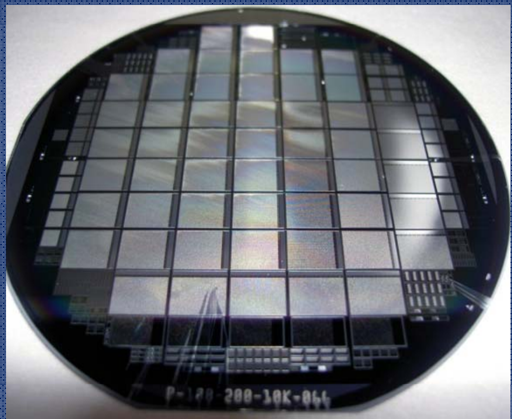
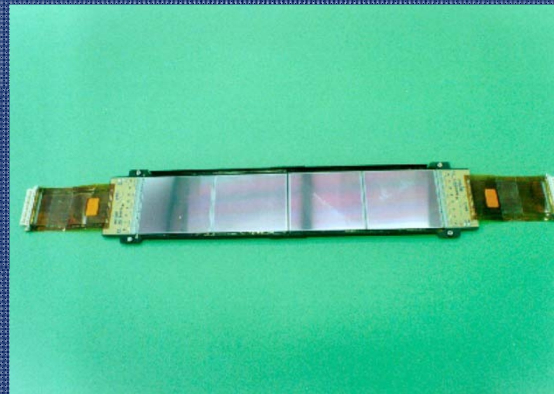
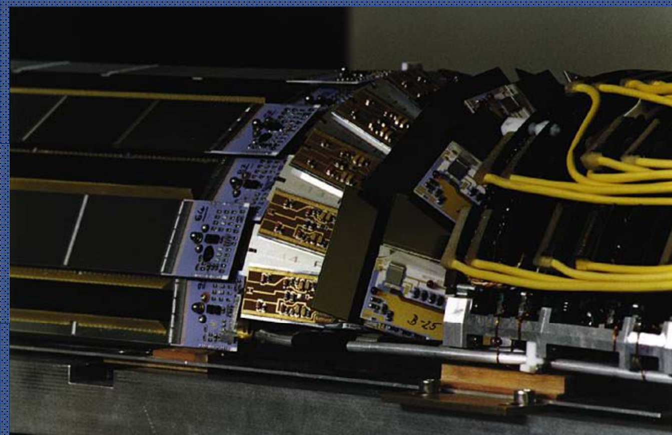
MANCHESTER 1824

Review of New Technologies in Semiconductor Detectors

Cinzia Da Via', The University of Manchester UK







http://wwwhephy.oeaw.ac.at/p3w/halbleiter/index.html

OUTLINE

❖Introduction:

- o brief overview, silicon detectors and signal formation
- υ rationale in the choice of new (semiconductor) technologies

❖The current market (driven mainly by HEP and radiation damage):

- Si with control of impurities and dopants : Oxygen
- Device structures: n-on-n, n-on-p, 3D
- New materials
- Optimisation of operational conditions: cryoT, Forward bias

❖Other exotic semiconductor technologies:

➢Organic, Curved radiation detectors, SOI, Gossip, thin+3Dinteconnect, TFA Micro-machined MCP

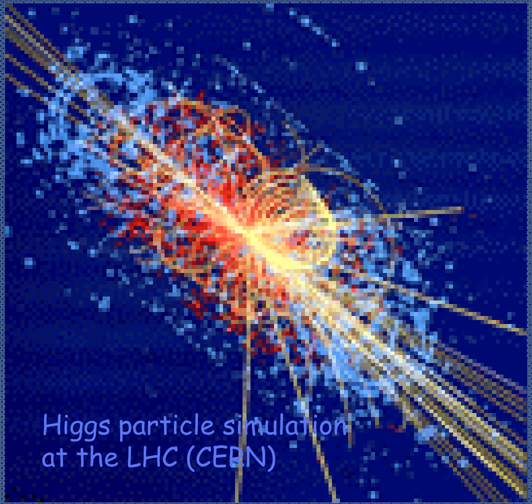
The semiconductor technology and the environment

➢Common aspects in semiconductor detectors:

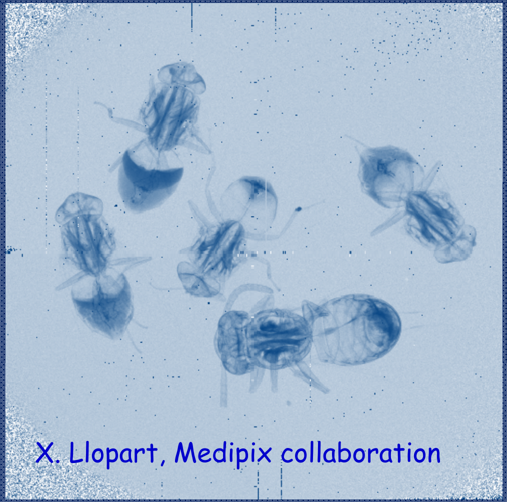
➢SENSOR : MANY ASPECTS

- DETECTOR MATERIAL
- DEVICE STRUCTURE
- DETECTOR MANUFACTURING PROCESS
- ENERGY DEPOSITION - DQE
- CHARGE COLLECTION
- NOISE
- SIGNAL FORMATION / SHAPING by AMPLIFIER
- FRONT-END SIGNAL PROCESSING

➢ NEXT STAGES of READOUT ELECTRONICS – application dependent

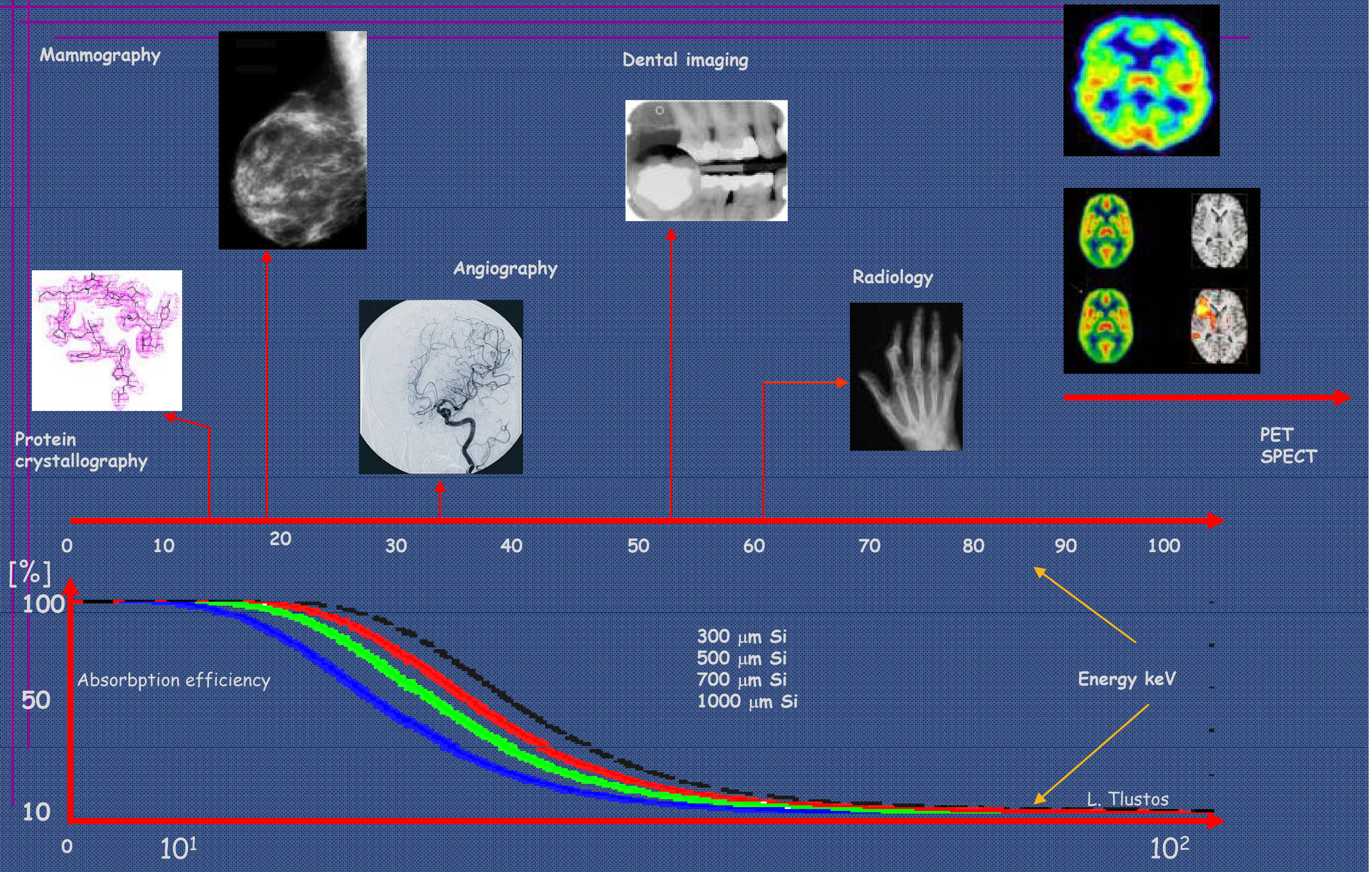


Higgs particle simulation at the LHC (CERN)



X. Llopart, Medipix collaboration

X-ray energy of the most common medical and biological applications and Silicon detectors: trade-off between efficiency and spatial resolution → next time

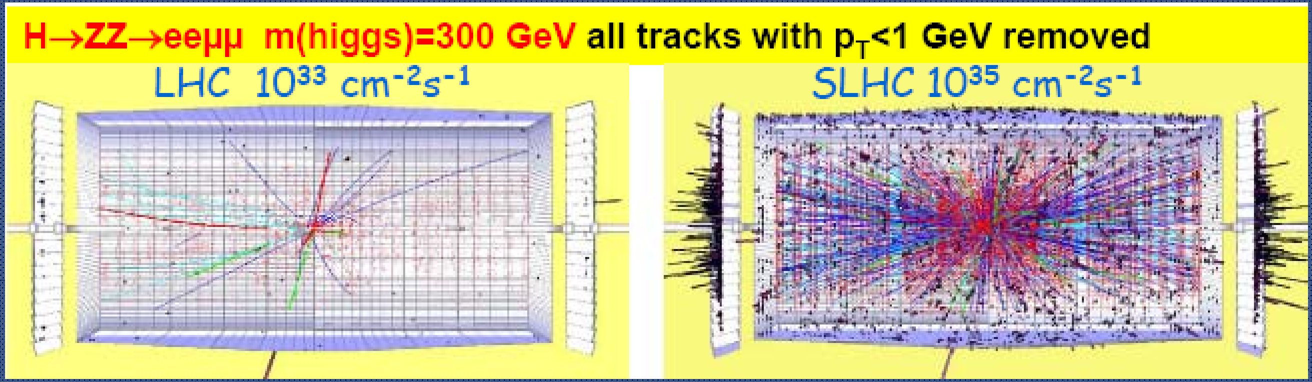


Classic example in HEP : ILC vs LHC vertex detector parameters challenges depend on environment

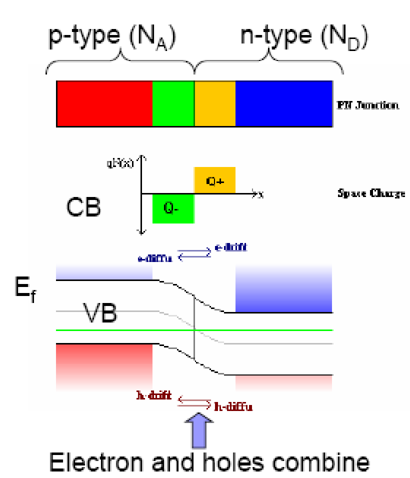
from C. Damerell (2008)

Parameter	LHC	ILC	ILC/LHC performance
Sensitive time window	25 ns	~50 μs	0.0005
Radiation resistance	~20 Mrads	~100 krad	0.005
Tracking precision	~45 μm	~3 μm	15
Layer thickness	2 % X_0	0.1% X_0	20

Next talk



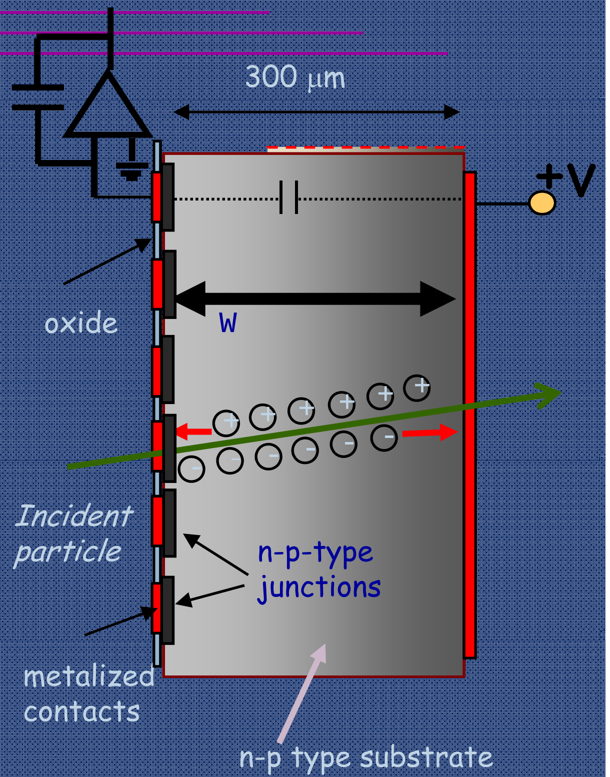
2-Standard silicon sensors working principle



Solve Poisson eq.

$$-\frac{d^2}{dx^2}\phi(x) = \frac{q_0}{\varepsilon\varepsilon_0} N_{eff}$$

- Reversed biased p-n junction to establish region with no mobile carriers
- Increase external reverse bias
  Increase E field ⇒ e- and h drift to electrodes
- Increase depletion region size
- Reduce capacitance $\varepsilon\varepsilon_0 A/dW($
  Measurement of C yields full
- depletion voltage)
- Small current flow
- Requires an external readout electronics
- Segmentation allows spatial resolution (strips, pixels, single and double-sided
  σ = pitch/sqr 12)

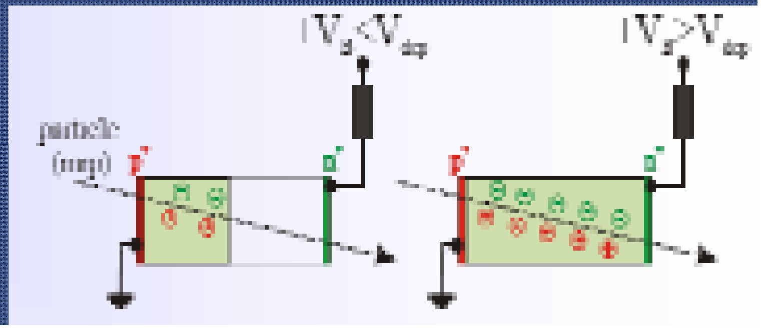


Substrate normally:

- n-type p-type
- 4 kΩ-cm FZ
- Doping of ~10^{12} cm^{-3}
- [O] ~10^{15} cm^{-3}
- [C] ~10^{15} cm^{-3}
- 300μm thick
- Orientation <111>

$$V_{FD} = \frac{(W)^2 \times e \times |N_{eff}|}{2\varepsilon_0\varepsilon_{Si}}$$

$$|N_{eff}| = |ND - N\,A|$$



3-Signal formation:
When does the current pulse begin?

From H Spieler lecture notes LBL

S. Ramo, Proc. IRE **27 (1939) 584**

a) When the charge reaches the electrode
b) When the charge begins to move

❖Although the first answer is quite popular (encouraged by the phrase"charge collection"), b) is correct.

❖When a charge pair is created, both the positive and negative charges couple to the electrodes and induce mirror charges of equal magnitude.

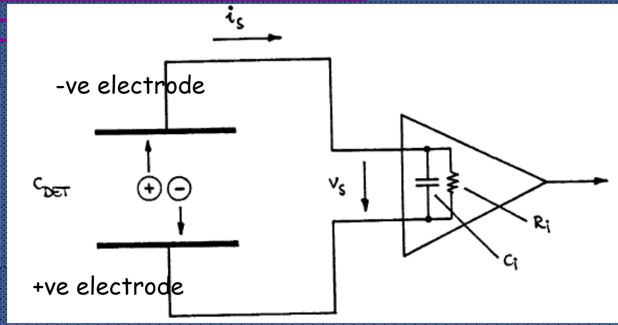
Ramo's theorem

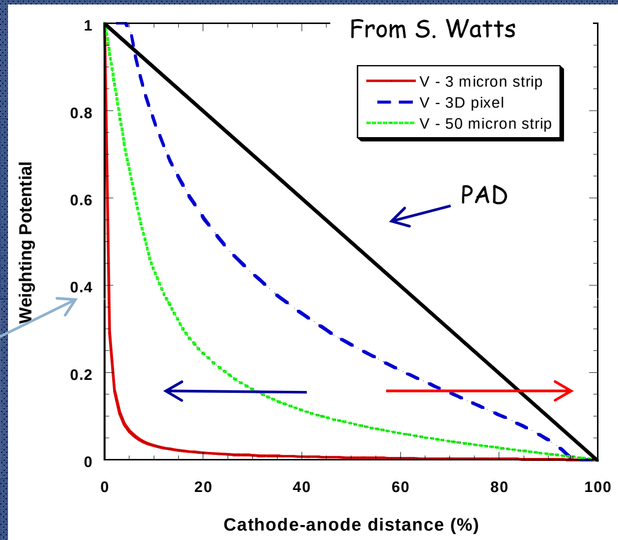
$$i_A = q\, v_x \frac{\partial V_{q1}}{dx}$$

$$\Delta Q_k = q(V_{q1}(2) - V_{q1}(1)) \equiv q(\Phi_k(2) - \Phi_k(1))$$

➢The electric field determines the charge trajectory and velocity
➢The weighting field depends only on geometry and determines how charge motion couples to a specific electrode.

Semiconductor detector equivalent circuit





❖"Weight "depends on pitch to thickness ratio "small pixel effect'. →

❖Loss of 1 carrier: CzTe, Trapping in irradiated Si

❖Induced signal in neighbour pixels non zero

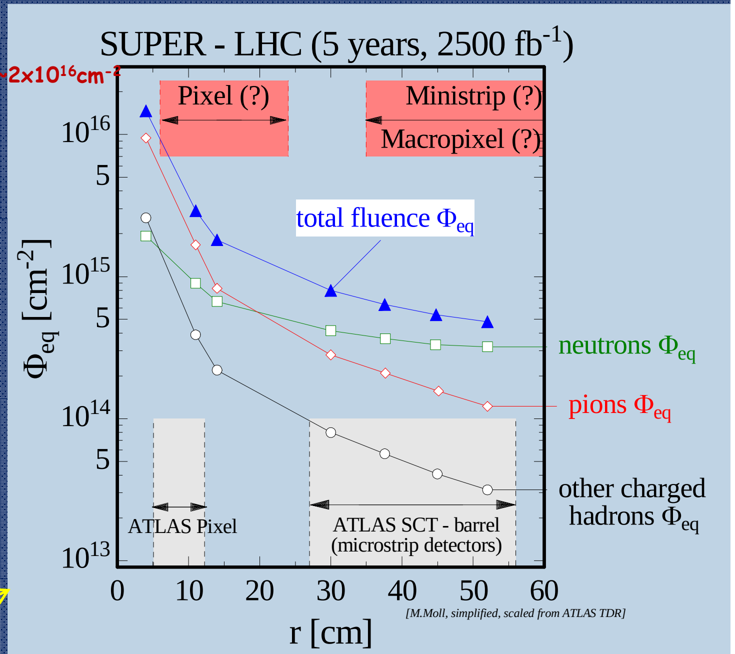
Environment 1-The LHC and SLHC challenge

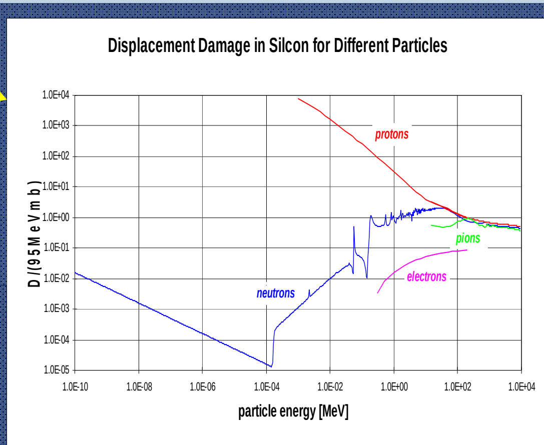
Cinzia Da Vià / Manchester -Heareus Seminar-28-04-09

at full luminosity **L=10^{34} cm^{-2} s^{-1}**:

- **~23** overlapping interactions in each bunch crossing every 25 ns (= 40 MHz)
- inside tracker acceptance (|h|<2.5) **750** charged tracks per bunch crossing
- per year: ~5x10^{14} bb; ~10^{14} tt; ~20,000 higgs; but also ~10^{16} inelastic collisions – impact parameter resolution important
- severe radiation damage to detectors:
  - Fast Hadron dose at 4 cm after 10 years/500 fb^{-1} is **3 x 10^{15} cm^{-2}**
  - Fast Hadron Dose at 22 cm after 10 years/ 500 fb^{-1} is **1.5 x 10^{14} cm^{-2}**
- Inner detector key requirements: radiation hardness

Expected fluences for trackers
Multiple particle environment



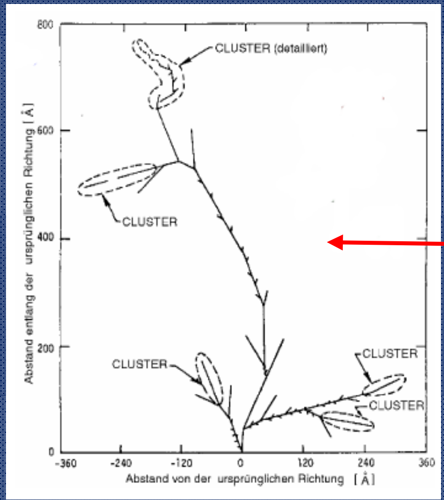


SLHC L=10^{35}cm^{-2}s^{-1}
Fast Hadron dose at 4cm after 5 Years is ~2x10^{16}cm^{-2}

2500 fb^{-1} after 5 years

~230 overlapping interactions Primary vertex detection!
~7000 ch-tracks/bc- (rejection)

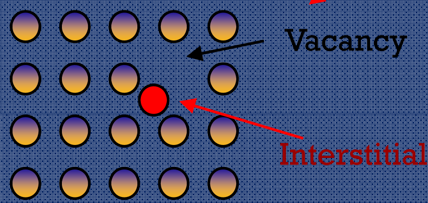
Radiation Induced Bulk Damage in Silicon



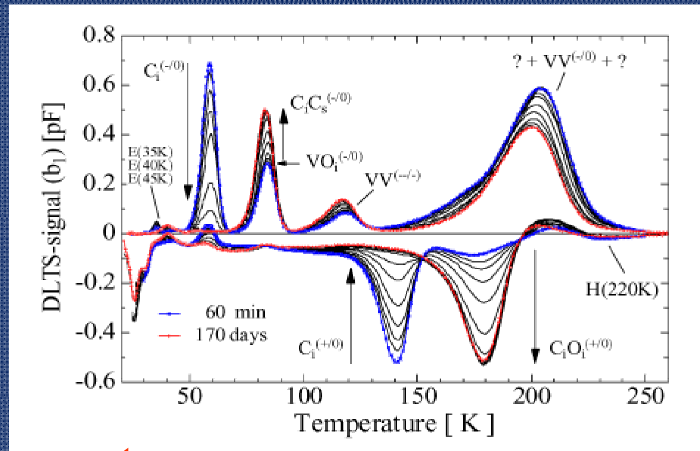
Van Lint 1980

Primary Knock on Atom

Displacement threshold in Si:
Frenkel pair E~25eV
Defect cluster E~5keV

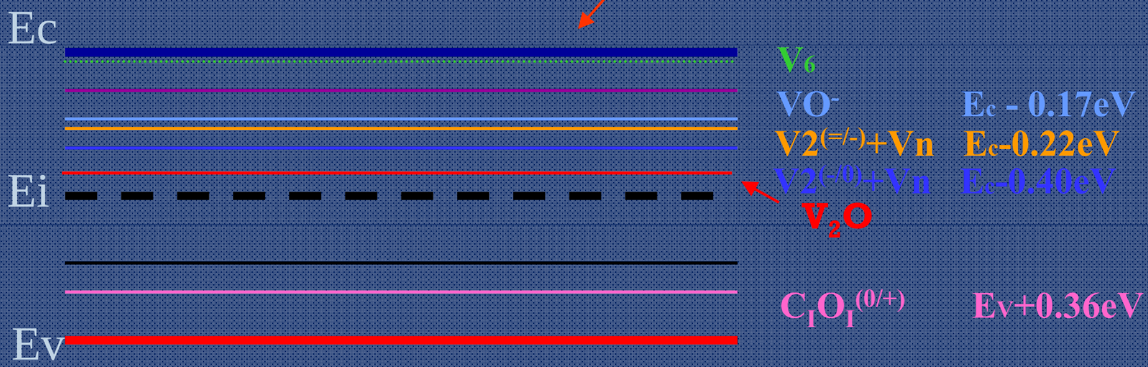


From RD48/ROSE



V,I MIGRATE UNTIL THEY MEET IMPURITIES AND DOPANTS TO FORM STABLE DEFECTS

Effect on sensors



CHARGED DEFECTS==>N_{EFF}, V_{BIAS}

DEEP TRAPS, RECOMBINATION CENTERS ==>CHARGE LOSS

DEEP TRAPS, GENERATION CENTERS==>LEAKAGE CURRENT

Silicon sensors macroscopic parameters changes observed up to $1x10^{15}$ n_{1MeV}/cm^2

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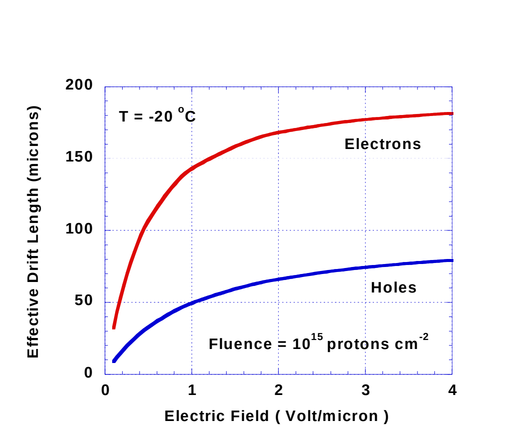
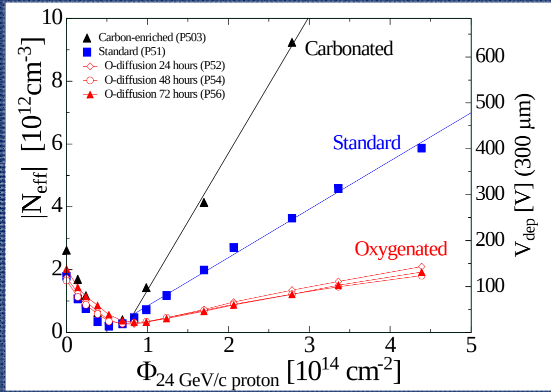
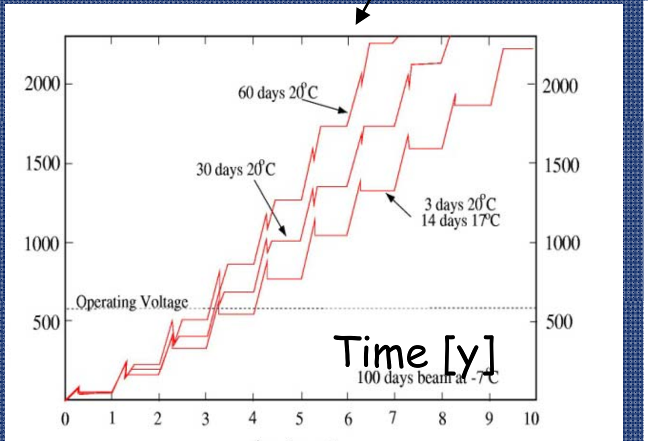
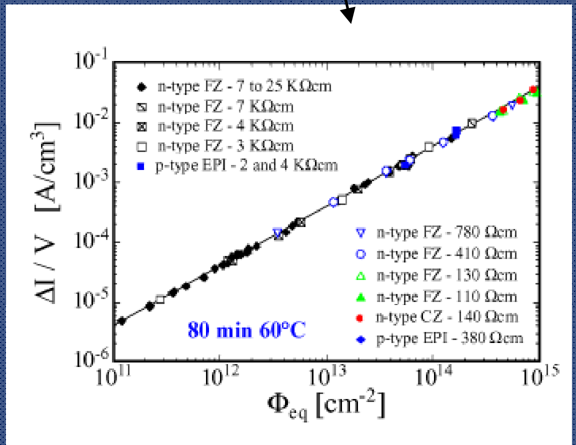
STANDARD 300μm n-type SILICON at 10^{15} n/cm2
10 years of operation at $L=10^{34}$ $cm^{-2}s^{-1}$ at R=4 cm



e^- and h^+ TRAPPING	SHORT τ_{trap} affects signal formation
SPACE CHARGE INCREASE TYPE INVERSION-double junction	-ve N_{eff} ($10^{13}/cm^3$) ~ V_{FD} (5000V)~ Φ OXYGEN HELPS!
REVERSE ANNEALING	INCREASE OF -ve N_{eff} after irradiation LOW T STORAGE HELPS
LEACKAGE CURRENT HELPS	prop to Φ (I/V ~$5x10^{-17}$ Φ) LOW T





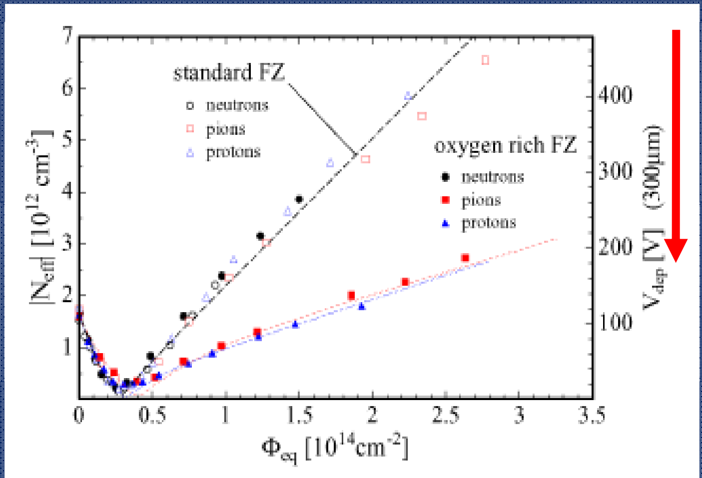


Needs to tackle all those issues:

- For Neff and Reverse annealing→ Oxygen and operational conditions
- **For trapping→ device engineering**
- New materials for low leakage current and Low noise

Lots of pioneering work from RD48/Rose
Now continued by RD50

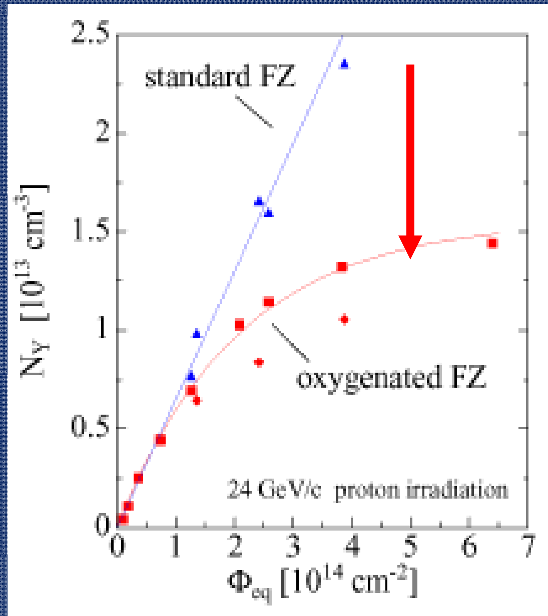
Playing with impurities: OXYGEN : ROSE/RD48 AND RD50

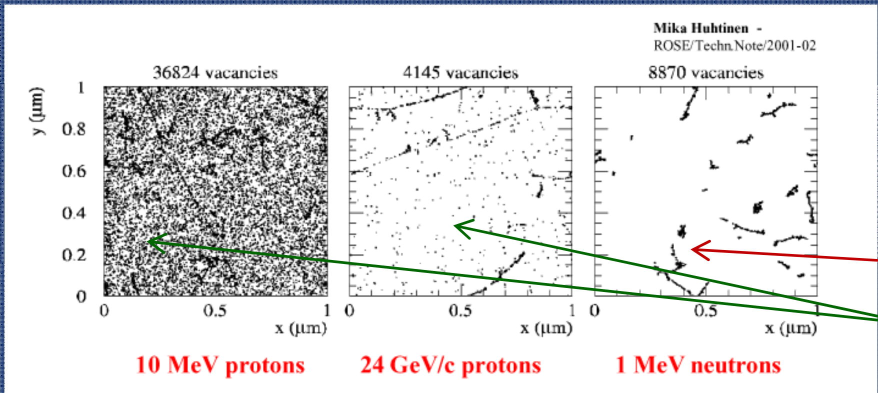


Nucl. Instr. Meth. A 466 (2001) 308

REDUCED V_{FD} 3 times With p and pions but Not neutrons!

Reduced Reverse Annealing Saturation (2 times)

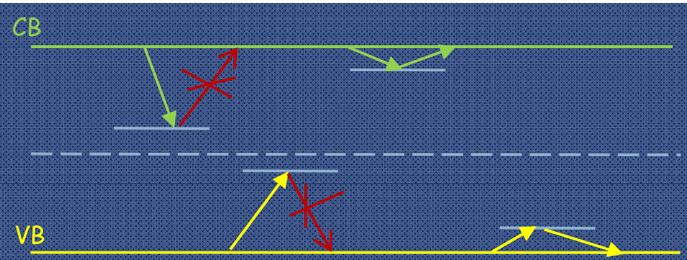




But.. Neutron proton puzzle
Competing mechanism due to Coulomb Interaction: more point defects when Irradiated with charged particles

V2+O=V_2O contributes to Neff
V+O=VO do not contribute to Neff

The effect of trapping

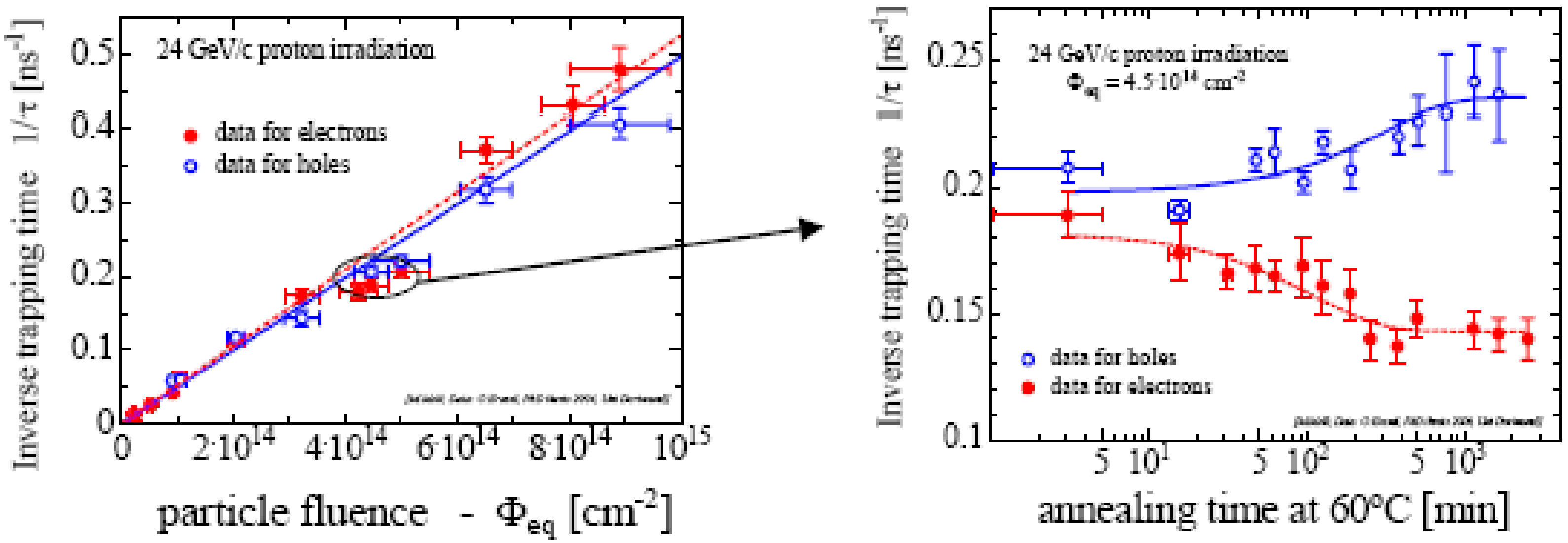


The carriers move less → less signal because of Ramo's theorem

Trapping is characterized by an effective trapping time τ_{eff} for e^- and h:

$$Q_{e,h}(t) = Q_{0_{e,h}} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t\right) \quad \text{where} \quad \frac{1}{\tau_{eff\ e,h}} \propto N_{defects} \propto fluence$$

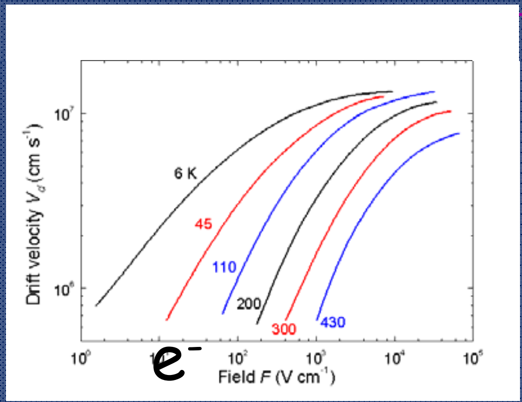
Increase of 1/τ with fluence | **1/τ changes with annealing**

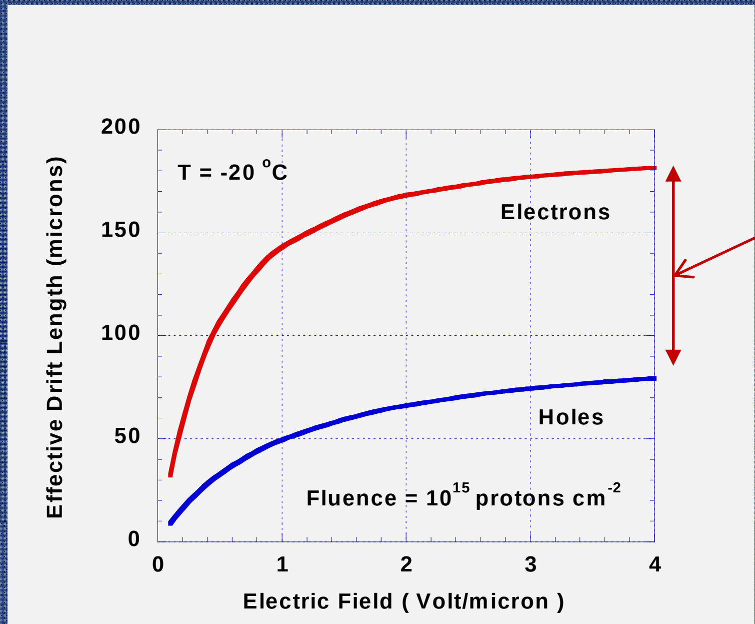


Trapping has been measured for electrons and holes by G. Kramberger (Ljiubliana) NIMA 481 (2002) 100

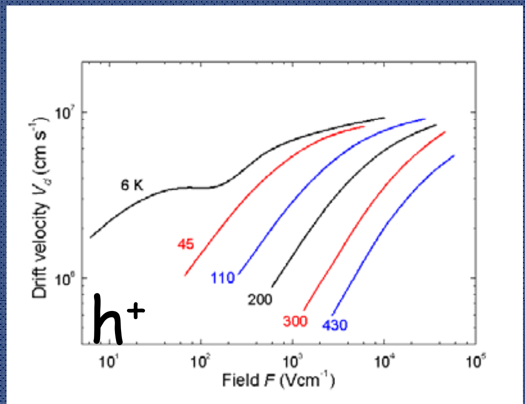
Effective drift length due to trapping

$$L_{eff} = v_{drift} \times \tau_{trap}$$





e^- mobility 3 times bigger!



For max signal:

- Collect e^-
- Work at V_{drift} Saturated -> e-field >2V/μm

Ottaviani, Canali et al.

Trapping times from Kramberger et al. NIMA 481 (2002) 100
Simulations CDV and S.Watts NIM A 501(2003) 138 (Vertex 2001)

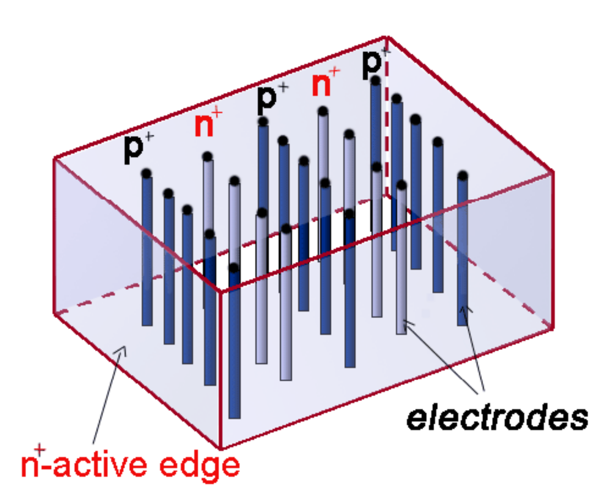
Device engineering: a possible way to overcome trapping due to radiation but also for other applications!!

•Use geometry to readout electron signals and allow high electric fields while keeping S/N

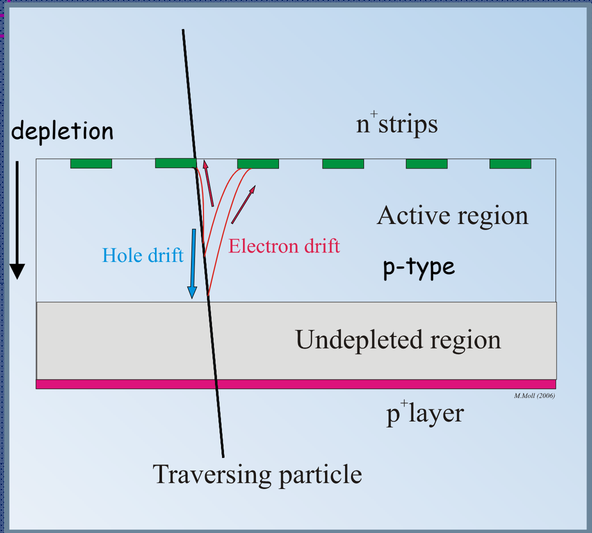
•Adapt the shape to optimise surface coverage and low dead volume

•Choose proper substrate material to combine advantages

- n-on-n and n-on-p silicon
- 3D sensors with active edges
- Thin silicon (with low noise ROC)
- And more.....

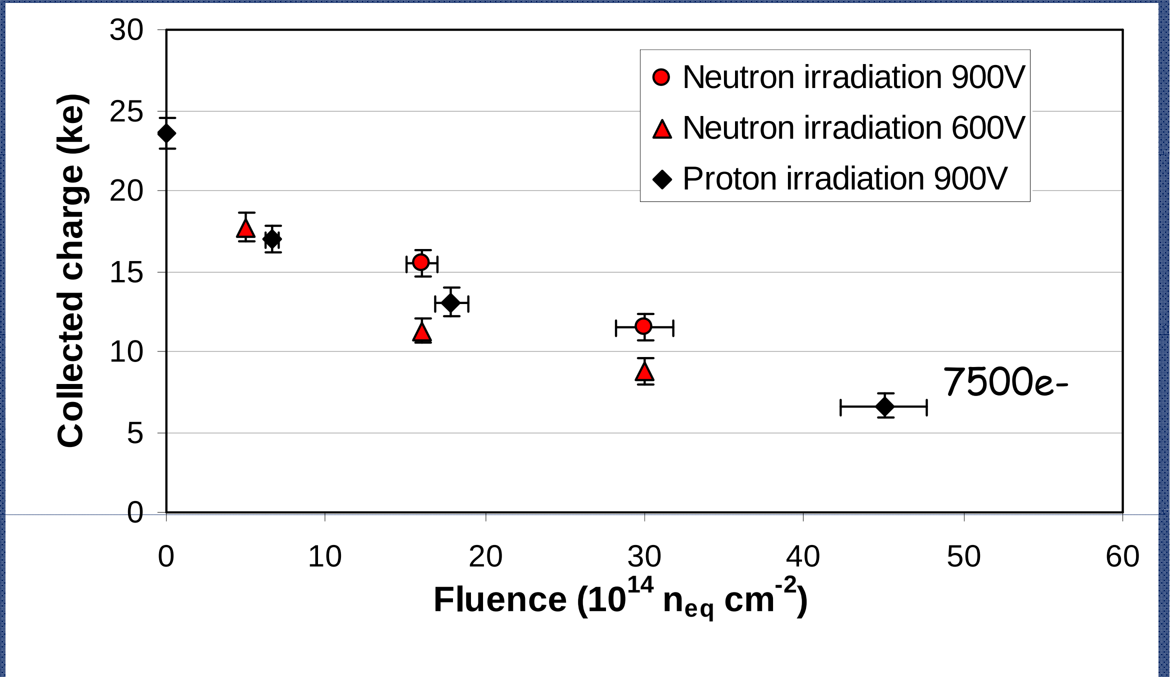


Electron signal readout: n-on-p (n-on-n after irradiation) silicon sensors



- Collects electrons
- Do not type invert
→depletion always from the same electrode
- Good annealing stability
- However for pixels better n-on-n (guard rings on back side) since n-on-p have high field close to electronics input

Miniature microstrip p-type detectors irradiated with 24GeV/c protons (black) and reactor neutrons (red)

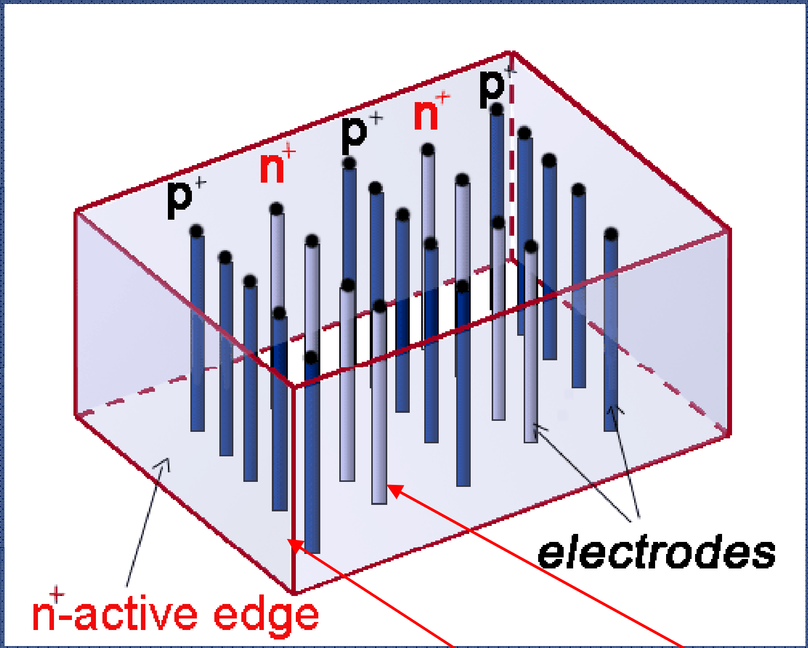


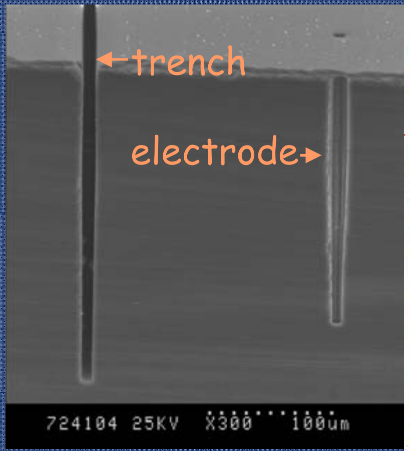
Micron and CNM sensors

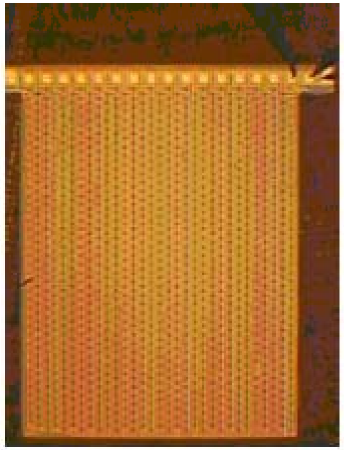
Measurements: Liverpool

Electronics: SCT128, 40MHz analogue chip

3D silicon sensors originally fabricated at Stanford by J. Hasi (RA-Manchester) and C. Kenney (MBC)



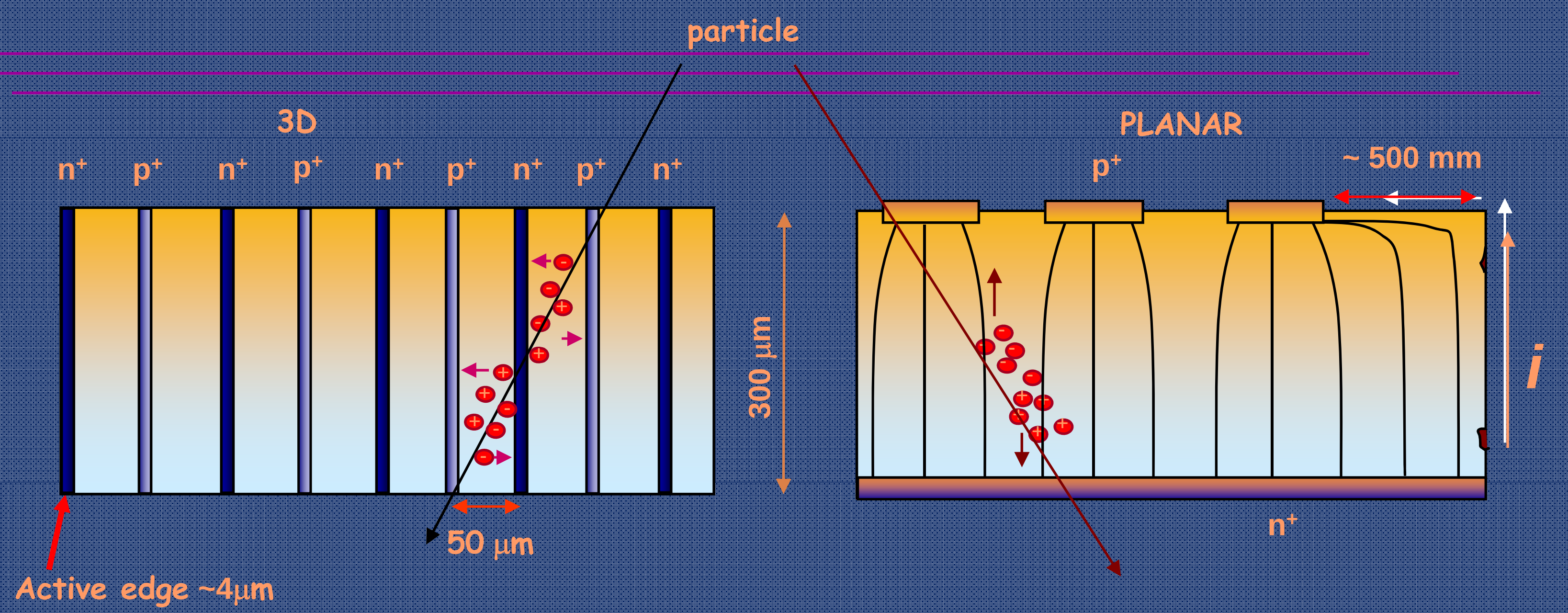


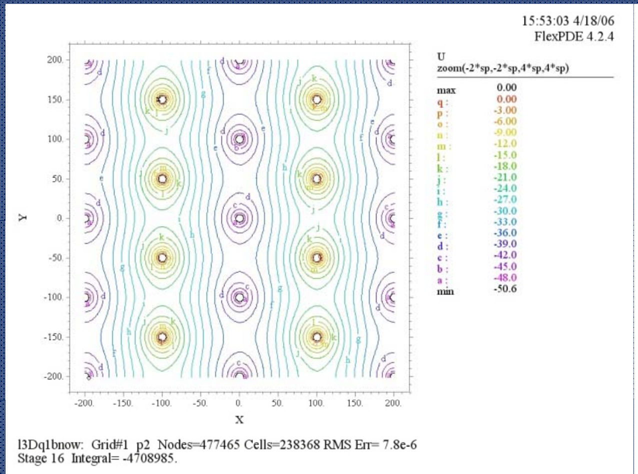


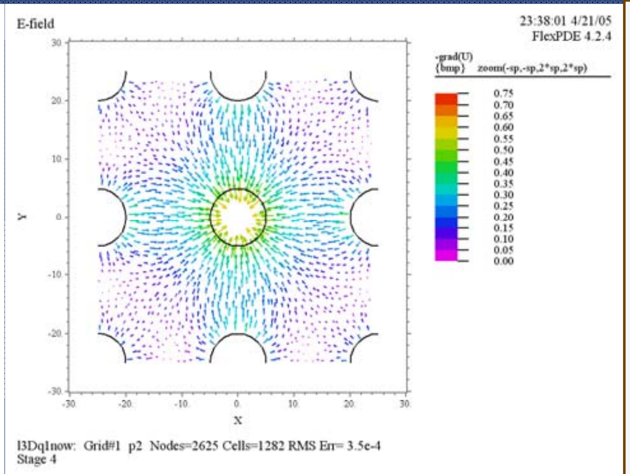
- 3D silicon detectors were proposed in 1995 by S. Parker, and active edges in 1997 by C. Kenney.
- Combine traditional VLSI processing and MEMS (Micro Electro Mechanical Systems) technology.
- Both electrode types are processed inside the detector bulk instead of being implanted on the Wafer's surface.
- The edge is an electrode! Dead volume at the Edge < 5 microns!

1. NIMA 395 (1997) 328
2. IEEE Trans Nucl Sci 46 (1999) 1224
3. IEEE Trans Nucl Sci 48 (2001) 189
4. IEEE Trans Nucl Sci 48 (2001) 1629
5. IEEE Trans Nucl Sci 48 (2001) 2405
6. Proc. SPIE 4784 (2002)365
7. CERN Courier, Vol 43, Jan 2003, pp 23-26
8. NIM A 509 (2003) 86-91
9. NIMA 524 (2004) 236-244
10. NIM A 549 (2005) 122
11. NIM A 560 (2006) 127
12. NIM A 565 (2006) 272
13. IEEE TNS 53 (2006) 1676
14. NIM A 587(2008) 243-249

3D versus planar







	3D	planar
V_{dep}	< 5-10 V	50-70 V
Q_{1mip}	24000e-	24000e-
C	40-80fF	50-200fF
Lorentz angle	no	yes

Simulations using FlexPDE by S. Watts (Manchester)

Back to rad-hardness:
Example: Signal Efficiency and Signal Charge

Cinzia Da Viá / Manchester -Heareus Seminar-28-04-09

SE=signal after irradiation/signal before irradiation

Ramo's theorem with trapping

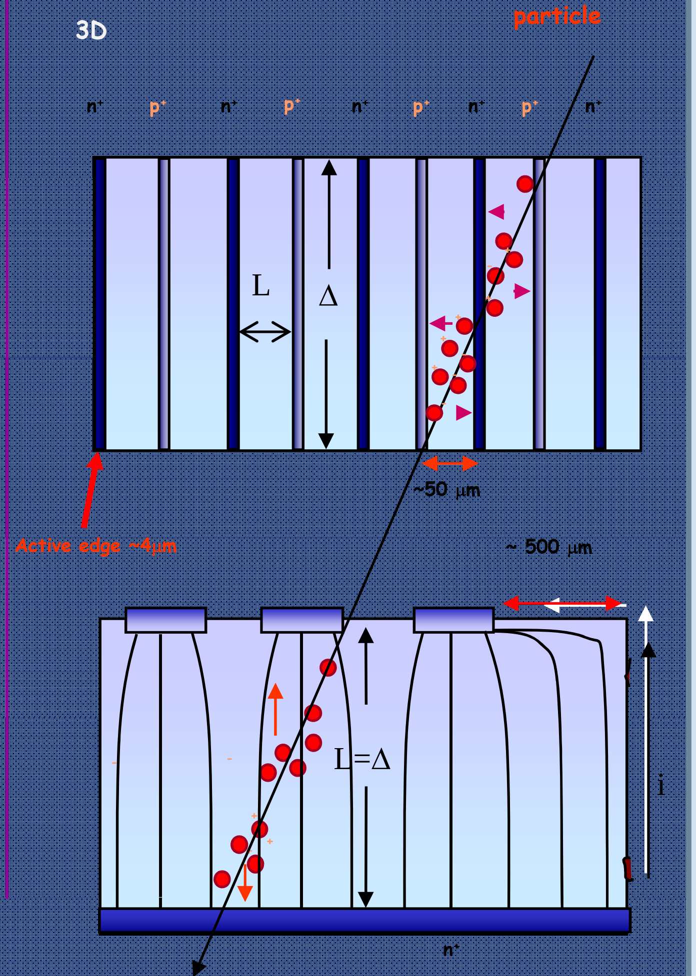
$$\frac{dS}{dt} = q\frac{dV_W}{dx}\frac{dx}{dt}\exp(-\frac{x}{\lambda})$$

$$S = \frac{\lambda}{L}\left[1-\exp(-\frac{x}{\lambda})\right]$$ ← signal

$$SE = \frac{\lambda}{L} - \left(\frac{\lambda}{L}\right)^2 + \left(\frac{\lambda}{L}\right)^2 \exp(-\frac{L}{\lambda}) \rightarrow$$

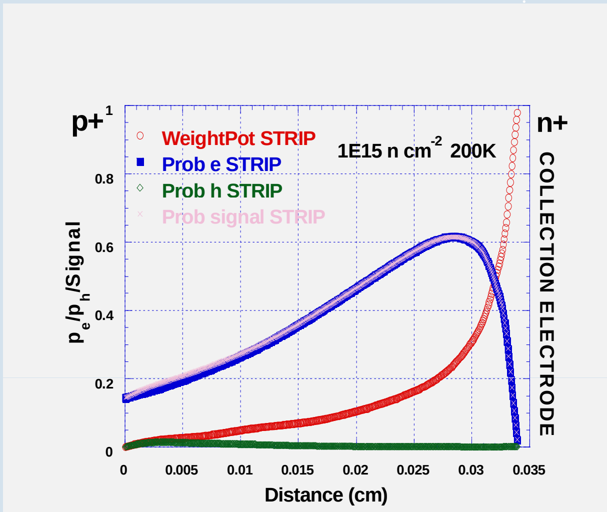
$$SE = \frac{1}{1+0.6L\frac{K_\tau}{v_D}\Phi}$$

3D



PLANAR

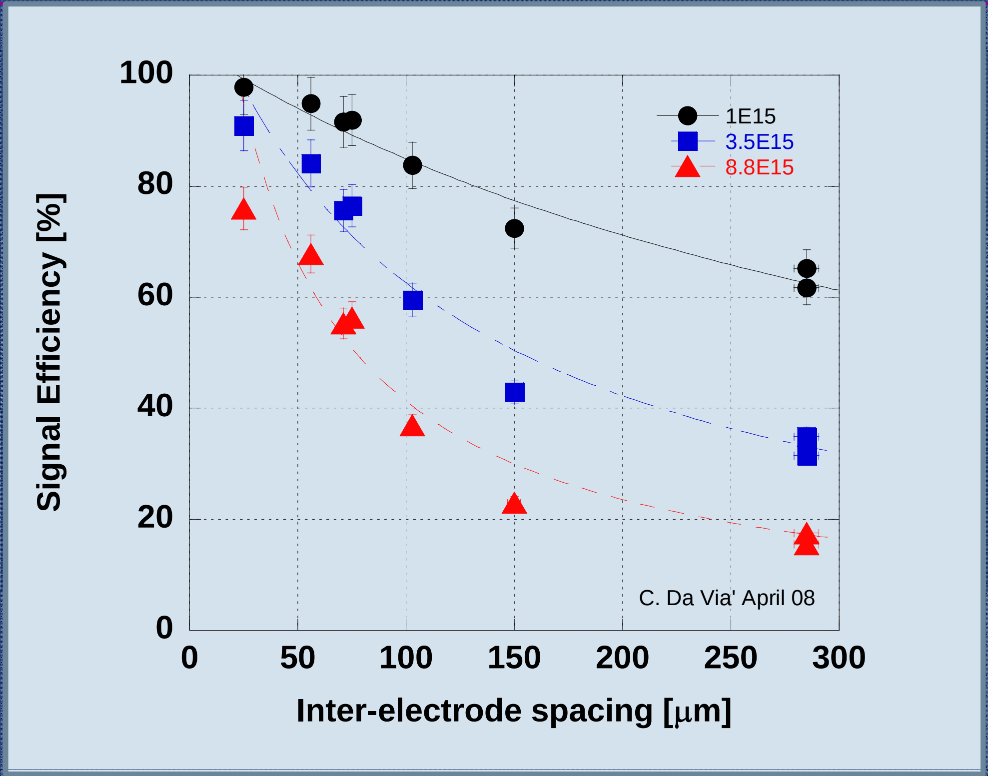
L=Inter electrode distance



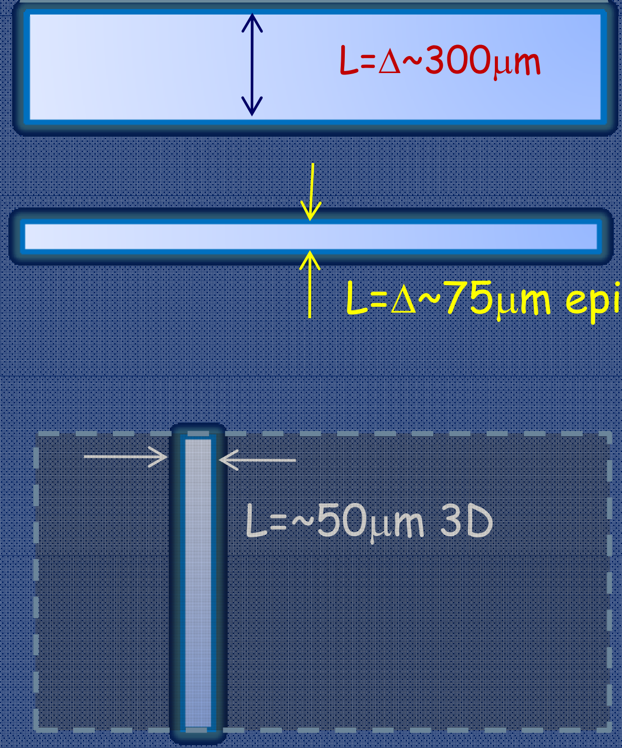
- ❖L=inter electrode spacing
- ❖λ= effective drift length
- ❖VD=vdrift (saturated)
- ❖Φ=fluence
- ❖Kτ=trapping time damage constant
- ❖Δ= substrate thickness (determines the amount of generated charged by a MIP)

Trapping times from Kramberger et al.
NIMA 481 (2002) 100
NIM A 501(2003) 138 (Vertex 2001)

The geometrical dependence of the signal efficiency on the inter-electrode spacing L



$$SE \propto \frac{1}{L}$$

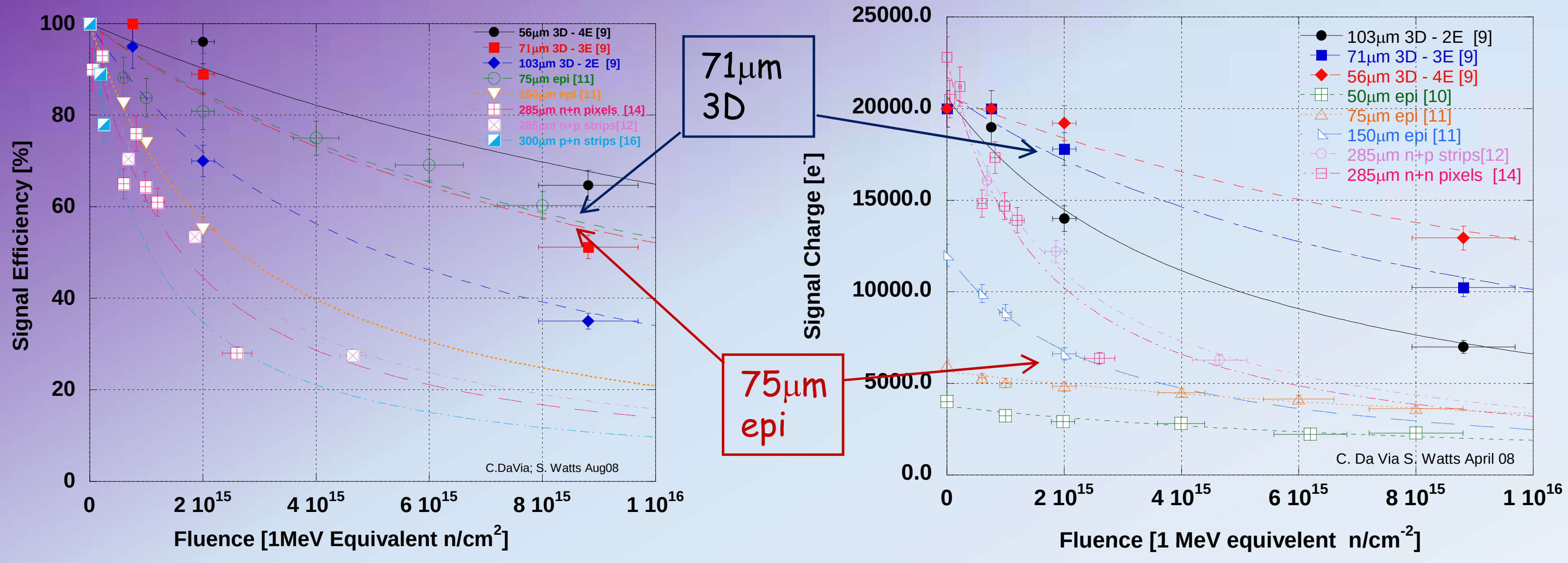


[3D- 56-71-103 µm] C. Da Via et al.", (NIMA-D-08-00587)
[epi 25 - 50µm] G. Kramberger at al., Nucl. Instr. Meths. A 554 (2005) 212-219
[epi 75 µm] G. Kramberger, Workshop on Defect Analysis in Silicon Detectors, Hamburg, August 2006. http://wwwiexp.desy.de/seminare/defect.analysis.workshop.august.2006.html
[planar 285µm] G. Casse et al., Nucl. Instr. Meths. A (2004) 362-365
[planar 285µm] T. Rohe et al. Nucl. Instr. Meths. A 552 (2005) 232-238
[F planar 300µm]. Lemeilleur et al., Nucl. Instr. Meths. A 360 (1995) 438-444

Signal efficiency and signal charge

[9] C. Da Via et al.", (NIMA-D-08-00587)
[10] G. Kramberger at al., Nucl. Instr. Meths. A 554 (2005) 212-219
[11] G. Kramberger, Workshop on Defect Analysis in Silicon Det, Hamburg, August 2006. http://wwwiexp.desy.de/seminare/defect.analysis.workshop.august.2006.html
[12] G. Casse et al., Nucl. Instr. Meths. A (2004) 362-365
[14] T. Rohe et al. Nucl. Instr. Meths. A 552 (2005) 232-238
[16] F. Lemeilleur et al., Nucl. Instr. Meths. A 360 (1995) 438-444

Signal Efficiency (prop 1/L) — Signal charge (depends on Δ)



Example at 10^{16} ncm^2

S_{MIP} planar ~ 80 (λ/~~L~~) x ~~Δ~~ ~ 80λ ~ 80x30 ~ 2400e$^-$

S_{MIP} 3D ~ 80λ x (Δ/L) ~ 2400 x 210/(71-22$_{\text{electrode implant}}$) ~ 10290e$^-$

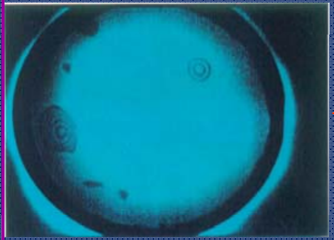
3D if big signal needed

Thin if low noise electronics

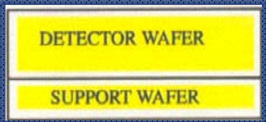
Key processing steps (25-32) based on Deep-Reacting Ion Etching

1- etching the electrode | **2-filling them with dopants**

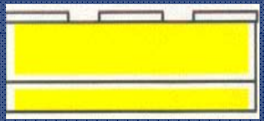
Aspect ratio: D:d = 11:1



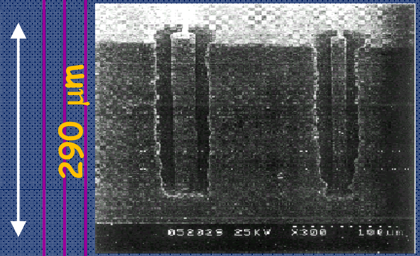
WAFER BONDING
(mechanical stability)
Si-OH + HO-Si -> Si-O-Si + H_2O



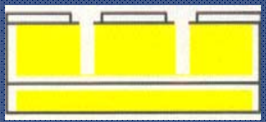
Step 1-3 field implant, oxidize and fusion bond wafer



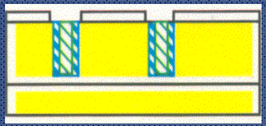
Step 4-6 pattern and etch p^+ window contacts



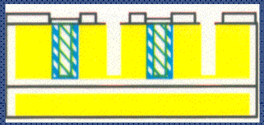
DEEP REACTIVE ION ETCHING (STS)
(electrodes definition)
Bosh process
SiF_4 (gas) +C_4F_8 (teflon)



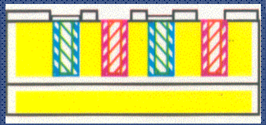
Step 7-8 etch p^+ electrodes



Step 9-13 dope and fill n+ electrodes

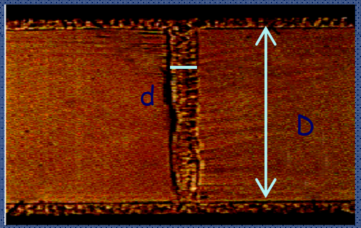


Step 14-17 etch n^+ window contacts and electrodes



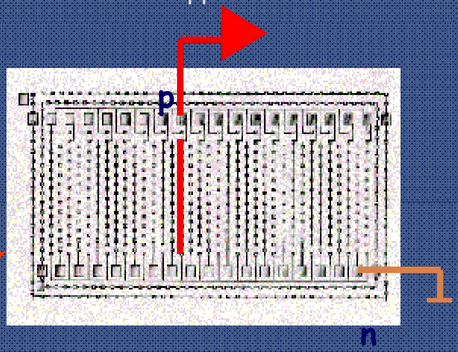
Step 18-23 dope and fill p+ electrodes

Step 24-25 deposit and pattern Aluminum



LOW PRESSURE CHEMICAL VAPOR DEPOSITION
(Electrodes filling with conformal doped polysilicon
SiH4 at ~620C)
$2P_2O_5$ +5 Si-> 4P + 5 SiO_2
$2B_2O_3$ +3Si -> 4 B +3 SiO_2

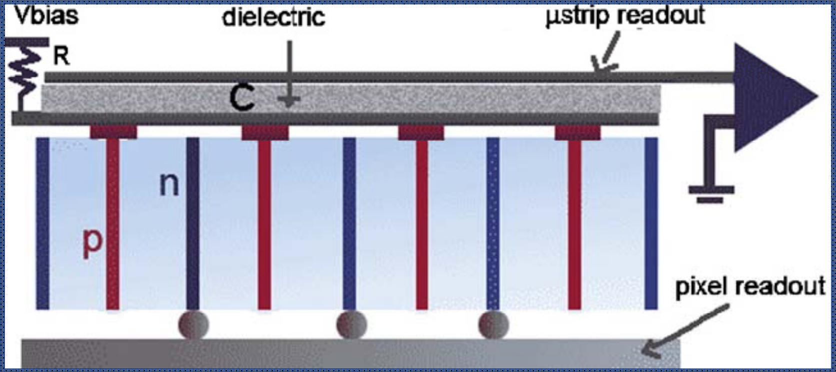
Both electrodes appear on both surfaces

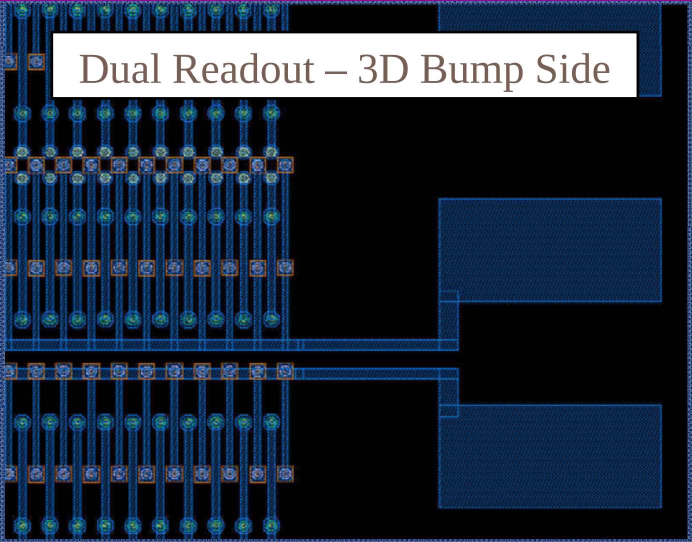


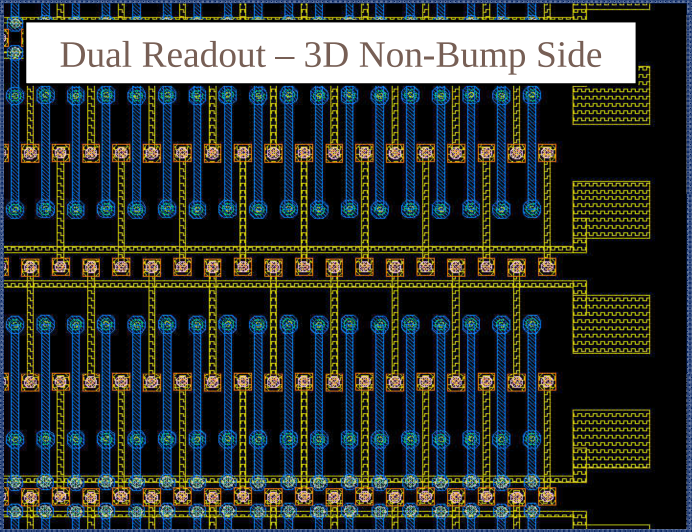
METAL DEPOSITION
Shorting electrodes of the same type
with Al for strip electronics readout
or deposit metal for bump-bonding

Example Dual readout

From Kenney US Atlas Upgrade meeting
September 08







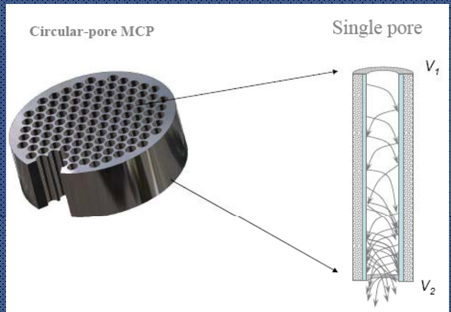
- ❖Improves spatial resolution
- ❖Reduces ambiguities

Devices being presently processed
Prototypes available in spring-summer09. Might be used for trigger at AtlasFP

C. Da Via et al., "Dual readout - strip/pixel systems", NIM A594, pp. 7-12 (2008).

Example: Micro-Machined Micro-Channel Plate

From D.R. Beaulieu IWORID 2008



❖Fast Photomultiplier Widely used

❖Pores normally coated glas

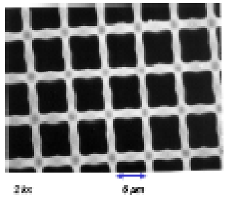
❖Various applications

❖Aging at high rates is an Issue

❖Pores dimension 10μm or less

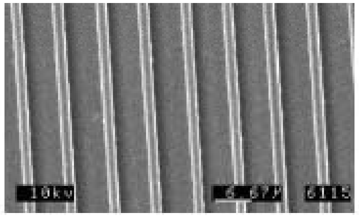
❖Speed depends on pore
❖dimension

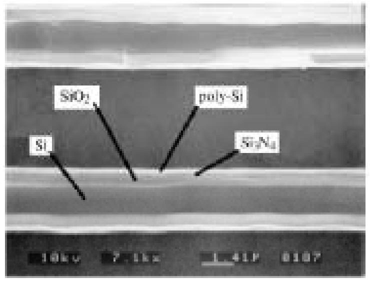
Previously tried: Silicon micromachined MCPs

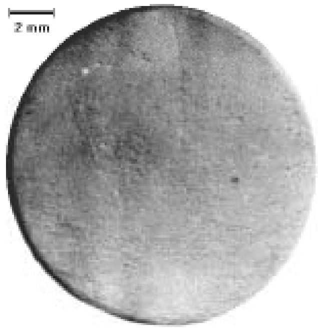


Pore pattern is set by photolithography

CVD growth of conduction layer and emission layer

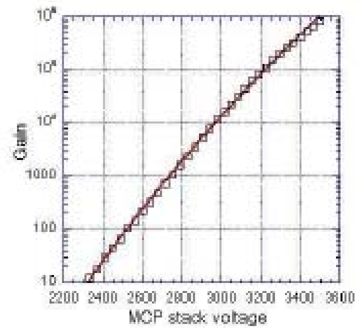






Full field UV image
(stack of 4 MCPs).
Residual distortions are seen

Relatively low gain.
No solid edge.
Long term stability.



Gain of 4 MCP stack (40:1 each)

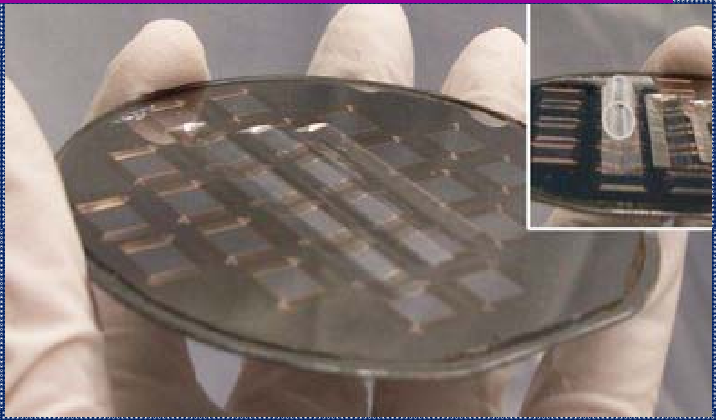
C.P. Beetz, et al., Nucl. Instr. Meth. A 442 (2000) 443

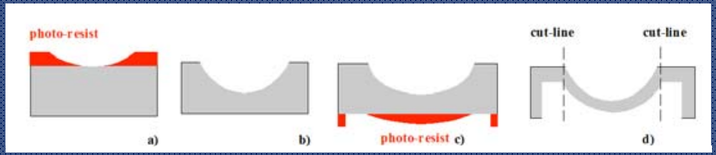
Improvements of gain and lifetime
due to novel emission and conduction layers

Curved semiconductor detectors

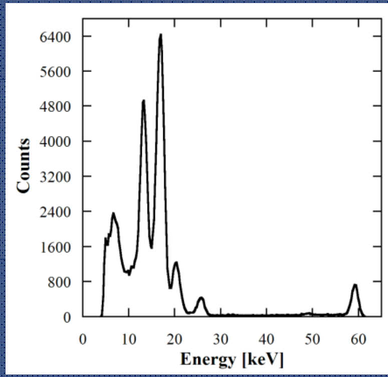
Bernard F. Phlips, *Member, IEEE, and Marc Christophersen*
Presented at IEEE-NSS 2008, Dresden Germany

- Done on Si , GaN and SiC already tried
- Uses Deep reaction Ion Etching
- Key to technology:
- Photo Lithography works: pixels and strips made using 'GrayTone Lithography' (selects photoresists differently at different depths)
- Wafer thinning uses standard processing
- Indium bump-bonding still works on curved structure
- Can be used on all material that allow DRIE
- Resist spray coating
- Alternatives to CMP to improve flatness

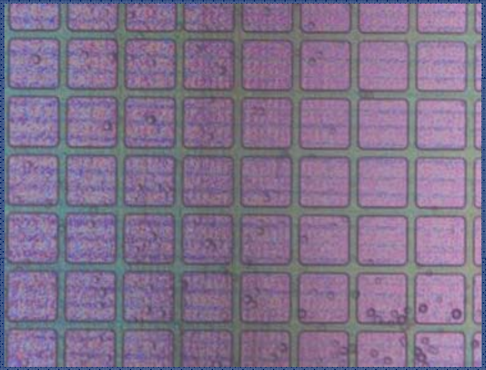




Principle of gray-tone technology: The 3-D resist profile, a) and c), is directly transferred into silicon topography, b) and d).



Am-241 photon spectrum taken with a fully depleted curved pixel detector, half-pipe (1.73 keV FWHM at 59.54 eV).



Top-view optical micrograph of a pixel array on a curved detector(pixel dimensions 150 x 150 µm).

Thin silicon and 3D interconnect
an alternative to bump-bonding

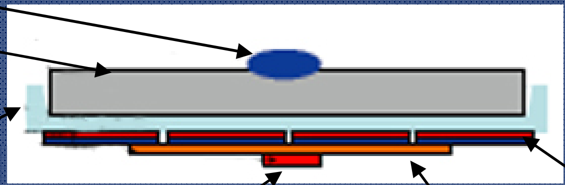
Courtesy R. Nisius, HG Moser
Munich and IZM

Example of detector module

Cooling pipe

Support/heat spreader

Thinned sensor/frame

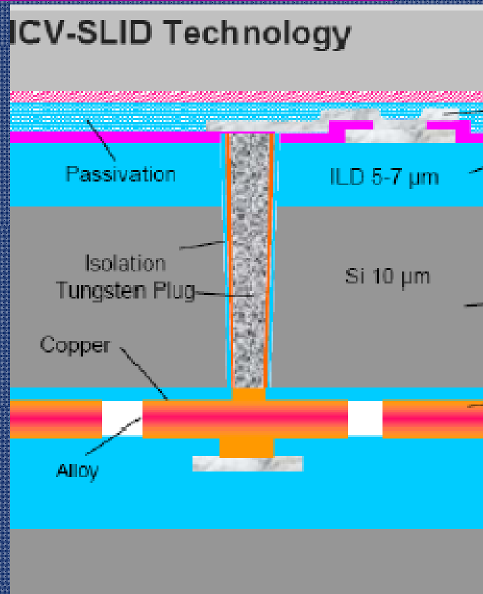


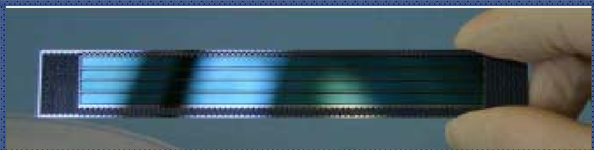
Multilayer chip

Module control data link

Flex-bus

Solid-Liquid Inter Diffusion
Connection -IZM

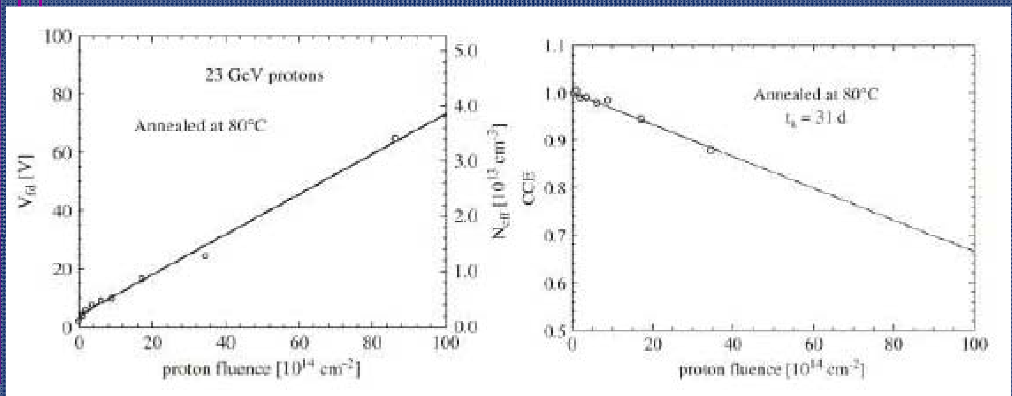


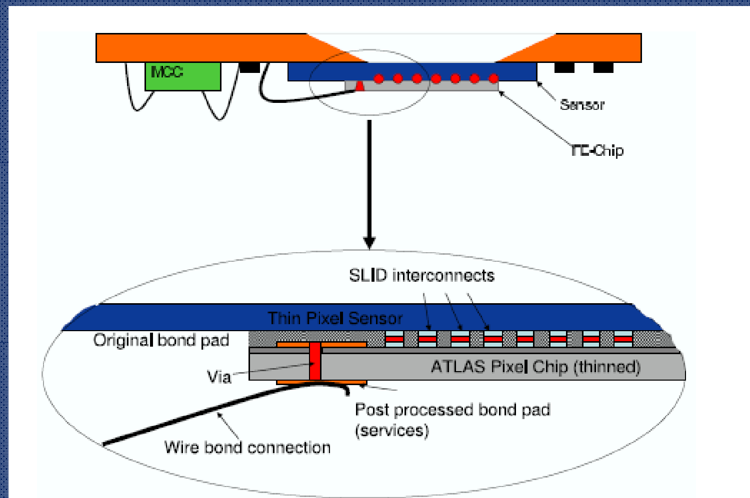


50µm thick prototype
n-type

Behaviour after irradiation

This silicon requires
New ROC development



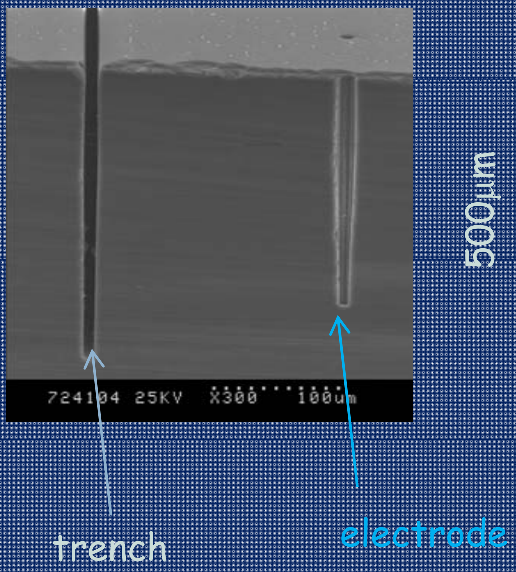


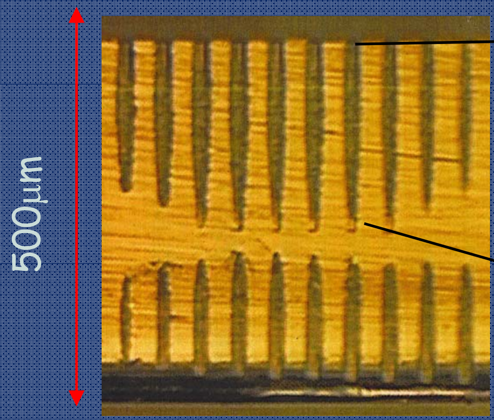
Improving the aspect ratio (D/d) in thick wafers

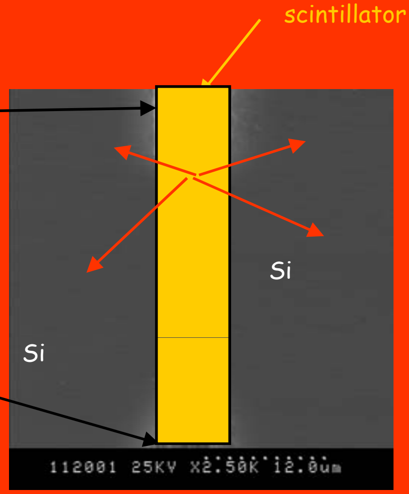
→less loss due to electrode inefficiency and possible use as x-ray and n detector

- ❖Aspect ratios as good as 24:1 ->narrow electrodes
- ❖Lower charge sharing → spectroscopy, medical imaging
- ❖Good selectivity to optimize hole size: example fill electrode with converter, scintillator, etc..

J. Hasi PhD thesis



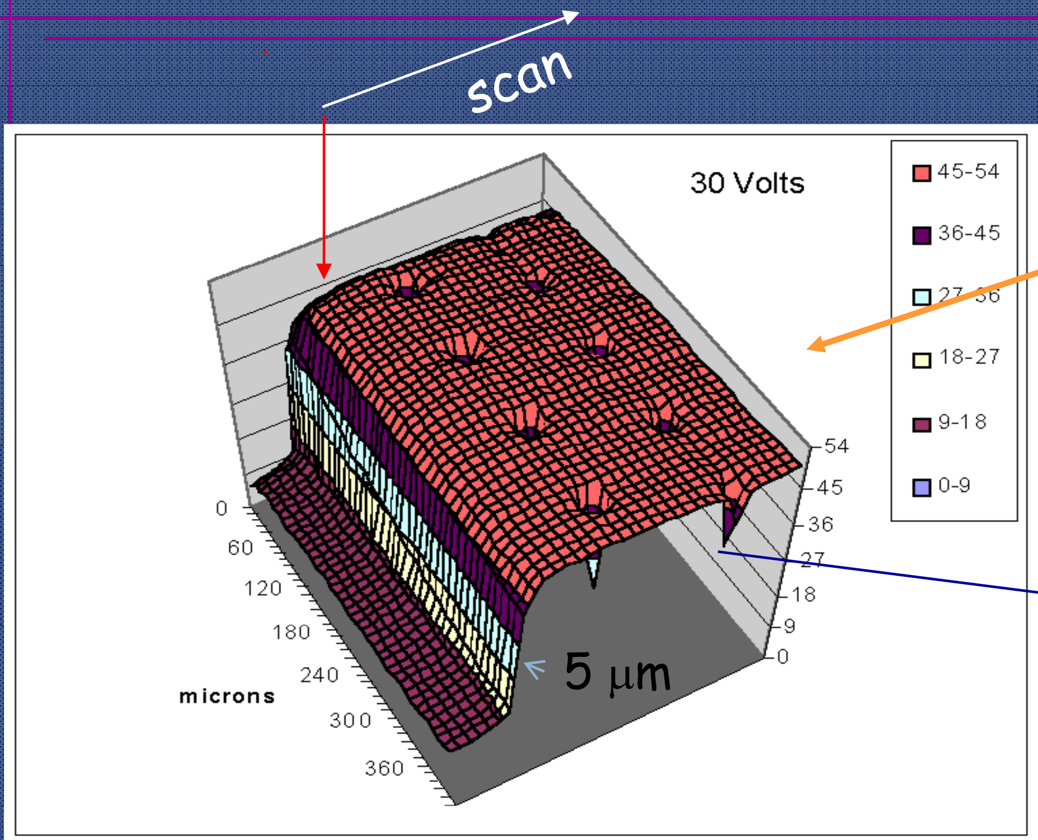


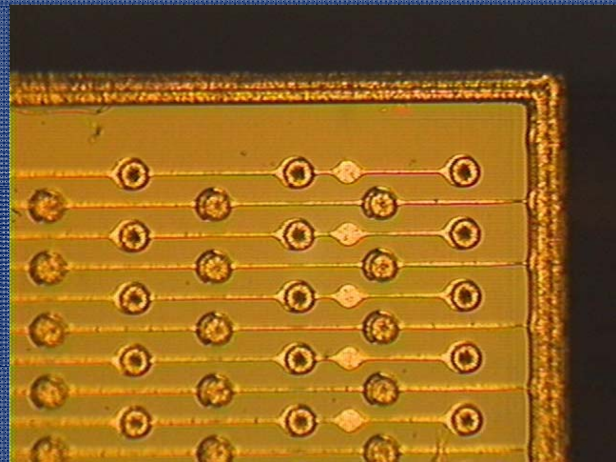


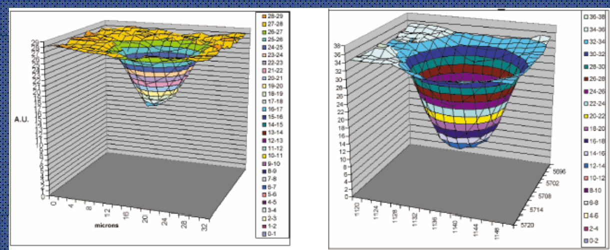
Optimised aspect ration for gamma detection

Active edge and electrode response of 3D sensors

Fabricated at Stanford, J. Hasi (Manchester PhD thesis)







N – Electrode

Signal Reduction 43%

P – Electrode

Signal Reduction 66%

Differences between N and P:

Grain size of poly, Diameter, Diffusion rate, Trapping, Doping

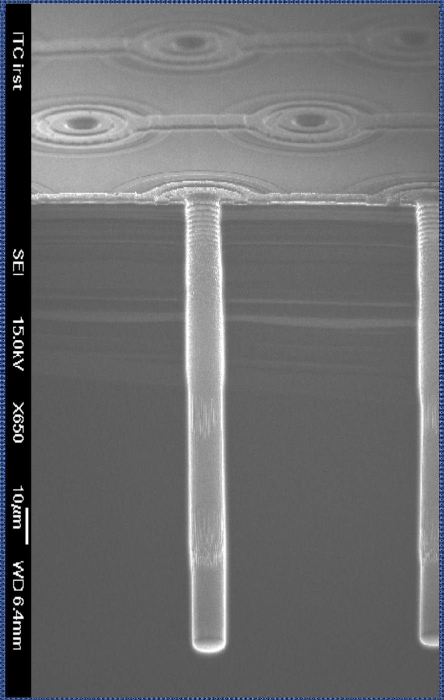
Electrodes ~ 1.8% of total area

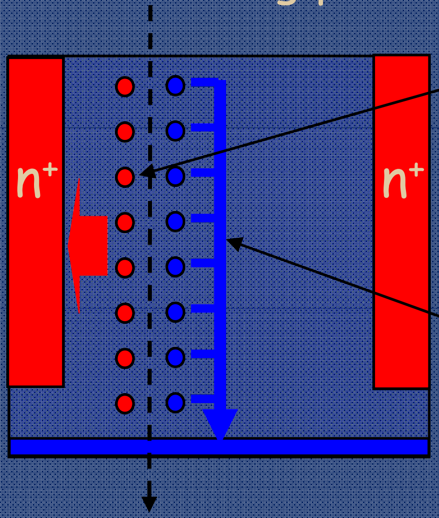
X-ray micro-beam scan, in 2 µm steps, of a 3D, n bulk and edges, 181 µm thick sensor.
The left electrodes are p-type

Electrode response

Other kinds of 3D:
Single-Type-Column - IRST and CNM

[C. Piemonte et al NIMA 541 (2005)]





Fabrication process is much simpler:

- column etching and doping performed only once
- holes not etched all through the wafer

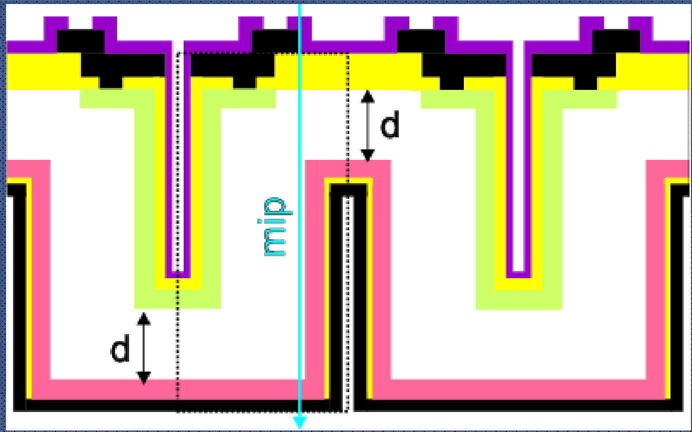
…**BUT** collection mechanism is less efficient and no active edges

Modified 3D at FBK-IRST: Double Type Column

- **3D-DDTC concept**

(Double-side Double Type Column)

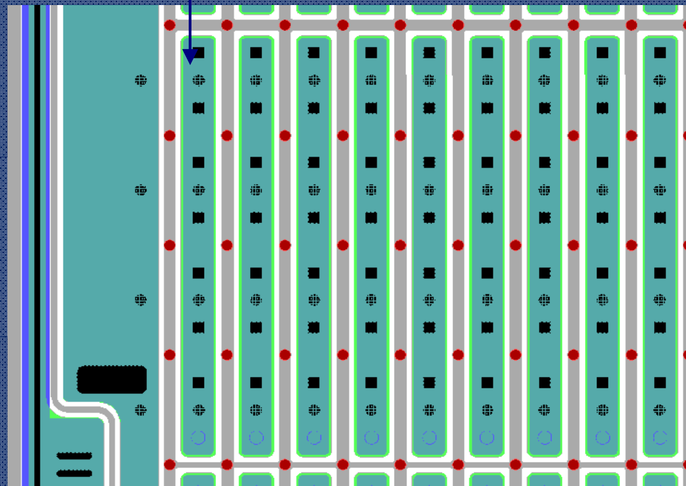
- Expected to have performance comparable to standard 3D detectors (if d is small enough)
- 2 batches under fabrication
- Will be ready for testing in common test beam This Autumn



Batch	DDTC 1	DDTC 2
Substrate type	n-type	p-type
Subst. thickness (µm)	300	205 – 255
Column depth (µm)	200 (not optimized)	180 – 200 (optimized)
Strip design and pitch (µm)	AC/DC coupled, 80 – 100	AC/DC coupled, 80 – 100
Pixel design	ALICE, MEDIPIX	ATLAS, CMS
Due by	August 2007	September 2007

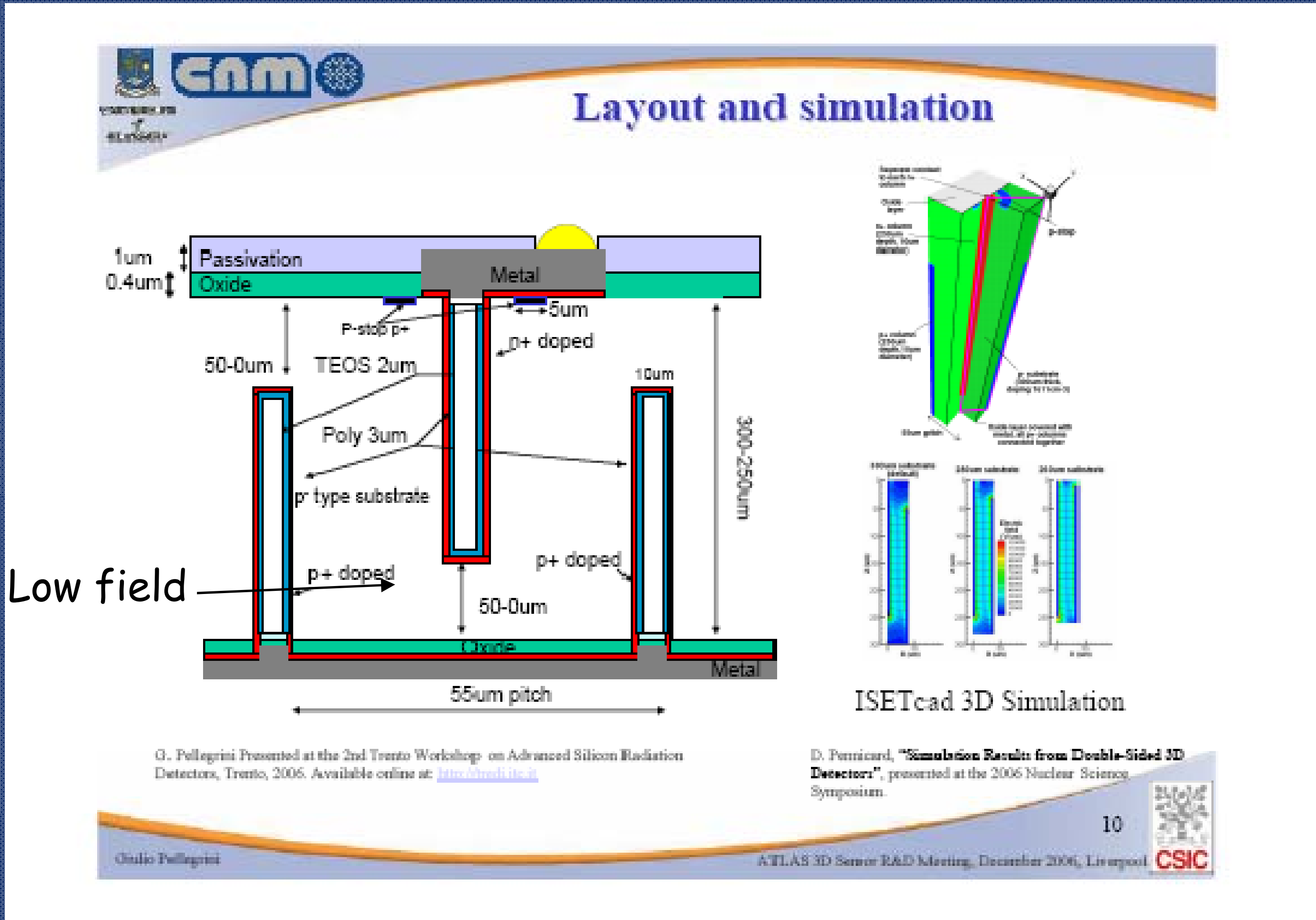
ATLAS pixel, single-chip

(2, 3, 4 or 7 columns/pixel)

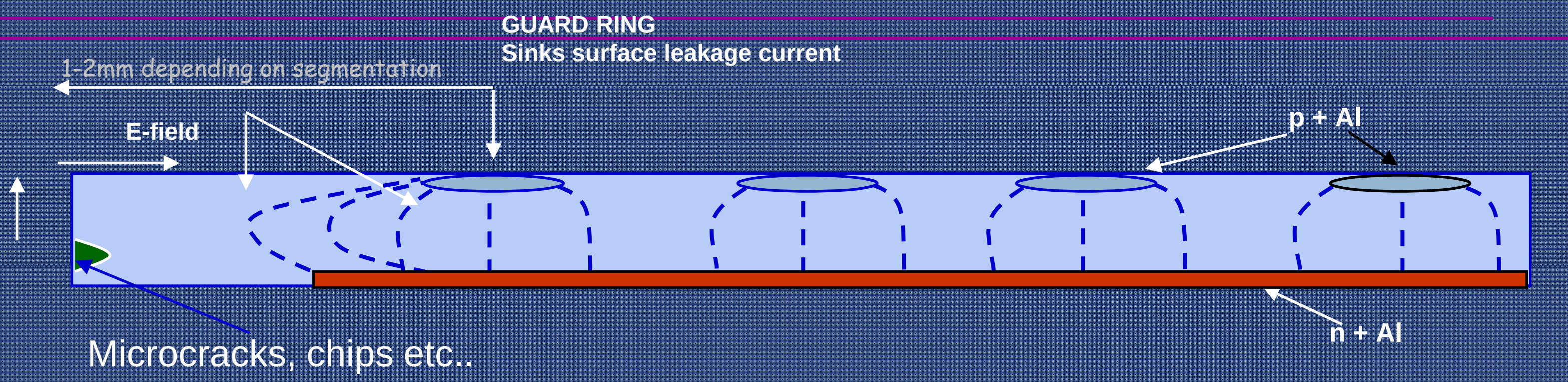


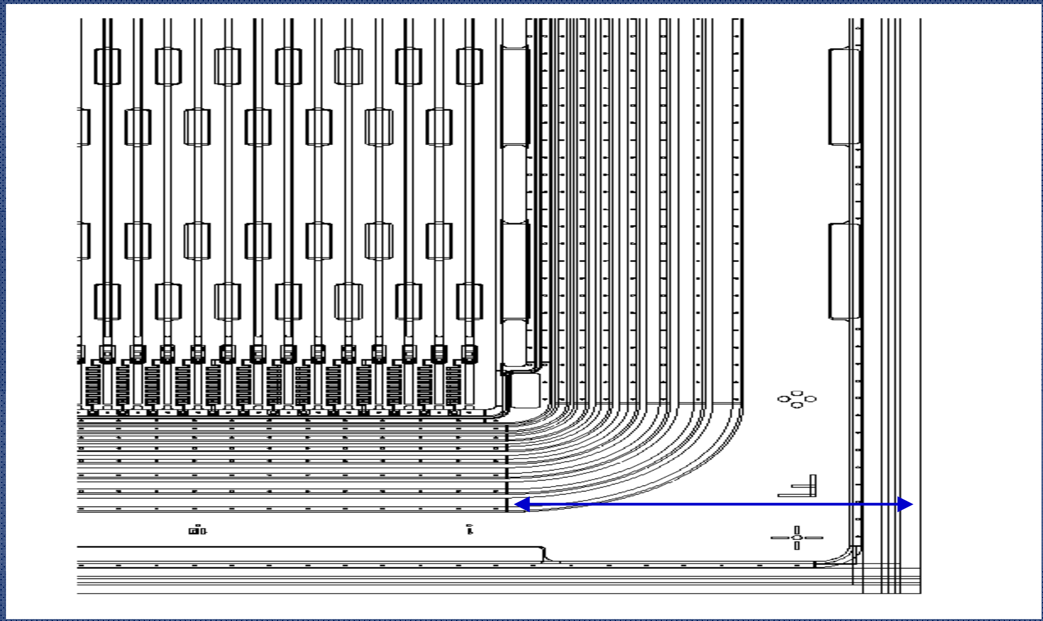
Modified 3D at CNM/ Glasgow : production of partial-and full-double column design

Celeste Fleta Richard Bates, Chris Parkes, David Pennicard – University of Glasgow
Manuel Lozano, Giulio Pellegrini – CNM (Barcelona)

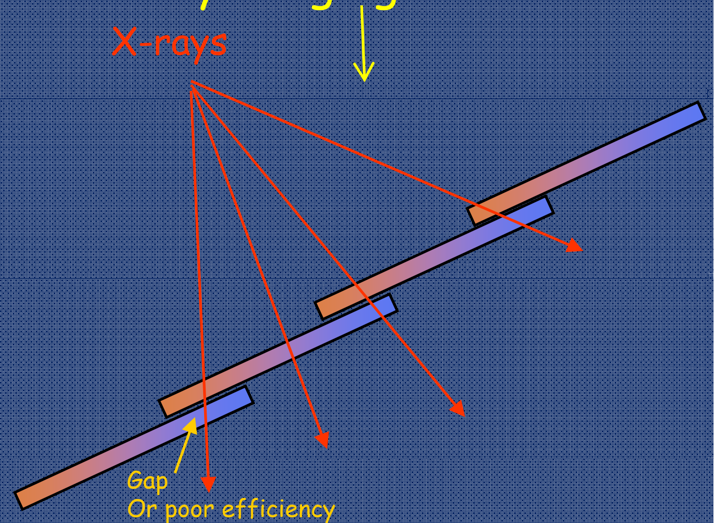


Reducing the dead volume: active, slim edges





Example large area coverage
For x-ray imaging:

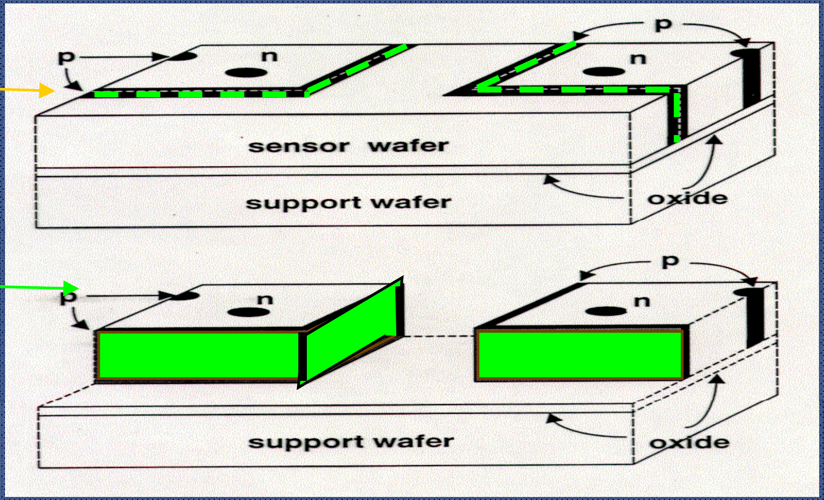


ATLAS microstrips guard rings ~1mm -> material budget, system aspects in pixels
special applications: forward physics

Example 1- Active edge processing

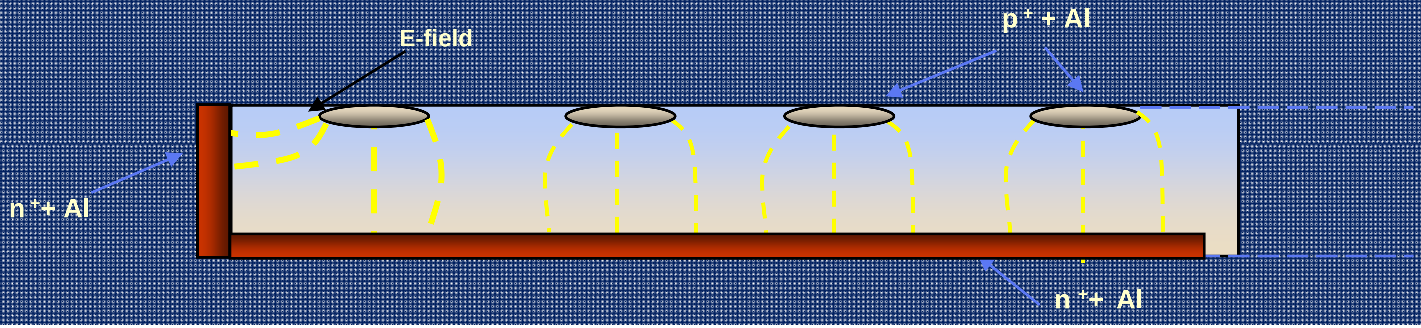
A TRENCH IS ETCHED AND DOPED TO TERMINATE THE E-FIELD LINES

AFTER THE FULL PROCESS IS COMPLETED THE MATERIAL SURROUNDING THE DETECTORS IS ETCHED AWAY AND THE SUPPORT WAFER REMOVED : NO SAWING NEEDED!!!
(NO CHIPS, NO CRACKS)



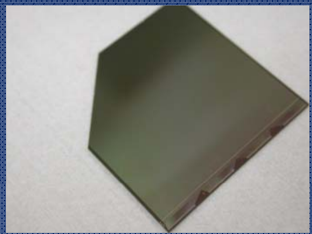
Natural development → PLANAR+3D = planar/3D

PLANAR DETECTOR + DOPANT DIFFUSED IN FROM DEEP ETCHED EDGE THEN FILLED WITH POLYSILICON (C. Kenney 1997)

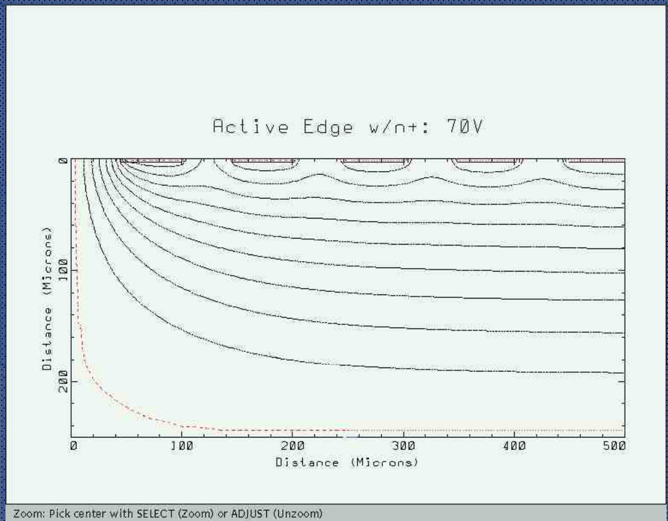


Planar sensors with active edge

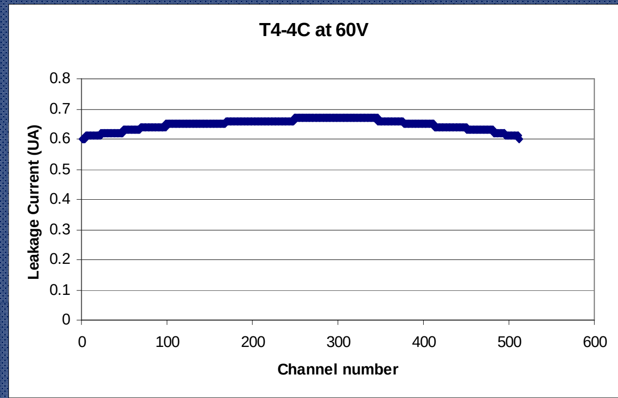
- PLANAR DETECTOR + DOPANT DIFFUSED IN FROM DEEP ETCHED EDGE THEN FILLED WITH POLYSILICON (C. Kenney 1997).
- The back plane (either n+ or p+) physically extends at the edge.
- The active volume is enclosed by an electrode: "active edge"



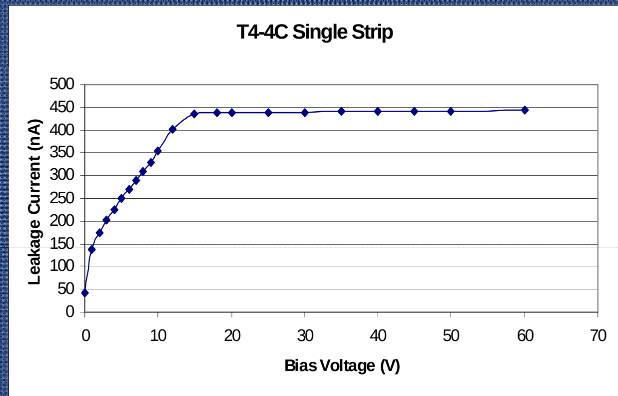
TOTEM detectors
3x4cm^2 512 μstrips



Medici simulation of the equipotential lines of a p on n planar/3D structure (J. Segal)



all the 512 strips at 60V



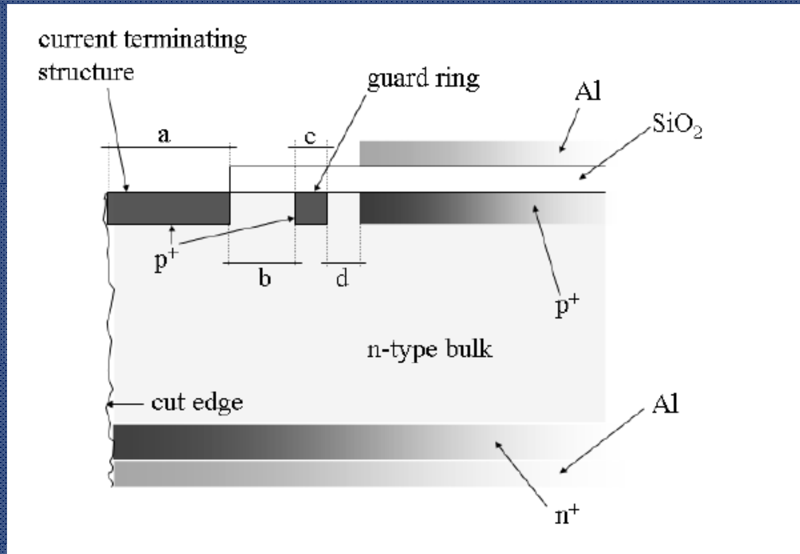
IV of one strip

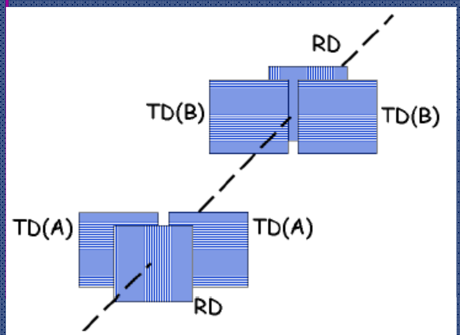
IV of one of the pre-production detectors.

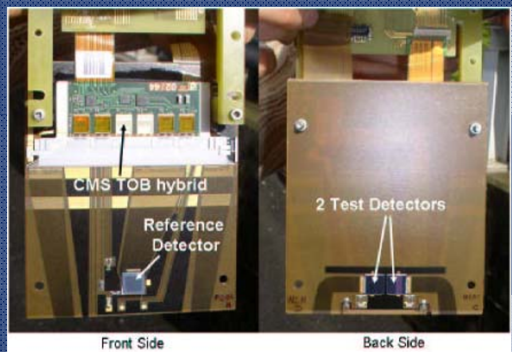
Current terminated structure

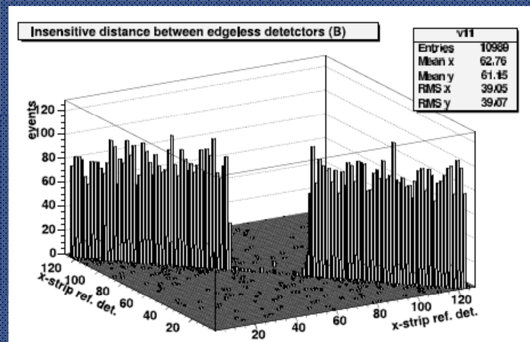
From the TOTEM TDR CERN LHCC 2004-002

- Decouples the active bulk current and the surface edge current
- Currently being installed in the TOTEM Roman Pots to measure elastic scattered protons in IP5 (CMS)
- Measured edge sensotivity ~ 50 µm
- Measured Radiation Hardness ~1×10^{14} ncm^2







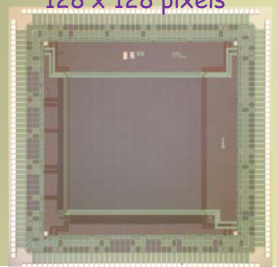


SOI pixels

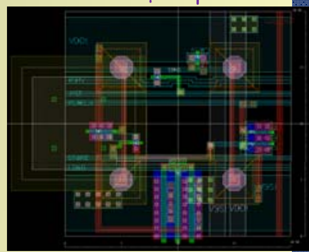
Mar. 13, 2009@TIPP09
Yasuo Arai (KEK)

- Bonded wafer : High Resistivity (Sensor) + Low Resistivity (CMOS) .
- Truly Monolithic Detector (-> High Density, Low material, Thin Device).
- Standard CMOS can be used (-> Complex functions in a pixel).
- No mechanical bonding (-> High yield, Low cost).
- Fully depleted sensor with small capacitance of the sense node (~10fF, High conversion gain, Low noise)
- Based on Industrial standard technology (-> Cost benefit and Scalability)
- No Latch Up, Rad Hard.
- Low Power
- Low to High Temp (4K-300C) operation
- Example OKI process:

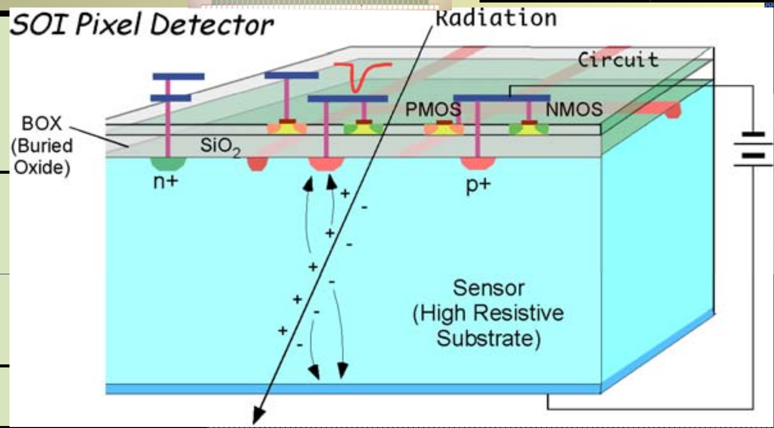
128 x 128 pixels



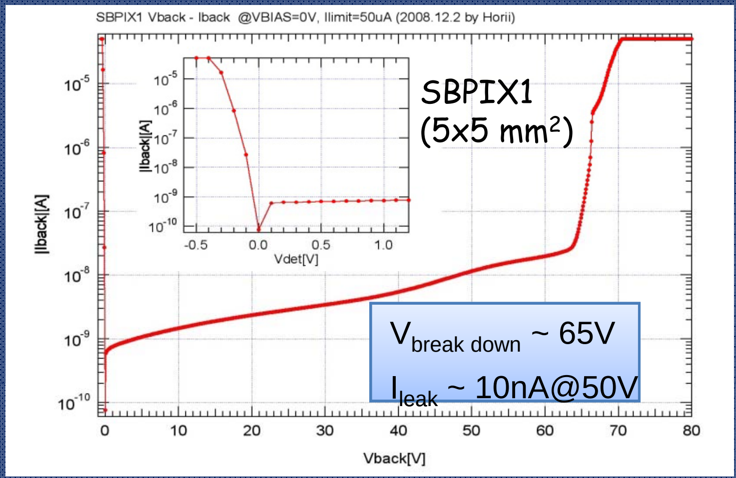
20x20 μm² pixel

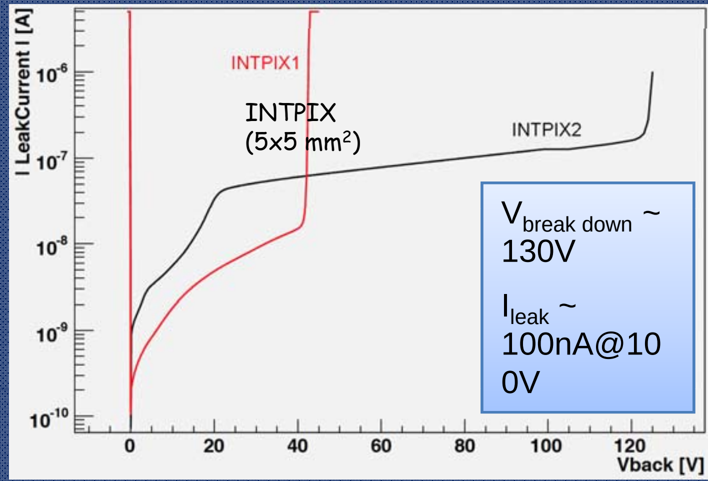


Process	0.2μm Low-Leakage Fully-Depleted SOI CMOS (OKI) 1 Poly, 4 Metal layers, MIM Capacitor, DMOS option Core (I/O) Voltage = 1.8 (3.3) V
SOI wafer	Diameter: 200 mmϕ, Top Si : Cz, ~18 Ω-cm, p-type, ~40 nm thick Buried Oxide: 200 nm thick Handle wafer: Cz、700 Ω-cm (*n-type)*, 650 μm thick
Backside	Thinned to 260 μm, and sputtered with Al (200 nm).



Break Down Voltage & Leak Current

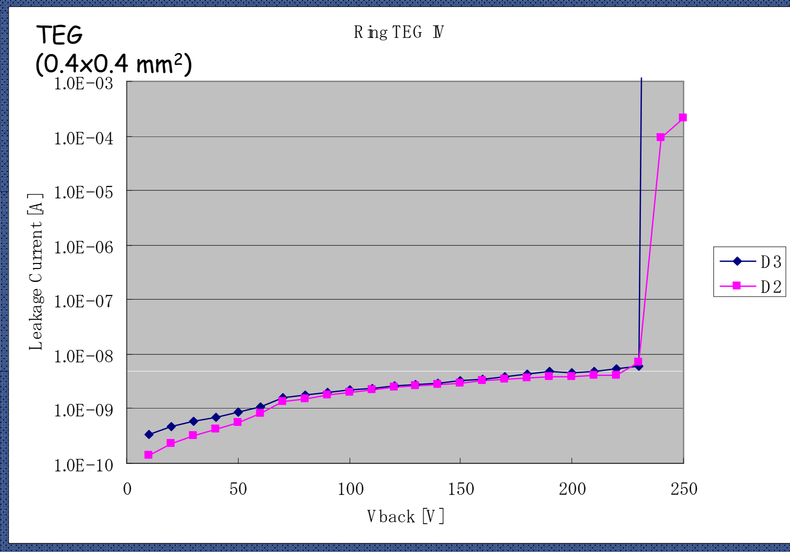




Break Down Voltage can be ~230V with proper guard ring design.

$V_{break\ down}$ ~ 230V

I_{leak} ~ 80nA@230V



On Going SOI R&D

ISSUES:

Sensor and Electronics are placed very near position (~200nm) in SOI pixel. This may cause following problems.

•Back Gate Effect (BGE) : Electric field from sensor will change the transistor characteristics.

•There may be Crosstalk between circuit and sensor node.

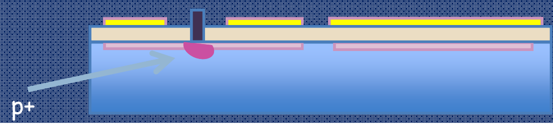
•Electric field in oxide will accelerate chance of hole trap at $Si\text{-}SiO_2$ interface, and this may reduce Radiation tolerance.

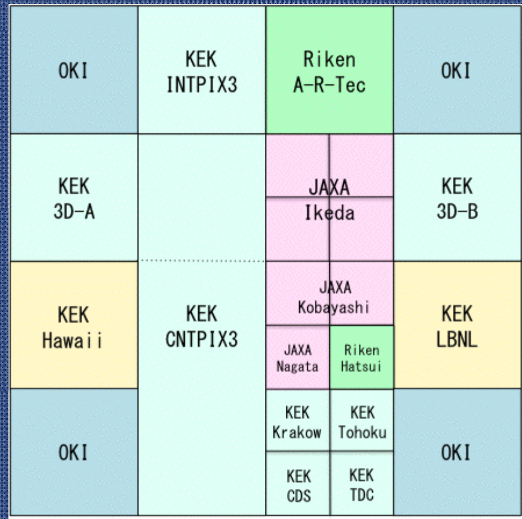
PROPOSED SOLUTIONS:

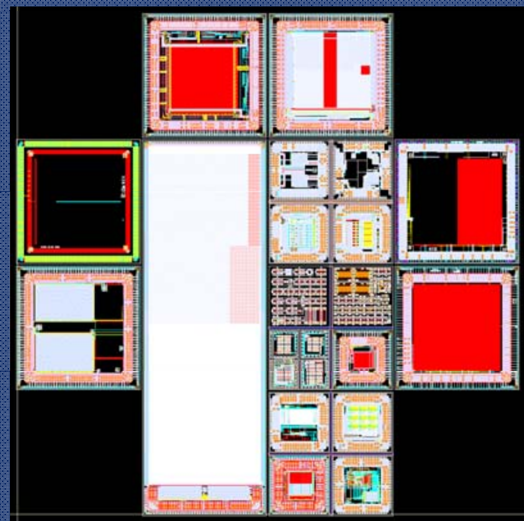
• *Wafer Improvement : Double SOI Layer wafer*

•Process Improvement to solve BGE : Buried p-well process (reduces electric field around p+ electrode)

•Integration Improvement : Vertical Integration







Other semiconducting materials

Property	Diamond	GaN	4H SiC	Si
E_g [eV]	5.5	3.39	3.26	1.12
$E_{breakdown}$ [V/cm]	10^7	$4 \cdot 10^6$	$2.2 \cdot 10^6$	$3 \cdot 10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2 \cdot 10^7$	-	$2 \cdot 10^7$	$0.8 \cdot 10^7$
Z	6	31/7	14/6	14
ε_r	5.7	9.6	9.7	11.9
e-h energy [eV]	13	8.9	7.6-8.4	3.6
Density [g/cm^3]	3.515	6.15	3.22	2.33
Displacem. [eV]	43	19.2±2	25	13-20

- Wide bandgap
  diamond=5.5
  SiC=3.3eV

< leakage current than silicon

- Signal:
  Diamond 36 e/μm
  SiC 51 e/μm
  Si 89 e/μm

  > charge than diamond

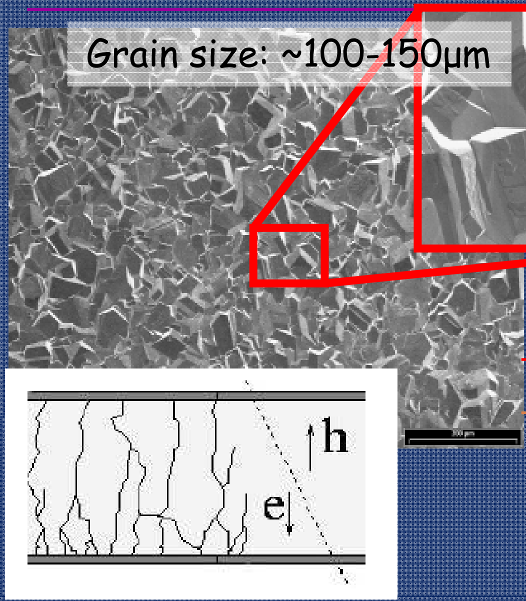
- > displacement threshold than silicon

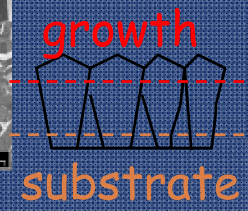
⇒radiation harder than silicon (?)

- Diamond:
  - Dielectric constant (2.1 × lower than SI) → low capacitance
  - Higher Electron and hole mobility →fast collection times

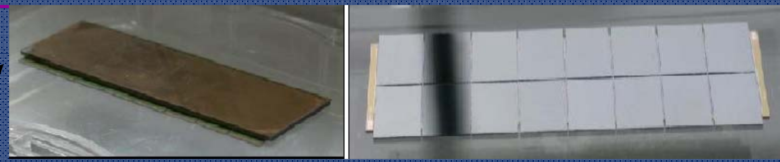
pCVD Diamond (Element Six Ltd.) as detector material now well established with BCM as first large scale (HEP) application – Atlas-pixel modules fabricated and tested successfully –

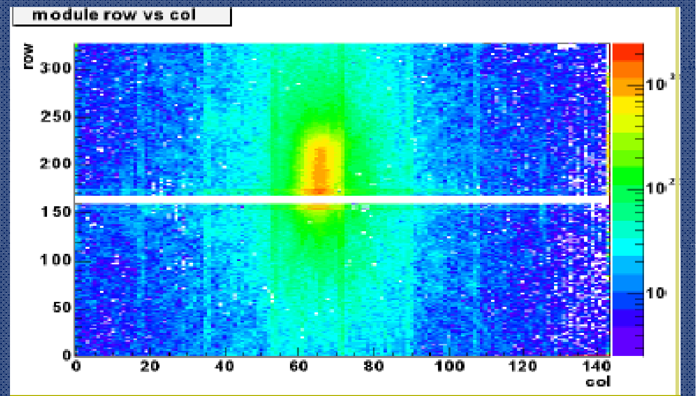
H Kagan for RD42





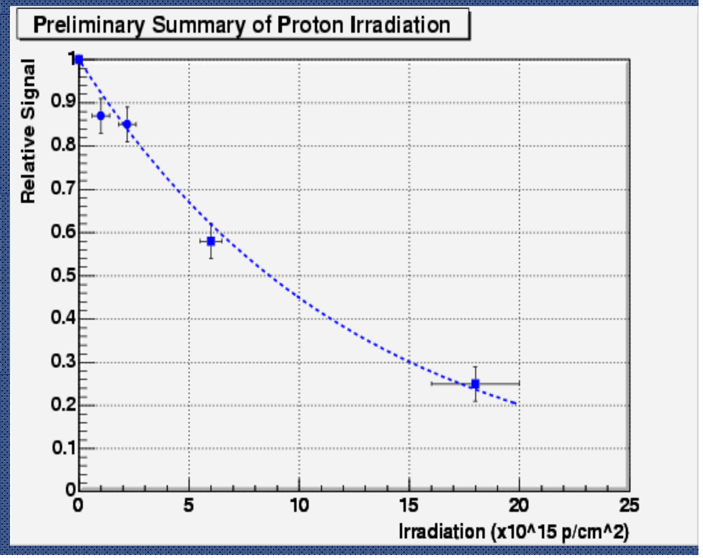
ATLAS pixel module





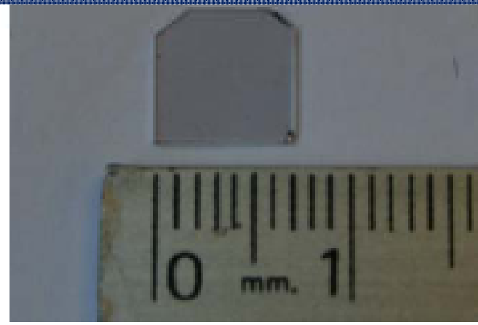
hitmap

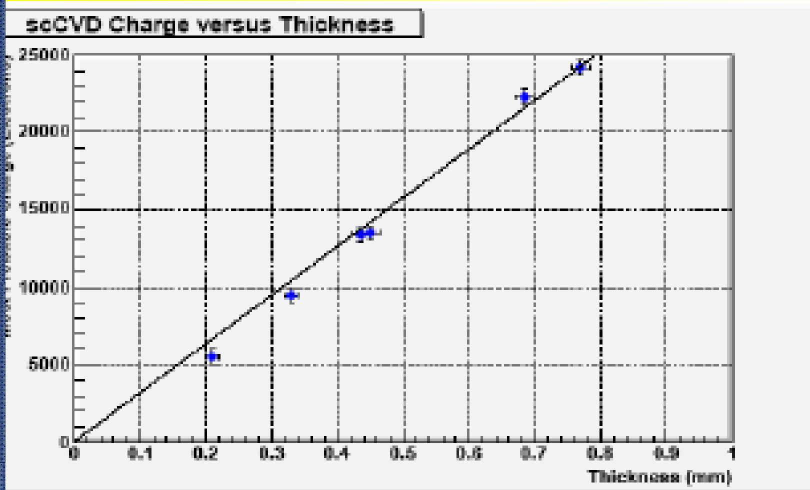
- large band gap and strong atomic bonds
- low leakage current and low capacitance both give low noise
- 3 (1.5) times better mobility and 2x better saturation velocity give fast signal collection
- Ionization energy is high: MIP≈ 2x less signal for same X_0 of SI
  - Diamond: ~13.9ke$^-$ in 361 μm
  - SI: ~26.800 ke$^-$ in 282 μm
- In Polycrystalline Diamond grain-boundaries, dislocations, and defects: limits carrier lifetime, mobility and charge collection distance and position resolution
- Available Size ~2 x 6 cm^2



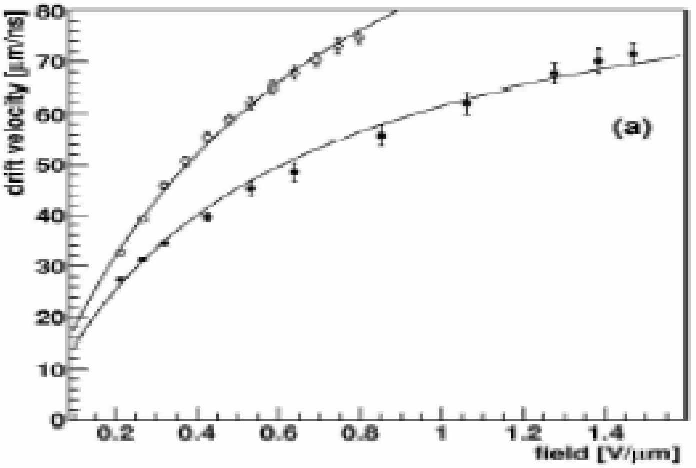
Single Crystal Diamond

- Single crystal diamond has been fabricated with Element six ≈ 10 mm × 10mm, >1 mm thickness.
- Largest scCVD diamond ≈ 14 mm × 14 mm.





- High quality scCVD diamond can collect full charge
- Width of Landau distribution is ≈ 1/2 that of silicon, ≈ 1/3 that of pCVD diamond



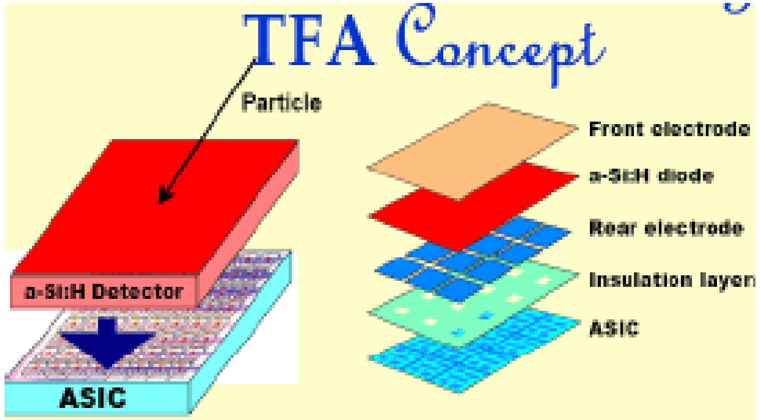
- Excellent mobility. For this sample:
  - μ_{0h} = 1714 cm²/Vs, μ_{0e} = 2064 cm²/Vs

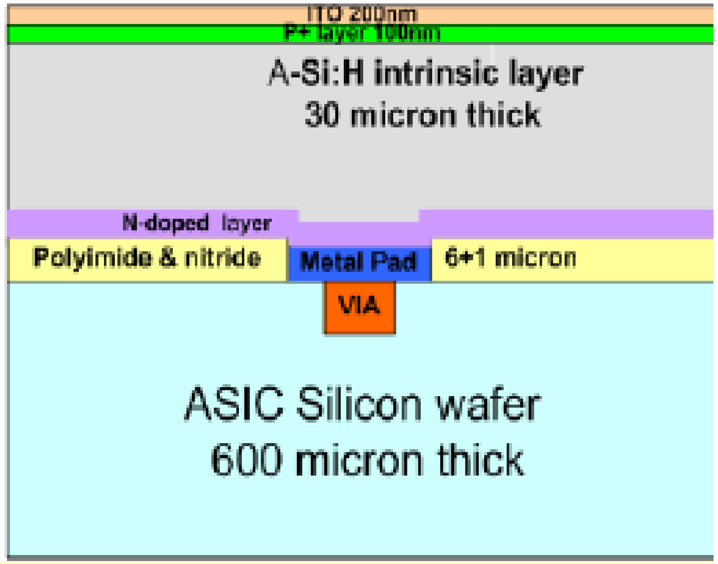
  High drift velocity ⇒ better lifetimes ⇒ charge trapping might not be an issue

Amorphous silicon a-Si:H = Thin Film on Asic

from D. Bortoletto, CERN07, developement from P. Jarron et al, CERN

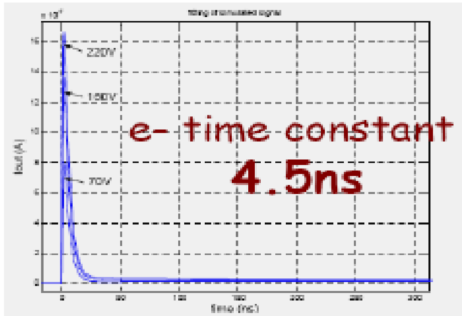
- TFA is an emerging pixel sensor technology
- Deposition of a-Si:H layer above readout ASICs





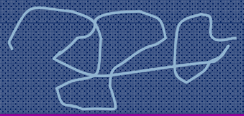
Amorphous structure

- Dangling bonds compensated by H
- H compensates impurities or radiation-induced defects
- Short time annealing
- Band tail formation due to bonding disorder



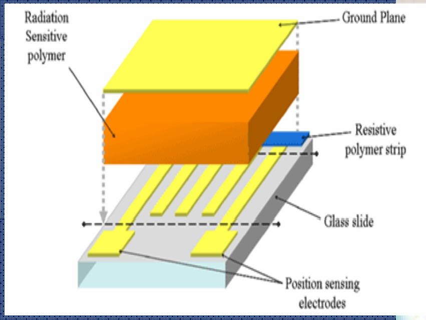
a-Si:H detector film signal
- fast component from e⁻ drift

Organic semiconductors



Polymer chains

D. Kabra et al., *Appl. Phys. Lett. 85* (Nov. 22, 1994



. p-conjugated materials possess extended molecular orbitals analogous to the energy bands in crystalline semiconductors.

•The gap in pie-conjugated polymers is typically >2 eV,

•hole mobilities up to 1 cm2/vs have been reported for some exceptionally well ordered polymers

•Response time ~1ns

❑Linear (1-D) polymer of different lengths are fabricated by coating a 700-nm layer of semiconducting conjugated polymer onto patterned glass substrates,

❑Metals are used to form contacts: metal work functions need to match→

❑Excitons (bound electron-hole pairs states , formed by energy deposition need to dissociate to form e-h pairs:

1- high field

2-multiple layers + tunnelling

❑Anisotropic behaviour due to the linear extension of the molecules

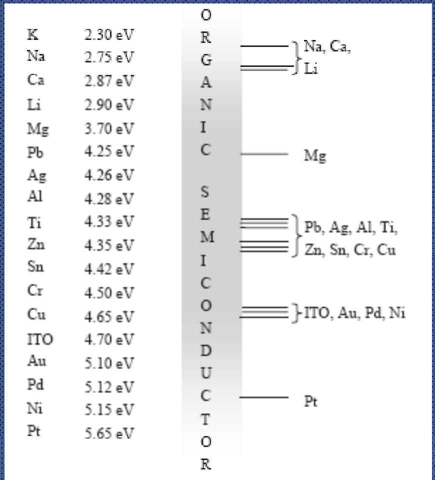


Fig. 2. Energy diagram of the work function of useful conductors for device contacts.

Organic semiconductors

Nuclear Instruments and Methods in Physics Research A 512 (2003) 419–426

The flexibility and ease of deposition of organic materials might be used in conjunction with scintillation crystals to form a g-ray detecting system.

The idea is to substitute the actual light detector (photomultiplier or silicon photodiode) with a coating of organic semiconductor directly deposited on the scintillator surface

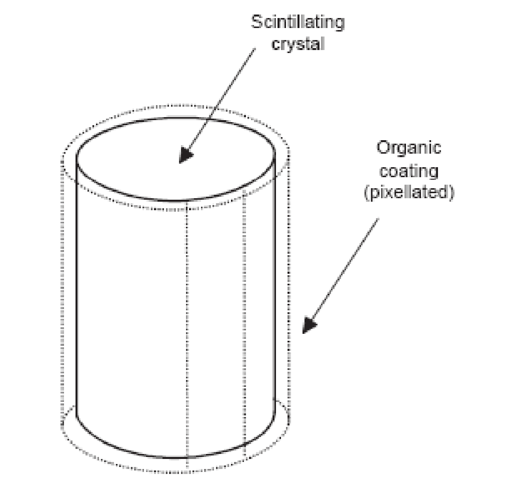


Fig. 9. Pictorial representation of a scintillation crystal coated with an organic semiconductor detector to produce a γ-ray detector.

The advantages may be of different kinds:

(i)increased light harvesting from all surfaces of the scintillating crystal,

(ii) the crystal may assume any shape, being no longer forced to drive the light toward one specific end and

(iii) by properly subdividing the organic photodetector into pixels, a position information along the longitudinal axis may also be retrieved.

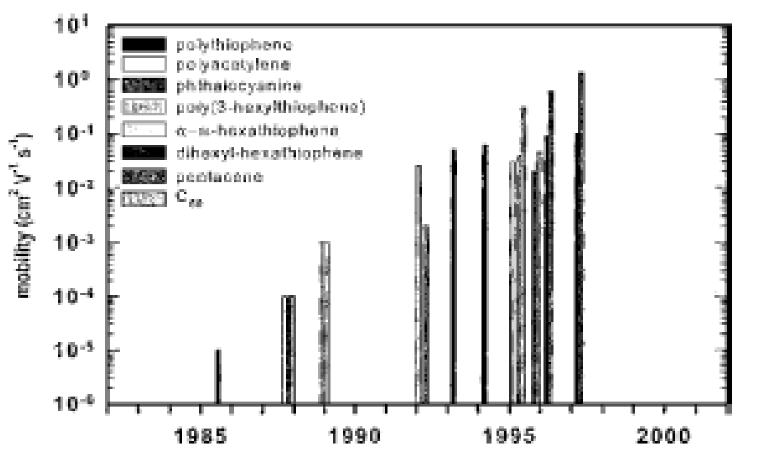


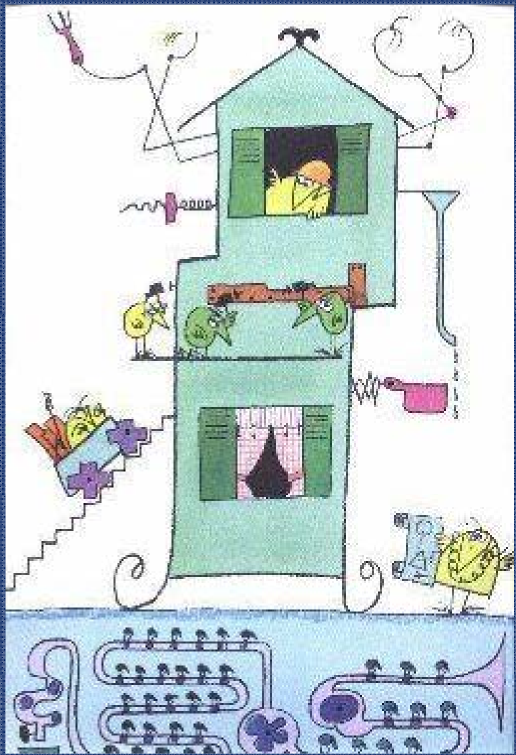
Fig. 1. Progress in the mobility obtained from organic semiconductors since fabrication of the first organic field-effect transistor (graph adapted from Ref. [16]).

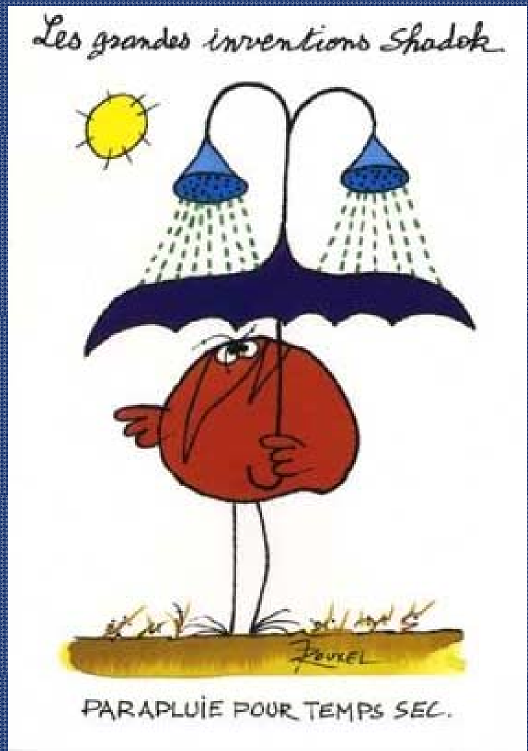
[16] Dimitrakopulos, Mascaro, IBM J. Res. Dev. 45 (2001) 11.

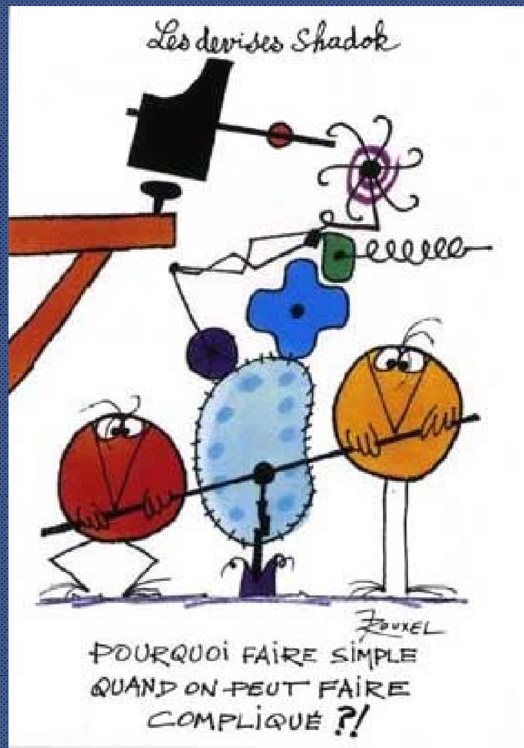
*M.C. Aragoni, M. Arca, F. Demartin, F.A. Devillanova, A. Garau, F. Isaia, F. Lelj, V. Lippolis, G. Verani, J. Am. Chem. Soc. 121 (30) (1999) 7098 and references therein.

In Conclusion: Always keep an eye for new detector technologies....

borrowed from P. Le Compte at the Liverpool Atlas Tracker Upgrade Workshop Dec 2006







Thanks to:

- *Stanford -3D work:*

C. Kenney (MBC), L. Reuen, R. Kohrs, M. Mathes, J Velthuis, N. Wermes (Bonn Univ.) S. Parker (U. of Hawaii) G. Anelli, M. Deile, P. Jarron, J. Kaplon, J. Lozano and the TOTEM Collaboration (CERN), V. Bassetti (Genova), M. Garcia-Sciveres, K. Einsweiler (LBL), J. Hasi, A. Kok (now Sintef), S. Watts (Manchester U.K.) V. Linhart, T. Slavicheck, T Horadzof, S. Pospisil (Technical University, Praha), M. Ruspa (Torino), O. Rohne, E. Bolle (Univ. of Oslo).

The ATLAS3D collaboration : in particular: GF Dalla Betta, M Boscardin, G. Pellegrini, U. Parzefal, C. Fleta, R. Bates, A. La Rosa, G. Darbo.

- *Other material from:*

P. Allport , R. Bates, M. Boscardin, G. Cassé, P. Collins, G. Della Betta, J. Harkonen, M. Moll, C. Fleta, T-E. Hansen, M. Hoeferkamp, H. Kagan, R. Nisius, H.G. Moser, G. Kramberger, G. Pellegrini, S. Saidel, U. Parzefall

Inspiration and transparencies from Daniela Bortoletto, Erik Heijne, C. Damerell,
H-G Moser, M. Moll, H. Sadrozinski, Y. Arai

References to papers and talks in the transparencies.