3D Sensor Technologies

C. Kenney, January 11, 2013

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

HL-LHC Vertex Needs

- Higher track density – better segmentation
- Many interactions – better vertex resolution along beam axis
- Improved radiation tolerance
- Better timing
- Lower system mass
- Hermeticity

What should be improved in vertex and tracking detectors?

Radiation tolerance – ideally 1 x 10^{17} n/cm2

- Reachable by smaller electrode pitch and internal gain

Spatial resolution – possible now, limited by electronics

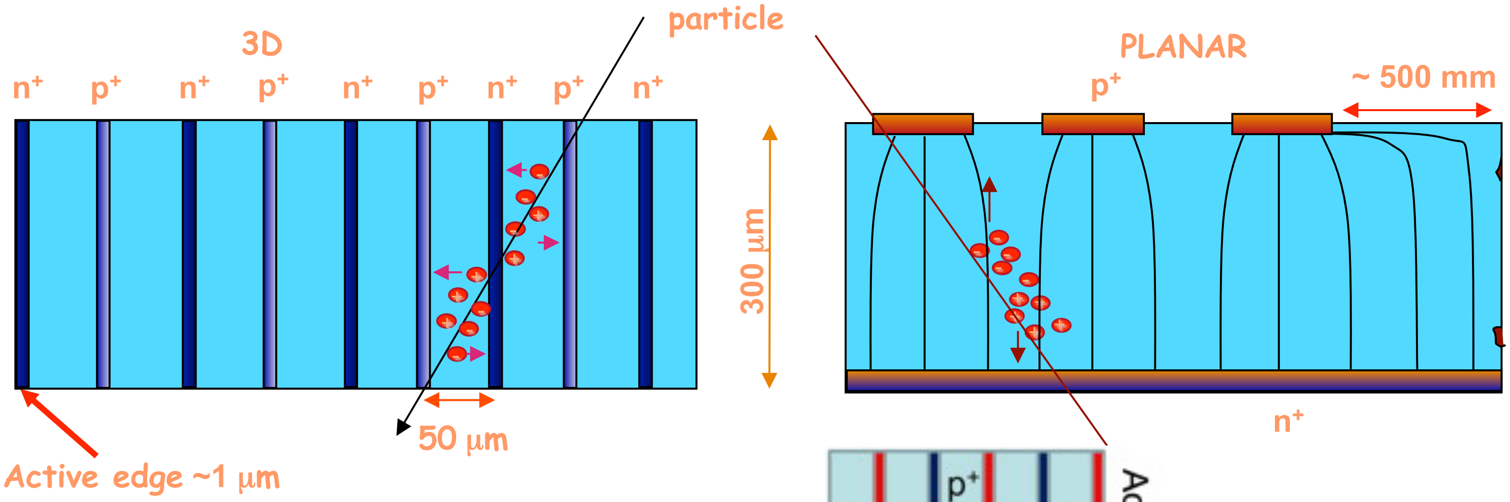
- improved fabrication techniques will help

System mass – active edges, integrated cooling, lower bias voltages may help

Vertex layer hermeticity – active edges help

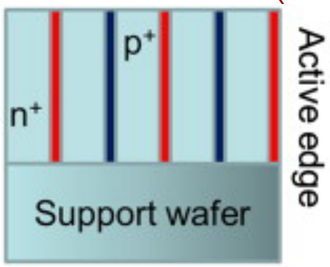
Timing to mitigate pileup – already fast enough, smaller pitches

Radiation hardness – 3D sensors

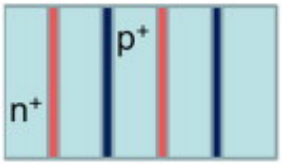


- Depleted perpendicular to the sensor surface
- Minimize signal drift distance and time
- Less trapping of signal
- Leads to improved radiation tolerance over planar design
- Lower bias voltages = lower power = less cooling load

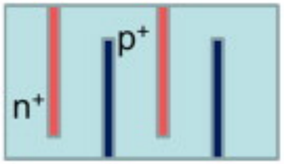
S. Parker, C. Da Via, J. Hasi



3D with active edges
Stanford/SINTEF

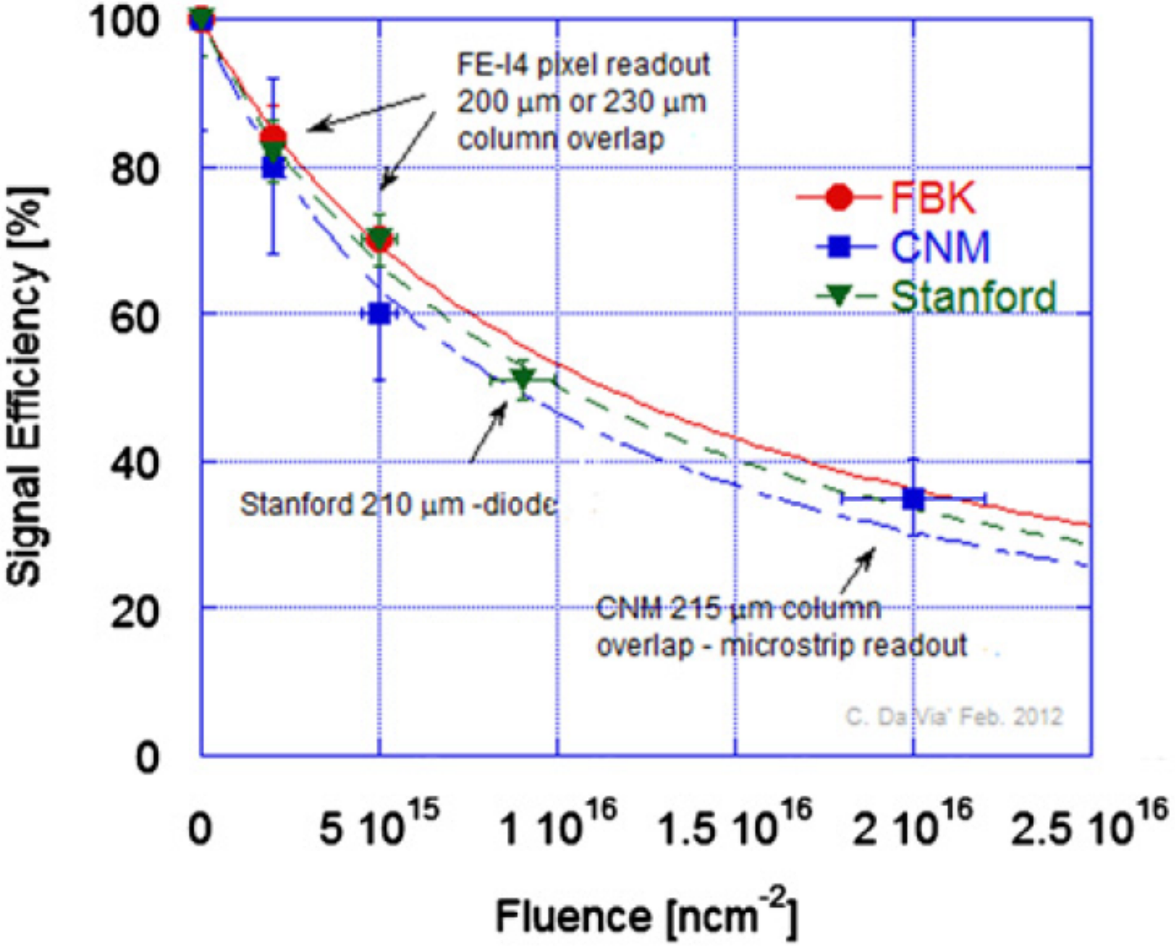


Double sided full-through
columns FBK



Double sided partially-through
columns CNM

Radiation Tolerance



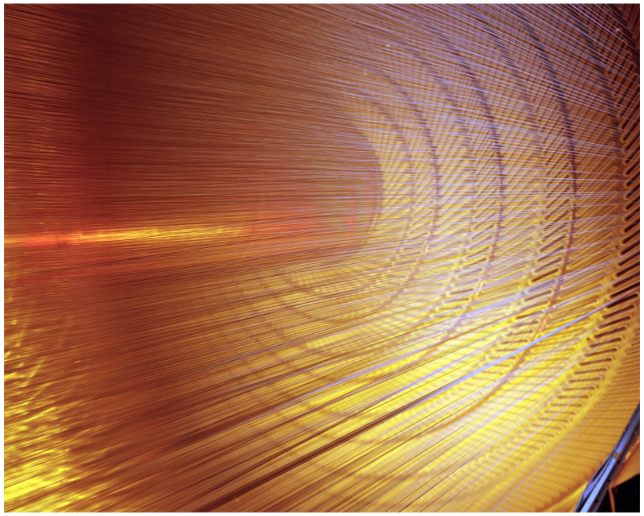
Internal amplification

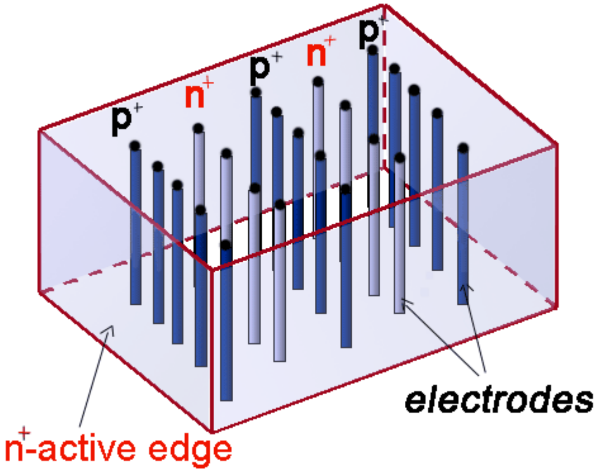
Observed in both planar and 3D sensors after irradiation

3D has a similar geometry to wire chambers

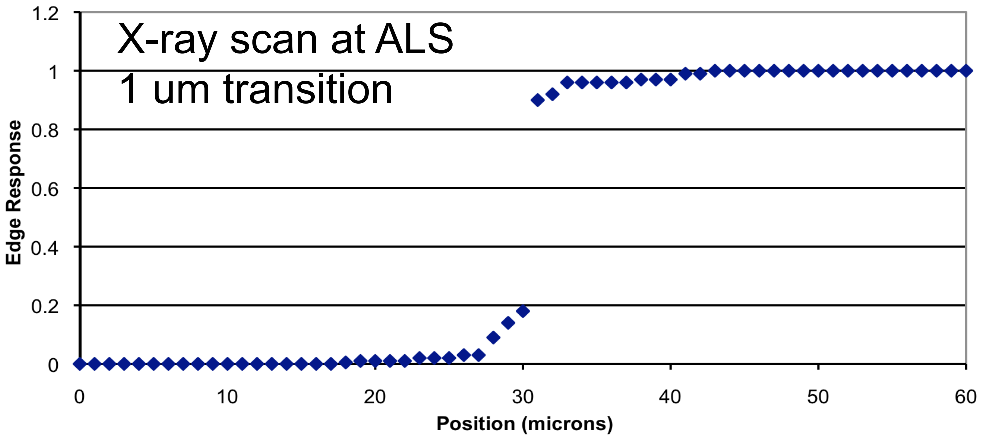
Design electrode configuration and doping levels to provide gain

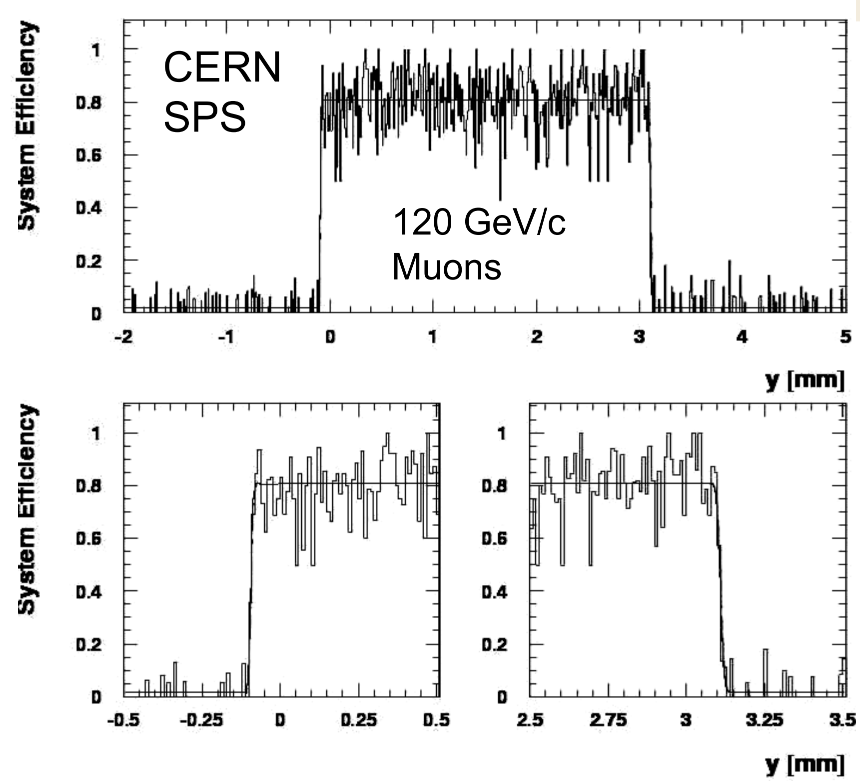
May improve radiation tolerance further





3D Measurements





Width (3.203 ± 0.004) mm (Expectation = drawn width = 3.195 mm)

Lower edge : *σ* (4.3 ± 4.1) µm; 10%-90% interval (11.0 ± 4.2) µm

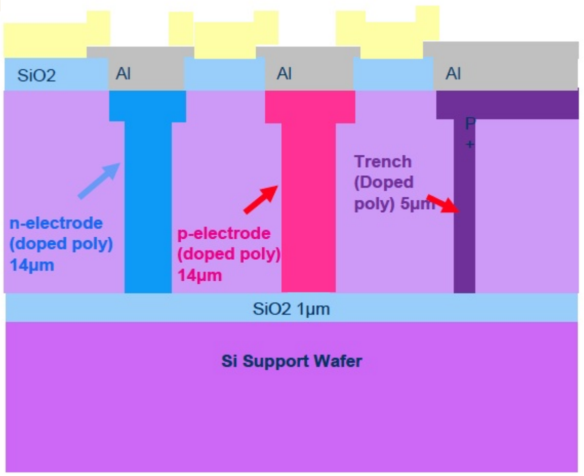
Upper edge: *σ* (9.7 ± 3.0) µm; 10%-90% interval (25.0 ± 8) µm

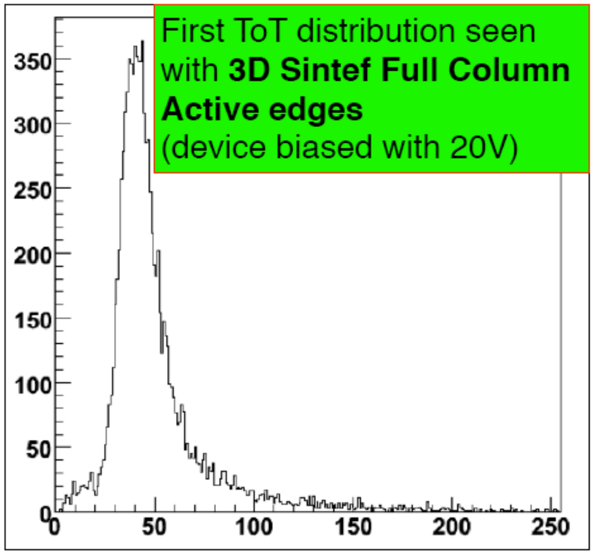
σ (edge) largely from beam telescope, alignment errors

Full 3D with Active Edges

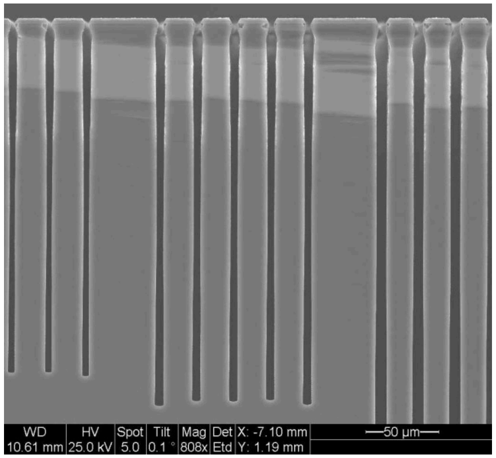
SINTEF – Norway

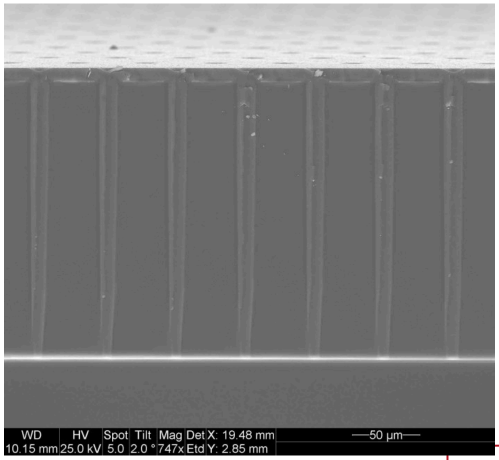
- Full 3D process
- Active edges
- Uses support wafer
- ~ 1 micron dead band on edge
- Bonded to ATLAS FE-I4





First ToT distribution seen with **3D Sintef Full Column Active edges** (device biased with 20V)

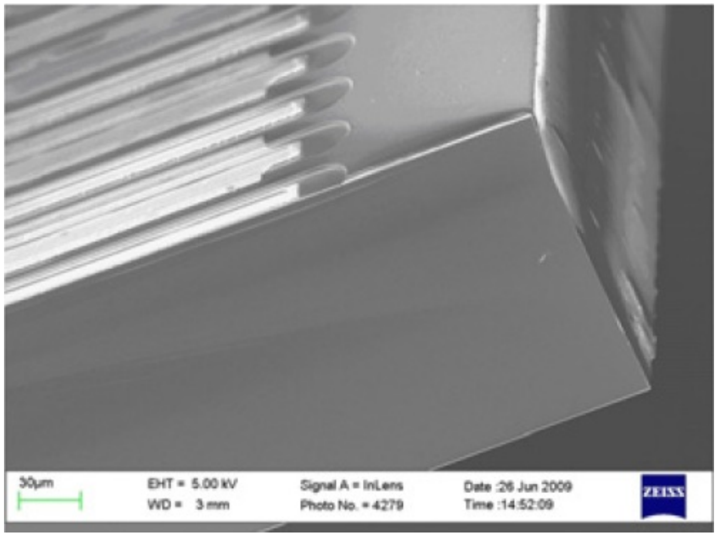




A.Kok et al., IEEE Nucl. Sci. Symposium, Conference Record, (2009) 1623 - 1627

Implanted Active Edges

- Similar to standard active-edge process
- Uses support wafer and deep plasma etch
- Uses angled implants to dope edges
- Does not fill the trenches for planarization
- Sub-micron dead band

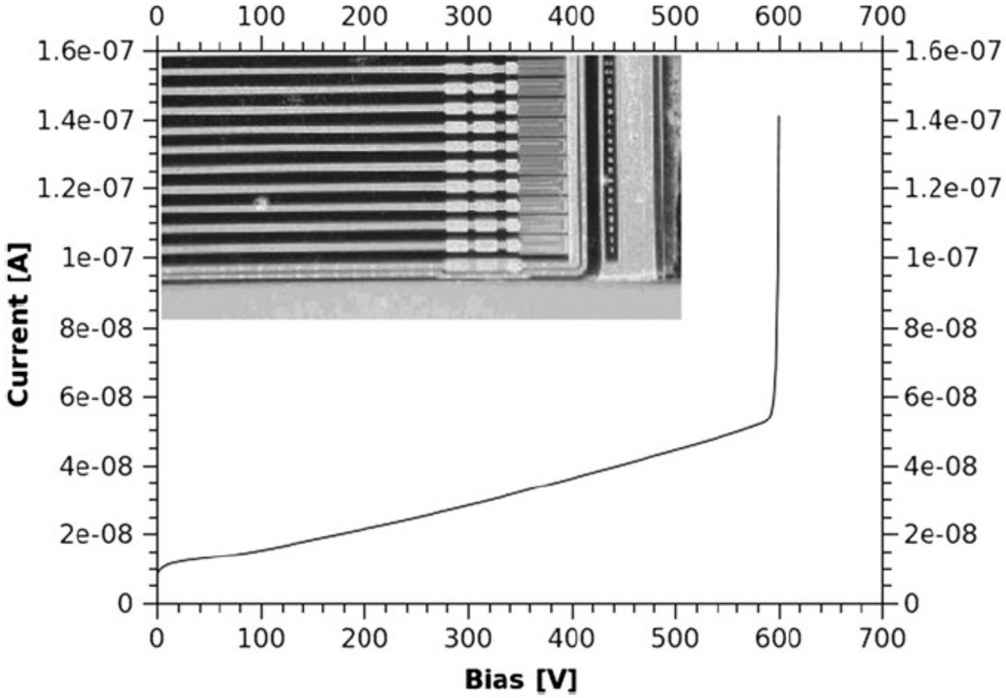


VTT – J. Kalliopuska, et al., Nuclear Instruments and Methods in Physics Research A 633 (2011) S50–S54

Cleaved Slim Edges

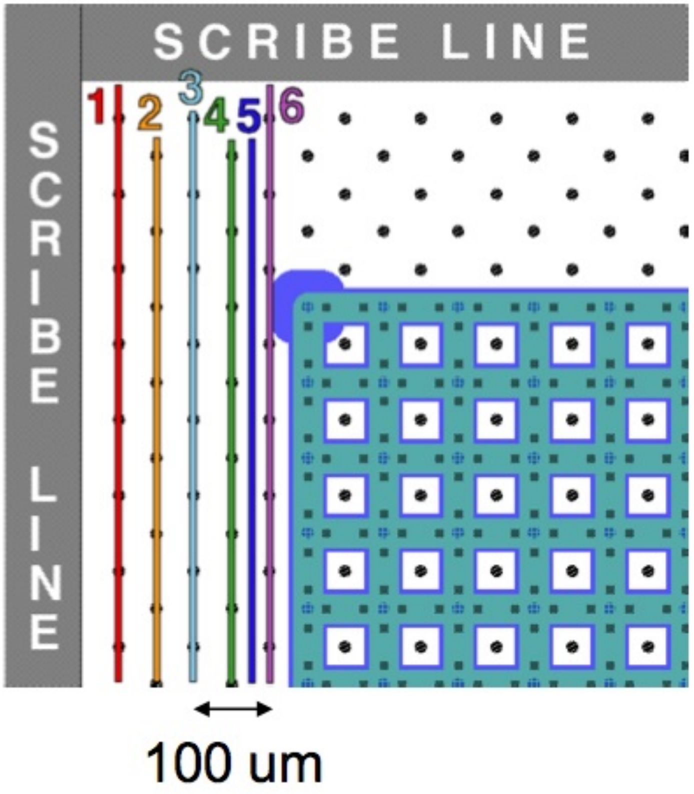
UCSC + NRL

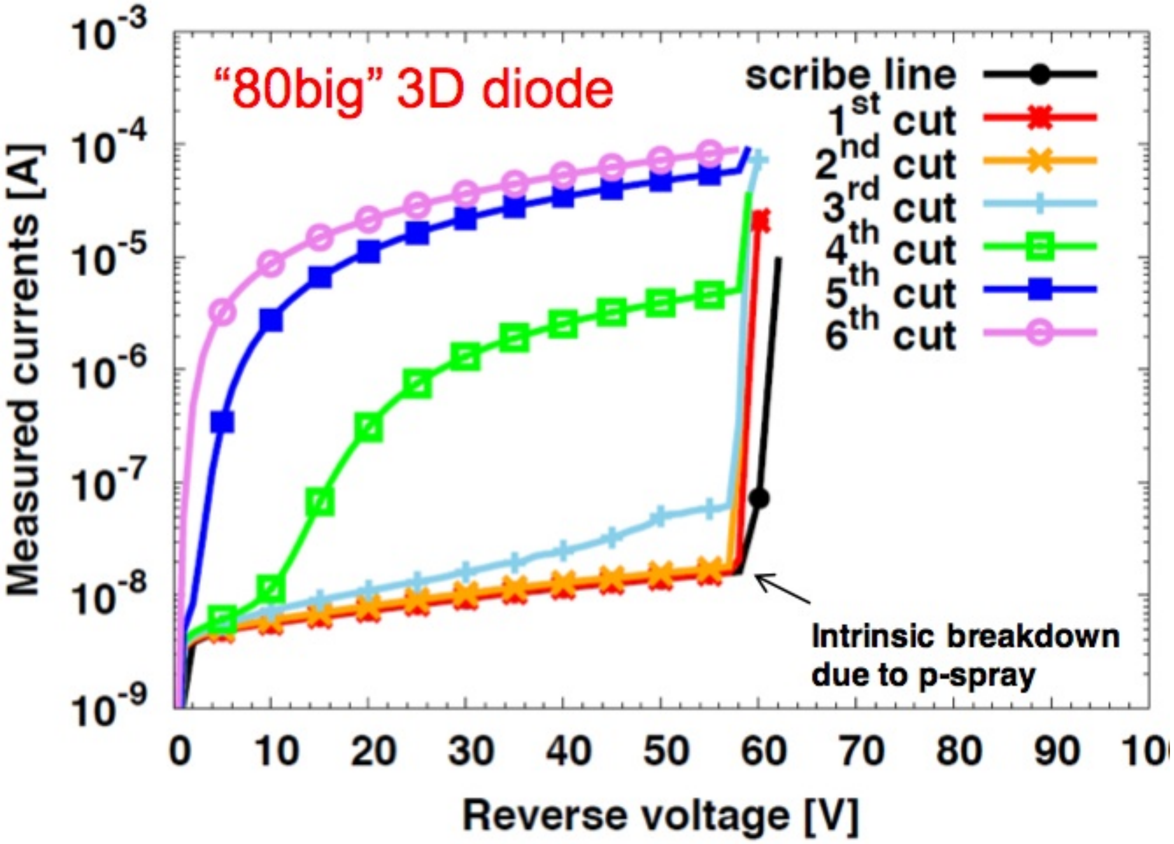
- Normal planar process
- Scribe
- Cleave
- Passivate the edge via ALD or PECVD
- Down to 14 micron dead band on the edge



M. Christophersen, et al., Nuclear Instruments & Methods In Physics Research A (2012), http://dx.doi.org/10.1016/j.nima.2012.04.077

Slim Edges

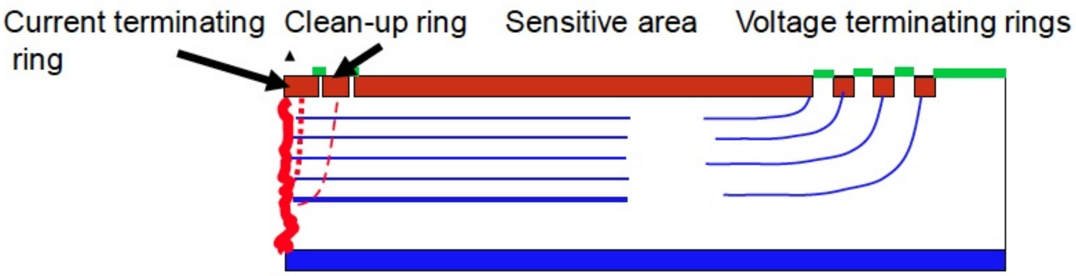




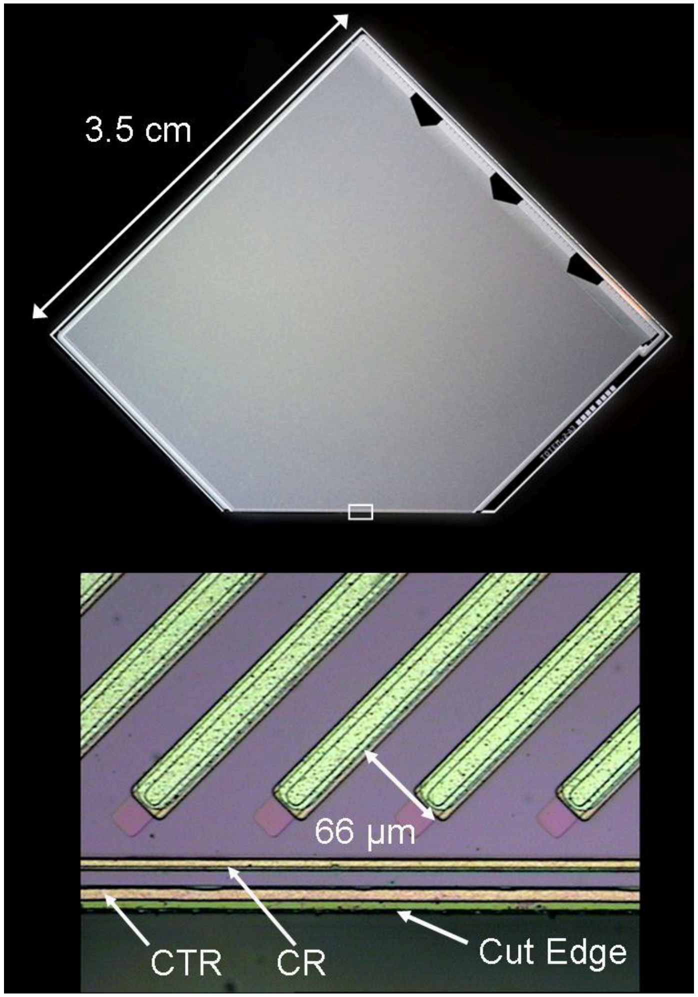
GF Della Betta et al., FBK + Trento

TOTEM – Slim Edge Design

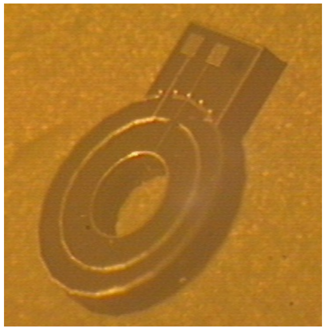
- One side is a slim edge
- Other sides have normal guard rings
- Has a diffusion ring to collect the large edge currents
- Has a diffusion ring to terminate electric fields
- 60 micron dead band on edge
- Used in LHC close to primary proton beam

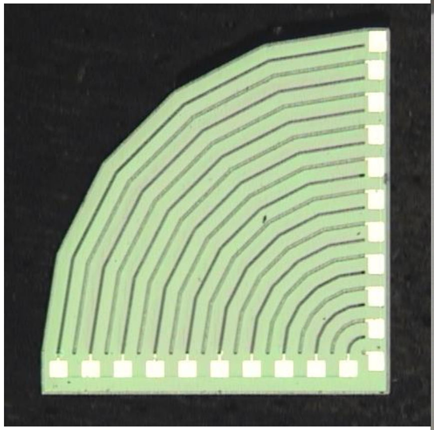


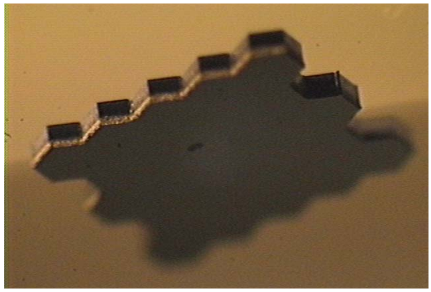
G. Ruggiero et al. IEEE Trans. Nucl. Sci. 52 (2005) 1899.

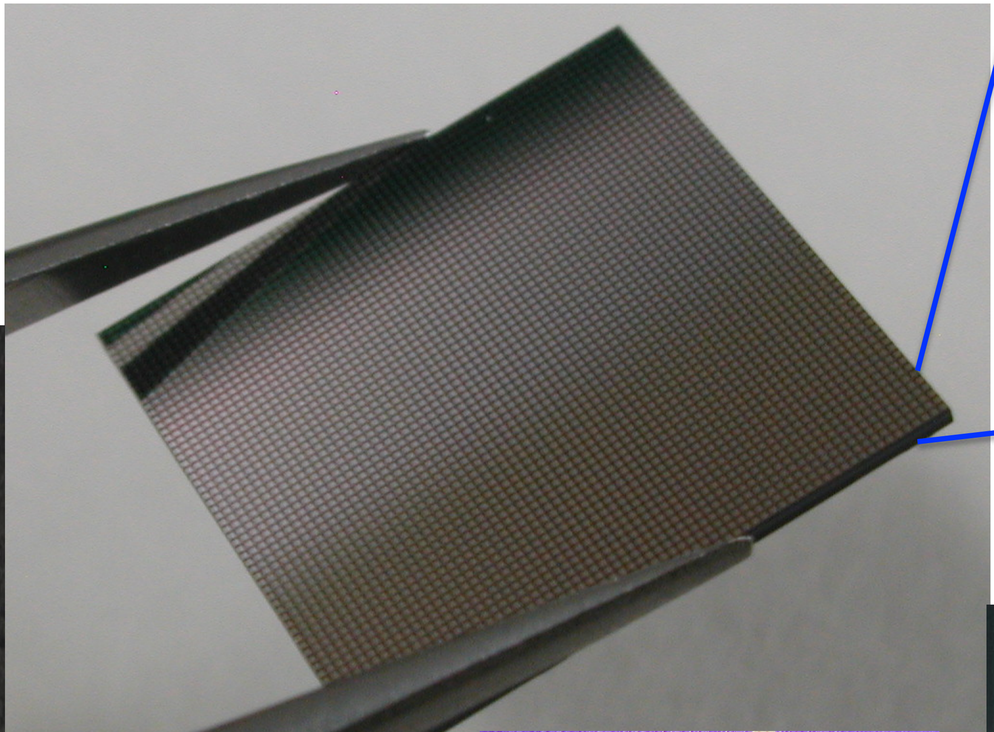


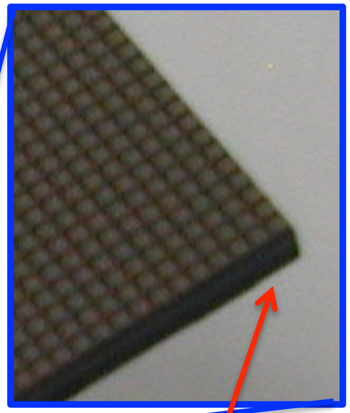
Examples of active-edge sensors



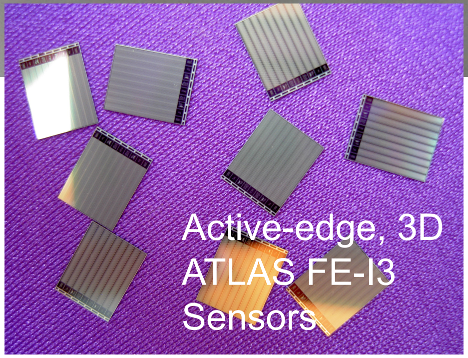




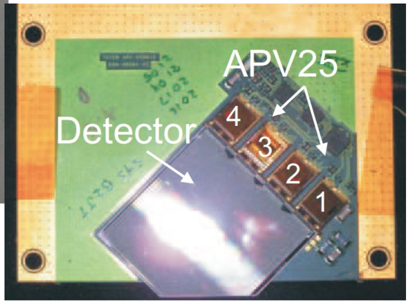




Plasma-diced
Active edge
Pixel sensor



Active-edge, 3D
ATLAS FE-I3
Sensors



Active-edge Planar
strip sensors

Active Edges

Many institutions are focused on this

Pursuing many variations

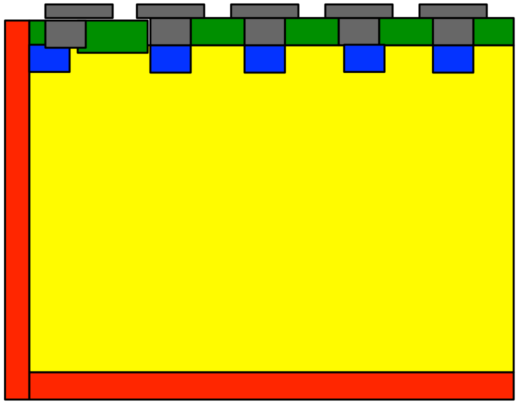
Already used some in photon science

Will be incorporated in growing fraction of HEP detectors

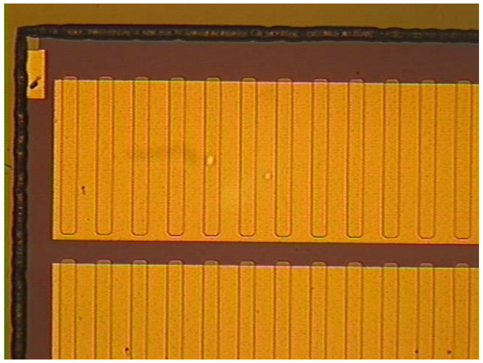
Front side Bias

Form abrupt junction to edge

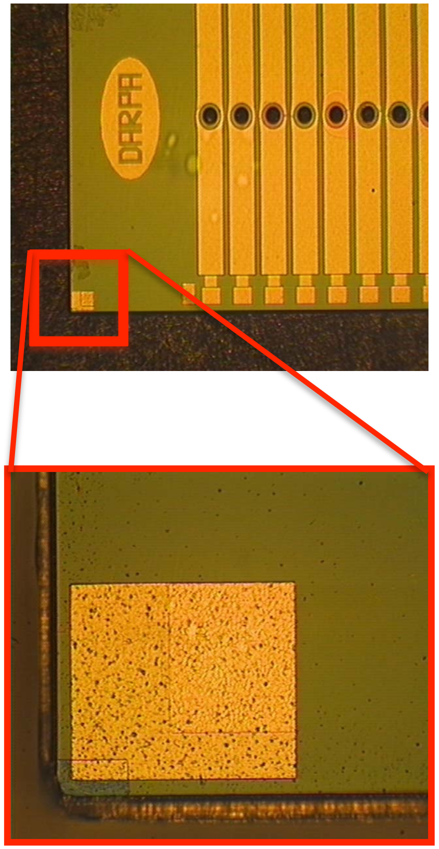
Carry potential to backside via doped active edge



🟥 Silicon bulk
🟧 n+ diffusion
🟦 p+ pixels
🟩 Oxide
⬛ Aluminum



FE-I4a prototype sensor



Front-side contact to supply backside bias via edge

Micro-cooling Channels

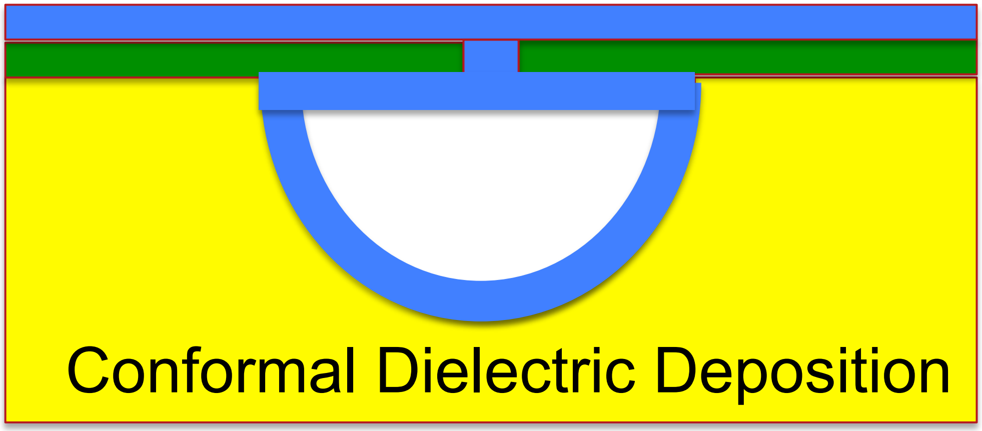
Done with
Shaday Edwards (St. Francis College
Joris van Heijningen (NIHKEF)

- Reduce mass within a vertexer
- Integrate the cooling pathways into the circuit chip
- Uses the silicon of the chip to both support the circuitry and serve as a coolant conduit
- Compatible with many different heat-carrying fluids

Self-sealing, cooling Channels

Done with
Shaday Edwards (St. Francis College
Joris van Heijningen (NIHKEF)

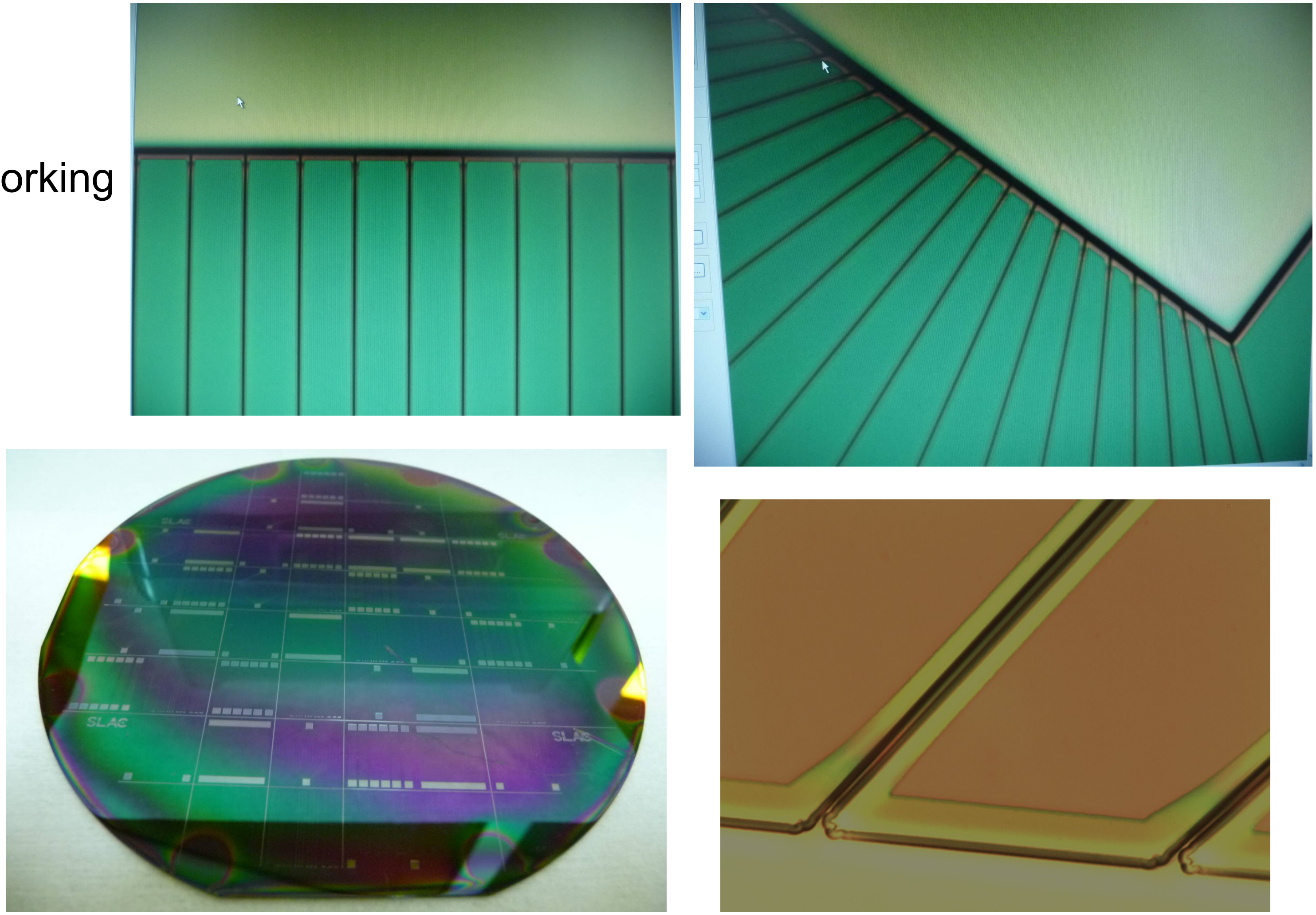
- Narrow apertures define channel geometry
- Isotropic etch via the apertures
- Deposit conformal film to seal apertures



Conformal Dielectric Deposition

Progress

Many groups working towards this

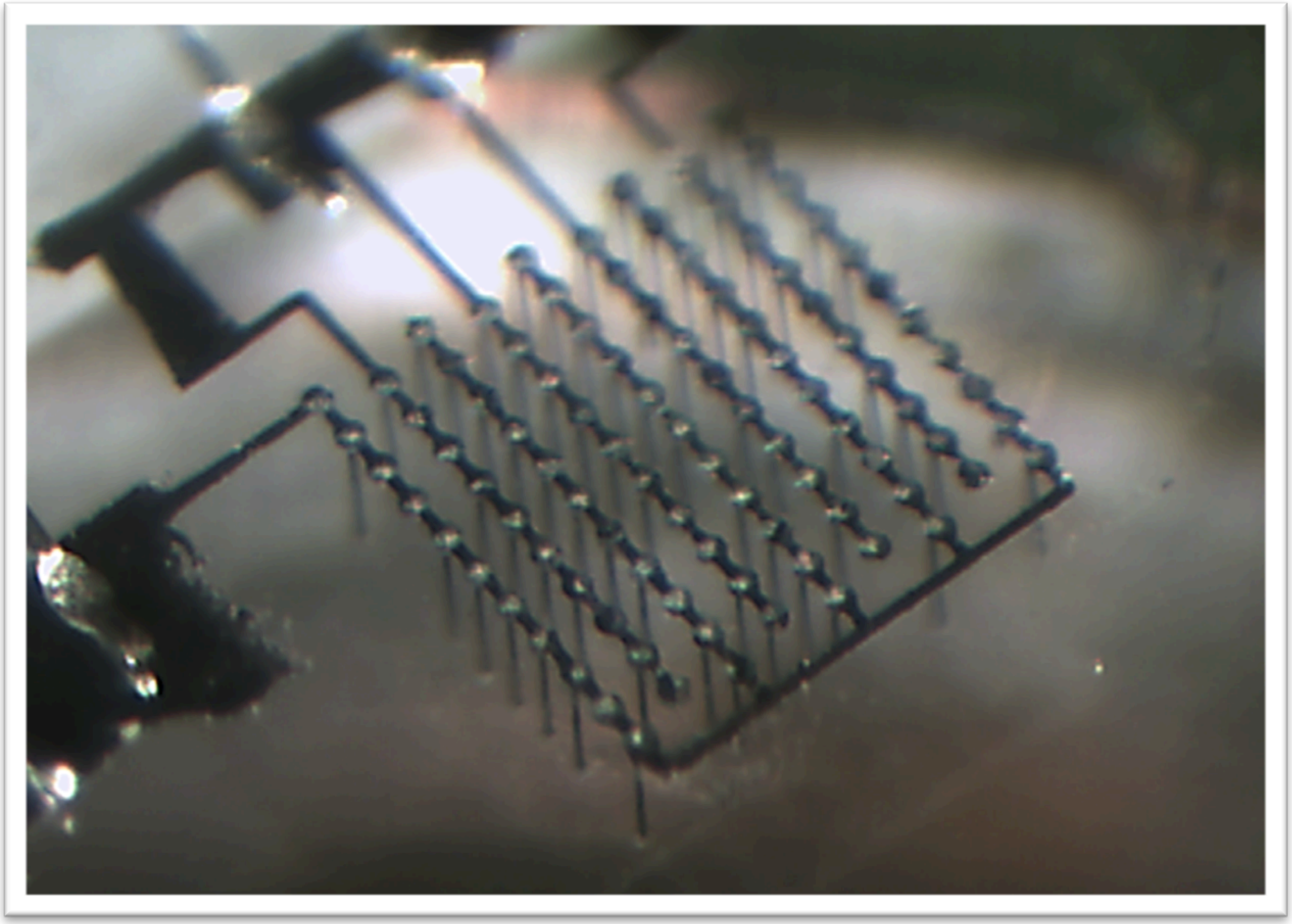


Extension to Diamond

Used femtosecond laser to form graphitized wires through diamond chips

Promising preliminary testbeam results

Manchester: A. Oh, S. Watts, M. Ahmed, C. Da Via, I. Haughton, V. Tyzhnevyi, D. Whitehead
Zuerich: L. Baeni, F. Bachmann, R. Wallney, D. Hits
Ohio: H. Kagan
CEA Saclay: B. Cayler, M. Pomorsji,
CERN: T. Wengler

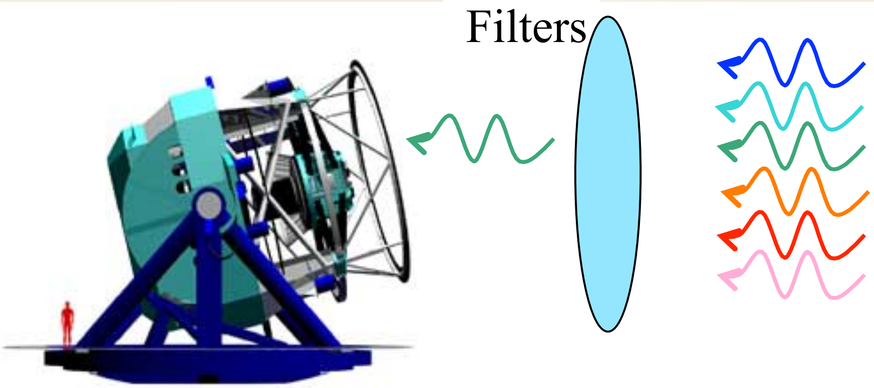


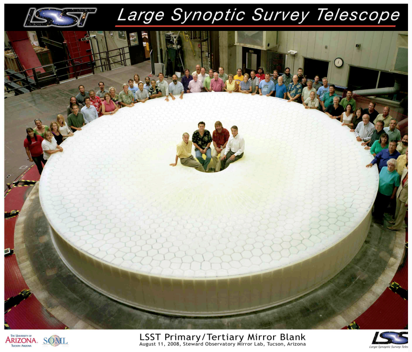
Survey telescopes

- Wide-area optical surveys for cosmology, such as SDSS, DES, LSST, all utilizing silicon optical sensors, CCDs or CMOS imagers combined with optical filters to determine some information about the spectral color of objects

- Determination of Photo-Z is critical for addressing many questions in cosmology

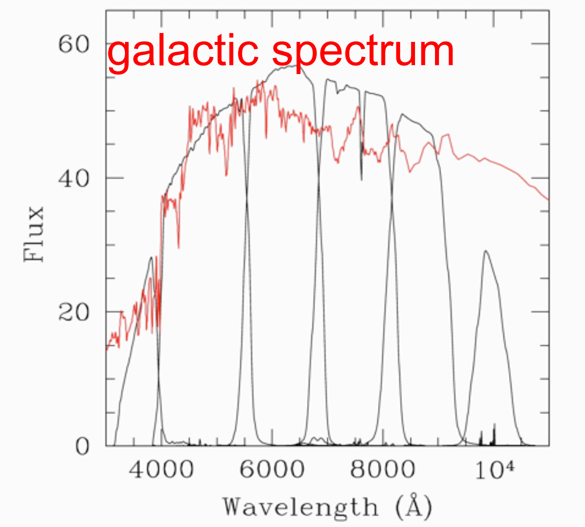
- SDSS and LSST use 5 and 6 filters, which respectively absorb 80% and 83% of the incident light.





LSST Primary/Tertiary Mirror Blank
August 11, 2008, Steward Observatory Mirror Lab, Tucson, Arizona

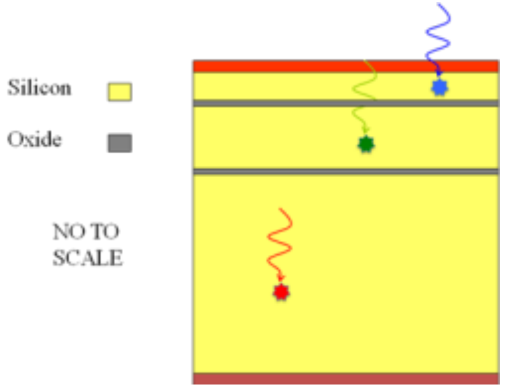
LSST filters

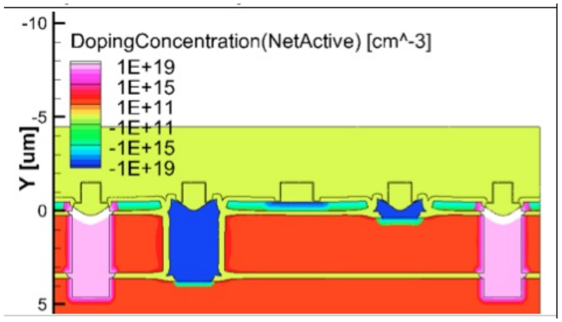


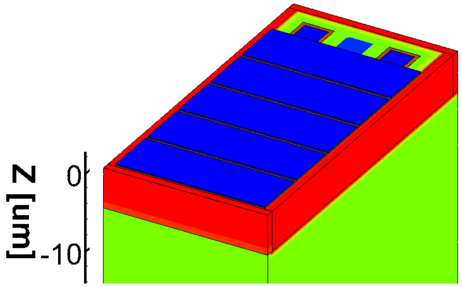
Chu-En Chang, J. Segal, R. Howe, A. Roodman

Multi-layer CCD - concept

- Clear need for color-sensitive sensors
- Replace monochromatic-CCD, filter-set combination with a polychromatic sensor.
- Use color-dependence of interaction depth in silicon.
- Basic idea is to make a multi-layer CCD
- All layers are clocked out simultaneously by the same set of gate electrodes
- Each layer readout separately, but simultaneously
- Employ micro-machining technology for channel stops and read-out contacts – similar to 3D sensors
- Alternative technologies use TES and MKIDs

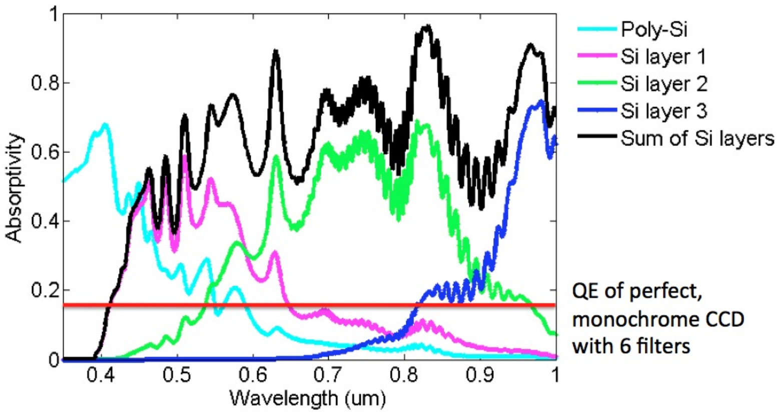




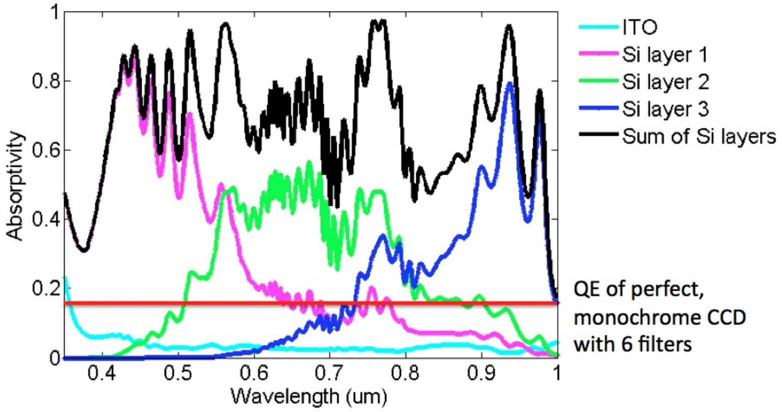


Multi-layer CCD

- Imager, which can record the intensity of light within multiple color bands and with high quantum efficiency
- Reduces the number of images to be taken -> Effectively increases light gathering ability of a telescope
- Easy to add more layers/colors
- Extension of standard CCD process
- Performed optical simulations, device simulations, process simulations, and begun fabrication of prototype devices
- Many other applications
- **Huge 4X improvement in effective system-level quantum efficiency**



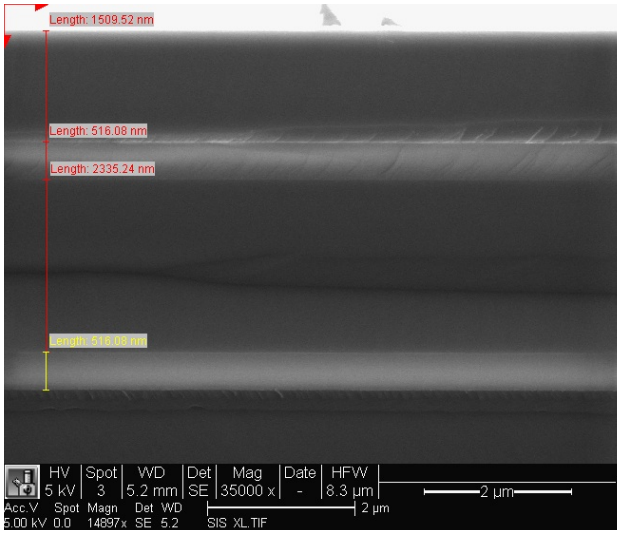
3-band with poly gates



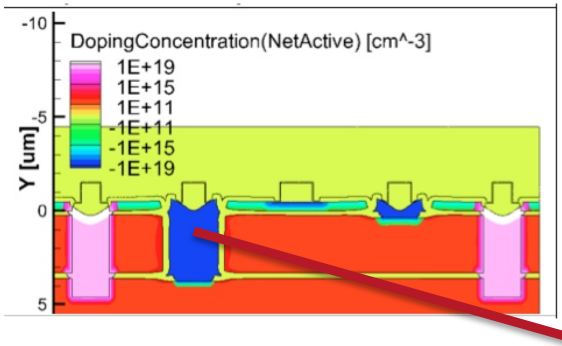
3-band with ITO gates

Multi-layer CCD - fabrication

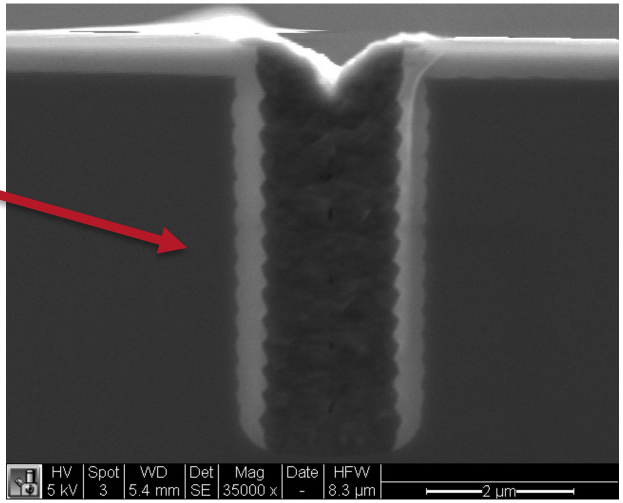
Fabrication of many layers of thin, float-zone silicon separated by oxide films done in partnership with local company



Channel-stop trenches same a used in 3D sensors



Isolated, conducting vias demonstrated



Complete prototype batch in early 2013

Near Term

- 3D silicon sensors routinely manufactured by several institutions
- Technology continues to improve
- Can be extended to HL-LHC fluences and time structure
- Possibility to incorporate internal signal gain
- Active edges/edgeless/slim edges could improve angular coverage in vertexers and trackers
- Internal gain enables thinner sensors
- Leading to other micro-machined features: thin sensors, μchannel cooling, novel CCDs, etc.
- Multi-band CCD may impact astrophysics and other fields
- Still an exciting dynamic period
- Lots of room left to explore in the creativity space associated with the third dimension