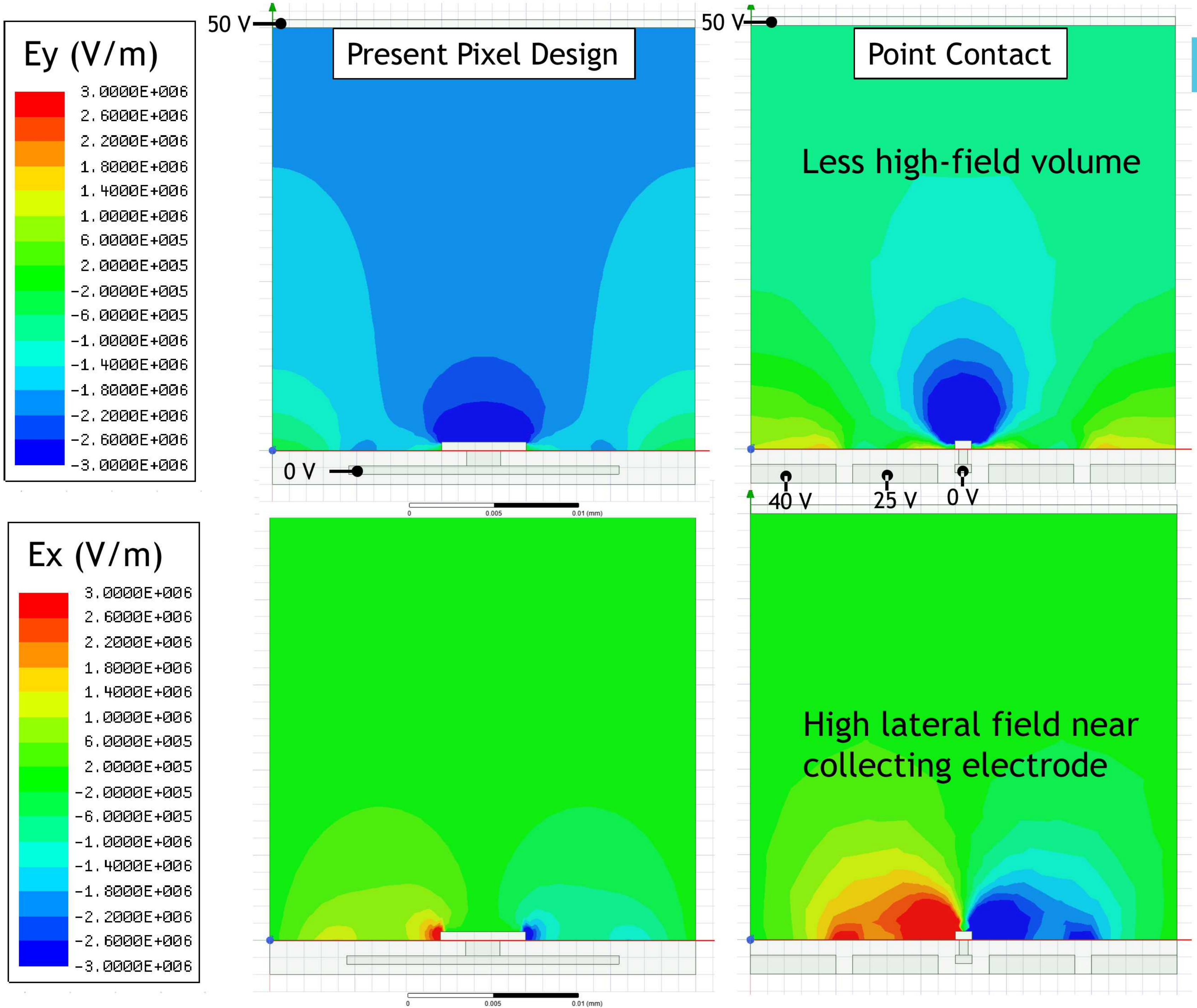
Pixel as it is now

Point Contact

Point Contact

‘Real’ Electric Field

Point contact configuration likely less efficient in charge collection compared to standard design



Present Pixel Design

Point Contact

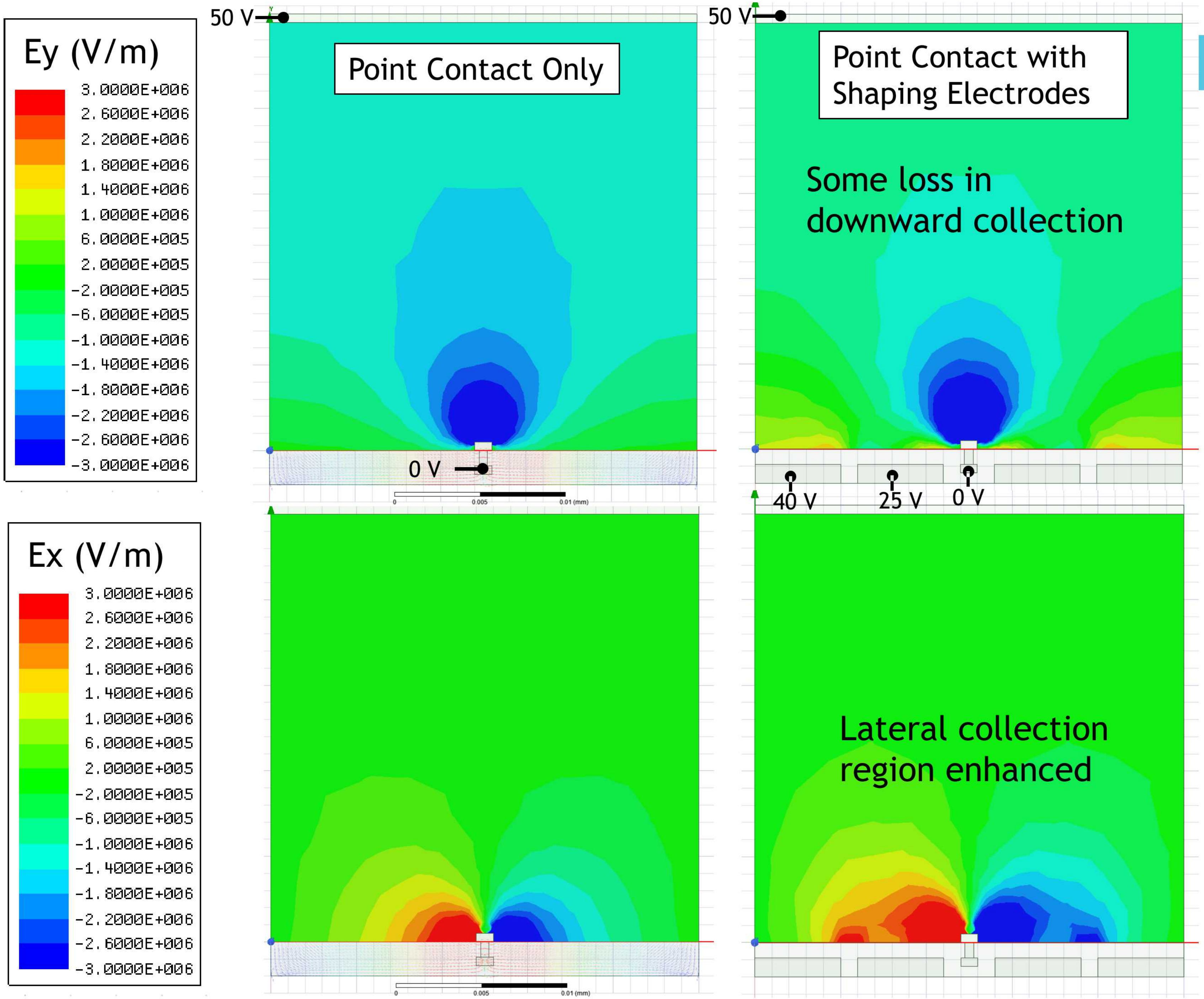
Less high-field volume

High lateral field near collecting electrode

Point Contact

‘Real’ Electric Field

This is why shaping electrodes are necessary



Point Contact Only

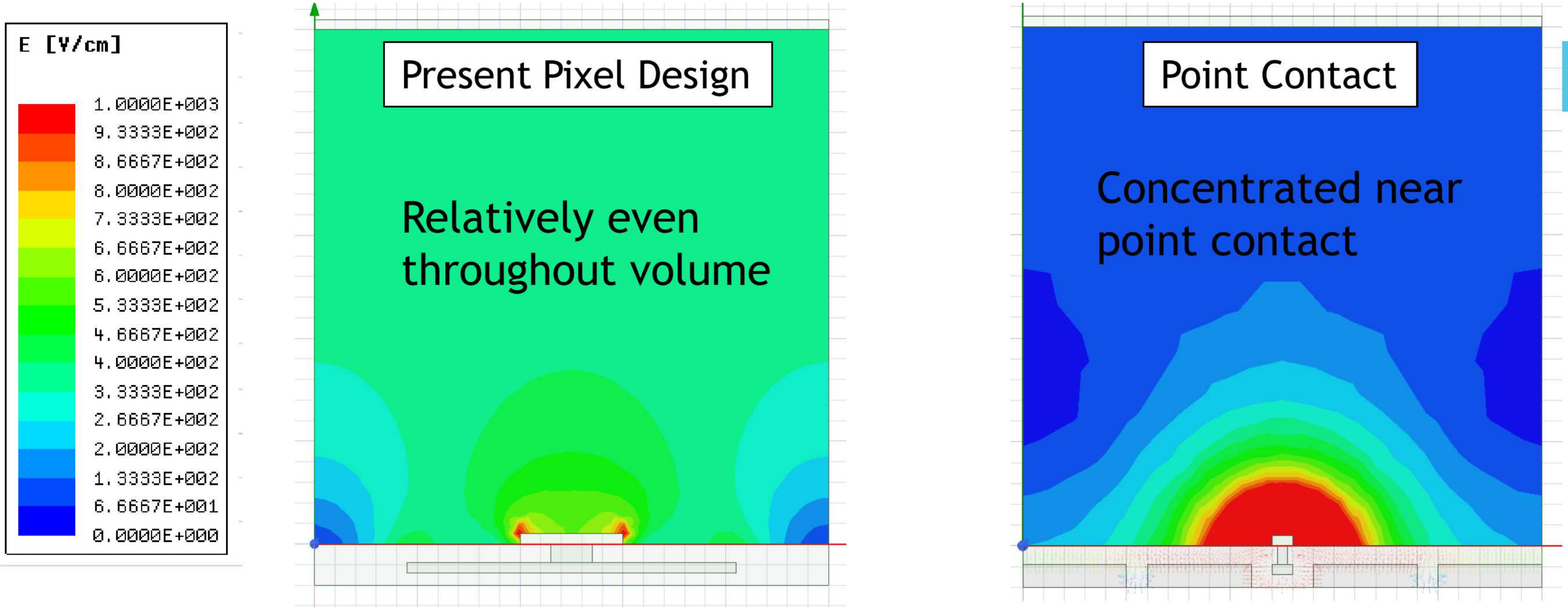
Point Contact with Shaping Electrodes

Some loss in downward collection

Lateral collection region enhanced

Point Contact

Weighting Field $|E_0|$
A measure of sensitivity
to moving charge



Present Pixel Design

Relatively even throughout volume

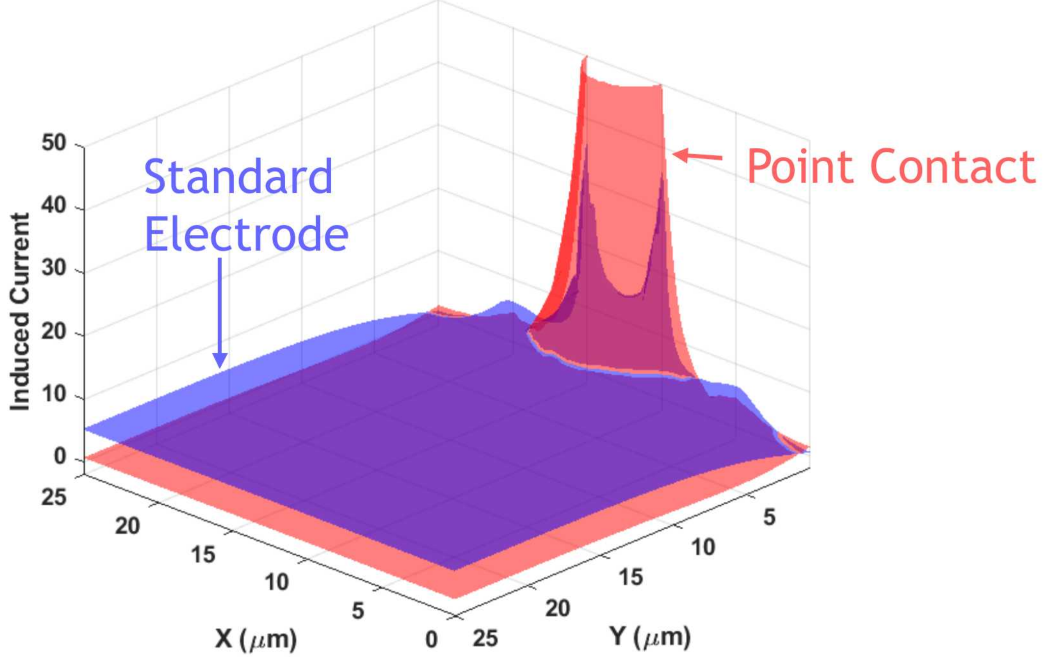
Point Contact

Concentrated near point contact

$$i = q\vec{v} \cdot \overrightarrow{E_0}$$

Velocity due to real field

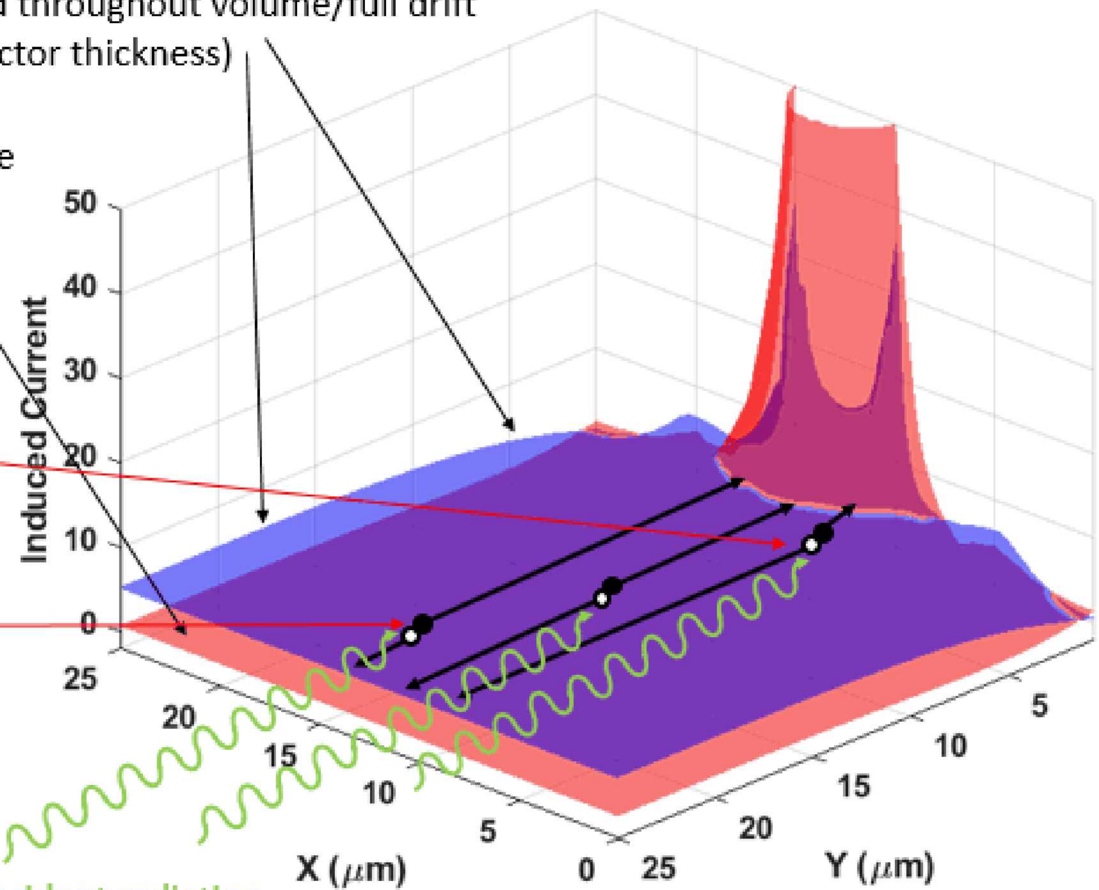
Weighting field



Standard Electrode

Point Contact

Point Contact



With standard electode, both electrons and holes sensed throughout volume/full drift length (detector thickness)

Point contact does not sense moving charge here; majority of hole drift ignored

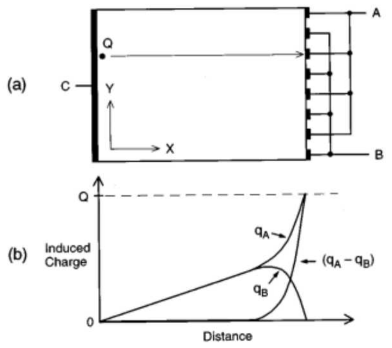
If we sense all moving charge, this case where holes drift much further than electrons is the limiting factor

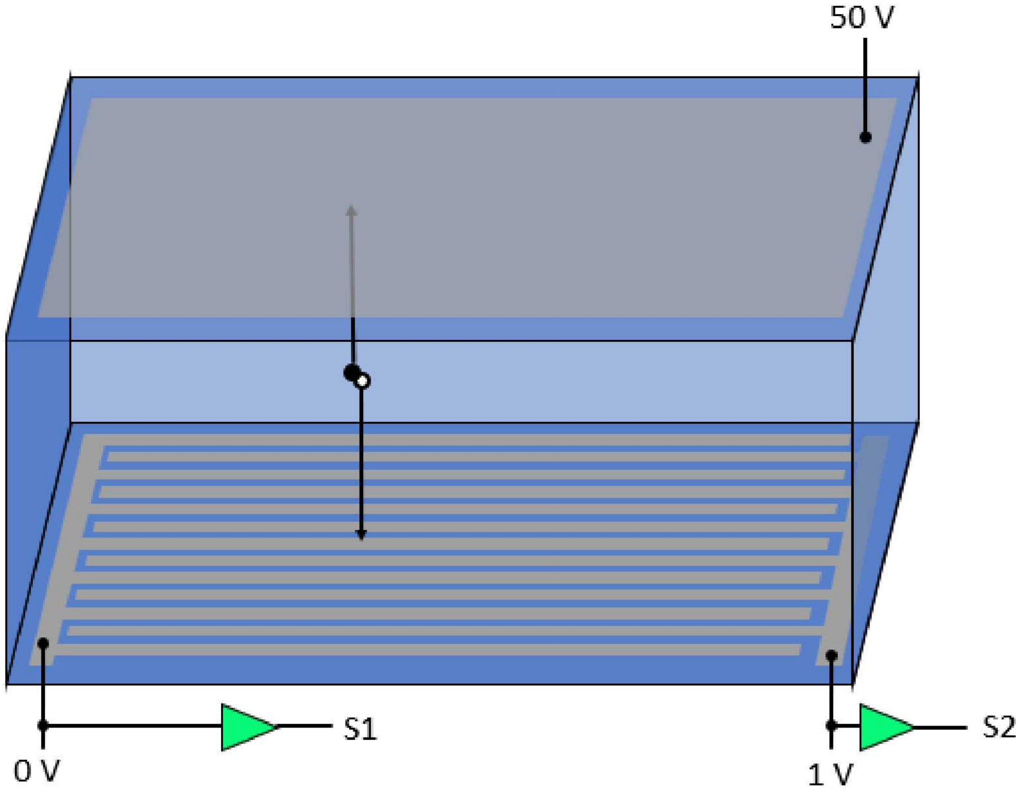
If we ignore hole drift, this case where electrons drift much further than holes is the limiting factor (~2x faster)

Incident radiation

Other Electrode Configurations
Coplanar Grid

P. Luke, APL 65, p.2884 (1994)





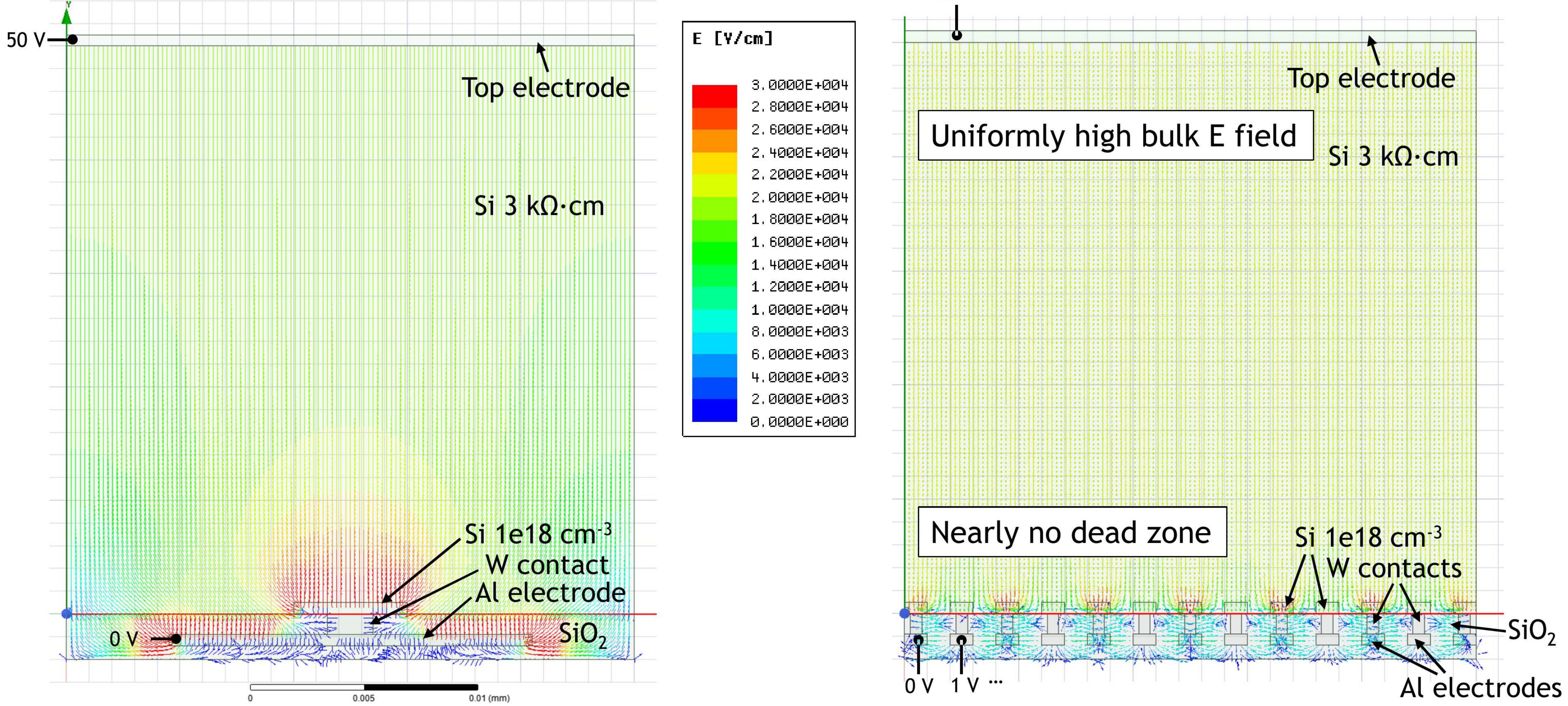
Key Features
- -Requires more in-pixel structure
- -Can operate as typical pixel when PV=S1+S2
- -Can increase dynamic range when PV=S1 .   S2 shunted to VRST.
- -Can reduce sensitive volume when PV=S1-S2 , similar to point contact
- -Unlike point contact, capacitance is higher

~40% reduction?

Feasibility: we can make it, but high risk

Coplanar Grid

‘Real’ Electric Field



Pixel as it is now

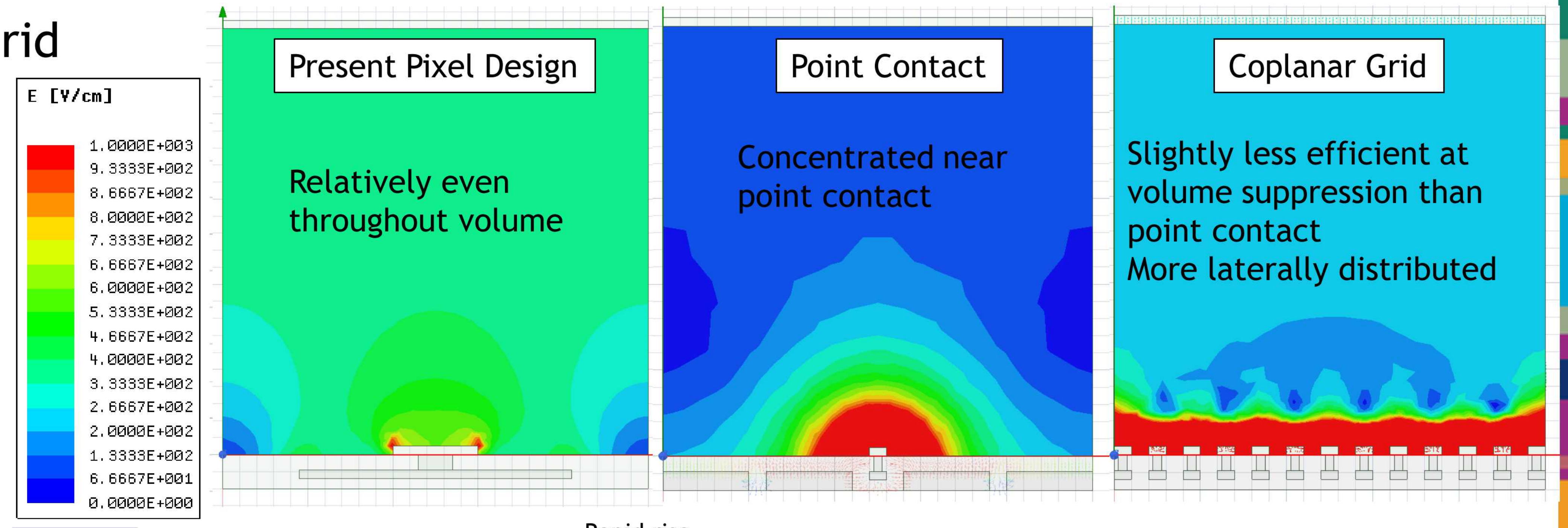
Coplanar Grid

Uniformly high bulk E field

Nearly no dead zone

Coplanar Grid

Weighting Field $|E_0|$
A measure of sensitivity to moving charge



Present Pixel Design

Relatively even throughout volume

Point Contact

Concentrated near point contact

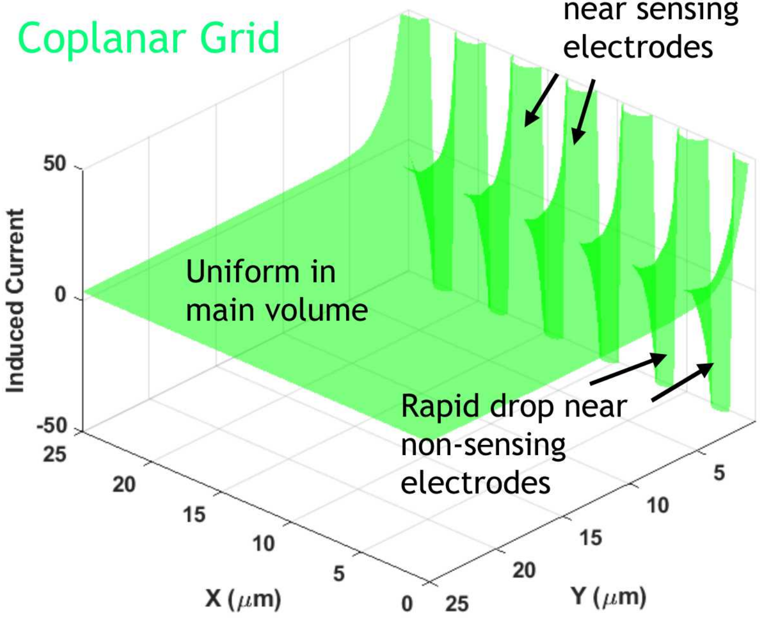
Coplanar Grid

Slightly less efficient at volume suppression than point contact
More laterally distributed

$$i = q\vec{v} \cdot \overrightarrow{E_0}$$

Velocity due to real field

Weighting field

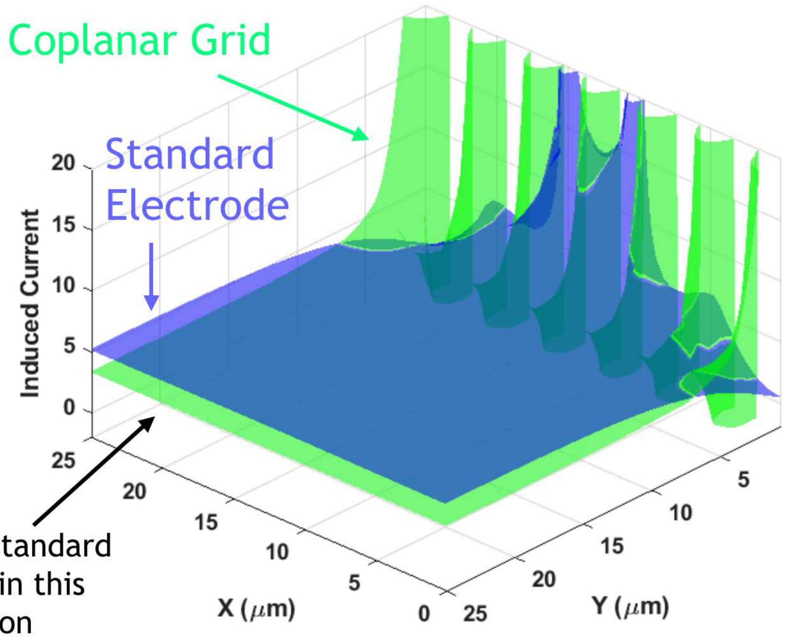


Coplanar Grid

Rapid rise near sensing electrodes

Uniform in main volume

Rapid drop near non-sensing electrodes



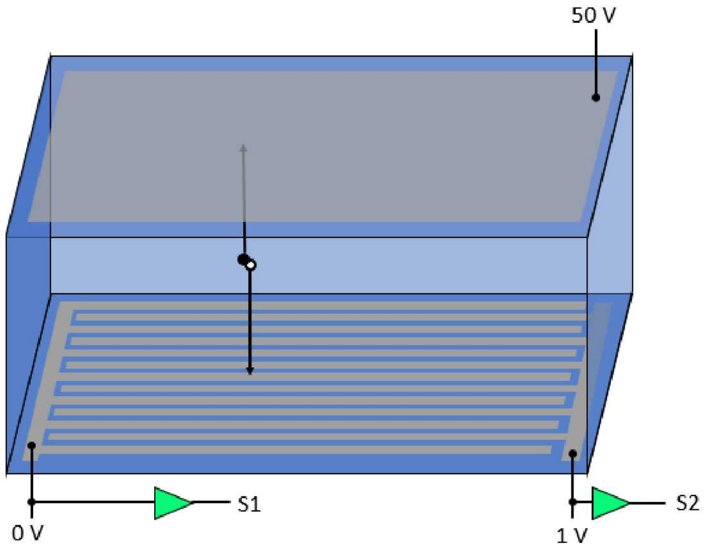
Coplanar Grid

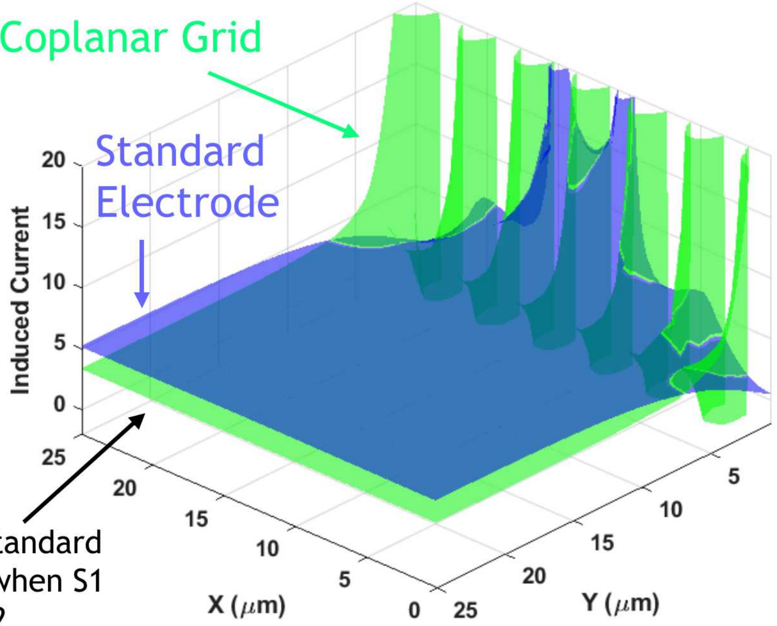
Standard Electrode

CPG ~1/2 standard sensitivity in this configuration

Coplanar Grid

Readout Options

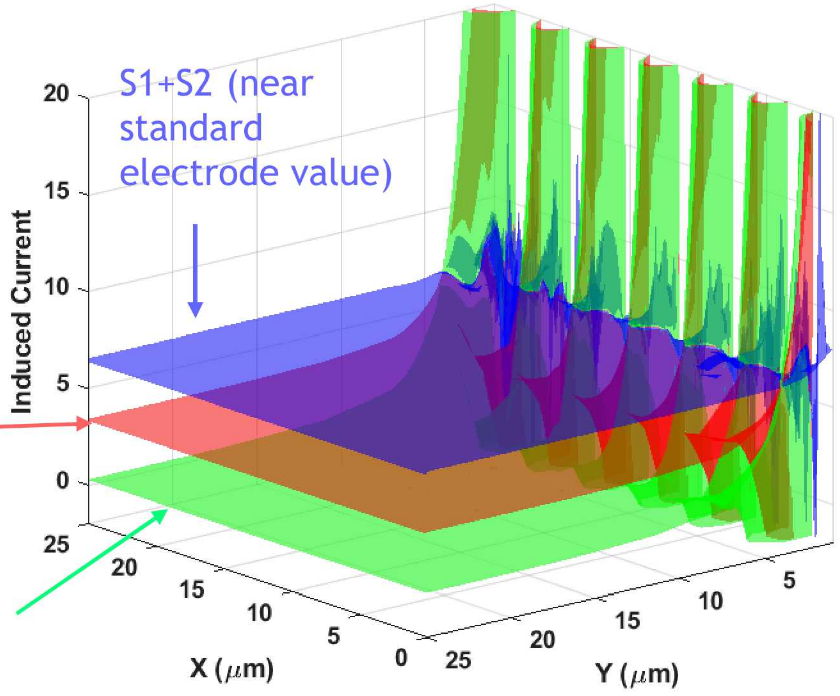




Coplanar Grid

Standard Electrode

CPG ~1/2 standard sensitivity when S1 read out, S2 shunted to VRST



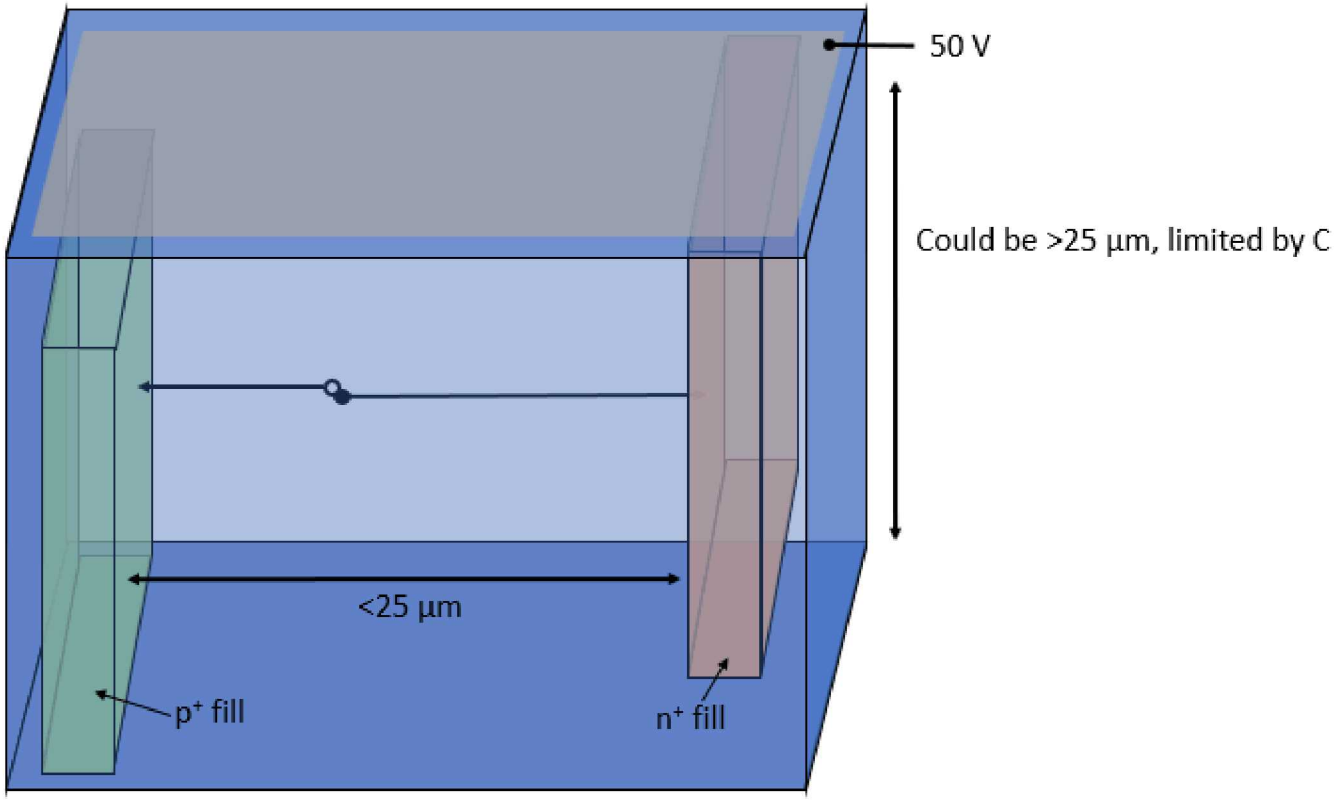
S1+S2 (near standard electrode value)

S1 only (~1/2 standard value)

S1-S2 (0 in most of volume)

3D Diode (Trench)

Doped polyfill column structures described in Parker 1997, Kenney 1999, Kok 2006, etc.



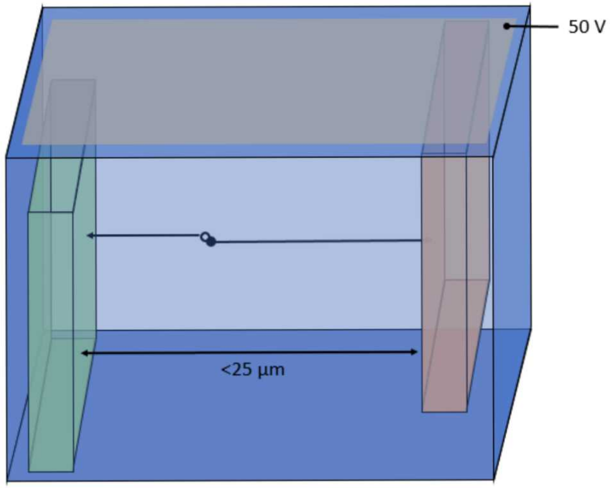
Key Features
-Can select width based on desired timing; may be connected to pixel size
-Thickness can be increased to keep high QE
-Need to develop dry etch and conductive fill process for thick device layers
-2nd electrode would need to be created after hybridization (need low T process)

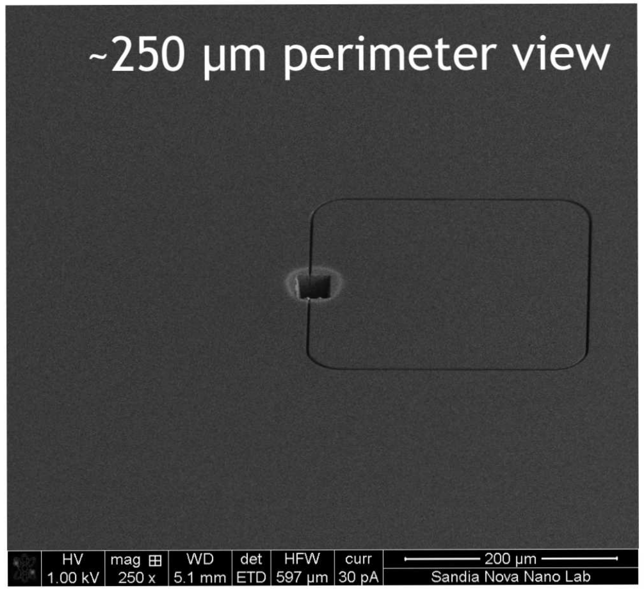
~50% reduction?

Feasibility: significant process development

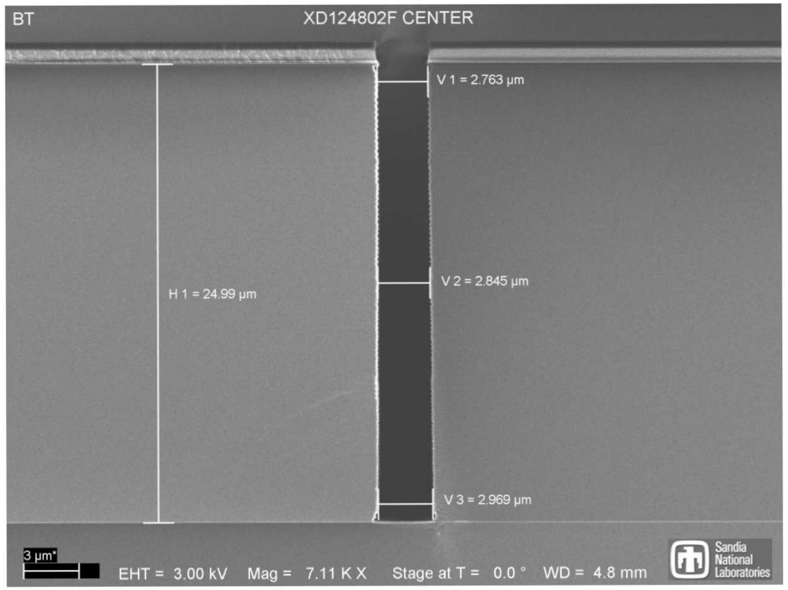
3D Diode (Trench)

Polysilicon-filled trenches

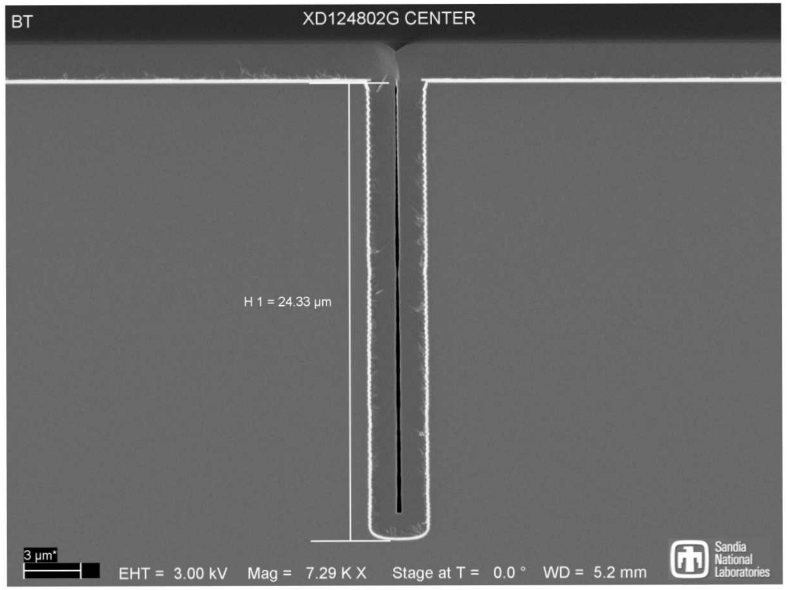



~250 µm perimeter view

Trench 25 µm deep with oxide stop

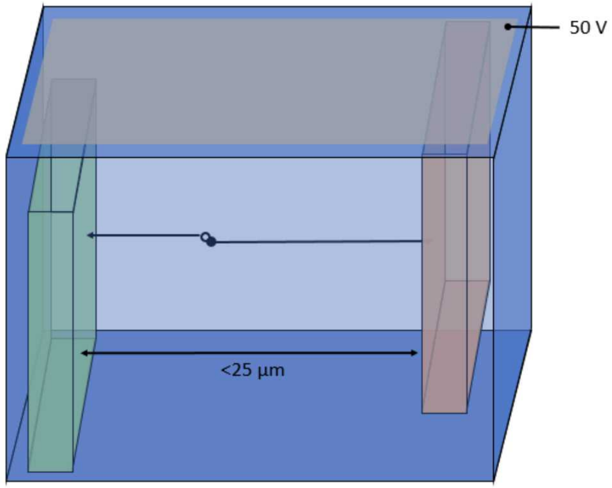


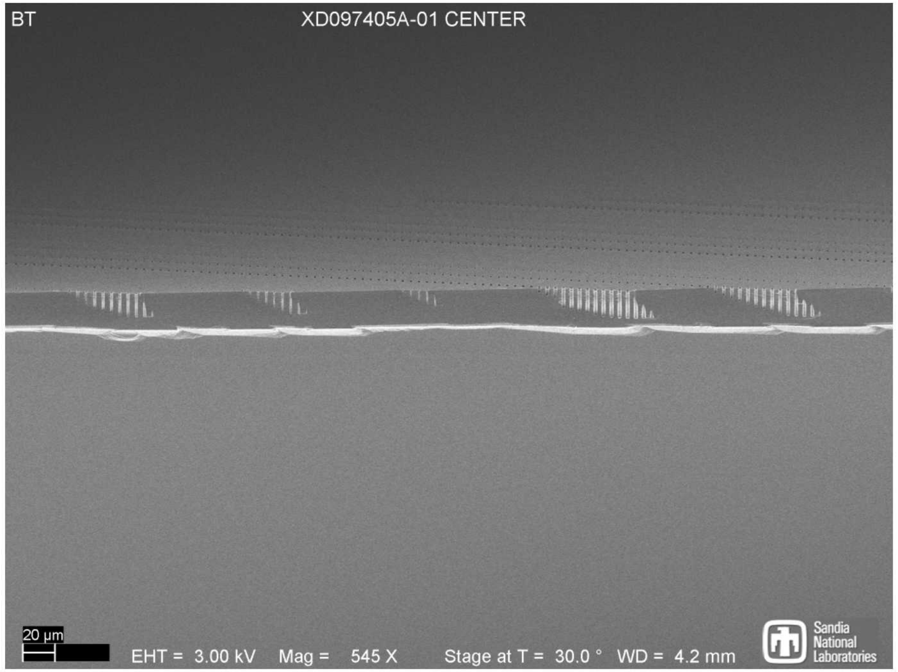
Poly-filled trench 25 µm deep

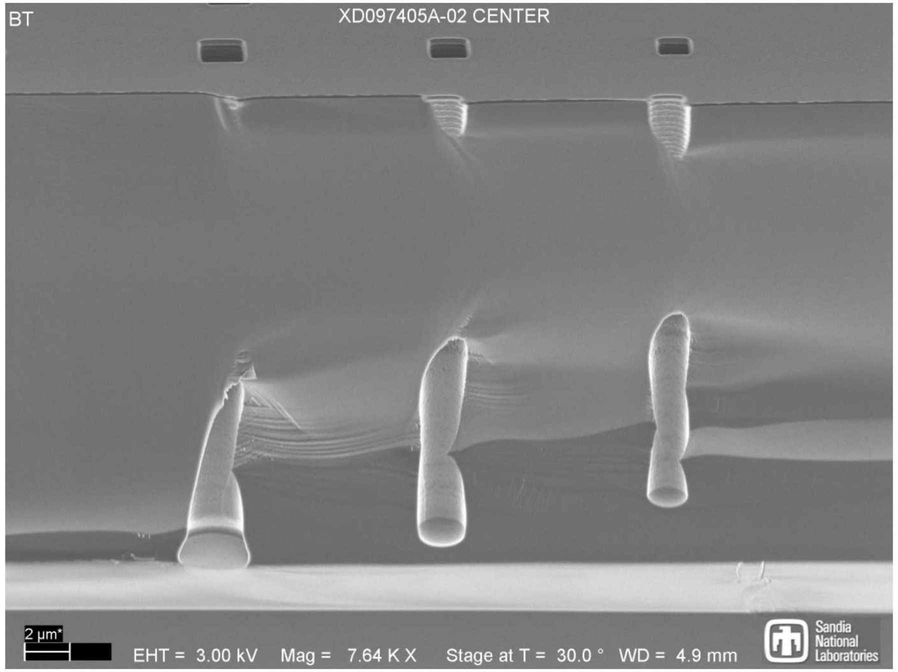


3D Diode (Trench)

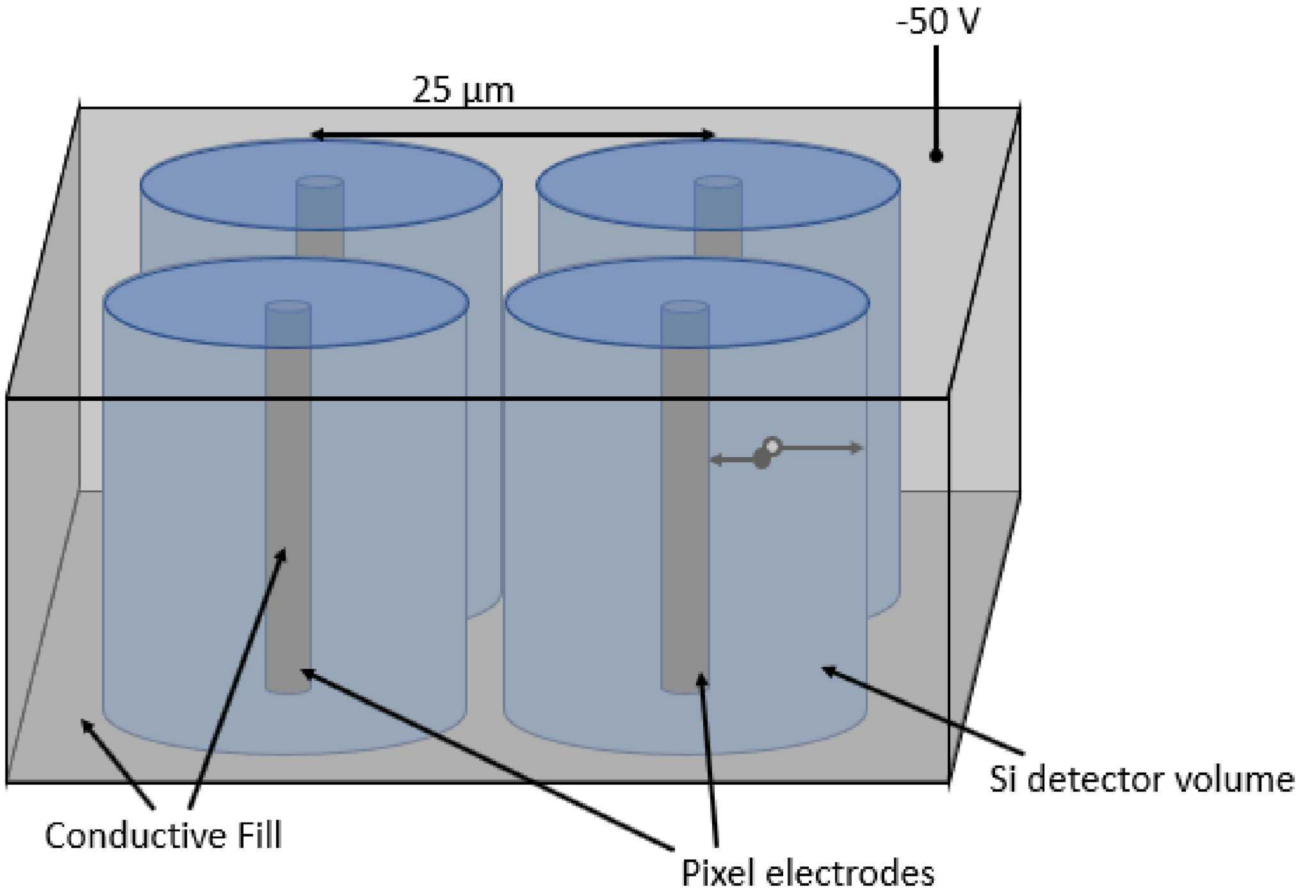
2 μm holes/trenches for W fill







3D Diode (Cylinder)

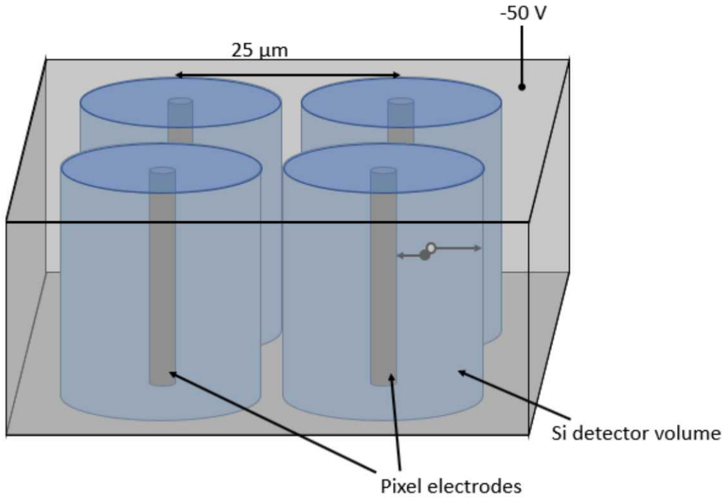


~60% reduction?

Feasibility: significant process development

Key Features
-Need mature dry etch and conductive fill process
-Better takes advantage of geometry to reduce hole contribution to signal

3D Diode (Cylinder)



Very high field throughout