Si Detectors in Nuclear and High Energy Physics Experiments and BNL's Detector Development and Processing Capabilities

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*This research was supported by the U.S. Department of Energy: Contract No. DE-AC02-98CH10886

OUTLINE

- **Detector material and configurations**

- **Various Si detectors**
  - **Existing technologies (good for sPHENIX, 5 years)**
  - **New technologies (good for ePHENIX, 10 years)**
- **Detector processing facilities**
  - **National labs and universities**
  - **Commercial**
  - **BNL detector development and processing capabilities**
- **Summary**

Semiconductor Materials For Particle Detectors

	Density (g/cm^3)	Bandgap (eV)	Dielectric constant	Displace-ment threshold energy (eV)	e-h creation energy (eV)	μ_e (cm/s/V)	μ_h (cm/s/V)	# of e-h pairs/0.3% X_0
Si	2.3	1.12	11.9	13.5	3.6	1450 Good e mobility	450 Good h mobility	24k Good signal
C **(Diamond)**	3.5	5.5 Very low leakage current at RT	5.7 Small capacitance	80 Much less lattice damage	13-17	1800 Good e mobility	1200 Very good h mobility	7.2k Low signal
SiC	3.2	3.3 Low leakage current at RT	9.7	30 Less lattice damage	9	400-900 Modest e mobility	20-50 Poor h mobility	13k
Ge	5.3 Hi Z, good for hard X-ray	0.66 Hi leakage current at RT	16 Large capacitance	15	3	3900 Very good e mobility	1900 Very good h mobility	16k
CdTe	5.9 Hi Z, good for hard X-ray	1.49	10	6.7	5	1050 Good e mobility	100 Poor h mobility	6.6k Low signal

Why do we concentrate our efforts on Si detectors?

Si is by far the most used material for particle detectors for its:

- **Abundance on earth**
- **Mature and reproducible wafer manufacture**
- **Natural oxide for passivation and masking**
- **Mature processing technology (easy for segmentation, small segmentations and integration)**
- **Radiation hardness**
- **Used extensively and successfully in experiments**
- **Choices: use something exist and working (less cost) or something new requires R&D**

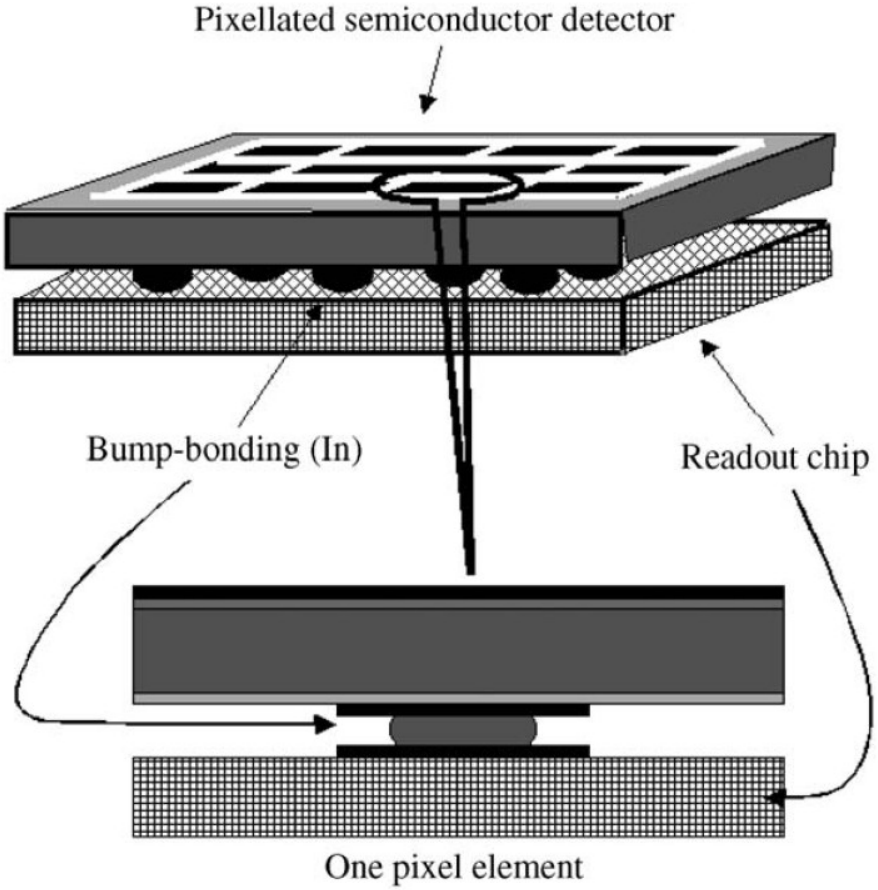
Semiconductor Detector Configuration (Conventional)

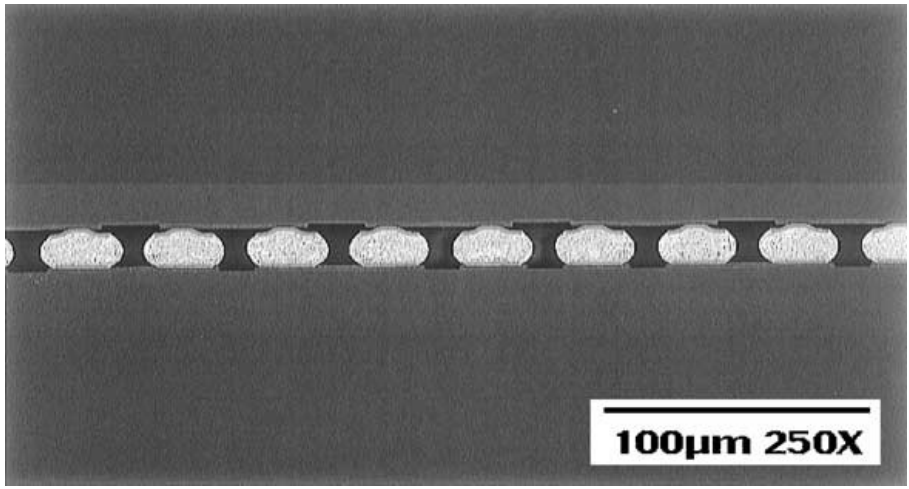
	Spatial Sensitivity	Mostly Used for	Rad-hardness	Processing	Readout
Pixel/Pad	2D Pixel size($\sqrt{A}$): 10 μm to mm's	HEP/NP	Good (small area – small leakage current)	Single-sided	Each pixel (fast, 10's ns)
Single-sided strip	1D Strip pitch: 10 μm to mm's	HE/NP	Modest	Single-sided	Each strip, e's or h's (fast, 10's ns)
Double-sided strip	2D Strip pitch: 40 μm to mm's	HE/NP	Not good (n-side not rad-hard)	Double-sided	Each strip, e's and h's (fast, 10's ns)
CCD (Charge-coupled-device)	2D Pixel size($\sqrt{A}$): >10's μm	X-ray and others (LSST)	Not good (very sensitive to trapping)	Single-sided	Each column (slow, μs's)
Drift (SDD) (Si drift detector)	2D Anode size >10's μm	X-ray and others (STAR, ALICE)	Not good (very sensitive to trapping, and to doping change)	Double-sided	Each anode, e's (slow, μs's)
AMPS (JFET) (Active matrix pixel sensor) **DEPFET (PMOS)** (Depleted P-channel FET) **Fully depleted**	2D Pixel size($\sqrt{A}$): ~100's μm	X-ray and others	Not good (very sensitive to trapping, and to doping change)	Double-sided	Each column (slow, μs's-ms)
MAPS (CMOS) (Monolithic active pixel sensor)	2D Pixel size($\sqrt{A}$): ~10 μm	X-ray and others HEP/NP (STAR)	Modest? (very low resistivity EPI Si)	EPI Si (20-50μm) SOI (fully depleted)	Each column (slow, μs's-ms)

Semiconductor Detector Configuration (new)

	Spatial Sensitivity	Mostly Used for	Rad-hardness	Processing	Readout
2D stripixel	2D Strip pitch: 10 μm to 100's μm s	HE/NP (PHENIX VTX)	Modest	Single-sided	Each strip (fast, 10's ns) (charge sharing)
3D stripixel	2D Strip pitch: 10 μm to 100's μm s D	HE/NP	Good	3D processing Single-sided or double-sided	Each strip, e's and h's (fast, <10 ns)
3D trench (pixel, strip, and stripixel), BNL, patent pending	2D Strip pitch: 100's μm to mm's	HE/NP X-ray	Very good	3D processing Single-sided or double-sided	Each pixel/strip, e's and/or h's (fast, <10 ns)

Pixel detector and ump-bonding technology (Used extensively, CERN, RHIC, etc.)

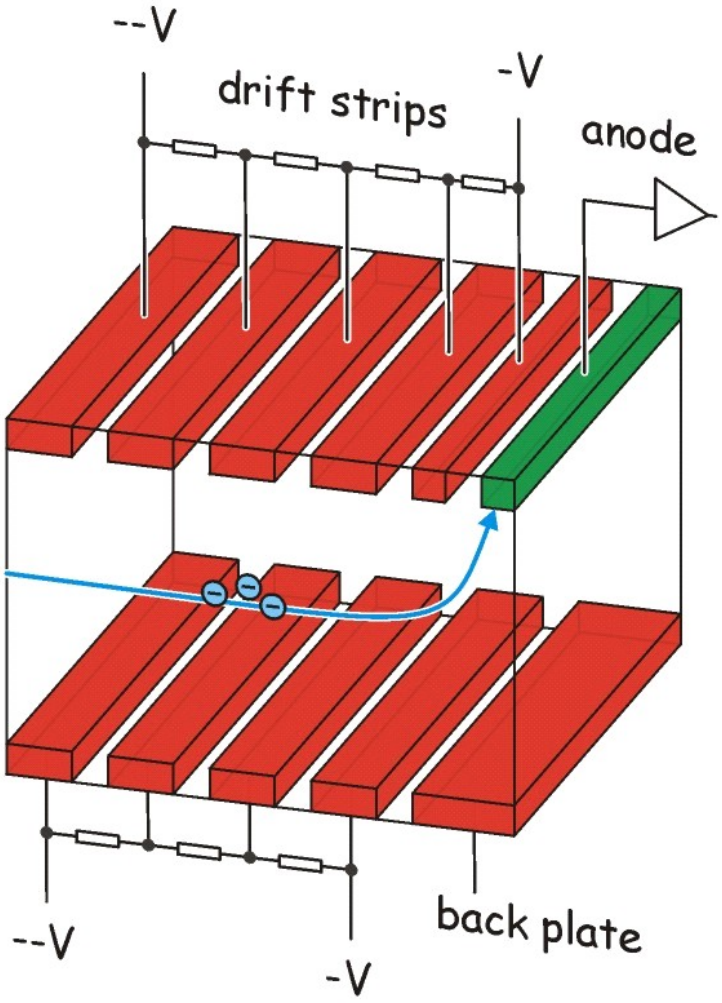


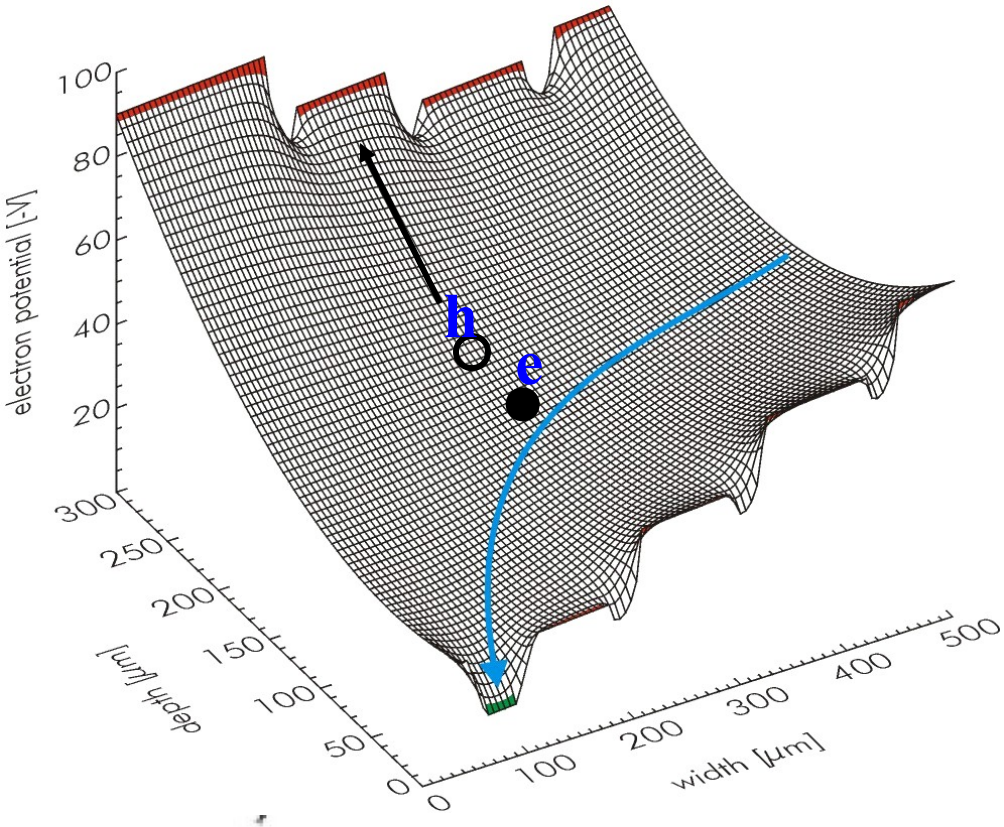


Solder bumps on a fluxless MCNC detector

S. Cihangir, S. Kwan
NIM A 476 (2002) 670–675

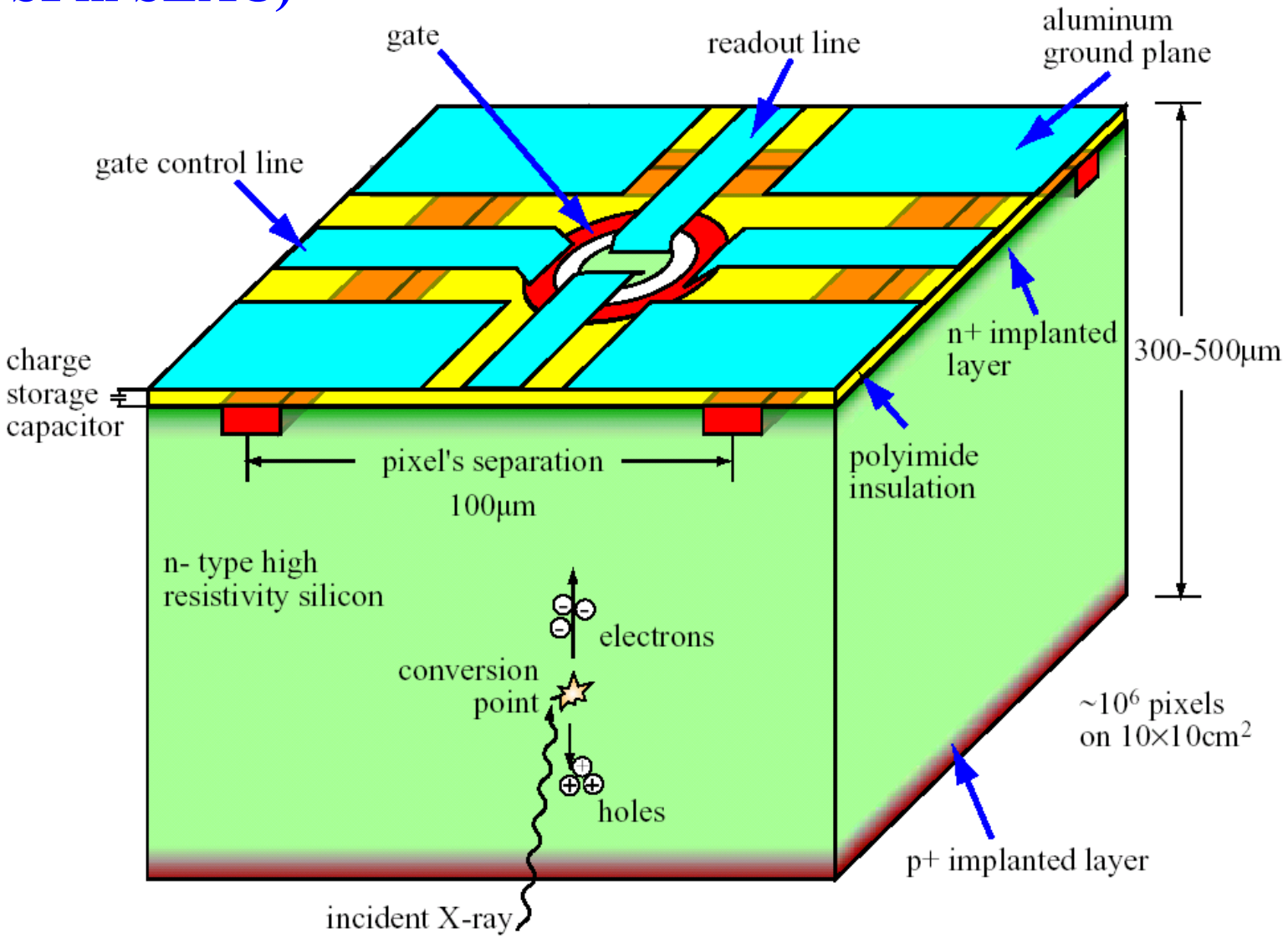
Si Drift Detector (SDD) (STAR, ALICE, X-ray, etc.)





E. Gatti and P. Rehak, "Semiconductor Drift Chamber" – An application of a novel Charge Transport Scheme", Nucl. Instr. and Meth., A 255, pp. 608-614, 1984.

X-ray Active Matrix Pixel Sensor (XAMPS, BNL)
(LUSI in SLAC)

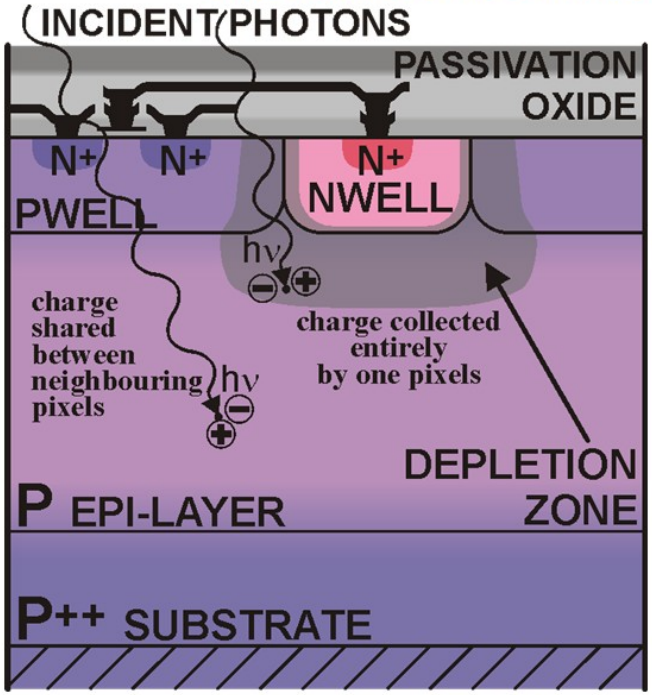


Monolithic Active Pixel Sensor (MAPS)-CMOS (STAR)

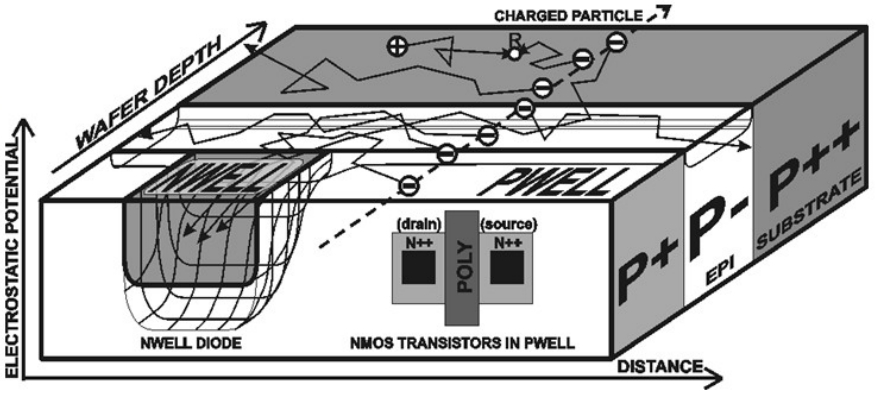
CMOS Image sensors in HEP - MAPS

- Operation principle of photodiode MAPS

Monolithic Active Pixel Sensors (MAPS)



structure proposed for visible light allowing 100% detection efficiency (tracking!)



operation:

- signal generated in epitaxial layer (low doping) $Q \approx 80 e^- h^+/\mu m \Rightarrow \sim 1000 e^-$,
- charge collection through thermal diffusion,
- signal sensed as voltage drop on N-WELL anodes,
- reflection bondaries at P-WELL and P-SUB.

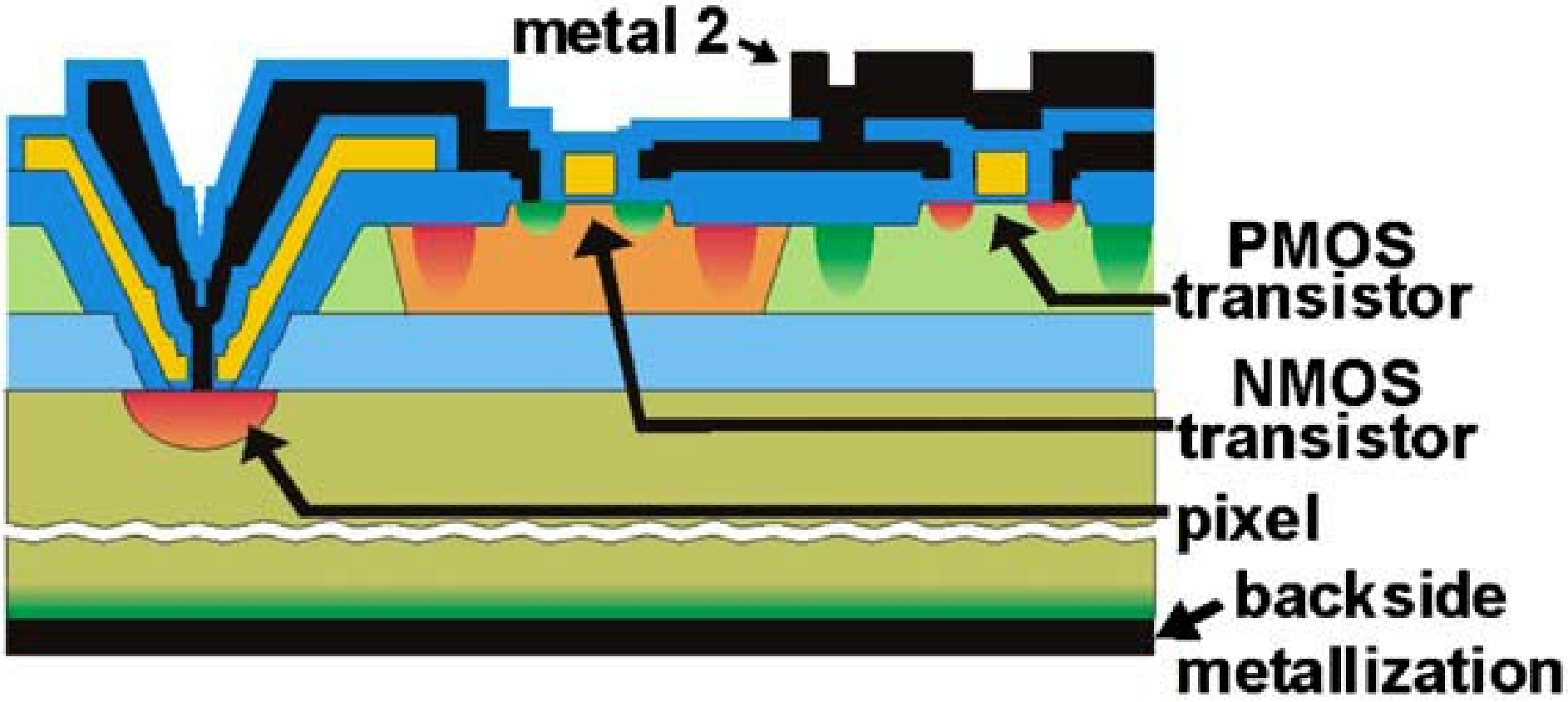
ADVANTAGES:

decoupled charge sensing and signal transfer (improved radiation tolerance, random access, etc.), small pitch (high tracking precision), low amount of material, fast readout, moderate price, SOC, etc.

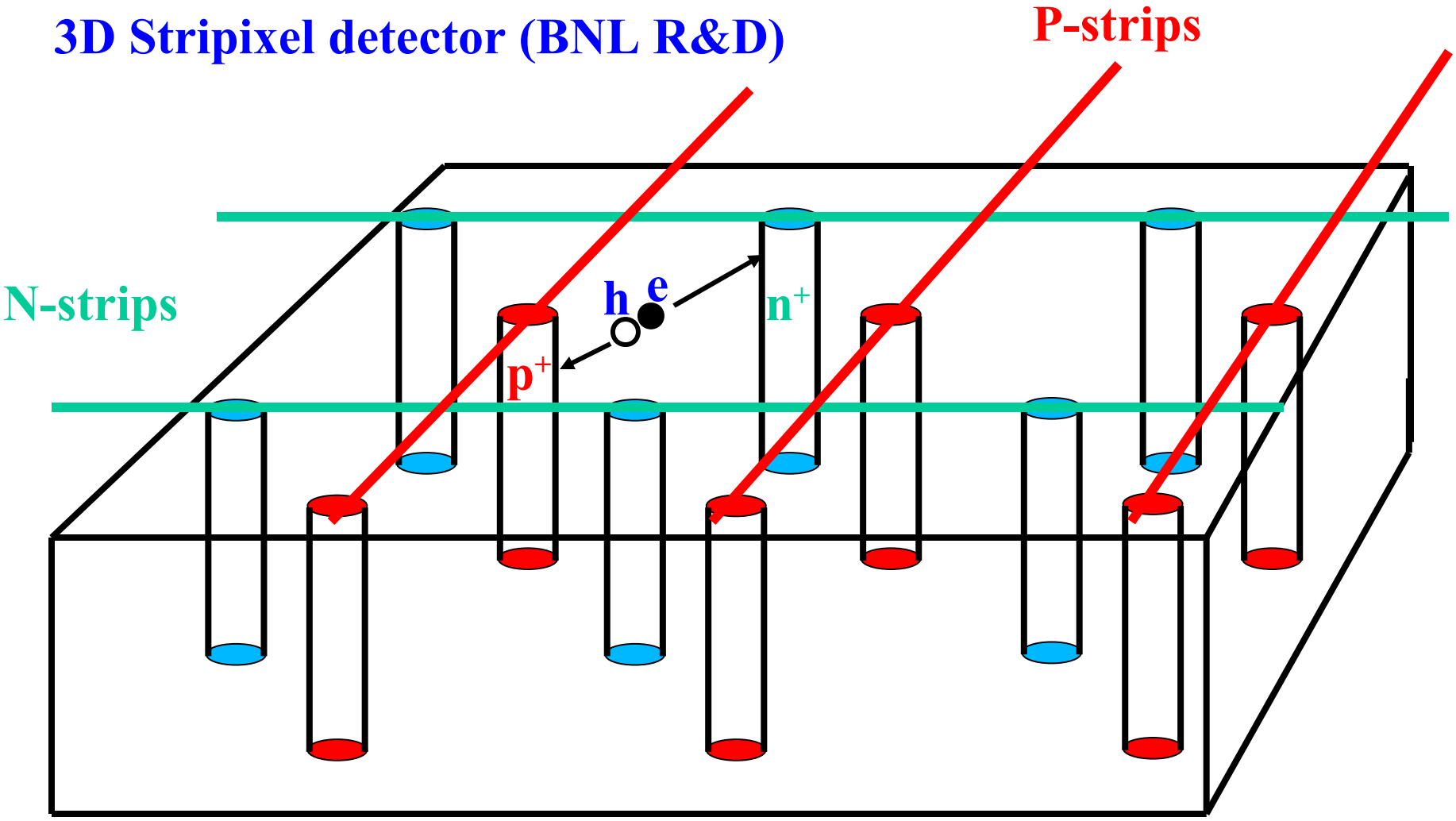
BROOKHAVEN NATIONAL LABORATORY

MAPS-SOI (R&D)

J. Marczewski et al., NIM A 549 (2005) 112–116



3D Stripixel detector (BNL R&D)



No charge sharing

ePHENIX

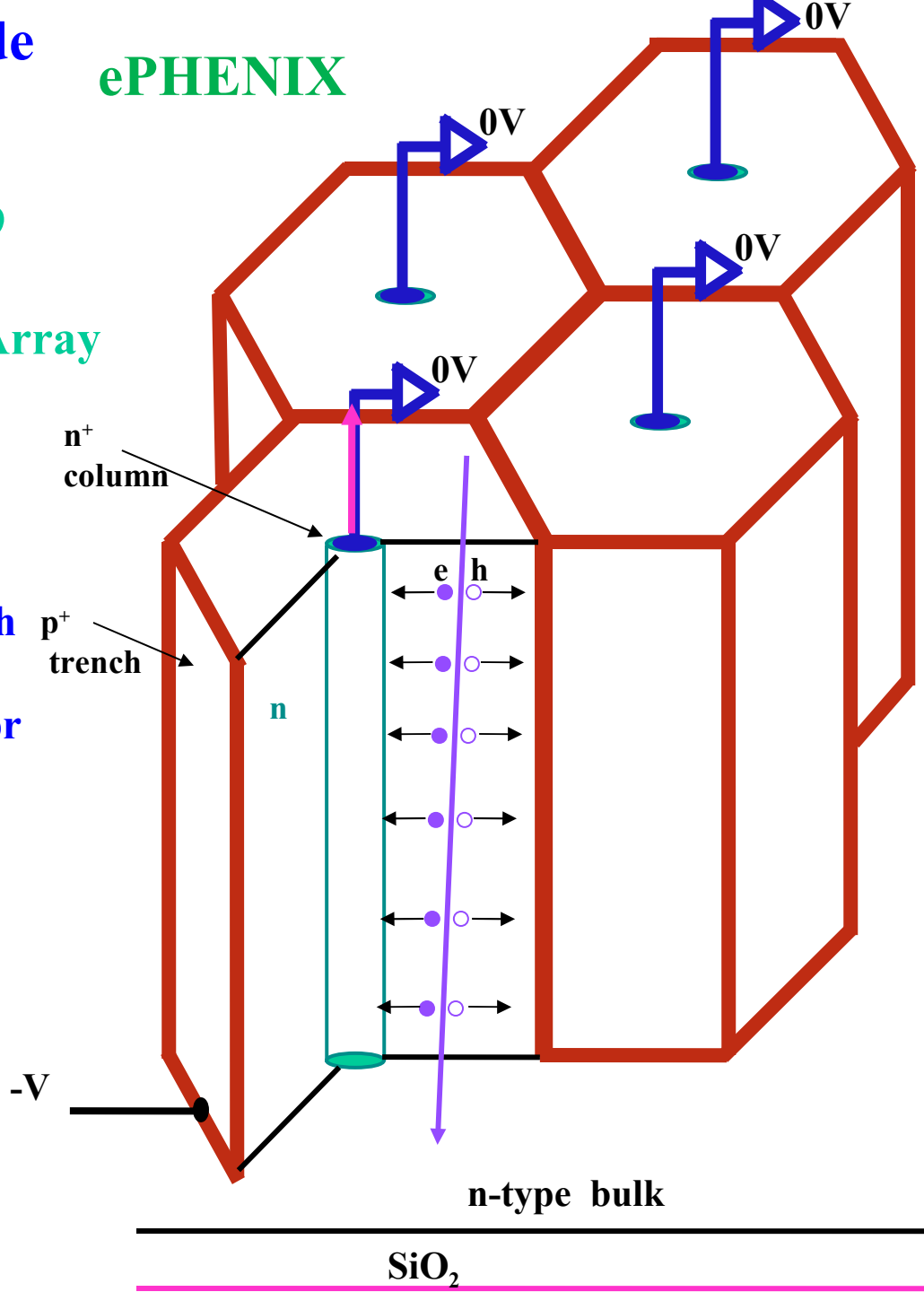
- **BNL's 3D-Trench Electrode Detector (R&D)**
  - New 3D-Trench electrode configuration (Z. Li, 10/2009 BNL)

or Independent Coaxial Detector Array (ICDA)

- Mask set has been design and made
- Processing of the first prototype batch will start in 10/2010 at CNM
- First prototype batch will be ready for testing in May 2011.

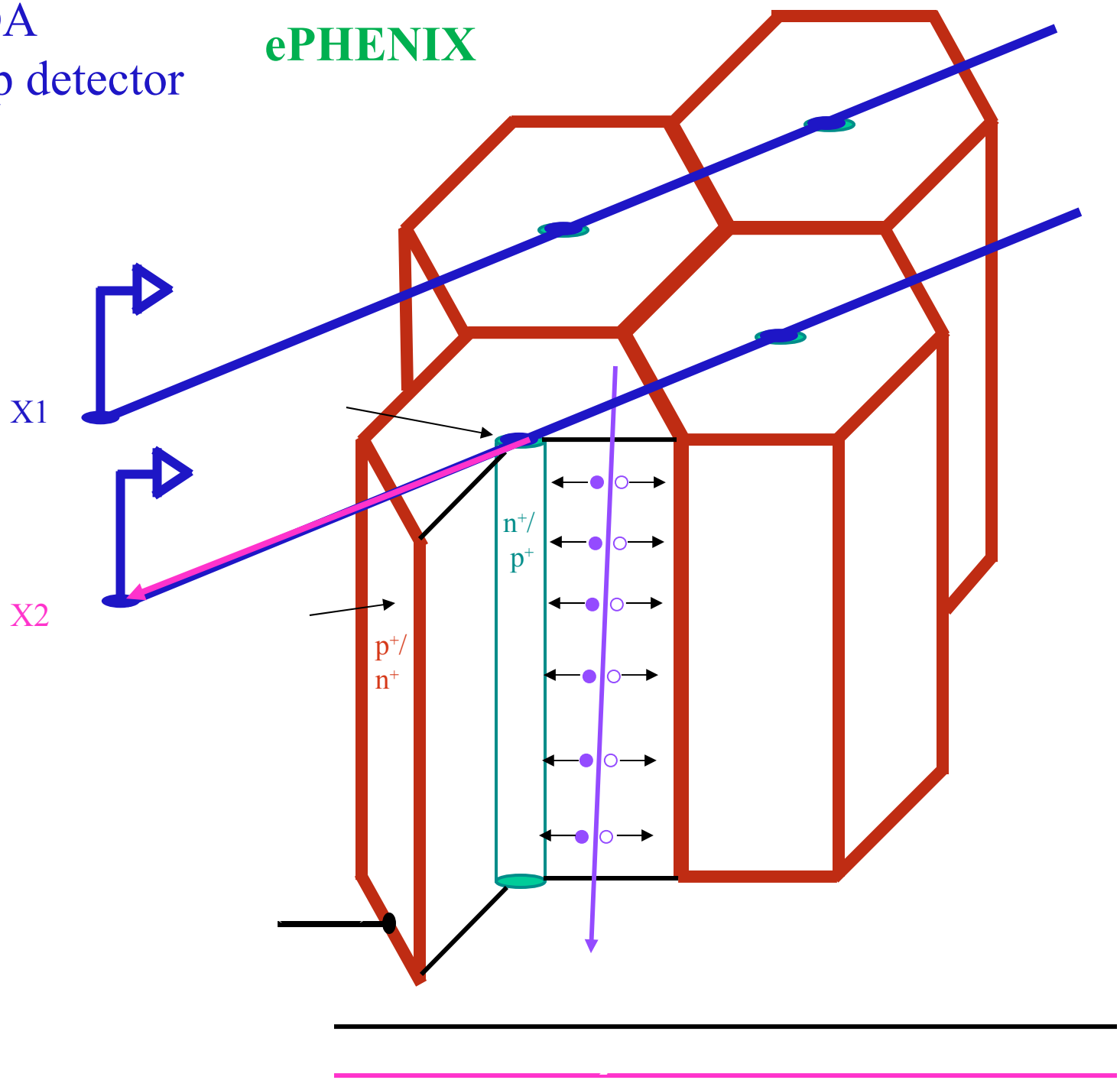
BNL new 3D-Trench Electrode detector

CT filed on 10/15/2010
CT/US2010/52887)



ICDA
Strip detector

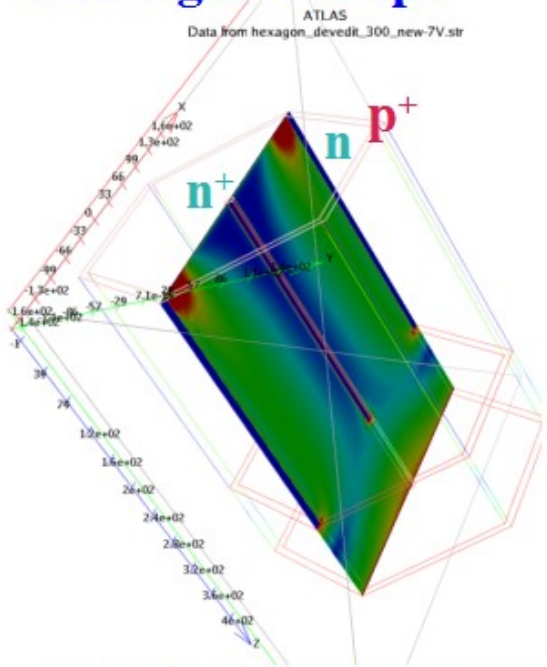
ePHENIX



3D simulations of electric field

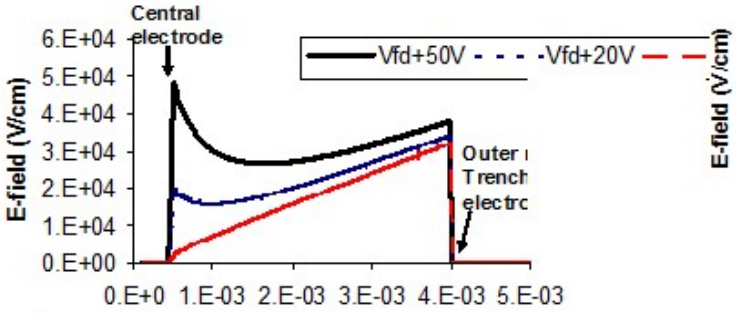
Hexangular shape

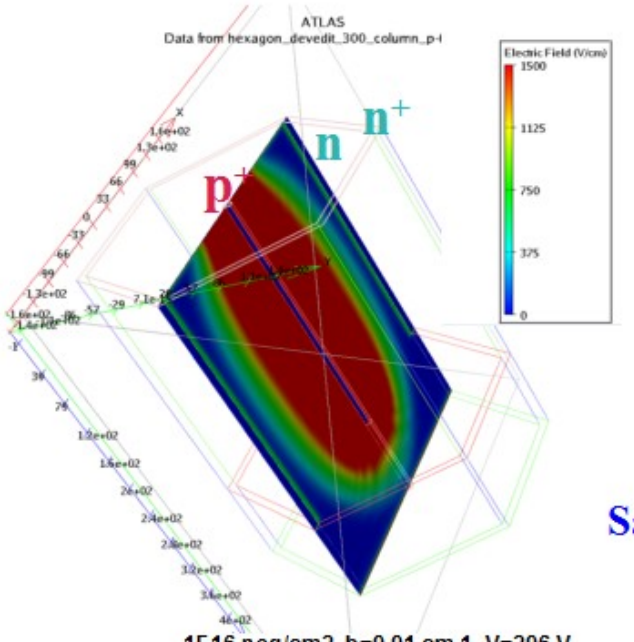
ePHENIX



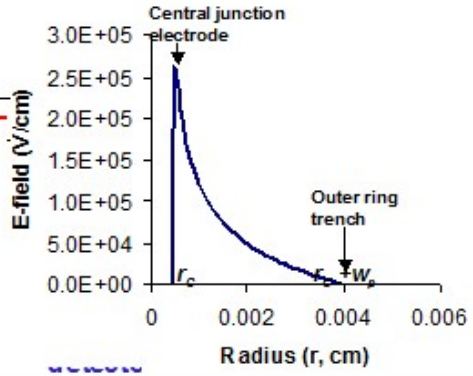
1E16 neq/cm2, b=0.01 cm-1, Vfd=59 V

3D-Trench-ORJ, R = 40 um

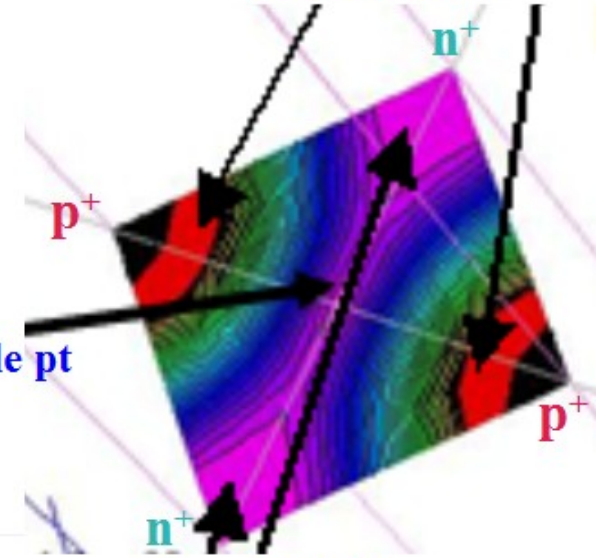




1E16 neq/cm2, b=0.01 cm-1, V=206 V



High E-field



Saddle pt

Low E-field

BNL 3D-Trench (Trench Junction)	BNL 3D-Trench (Column Junction)	Early 3D
Full depletion voltage (150 µm electrode spacing):		
8 V, very uniform	52 V, uniform	>52 , very non-uniform

- **Detector Processing Facilities -1**

University and National Labs

	Main Detector Technology	Main Material	Wafer size	Particle Physics related
BNL USA	Pixel, Strip/Stripixel SDD, AMPS 3D (Development, simulation, and design)	Si	4", 6"	US ATLAS CERN RD39 CERN RD50 RHIC (X-ray det for photons)
CNM Spain	Pixel, Strip, 3D	Si	4"	ATLAS CERN RD50
HIP Finland	Pixel Strip	Si	4"	CMS CERN RD39 CERN RD50
LBL USA	Fully-depleted CCD, Strip	Si, Ge	4"	X-ray Astrophysics
MPI Halbleiterlabor Germany	Pixel, Strip, SDD AMPS, DEPFET	Si	4", 6"	X-ray Astrophysics

- **Detector Processing Facilities -- 2**

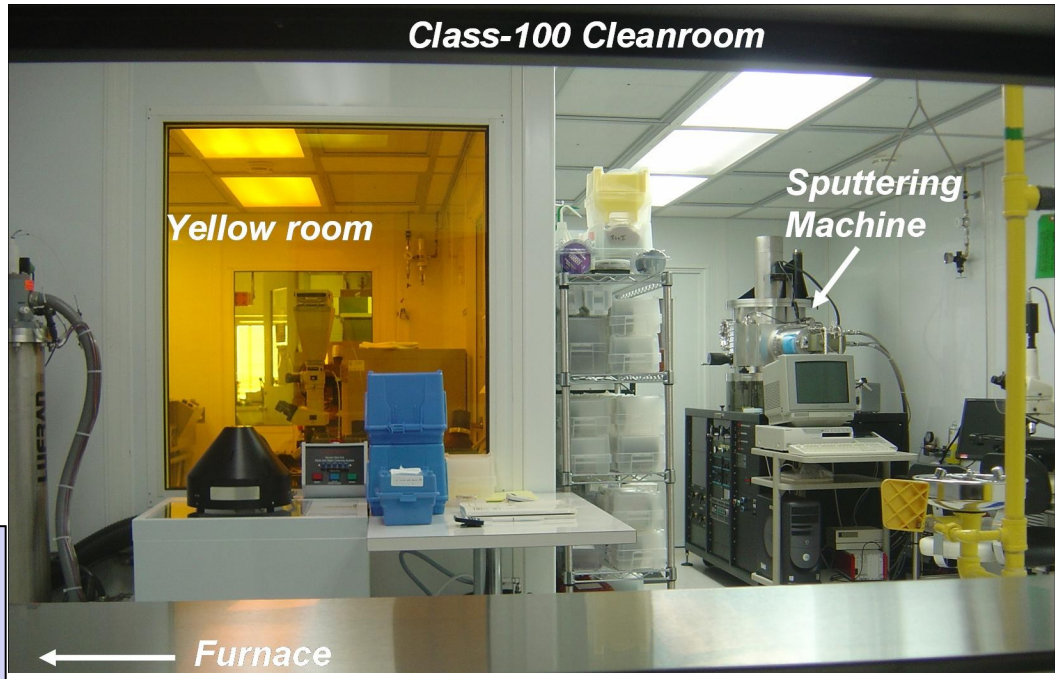
Commercial

	Main Detector Technology	Main Material	Wafer size	Particle Physics related
CiS-MSP Germany	Pixel, Strip	Si	4”	CERN RD50
FBK-IRST (Trento) Italy	Pixel, Strip, 3D	Si	4”, 6”	CERN RD50
Hamamatsu Japan	Pixel, Strip, Stripixel (No double-sided)	Si	4”, 6”	LHC/sLHC
KETEK Germany	SDD AMPS	Si	4”, 6”	X-ray
Micron Semiconductors UK	Pixel Strip	Si	4”, 6”	CMS CERN RD39 CERN RD50
SINTEF Norway	Pixel, Strip, 3D	Si	4”, 6”	ATLAS

BNL Si Detector R&D Program

- Scientific and engineering resources in the Instrumentation Div.
- Silicon detector processing facility

- Detector fabrication capability:
  - Process and device simulation
  - Detector and mask design
  - Processing steps (oxidation, photolithography, metallization)
  - Testing and characterization

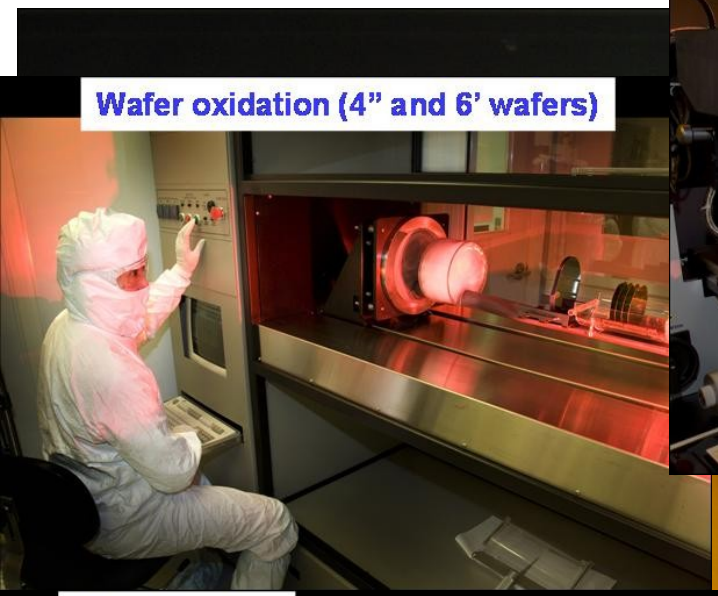


Detector R&D

Silicon Drift Detectors
Stripixels, strip, and pixel
Radiation resistant Silicon
XAMPS
For NP,HEP, Photon science

- **Fabrication**

550 ft² Class-100 cleanroom



Furnace

Summary

- Si detectors are still the detector of choice for NE, HEP, and photon sciences

- Many detector configurations and technologies are readily available for application needs (sPHENIX)

- New 3D technology and detectors are now developed, and can be used for future applications (ePHENIX)

- BNL is at the forefront of the prototype and novel detector development and fabrications