Semiconductor Detectors in High Energy Physics Experiments --- Radiation Limitations and Rad-Hard Technologies

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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**
- **Radiation induced degradation in Si detectors**
- **Current Rad-hard technologies (LHC and sLHC)**
  - **Material/Impurity/Defect engineering**
  - **New electrode configurations**
- **New Rad-hardness technologies (sLHC and beyond)**
  - **Current-injected-diodes (CID)**
  - **Charge multiplication**
  - **New 3D-Trench electrode detectors**
- **Detector processing facilities**
- **Collaborations between US National Labs and universities**
- **Summary and future needs**

Semiconductor Materials For Particle Detectors

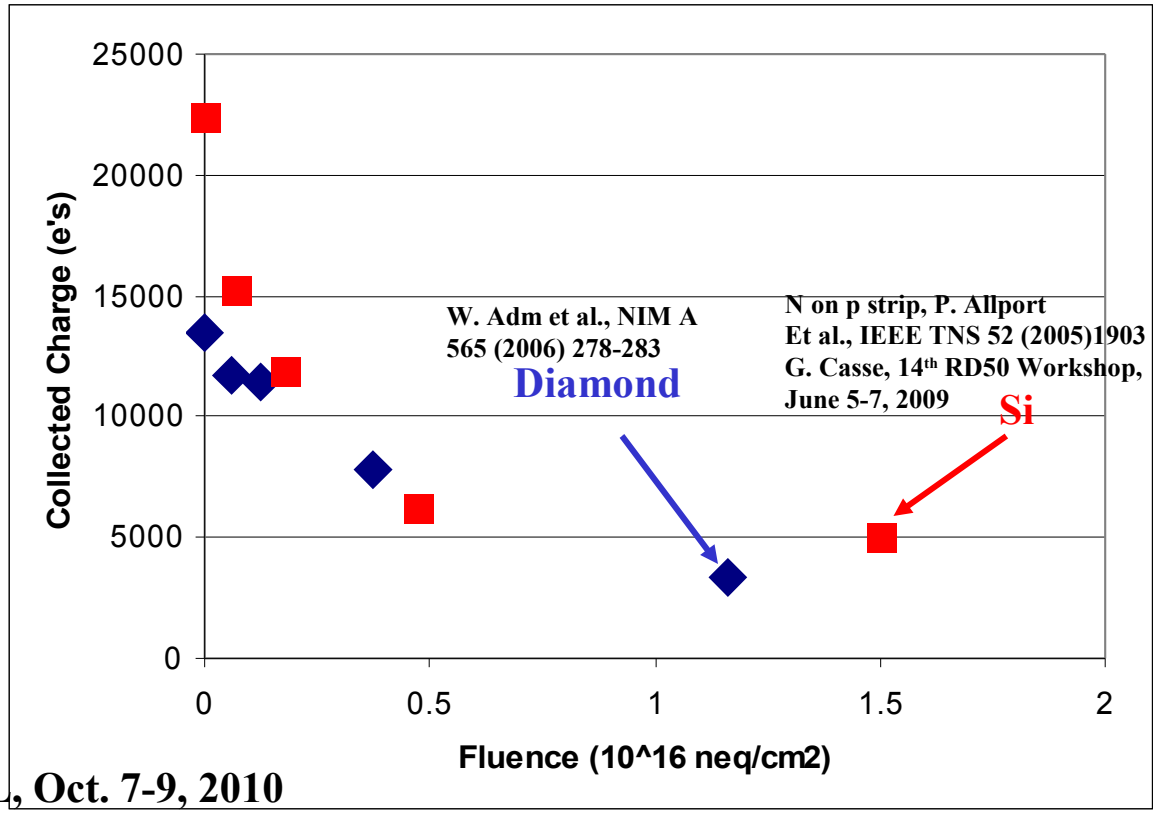
	Density (g/cm³)	Bandgap (eV)	Dielectric constant	Displace-ment threshold energy (eV)	e-h creation energy (eV)	μ_e (cm/s/V)	μ_h (cm/s/V)	# of e-h pairs/0.3% X_0
Si	2.3	1.12	11.9	13.5	3.6	1450 Good e mobility	450 Good h mobility	24k Good signal
C (Diamond)	3.5	5.5 Very low leakage current at RT	5.7 Small 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

At extremely high radiation fluences, Si is as hard as other semiconductor materials in charge collection

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
- Radiation hardness



Semiconductor Detector Configurations

	Spatial Sensitivity	Mostly Used for	Rad-hardness	Processing	Readout
Pixel	2D	HEP/NP	Good (small area – small leakage current)	Single-sided	Each pixel (fast, 10's ns)
Single-sided strip	1D	HE/NP	Modest	Single-sided	Each strip, e's or h's (fast, 10's ns)
Double-sided strip	2D	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	X-ray and others	Not good (very sensitive to trapping)	Single-sided	Each column (slow, μs's)
Drift (SDD) (Si drift detector)	2D	X-ray NP and others	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	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	X-ray and others HEP/NP	Modest? (very low resistivity EPI Si)	EPI Si (20-50μm) SOI (fully depleted)	Each column (slow, μs's-ms)

Radiation induced degradation in Si detectors

1. Leakage current

	Introduction rate at 20 °C $J = \alpha \Phi_n$	Temp dependence $J(T)/J(T_0) = \exp[-E_a/k(1/T - 1/T_0)]$	% of annealed out at 24 °C in 10 min	% of annealed out at 24 °C in 65 hrs	% of annealed out at 24 °C in 588 days
	α=4-6x10^{-17} A/cm	E_a = 0.65 eV	30	60	95

2. Bulk resistivity

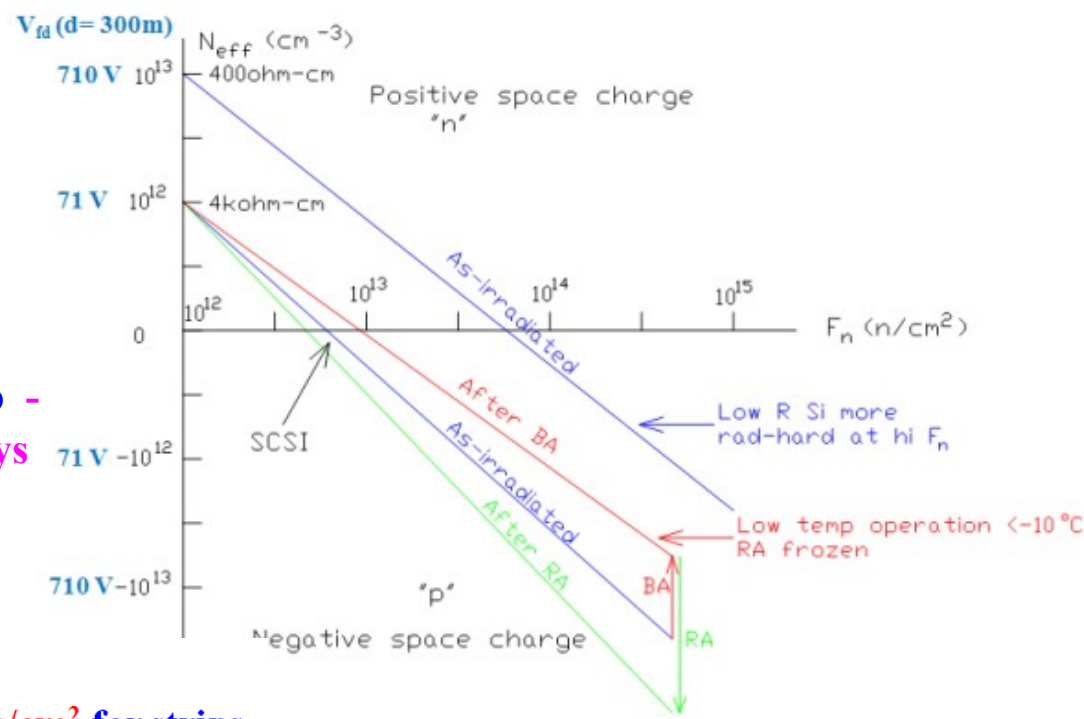
Si bulk resistivity increases with Fluence and saturates near the intrinsic value of about 300 k Ωcm

3. Space charges

- Space charge sign inversion (SCSI): + to -
- Beneficial annealing (BA), τ (RT) = 10 days
- Reverse annealing (RA), τ (RT) ≈ 1 year

$N_{eff} \sim - b\Phi_n$,

b= 0.02 for standard Si material



For 10 years LHC operation:

Total fluence: >10^{15} n/cm^2 for pixels, and > 10^{14} n/cm^2 for strips

For SLHC, it is about 10 times larger

Radiation induced degradation in Si detectors

4. Charge collection efficiency

$$d^e_{CCE} = v^e_{dr}\tau^e_t$$

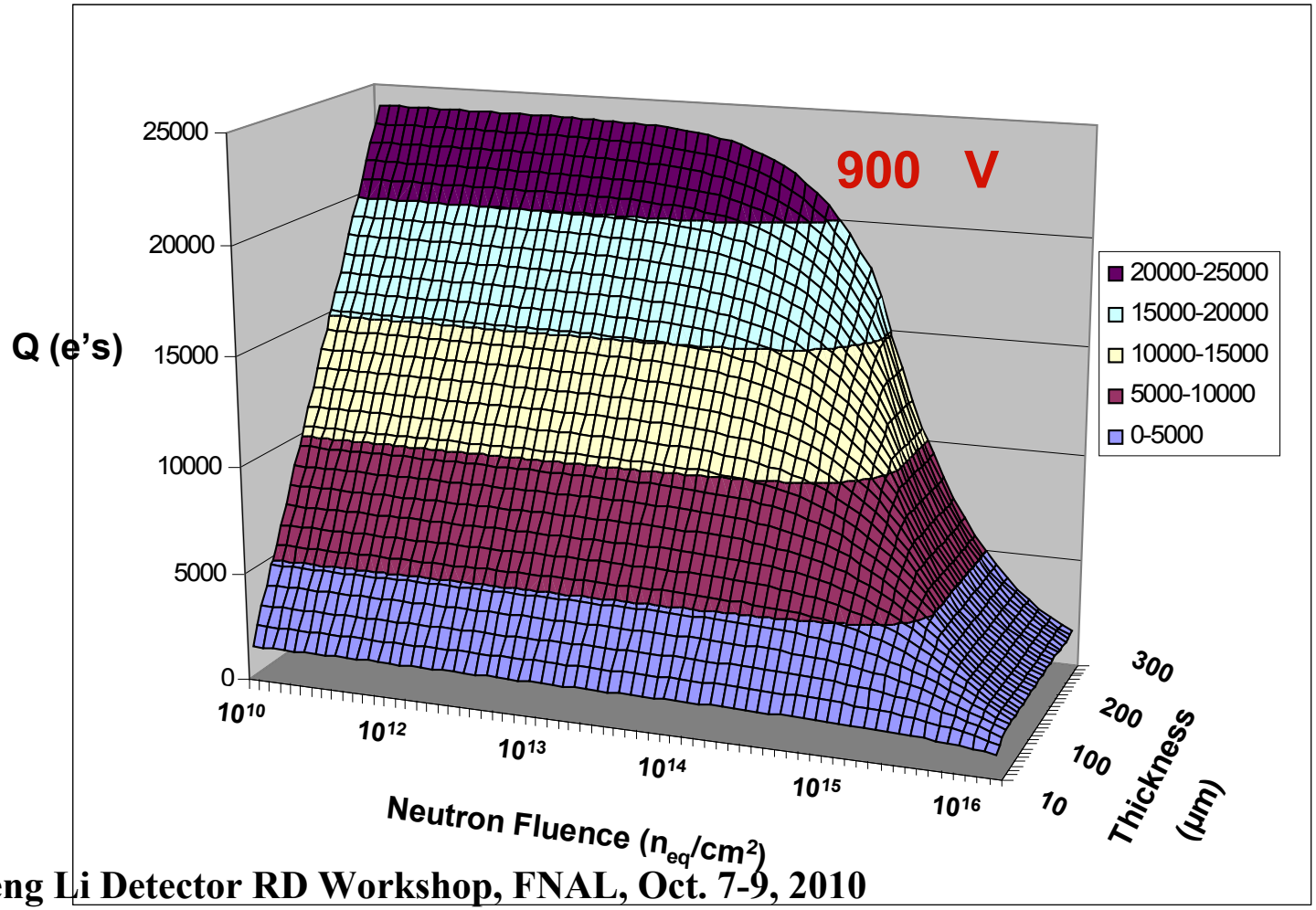
$$d^h_{CCE} = v^h_{dr}\tau^h_t$$

Charge collection or trapping distance

At 10^{16} n_{eq}/cm^2 (sLHC fluence for pixels/10 years) τ_t=0.2ns:

$d_{CCE} = v_{dr} \cdot \tau_t \leq v_s \cdot \tau_t \approx 20$ **μm (10^{16} n_{eq}/cm^2), near RT, no anneal**

$$Q_{2D} = 80 * (d^e_{CCE} + d^e_{CCE}) = 160 * 20 = 3200 e's$$



Very little effect of Q on detector thickness d for d> 100 μm near 10^{16} n_{eq}/cm^2

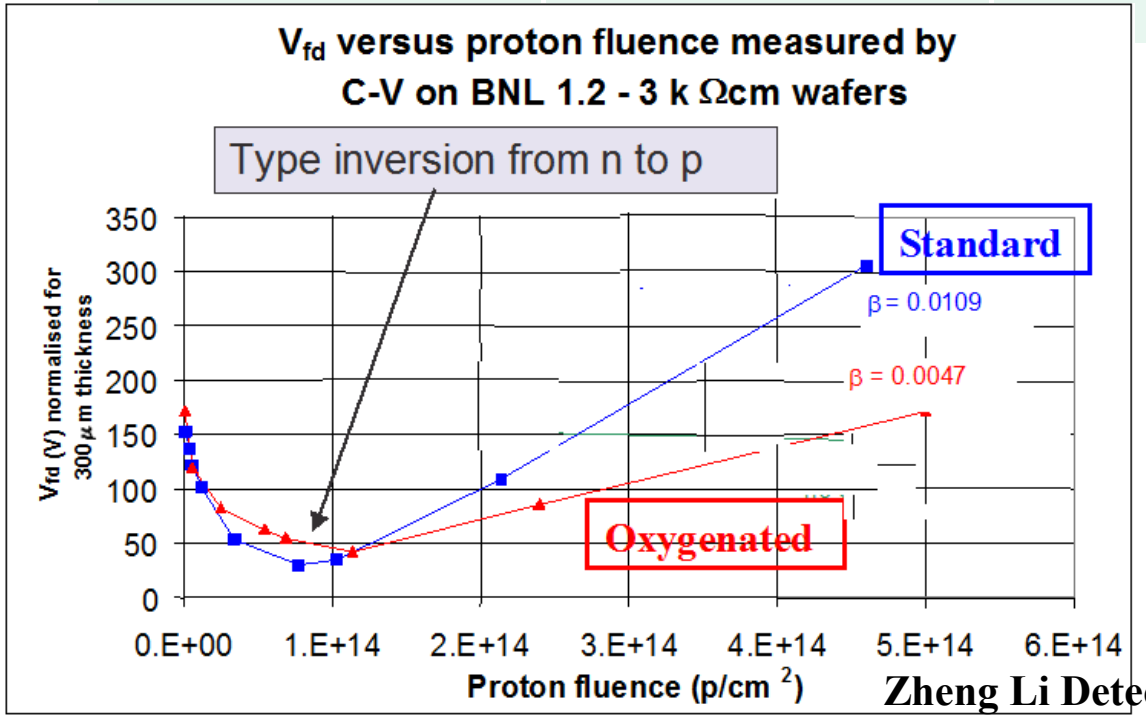
Very little effect of Q on bias V, for V> 900 V near 10^{16} n_{eq}/cm^2

• Current Rad-hard technologies (LHC and sLHC)-1

• Material/Impurity/Defect engineering

Oxygenated Si (O to getter the rad-induced defects)

Oxygenated Si	Process	[O]	Rad-hardness
HTLT (BNL) DOFZ (CERN RD48)	1150 to 1200 °C oxidation 24 to 216 hrs in O_2 (or N_2 after oxidation)	$4\text{-}5\times10^{17}/cm^3$ Uniform throughout the thickness (300 μm)	The rate of V_{fd} increase with fluence reduced by factor of 2 (charged particles only: p, π), not n
MCZ (HIP, BNL) (Magnetic Czochralski)	Crystal pulled in magnetic field	$\sim10^{18}/cm^3$ Uniform (~1k Ω–cm n-type 2k Ω–cm p-type)	The rate of V_{fd} increase with fluence reduced by factor of 3-4 (charged particles only: p, π), not n



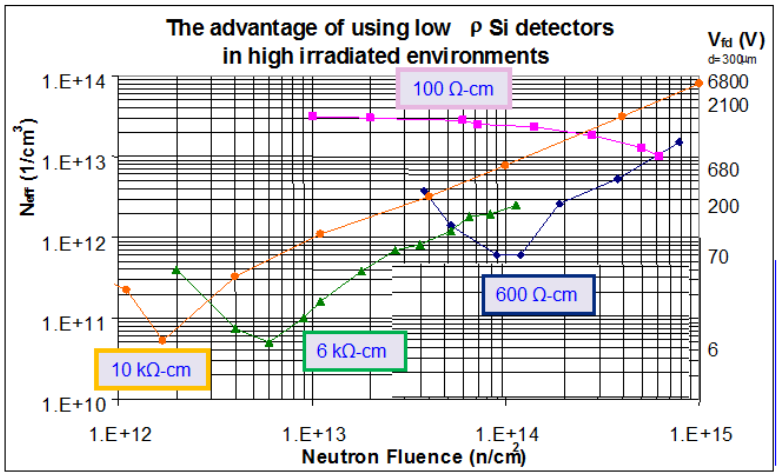
• Current Rad-hard technologies (LHC and sLHC)-2

• Material/Impurity/Defect engineering

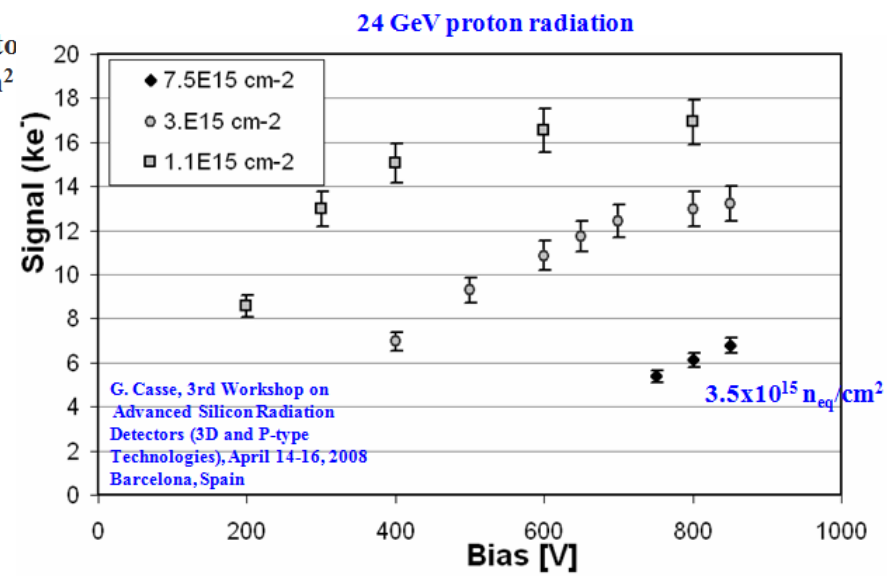
Non-conventional materials

Material type	SCSI (Space charge sign inversion)	Other rad-hard items
Low resistivity n-type Si (BNL)	Delayed inversion	Lower V_{fd} at high fluence than STD high resistivity Si
p-type Si (Liverpool, CERN RD50)	No inversion	Collection of e's slightly higher CCE than n-type

For relatively thin (~100 μm), low resistivity (100 Ω-cm) silicon, the detecto can be fully depleted at bias of 250 V in the fluence range of ~3x10^{15} n/cm^2



Type inversion occurs at a higher fluence with lower resistivity Silicon



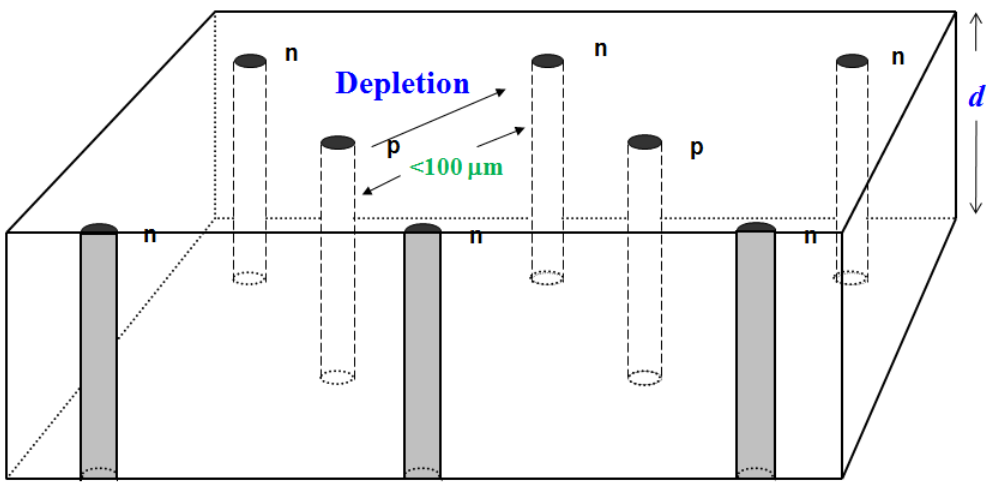
- **Current Rad-hard technologies (LHC and sLHC)-3**
  - **Detector structure engineering**

Non-conventional detector structures

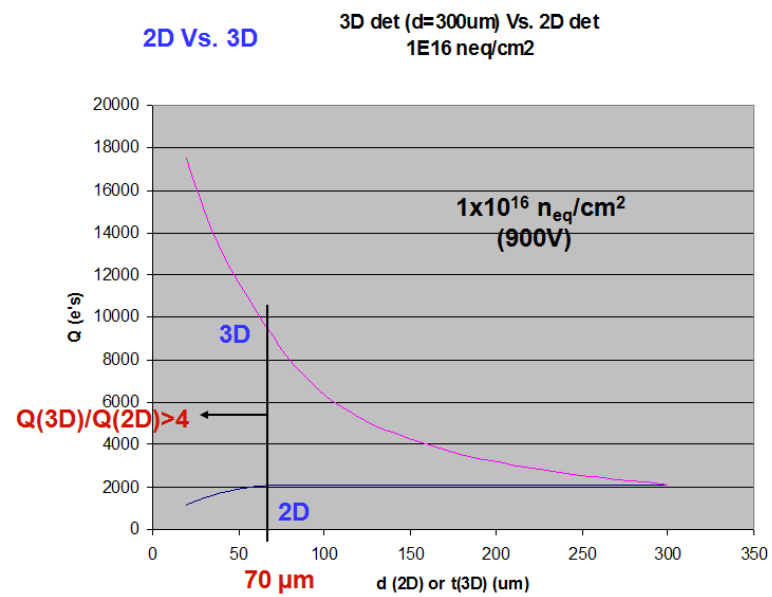
Detector Structure	Processing	Rad-hardness	Other issues
Thin detectors (Hamburg, MPI Munich)	2D-planar Etch-back may be required --- double-sided	Much lower V_{fd} Low resistivity Si may be used (100 Ω–cm)	Low total collected charge
Semi-3D (BNL)	2D-planar Single-sided	3-4 times lower V_{fd}	No CCE improvement at high fluences
Early 3D with column electrodes (Hawaii/Stanford CNM, Glasgow, Trento, Sintef, BNL)	3D processing Double-sided Single-sided possible	De-coupling of d with depletion depth --- much lower V_{fd}, much improved CCE at high fluences	Complicate E-field profile – low field regions; potential saddle points

Early 3D Detectors (Initial concept)

- p^+ and n^+ column electrodes are etched and dopants are diffused in along the detector thickness ("3D" processing)
- Depletion develops laterally (can be 50 to 100 μm): decoupled from thickness
- Much less V_{fd}--- much higher radiation tolerance
- Electrode spacing can be ~ d_{CCE} ---- much reduced trapping



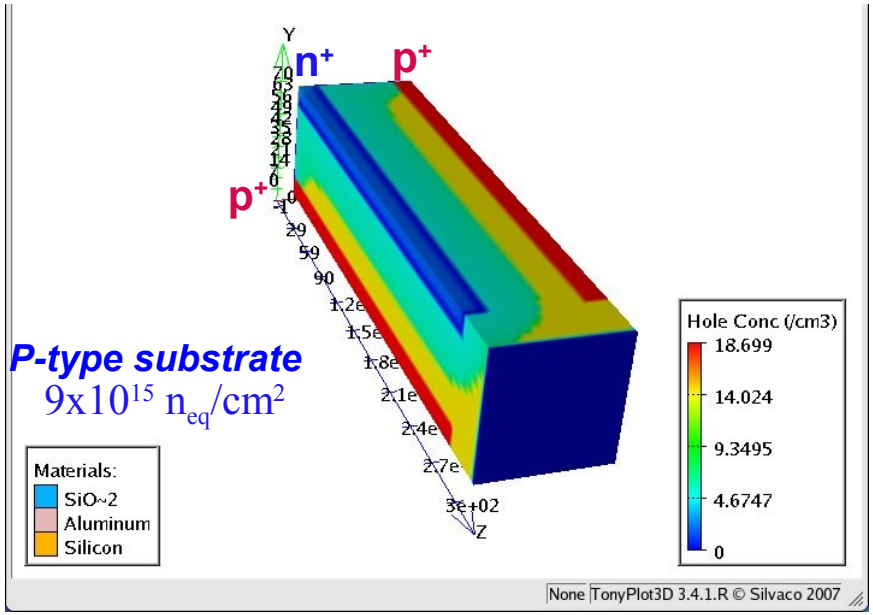
Sherwood I. Parker et al., UH 511-959-00

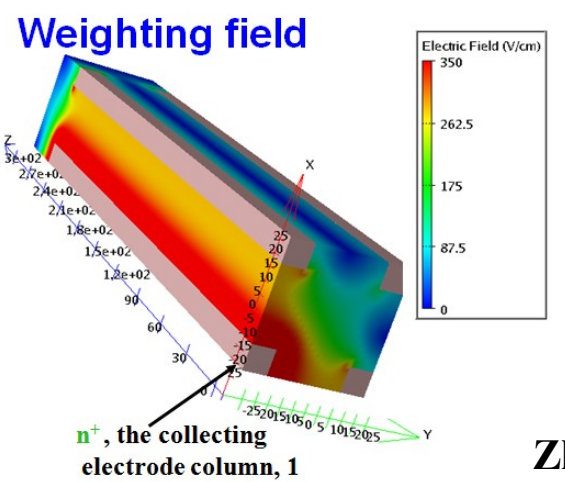


$$Q_{3D}(d,t) = Q_{2D}(t)\cdot\frac{d}{t} = Q_{2D}(t=d)$$

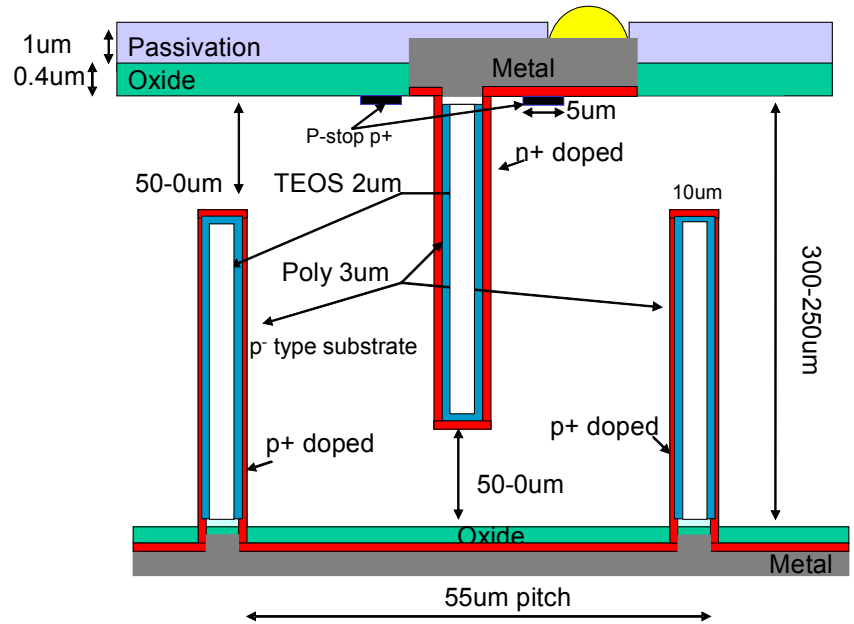
Different variants of early 3D detectors

Single-sided 3D (BNL)
True single-sided process and access
Same E-field, simple processing





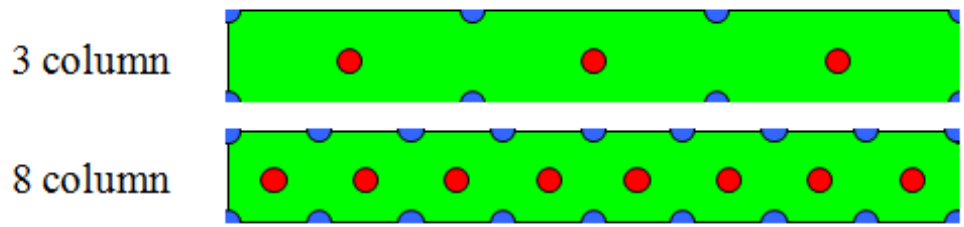
Double-sided access (CNM, Trento)---
Same E-field, separation of electrodes



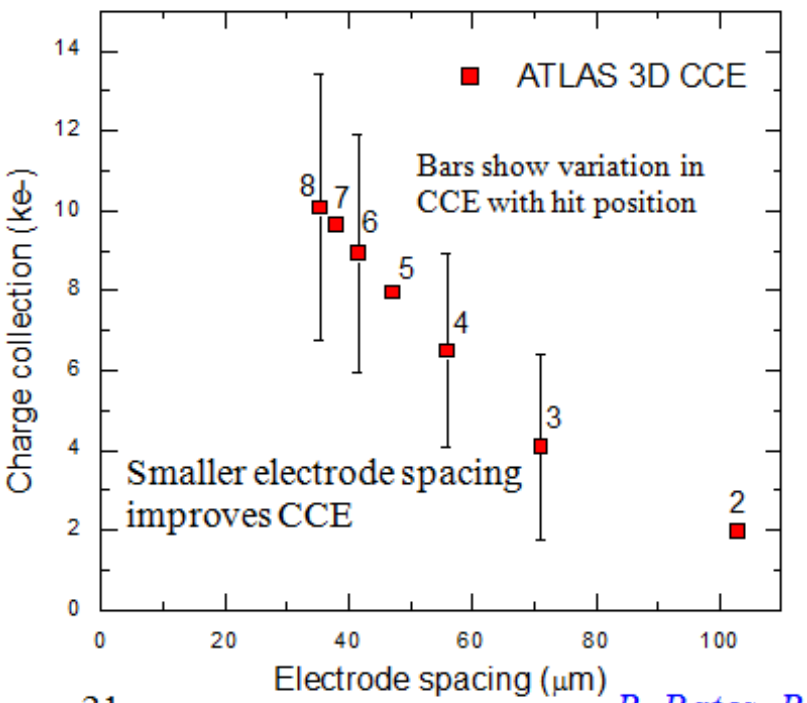
G. Pellegrini, 3rd Workshop on Advanced Silicon Radiation Detectors (3D and P-type Technologies), April 14-16, 2008 Barcelona, Spain

Charge collection in early 3D detectors

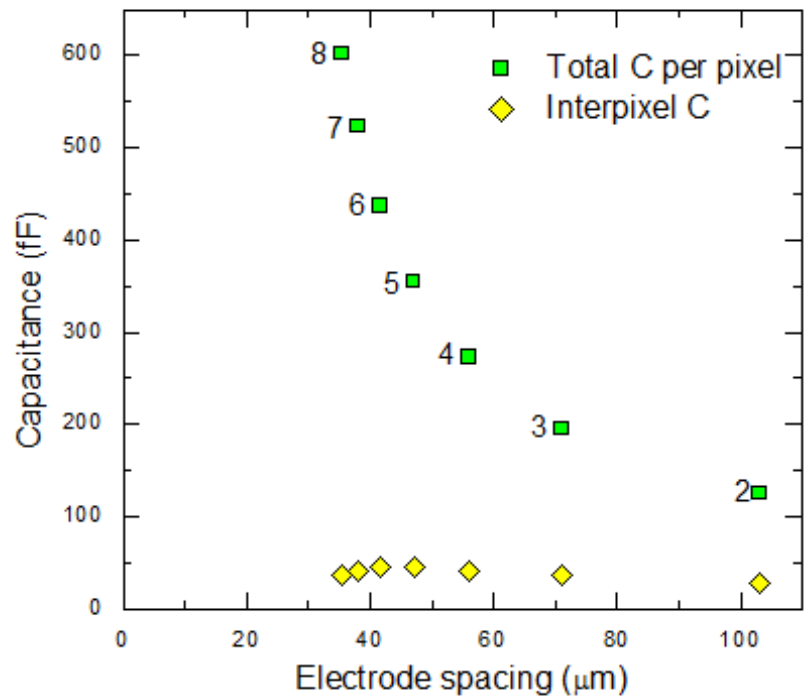
- ATLAS pixel is 400μm * 50μm
  - Different layouts available
  - Trade-offs between V_{dep}, CCE, capacitance, column area…



Charge collection with $10^{16} n_{eq}/cm^2$ radiation damage



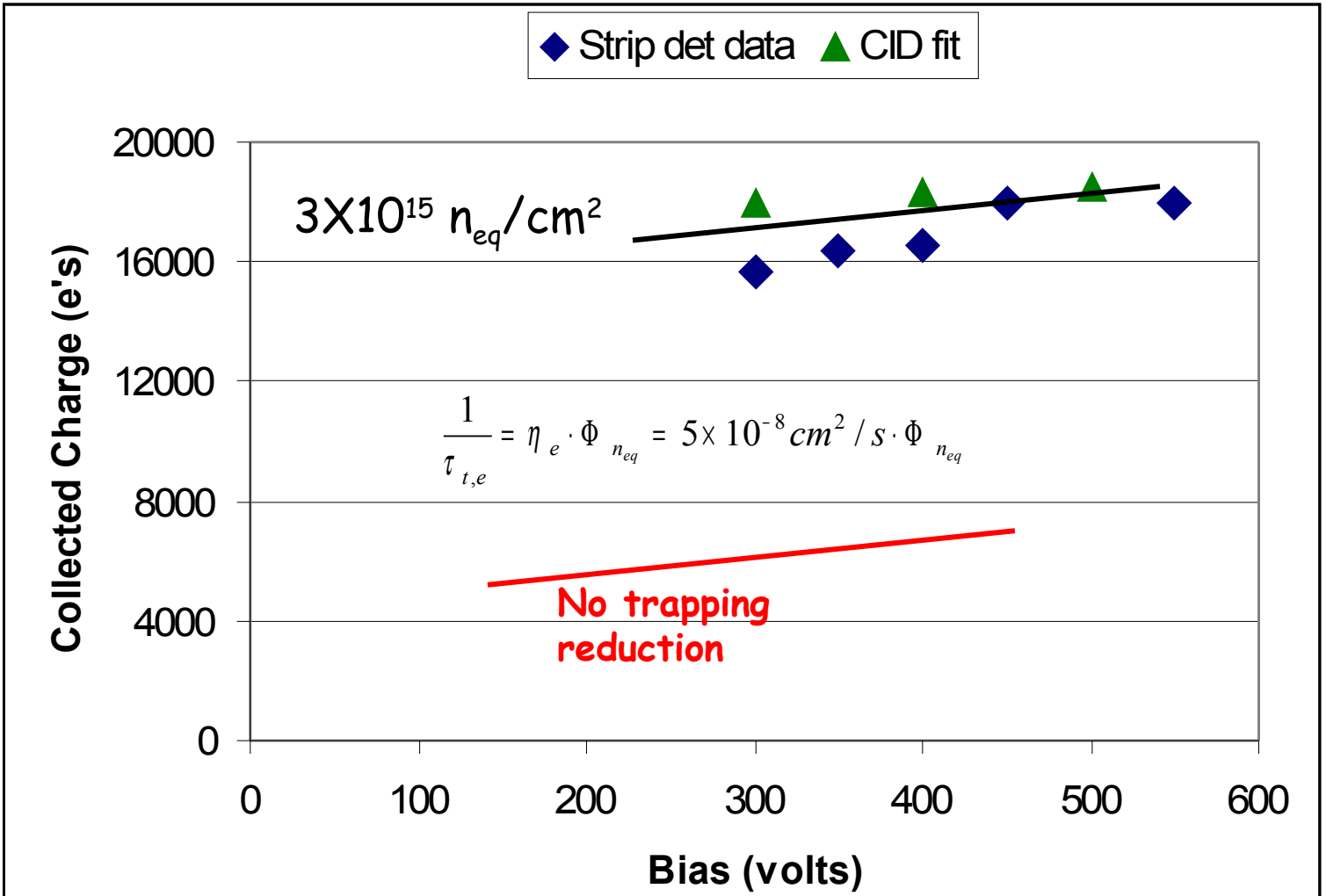
Capacitance at each pixel



R. Bates, RD50 Workshop, 11/2009

- **New Rad-hardness Technologies-1**
  - **Current-injected-diodes (CID) --- reduction of both V_{fd} and trapping**

RD39 CID strip detector test beam results (MIP charge)
CERN H2 muon, 225 GeV/c (-52 °C (221K))



CERN RD39 Status Report, 94th LHCC open session, 19th November 2008, CERN

Larger $\tau_{t,e}$ for electrons used to fit CID data
$\tau_{t,e}$ = 6.67 ns as compared 0.667 ns with no injection
(hole trapping stays the Same)

Election injection makes trapping 10 times smaller!

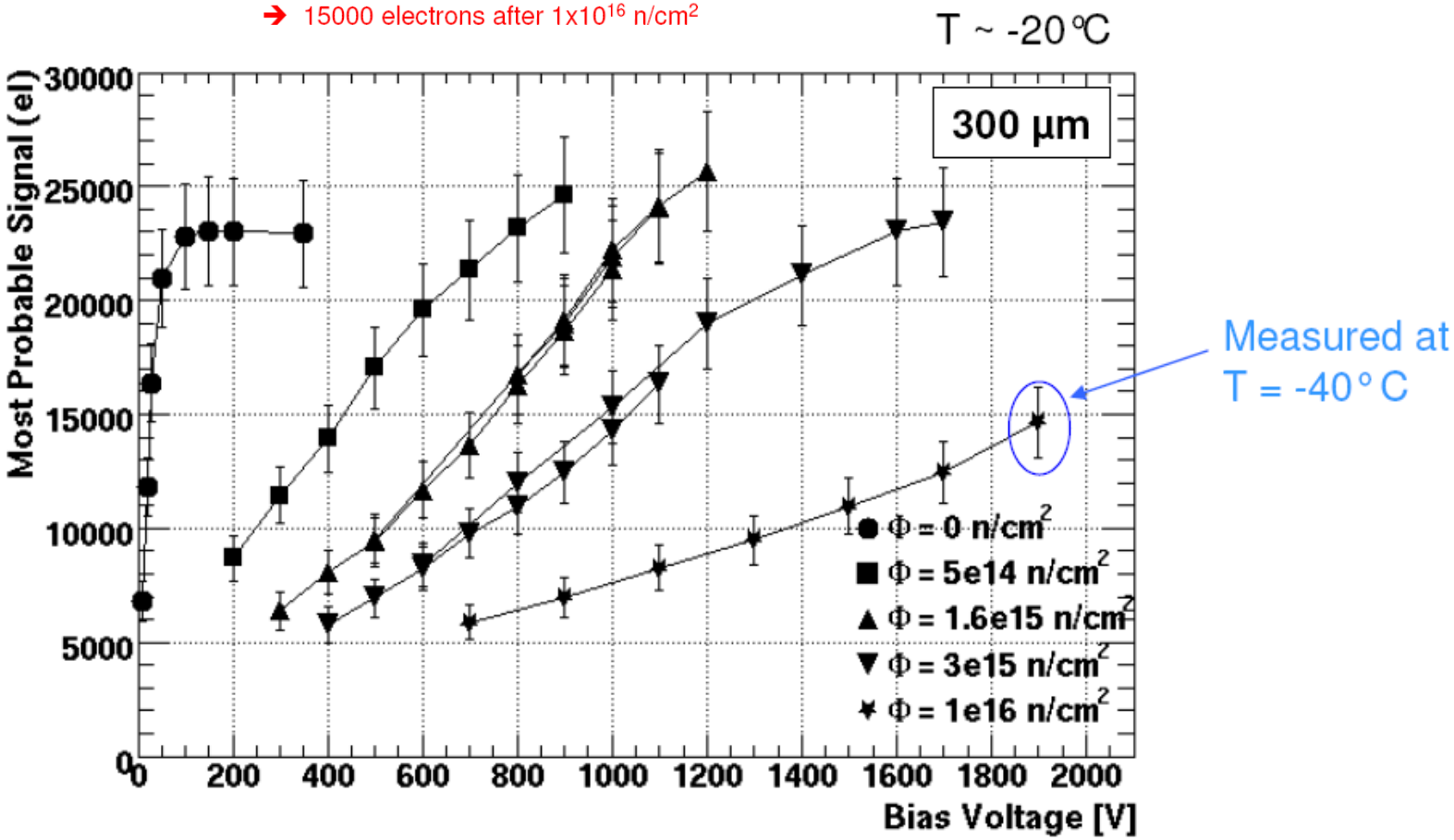
• New Rad-hardness technologies-2

• Charge multiplication

Signal vs. Bias Voltage

• highest voltage limited by breakdown

➔ 100 % CEE seen also after $3x10^{15}$ n/cm^2
➔ 15000 electrons after $1x10^{16}$ n/cm^2

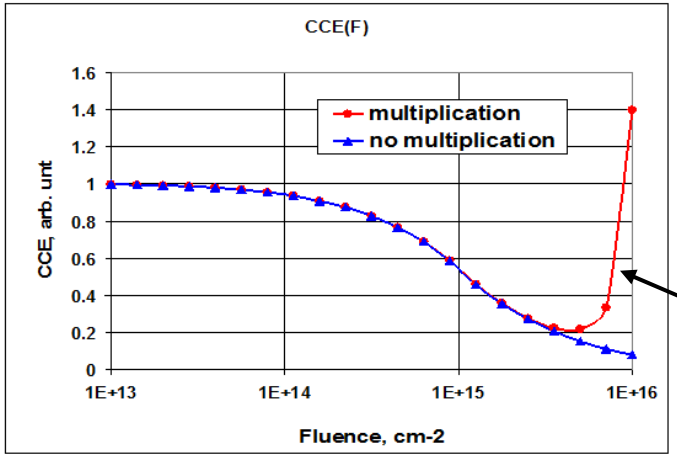


Fluence dependence of CCE

Single peak model

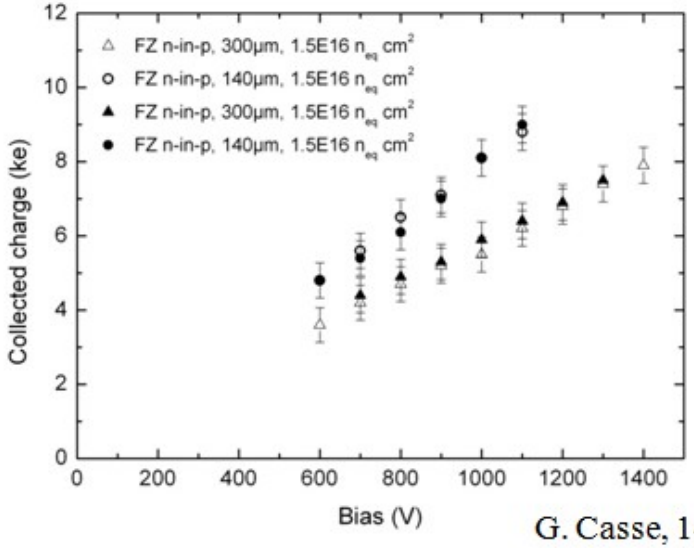
V. Eremin, RD 50 Workshop, Freiburg, 3 – 5 June, 2009

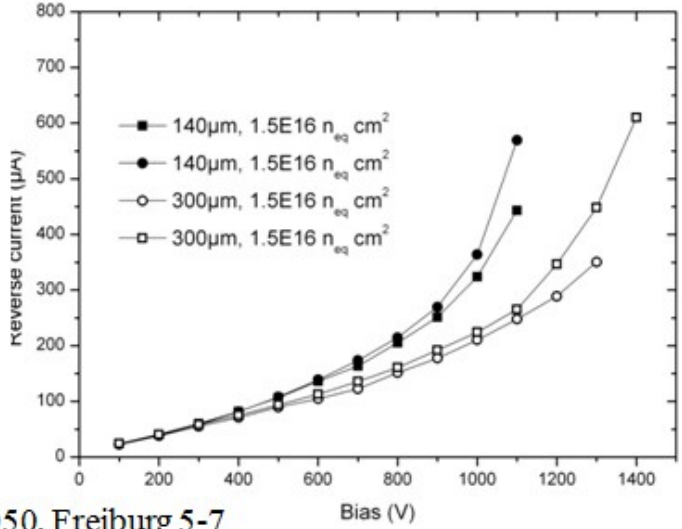
N on P
d = 300um
V = 1000V
β = 1.7e-2 cm^{-1}



Work in a non-stable region is also an issue

CCE and currents after neutron irradiations





G. Casse, 14th RD50, Freiburg 5-7 June 2009.

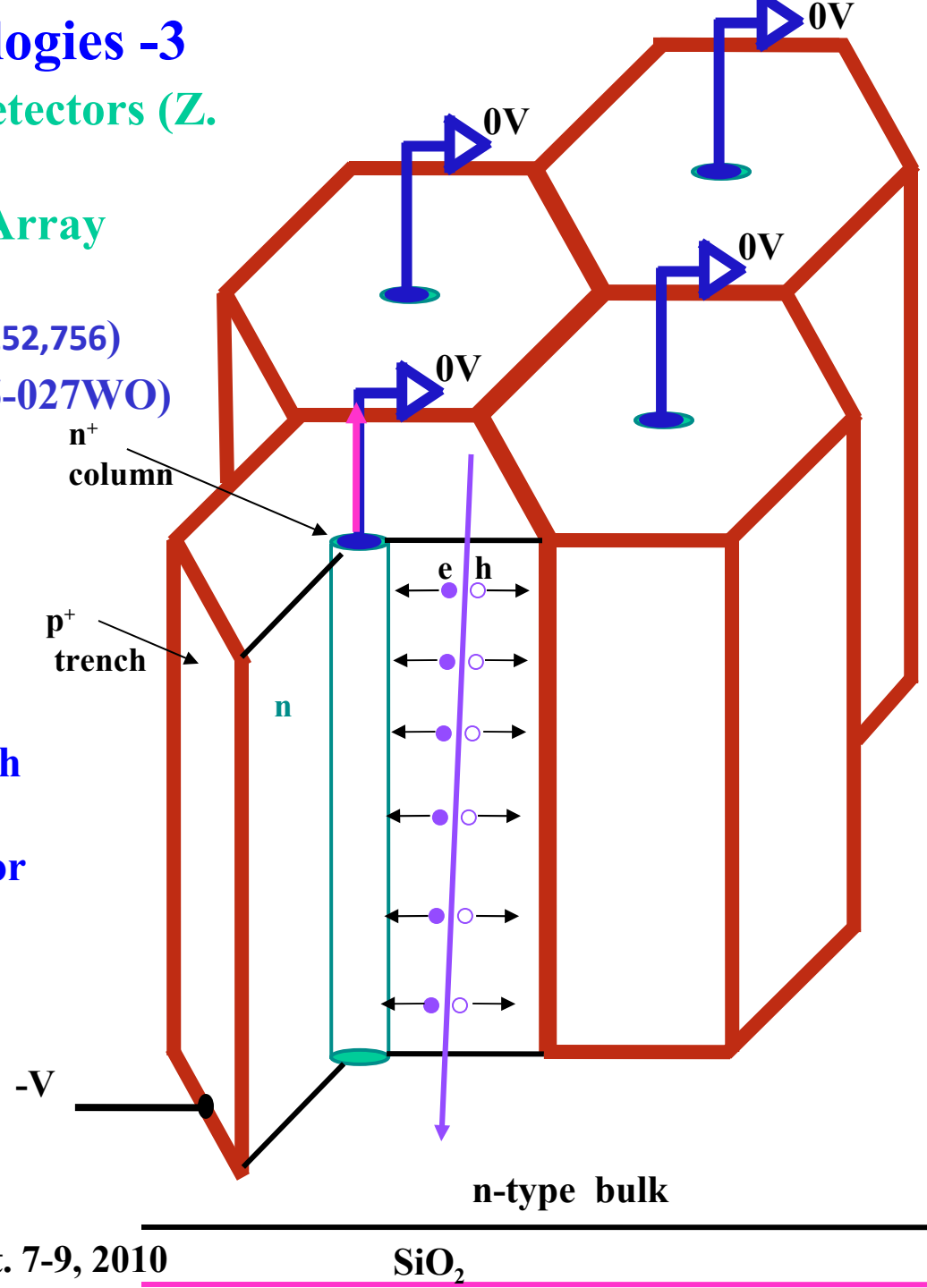
How to make the leakage current not being the dominant noise, and therefore control the S/N ratio remain a issue

- **New Rad-hardness technologies -3**
  - New 3D-Trench electrode detectors (Z. Li, 10/2009 BNL)

or Independent Coaxial Detector Array (ICDA)

US Patent pending (Prov. Applic. No. 61/252,756)

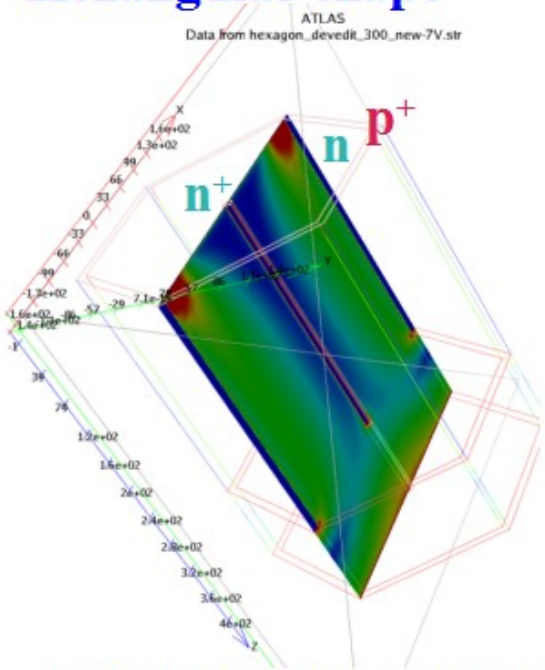
PCT to be filed by 10/19/2010 (1004305-027WO)



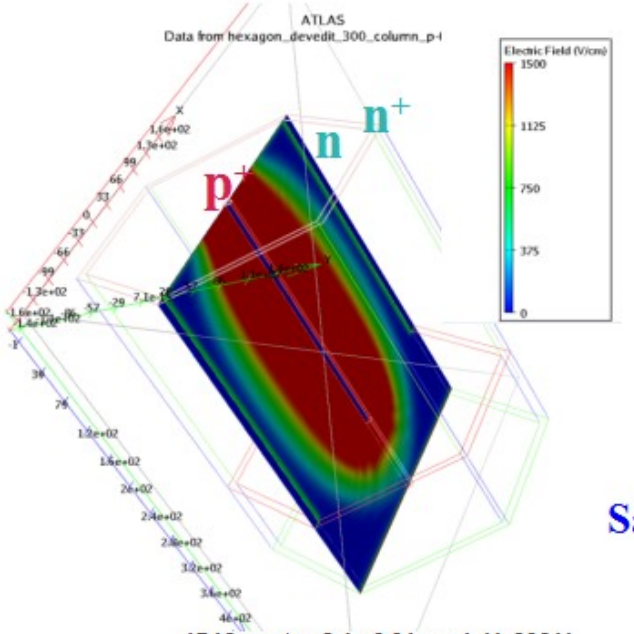
- Mask set has been design and made
- Processing of the first prototype batch will start in 10/2010 at CNM
- First prototype batch will be ready for testing in May 2011.

3D simulations of electric field

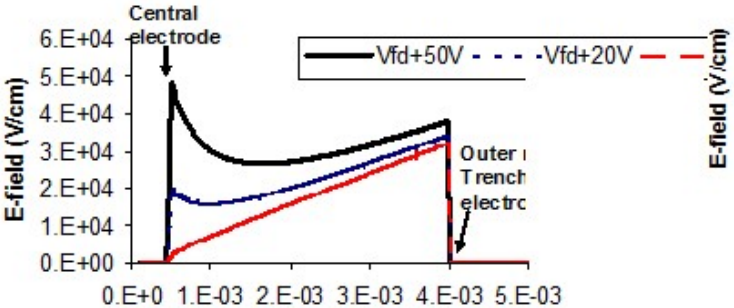
Hexangular shape

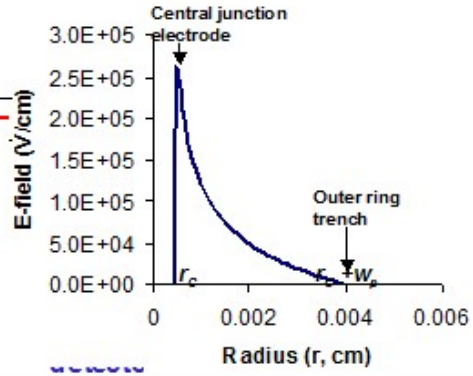


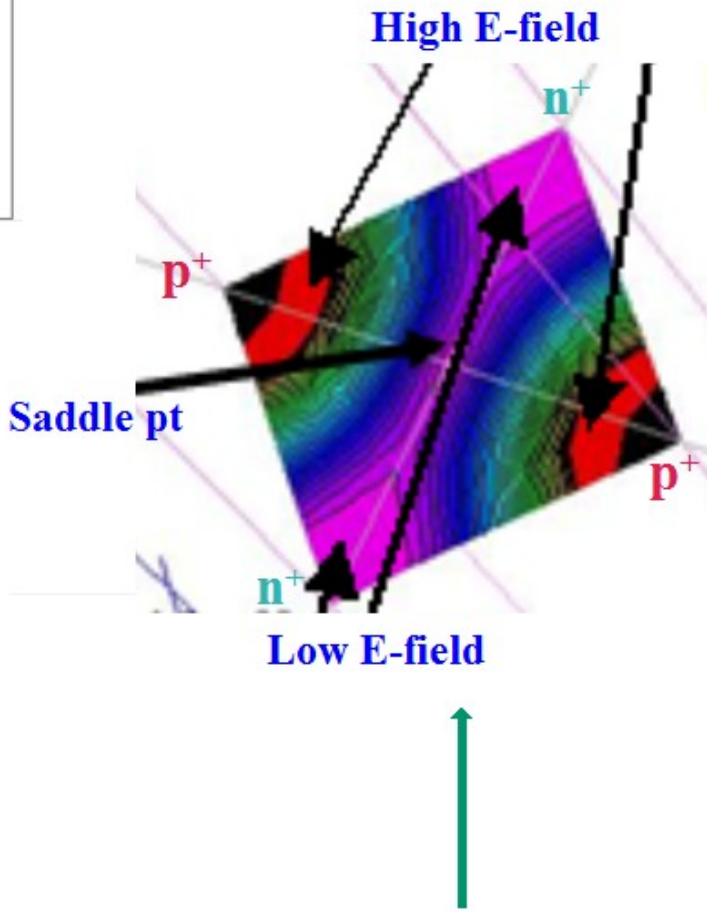
1E16 neq/cm2, b=0.01 cm-1, Vfd=59 V



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

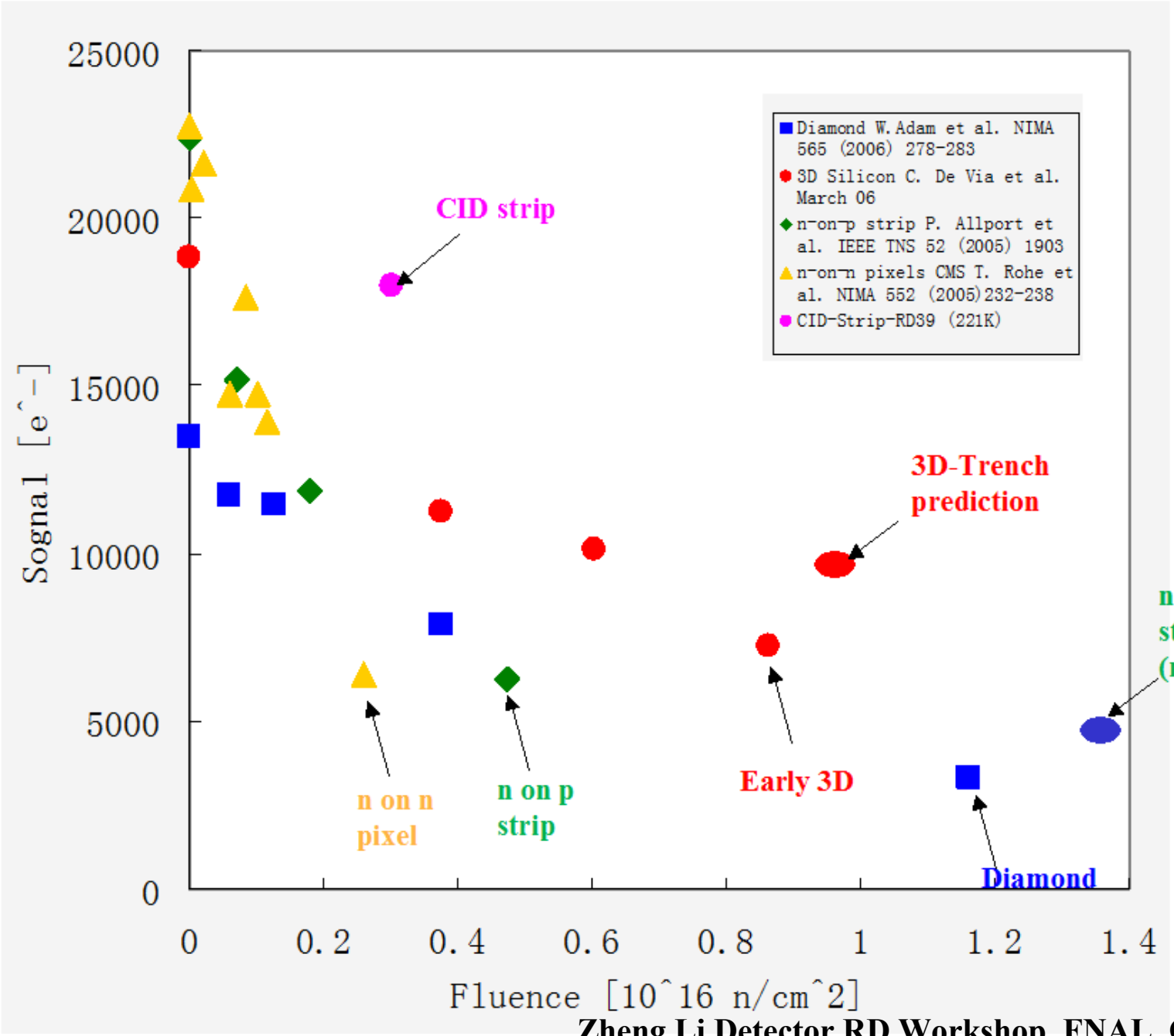






BNL 3D-Trench (Trench Junction)	BNL 3D-Trench (Column Junction)	Early 3D
Full depletion voltage (150 µm electrode spacing):		
8 V, very uniform	52 V, uniform	>52 , very non-uniform

Comparisons of various technologies



Possible Si pixel detector solutions for sLHC's most inner region and future colliders

Solution	CCE improvement due to	Technology/ implementation difficulties (Time scale)
Replacement every 1-2 years	New detectors	Hard to access the inner region (Available)
Early 3D Si detectors	Small V_{fd} Small drift distance t	Complicated processing technology Complicated E-field profile (Available)
CID	Fixed electric field (small bias) Freezing traps (low trapping) Low leakage current	Difficult to implement cryogenic system, more R&D needed (2-5 years)
Elevated temp annealing (MCZ Si only, $T_{ann} \geq 400$ °C)	Annealing out of defect levels related to: Leakage current, space charges and trapping	Difficult to implement annealing in a full detector system, more R&D needed (laser, microwave, leakage current itself, etc.) (3-5 years)
New 3D-Trench-Electrode detectors	Very Small V_{fd} Small drift distance t Near-uniform E-field profile	Complicated processing technology (3-7 years) Just started, much more R&D needed

• 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 (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

- **Collaborations between US National Labs and universities**

Past and current

Institutes	Subjects	Status
BNL, FNAL, U. NM, Purdue, Rochester, Rutgers, Syracuse	Rad-hard Si detectors, Semi-3D Si detectors	2002-2009
US ATLAS (various institutes)	New detectors for LHC Upgrade	On-going

Possible future collaborations

Institutes	Subjects	Status
BNL, FNAL, U. NM, Purdue, Rochester, Syracuse	Rad-hard Si detectors, New 3D-trench Si detectors	Discussions at this workshop
BNL, Argonne, FNAL	New detectors for Photon science	Already under discussion

Summary and Future Needs

- Radiation-induced damages cause detector electrical properties to degrade:
  - increase of detector leakage current
  - compensation of Si bulk (intrinsic bulk resistivity)
  - increase of negative space charge during radiation and annealing
  - reduction of collected charge due to trapping
- Conventional technologies may be rad-hard enough for LHC
  - Oxygenated Si and MCZ Si
  - Early 3D Si detectors

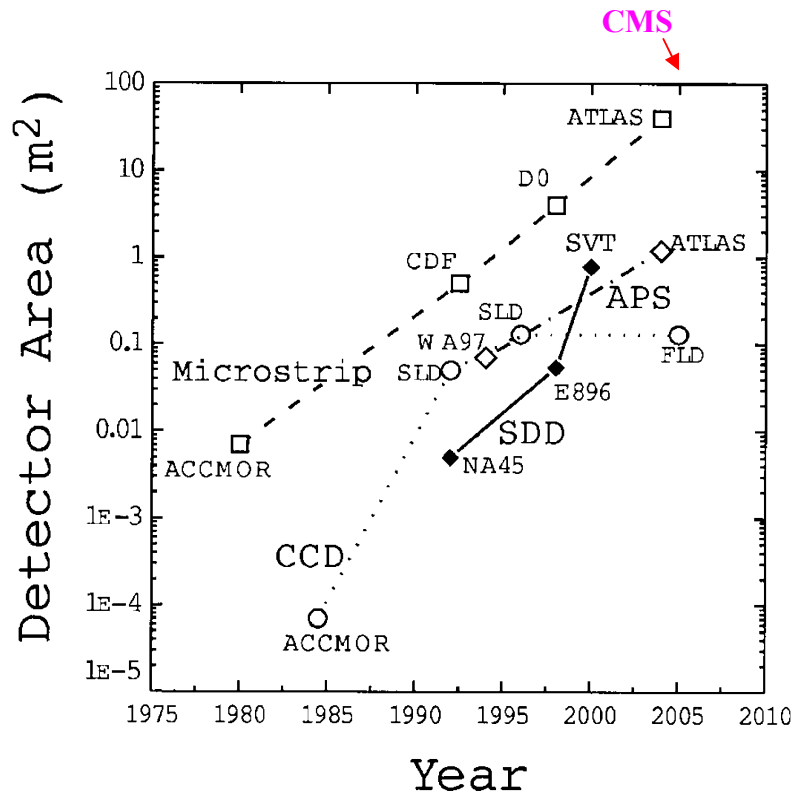
- To obtain ultra high radiation hardness/tolerance for sLHC, much more R&D are needed for new technologies:
  - New 3D-Trench-Electrode Si detectors --- much better E-field profile and larger *Q* and CCE --- Just started: much more work needed in fabrication and testing
  - 3D integration of electronics and detectors --- interconnections: --- More work needed in wafer bonding, SOI, TSV, etc. (FNAL, BNL, LBNL, etc.)
  - Current injected diodes (CID) operated at low temperatures for increased *Q* and CCE --- More work to implement low T system
  - Study of charge multiplication in heavily irradiated detectors --- large Q and CCE --- More work needed to control S/N

Back-up slides

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
- Modest radiation hardness

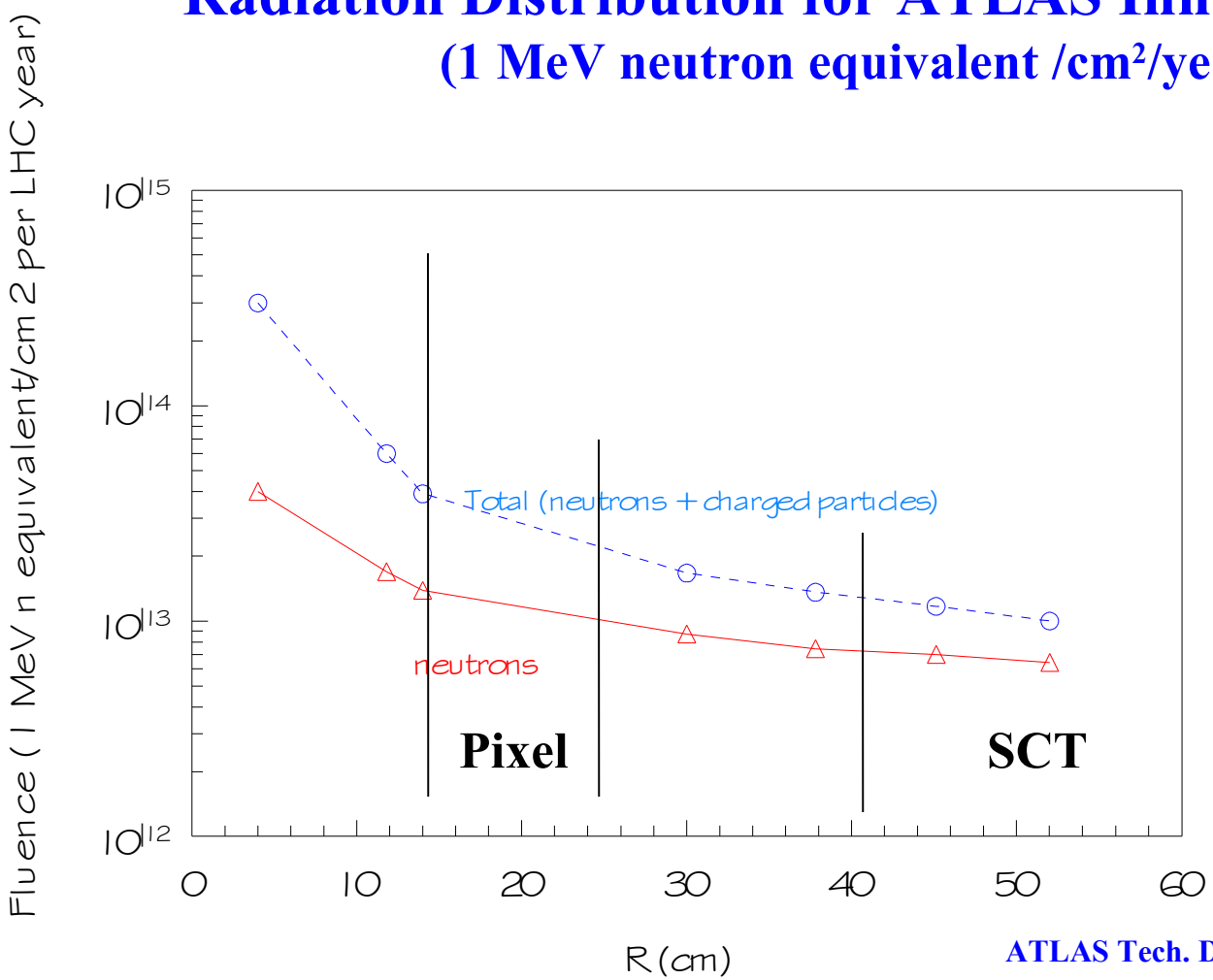
- **LHC Experiments:**
  - **ATLAS**
    - **1.7 m² pixel detectors**
    - **61 m² strip detectors (SCT)**
  - **CMS**
    - **All Si Tracker: over 200 m²**
- **SLHC: All-Si-tracker**



J Takahashi, et al, NIM A461 (2001) 139-142

Radiation Distribution for ATLAS Inner Detectors

(1 MeV neutron equivalent /cm²/year)



Clearly charged particle (p, π, etc.) dominate, especially at closer distances

ATLAS Tech. Design Report, 1997

For 10 years LHC operation:

Total fluence: >10^{15} n/cm² for pixels, and > 10^{14} n/cm² for strips

For SLHC, it is about 10 times larger

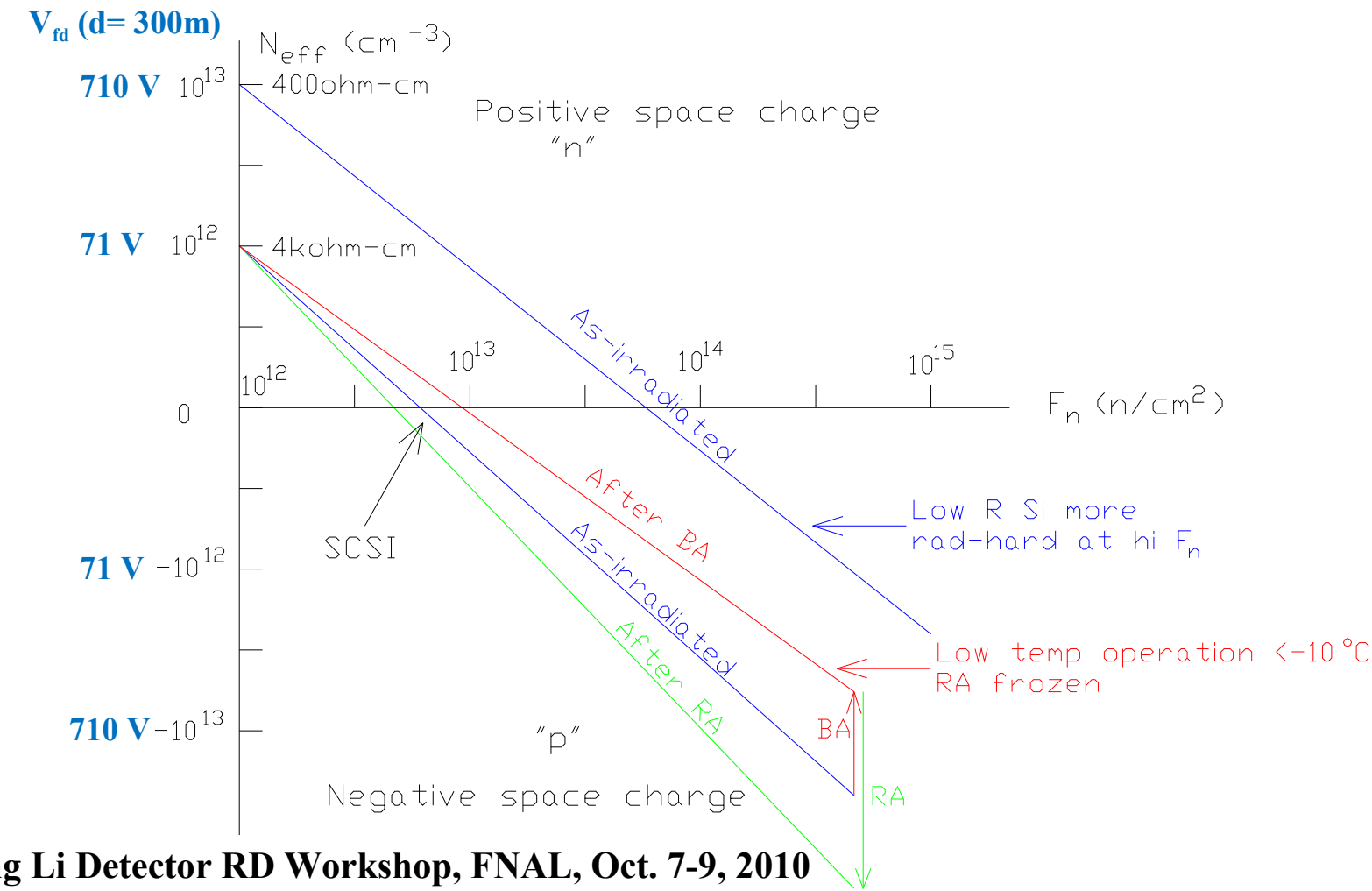
Radiation induced degradation in Si detectors

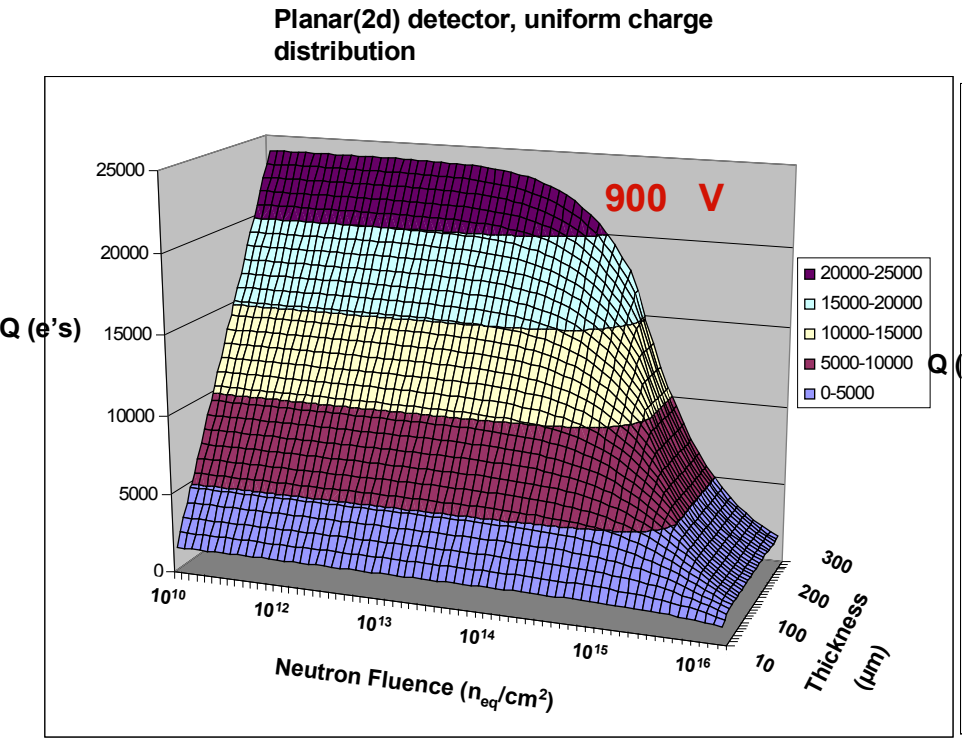
3. Space charges

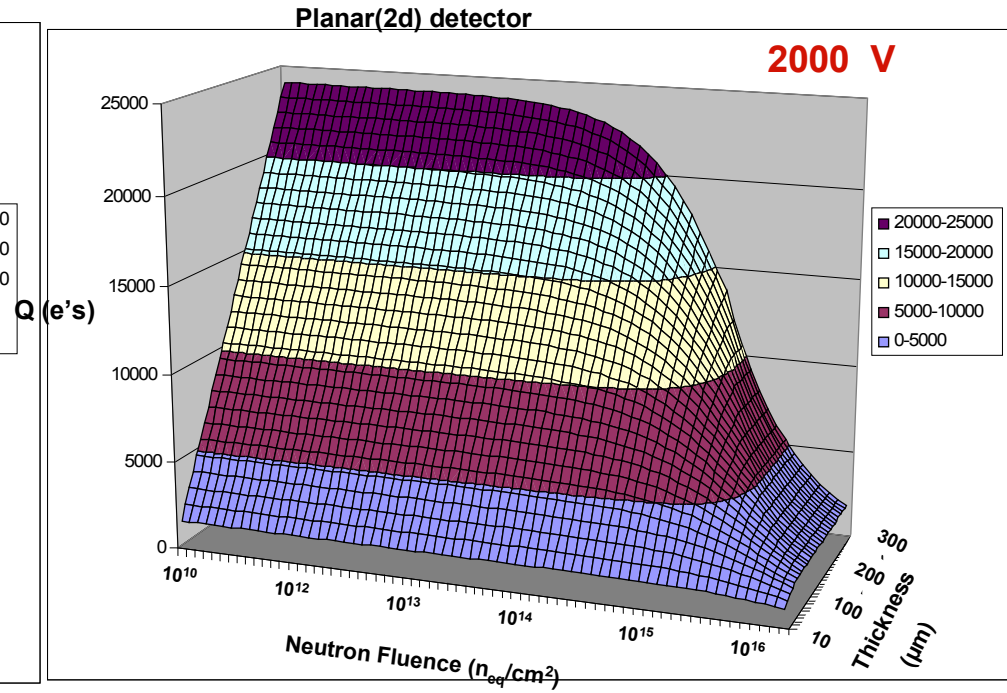
- o Space charge sign inversion (SCSI): + ⟶ -
- o Beneficial annealing (BA), τ (RT) = 10 days
- o Reverse annealing (RA), τ (RT) ≈ 1 year

$N_{eff} \sim - b\Phi_n$,

b= 0.02 for standard Si material







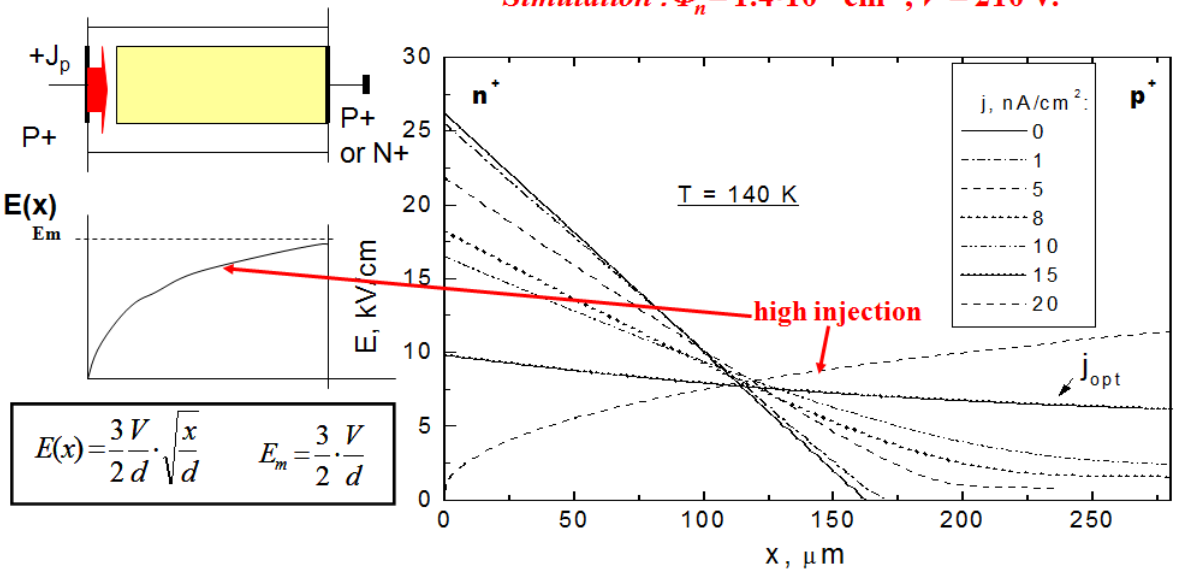
Very little effect of Q on bias voltage V for V > 900 volts near 10^{16} n_{eq}/cm^2

Very little effect of Q on detector thickness d for d> 100 μm near 10^{16} n_{eq}/cm^2

- **New Rad-hardness Technology**
  - **Current-injected-diodes (CID)**

- **CERN RD39**
  - **Cryogenic temperature operation (-130 to -40 °C)**
  - **Leakage current not a factor**
    - **Both trapping and N_{eff} reduced ⟶ CCE increase**

Simulation : $\Phi_n = 1.4 \cdot 10^{14}$ cm^{-2}; $V = 210$ V.



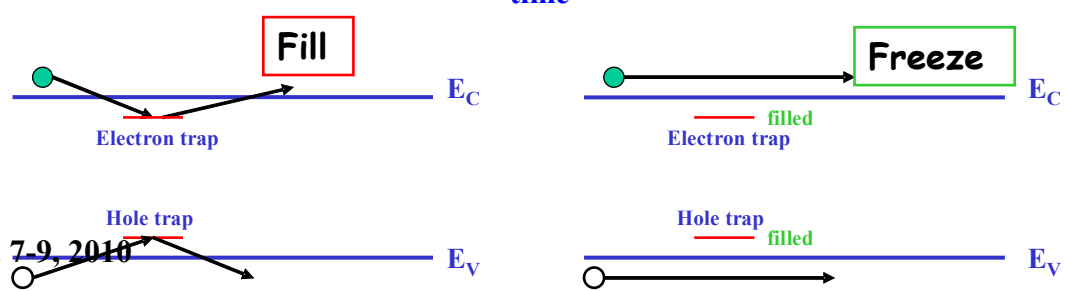
$$E(x) = \frac{3}{2}\frac{V}{d}\cdot\sqrt{\frac{x}{d}} \qquad E_m = \frac{3}{2}\cdot\frac{V}{d}$$

Injection to manipulate E-field

E. Verbitskaya et al., IEEE Nuclear Science Symposium, Lyon, October 2000

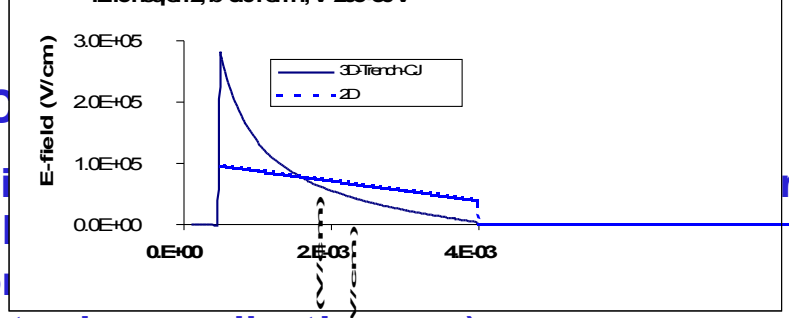
Trapping time $\tau_t = \dfrac{1}{\sigma v_{th} N_t^{empty}}$ ⬆

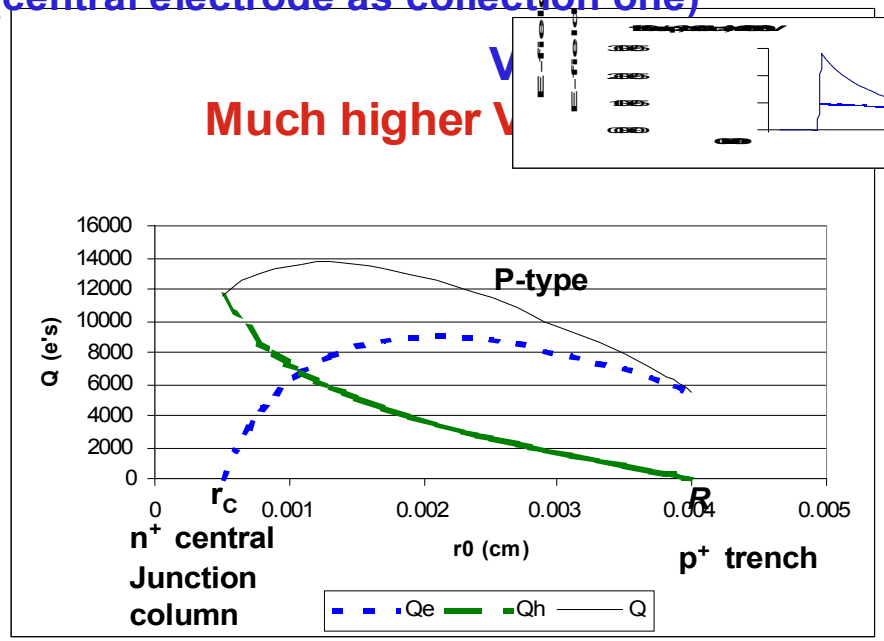
Injection to reduce charge trapping ⟶

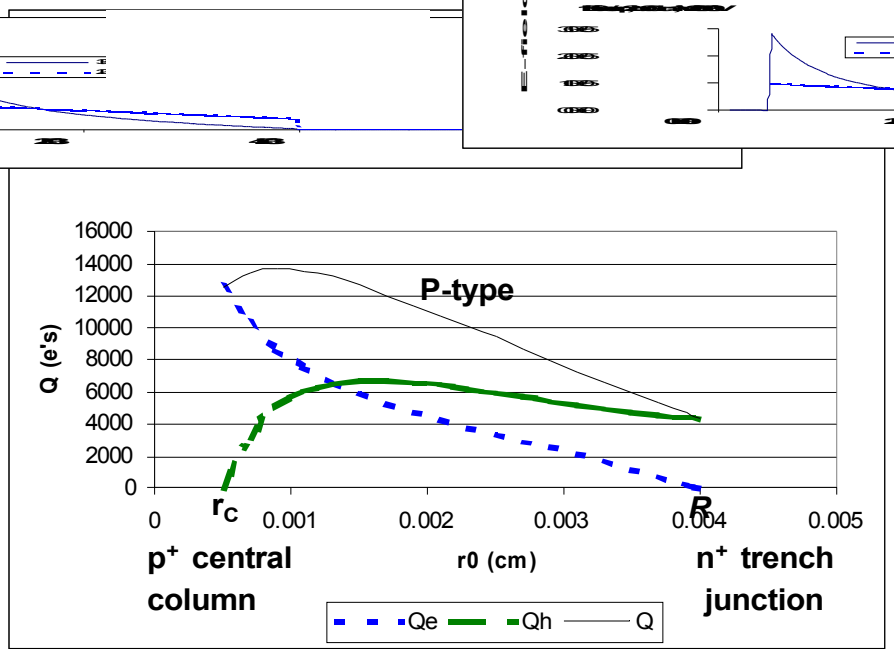


For heavily i rge depends on the hit position l fluences):
True also for
(central electrode as collection one)

Much higher V

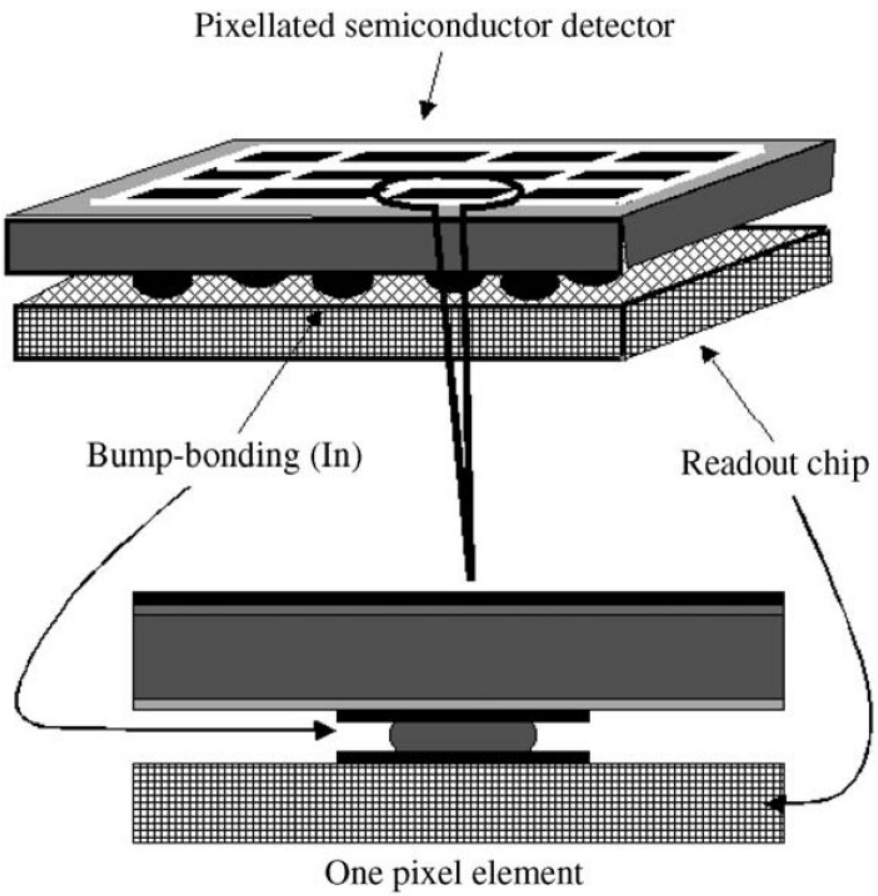


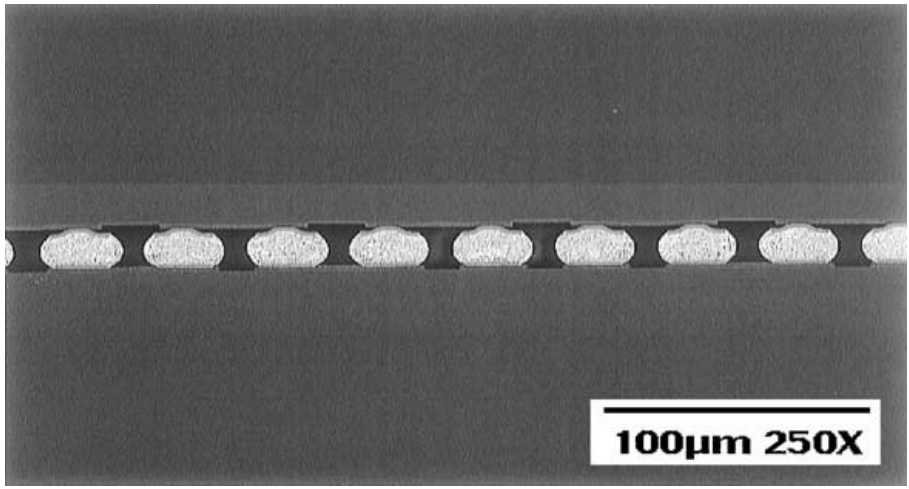




Ave Q can be about 10000 e's (>45%) at $1x10^{16}$ n_{eq}/cm^2

Bump-bonding technology

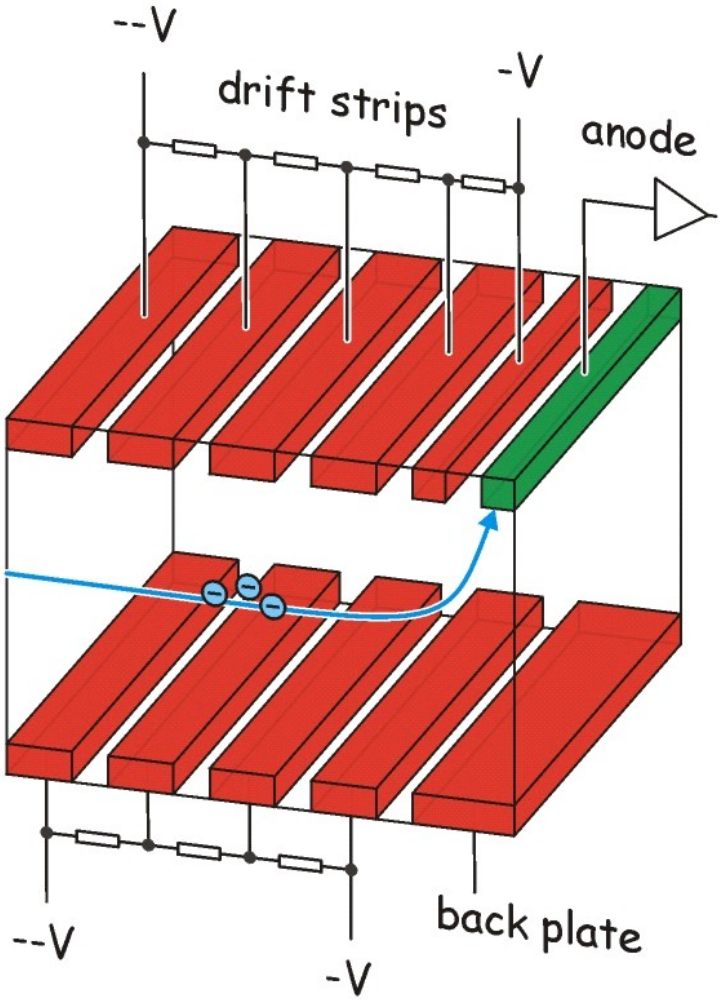


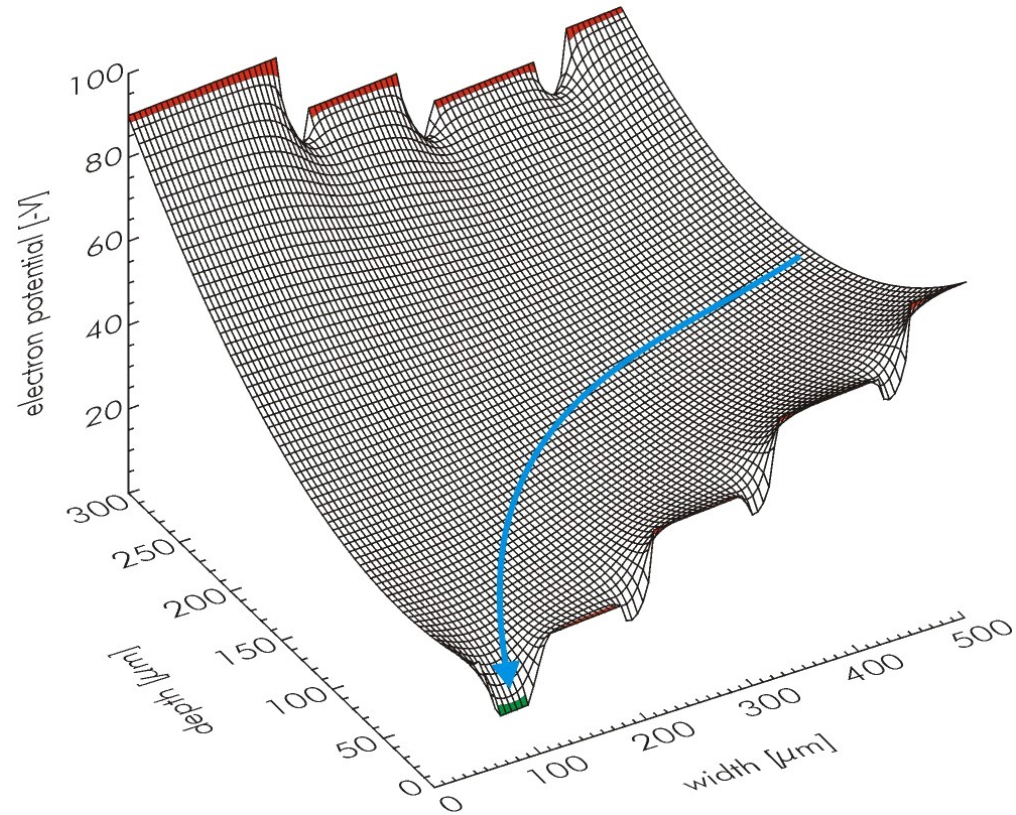


Solder bumps on a fluxless MCNC detector

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

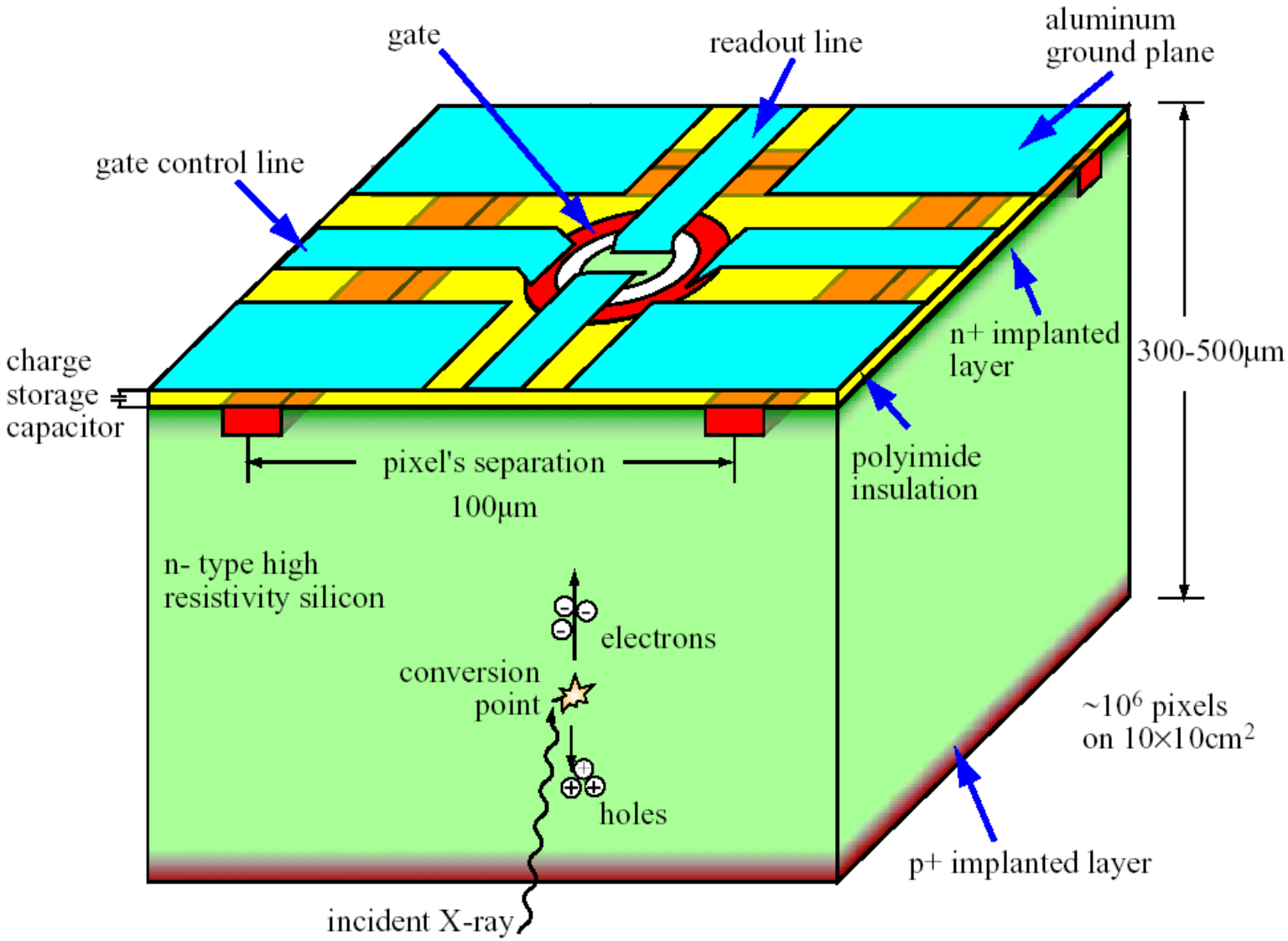
SDD



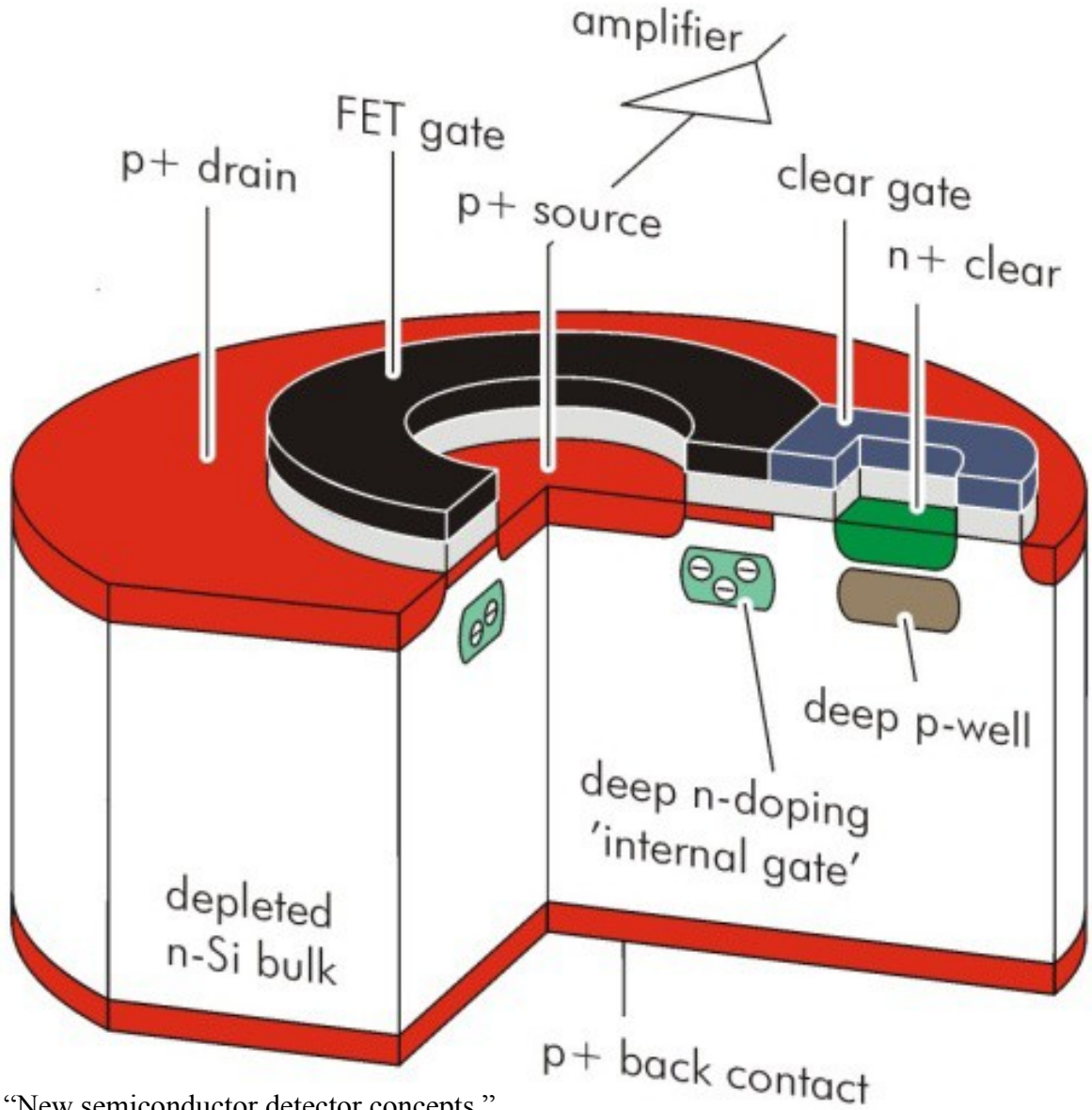


E. Gatti and P. Rehak, "Semiconductor Drift Chamber" – An application of a novel Charge Transport Scheme", Nucl. Instr. and Meth., A 255, pp. 608-614, 1984.

XAMPS (BNL)


gate
readout line
aluminum
ground plane
gate control line
charge
storage
capacitor
n+ implanted
layer
300-500μm
pixel's separation
100μm
polyimide
insulation
n- type high
resistivity silicon
electrons
conversion
point
holes
~10^6 pixels
on 10×10cm^2
p+ implanted layer
incident X-ray

DEPFET



J. Kemmer, G. Lutz, "New semiconductor detector concepts," Nucl. Inst. Meth. A 253, pp. 356-377, 1987.

H. Kruger, Nuclear Instruments and Methods in Physics Research A 551 (2005) 1–14

MAPS-CMOS

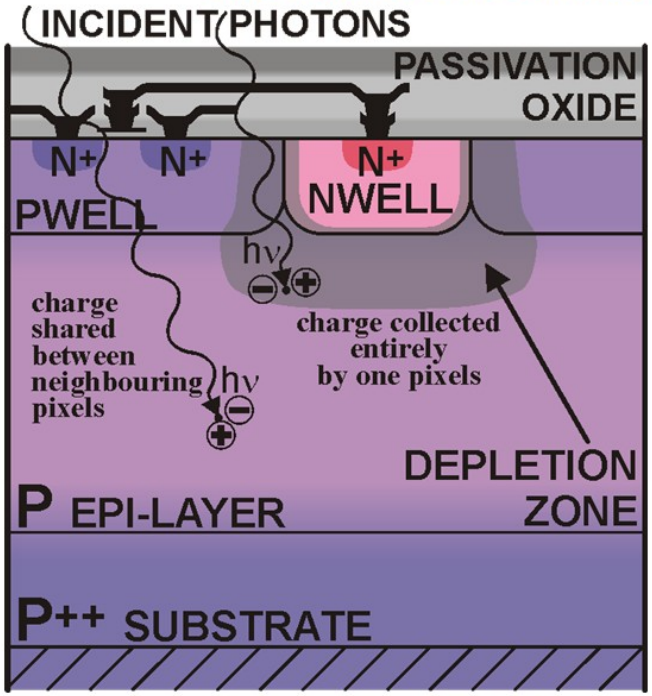
APS Argonne Nat. Lab., December 8-9 2005

Grzegorz DEPTUCH

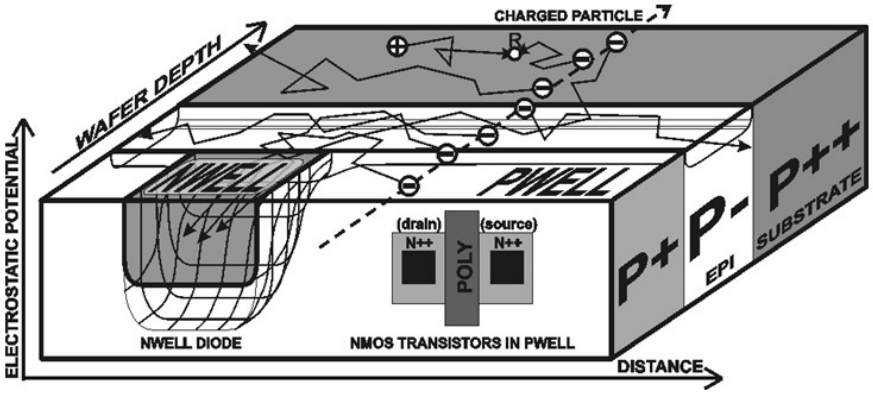
CMOS IMAGE SENSORS IN HEP - MAPS

- Operation principle of photodiode MAPS

Monolithic Active Pixel Sensors (MAPS)



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



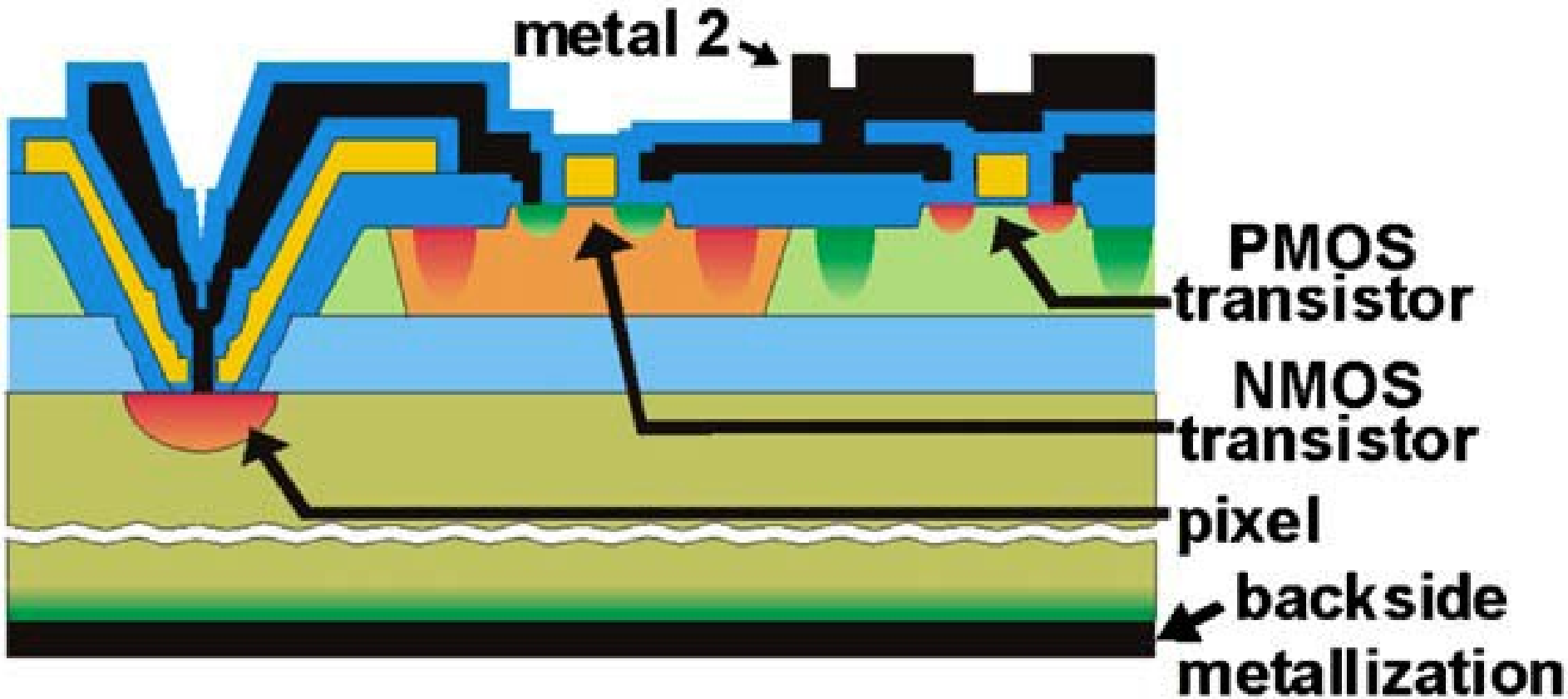
operation:

- 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

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