

5

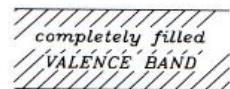
SEMICONDUCTORS AND SOLID STATE DETECTORS

Fabio Sauli - CHIPP Winter School 2010

ELECTRONIC STRUCTURE OF MATTER

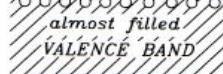
INSULATORS

*completely empty
CONDUCTION BAND*



SEMICONDUCTORS

*almost empty
CONDUCTION BAND*



CONDUCTORS

CONDUCTION BAND



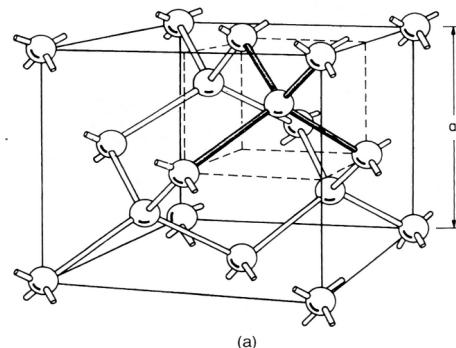
SEMICONDUCTORS:

Diamond, Si, Ge, GaAs, Silicon Carbide,

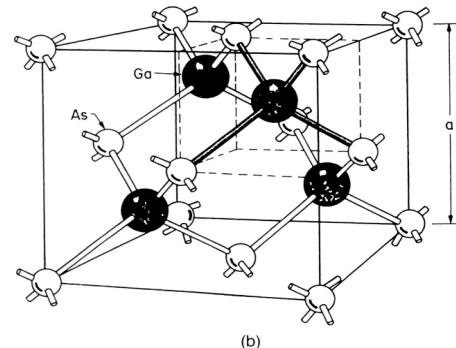
SEMICONDUCTOR CRYSTALS LATTICE

Interpenetrating face-centered cubic:

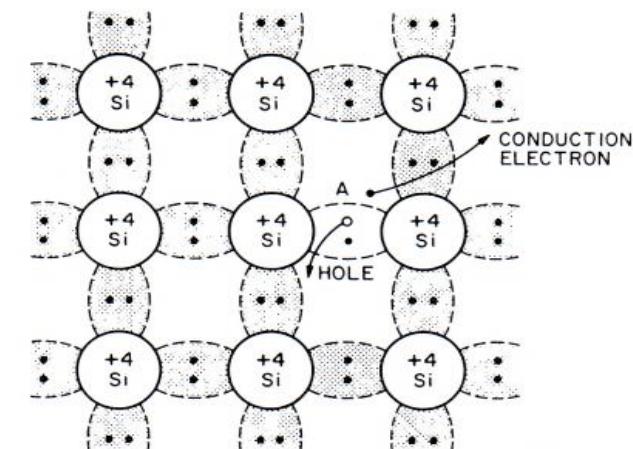
Diamond



Gallium Arsenide



SINGLE CRYSTAL WITH BROKEN BOND:



G. Lutz, Semiconductor Radiation Detectors (Springer 1999)

PROPERTIES OF SEMICONDUCTORS ((300°K))

CRYSTAL	Si	Ge	GaAs	Diamond
Minimum energy gap	1.12	0.664	1.42	5.48
Density of states in conduction band N_C (cm^{-3})	$3.2 \cdot 10^{19}$	$1.04 \cdot 10^{19}$		
Density of states in valence band N_V (cm^{-3})	$1.83 \cdot 10^{19}$	$6.9 \cdot 10^{18}$		
Intrinsic carrier concentration (cm^{-3})	$1.02 \cdot 10^{10}$	$2.33 \cdot 10^{13}$	$2.1 \cdot 10^{16}$	
Mean energy per electron-hole creation (eV)	3.63	2.93	4.35	13.1
Fano factor F	0.115	0.13	0.10	0.08
Electrons mobility ($\text{cm}^2\text{V}^{-1}\text{s}^{-1}$)	1450	3900	8800	1800
Holes mobility ($\text{cm}^2\text{V}^{-1}\text{s}^{-1}$)	505	1800	320	1600
Atomic number	14	32	31+33	6
Average atomic mass	28.09	72.59	72.32	12.01
Density (g cm^{-3})	2.329	5.323	5.317	3.515
Relative dielectric constant	11.9	16.2	12.9	5.7
Melting temperature (°C)	1392	917	1220	3907
Radiation Length (cm)	9.36	2.30		12.15
Resistivity ($\Omega \text{ cm}$)	$2.3 \cdot 10^5$	47		$3 \cdot 10^{14}$

G. Lutz, Semiconductor Radiation Detectors (Springer 1999)

THERMAL CARRIERS GENERATION

Probability of a jump of electron-hole pairs from the valence to the conduction band:

$$P(T) = CT^{\frac{3}{2}} e^{-\frac{E_G}{2kT}} \quad E_G = E_C - E_V$$

E_C , E_V : energy of conduction and valence bands

Density of free n and p carriers at the temperature T:

$$n = N_C e^{-\frac{E_C - E_F}{kT}} \quad p = N_V e^{-\frac{E_F - E_V}{kT}} \quad np = N_C N_V e^{-\frac{E_G}{kT}}$$

N_C , N_V : density of states in the conduction and valence bands

E_F : Fermi level

For intrinsic semiconductors (without dopants) the

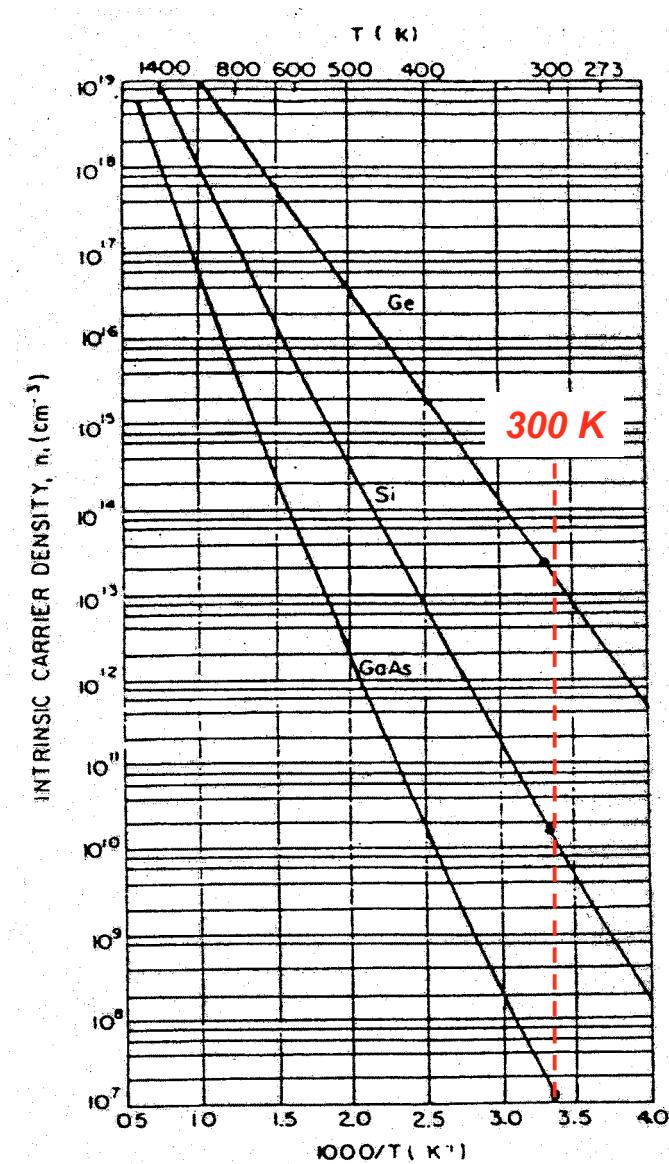
Fermi level is defined by the condition $n=p=n_i$

n_i : density of intrinsic carriers

$$n = n_i e^{\frac{E_F - E_i}{kT}} \quad p = n_i e^{\frac{E_i - E_F}{kT}}$$

$$np = n_i^2$$

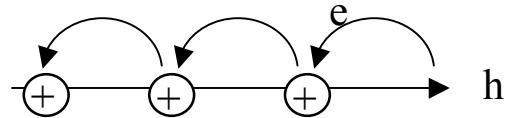
For silicon at 300°K $n \sim 10^{10} \text{ cm}^{-3}$ $np \sim 10^{20} \text{ cm}^{-3}$



CARRIERS MOBILITY

Drift under effect of electric field

- electrons: v_e direct motion
- holes: v_p backwards jump of electrons



Mobility:

$$\mu = \frac{v}{E}$$

EXAMPLE:

1 mm thick silicon at 300°K

$\Delta V = 100 \text{ V}$ ($E = 1 \text{ kV cm}^{-1}$)

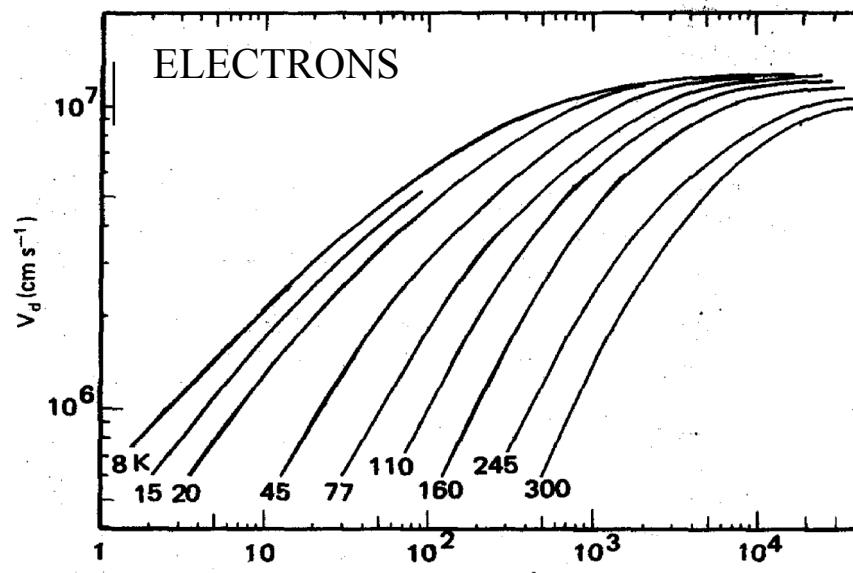
$$\begin{aligned} \mu_e &= 1450 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1} & v_e &= 1.45 \text{ cm } \mu\text{s}^{-1} \\ \mu_p &= 505 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1} & v_p &= 0.5 \text{ cm } \mu\text{s}^{-1} \end{aligned}$$

Total ionization collection time:

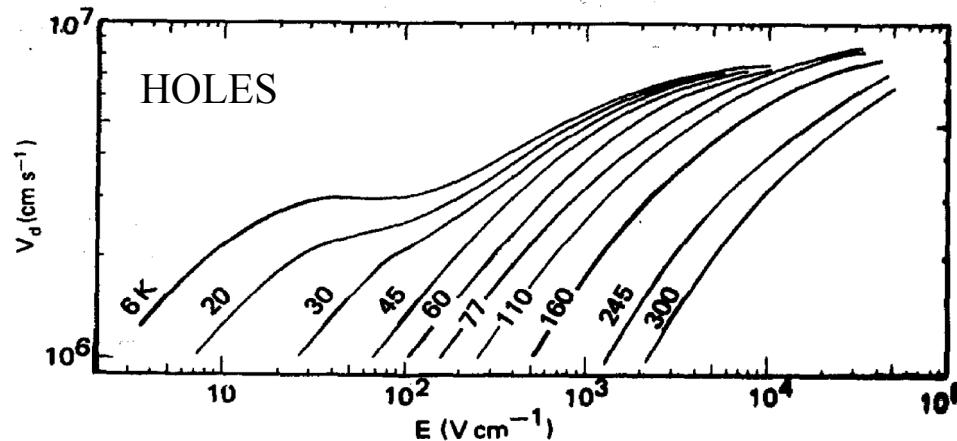
$$T_e = 70 \text{ ns}$$

$$T_p = 200 \text{ ns}$$

DRIFT VELOCITY OF CARRIERS IN SILICON



(a)



SOLID STATE IONIZATION CHAMBER

For 1 mm thick silicon:

Energy loss of minimum ionizing particle $\sim 0.2 \text{ MeV}$

Total electron-hole pairs

$$n = \frac{0.2 \cdot 10^6}{3.6} = 5 \cdot 10^4$$

Total electron collection time (100 V cm^{-1}) $\sim 70 \text{ ns}$

Signal current

$$I_s = \frac{\Delta Q}{\Delta t} = \frac{5 \cdot 10^4 \cdot 1.7 \cdot 10^{-19}}{15 \cdot 10^{-9}} = 0.6 \mu\text{A}$$

For 1 cm^2 detector, the leakage current due to the detector resistivity is:

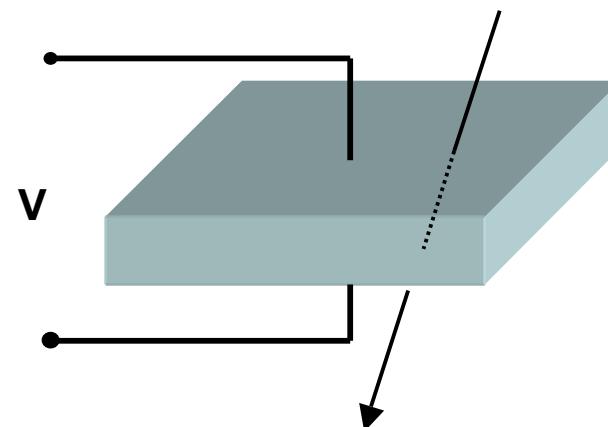
$$I_0 = \frac{V}{R} = \frac{V}{\rho \frac{s}{S}} \cong \frac{10^3}{2 \cdot 10^5 \frac{1}{10}} = 50 \text{ mA} \quad \rho = 2 \cdot 10^5 \Omega \text{ cm}$$

$$\frac{I_s}{I_0} = 10^{-5}$$

For diamond ($\rho = 3 \cdot 10^{14} \Omega \text{ cm}$) $I_0 \sim 3 \text{ nA}$

$$n = \frac{0.2 \cdot 10^6}{13.1} = 1.5 \cdot 10^4 \quad I_s \sim 0.17 \mu\text{A}$$

$$\frac{I_s}{I_0} \sim 60$$

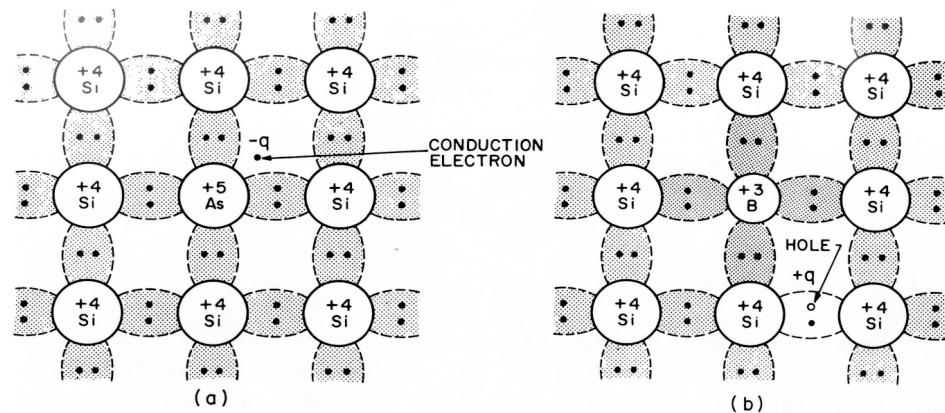


DOPED OR EXTRINSIC SEMICONDUCTORS

Addition to silicon of trace impurities (ppm), replacing the silicon atom in some nodes:

Donors (5 bonds): phosphor, arsenic: one free electron (n-type)

Acceptors (3 bonds): boron, aluminium: one missing electron (free hole): p-type



CARRIER DENSITY IN DOPED SILICON

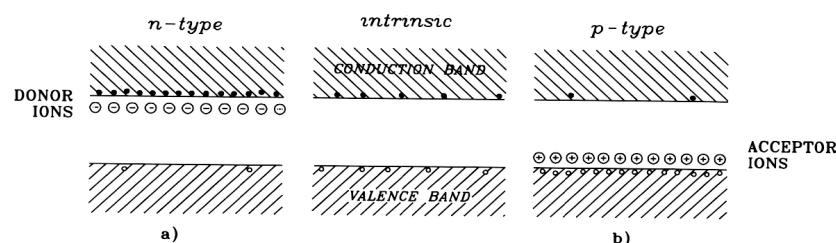
$$np = n_i^2$$

For 1 ppm addition of n-type impurity ($N_A = 10^{23} \text{ cm}^{-3}$):

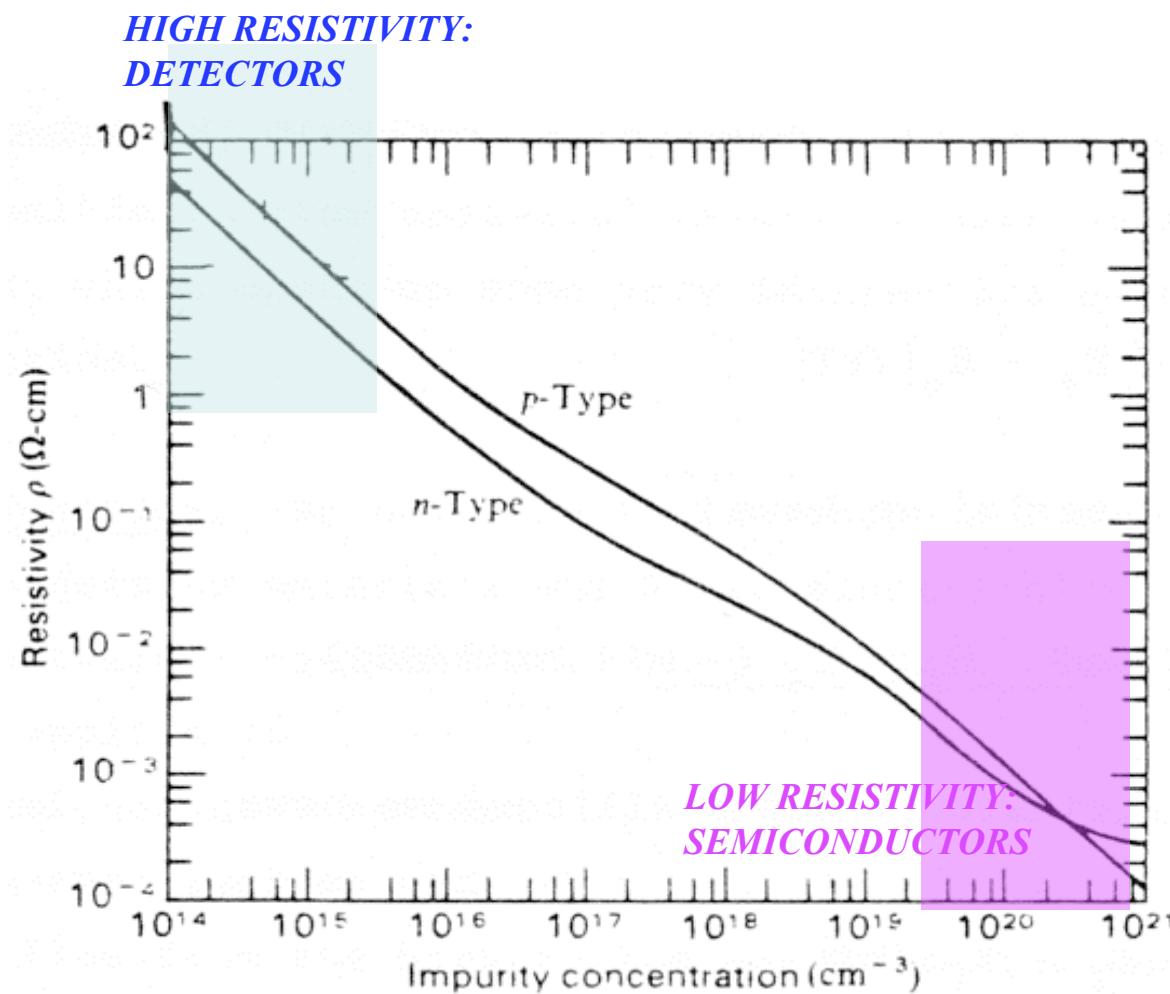
$n \sim 10^{17} \text{ cm}^{-3}$ -> majority carriers

and from $np = n_i^2 \sim 10^{20}$

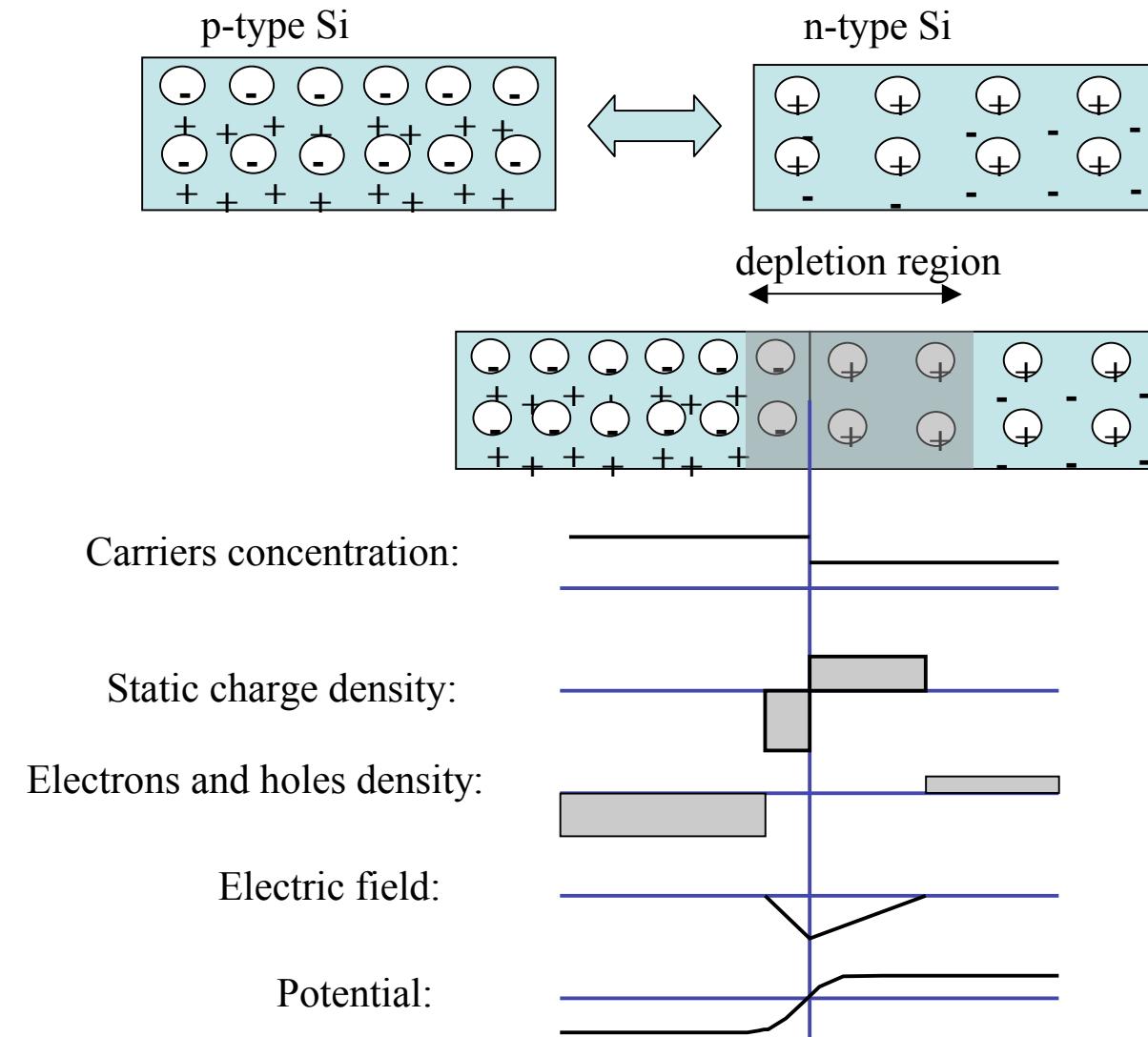
$p \sim 10^3 \text{ cm}^{-3}$ -> minority carriers



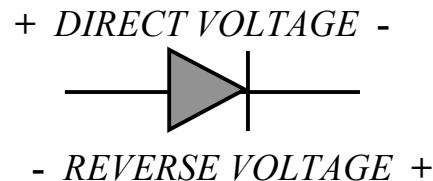
RESISTIVITY: STRONGLY DEPENDENT ON DOPANT CONCENTRATION



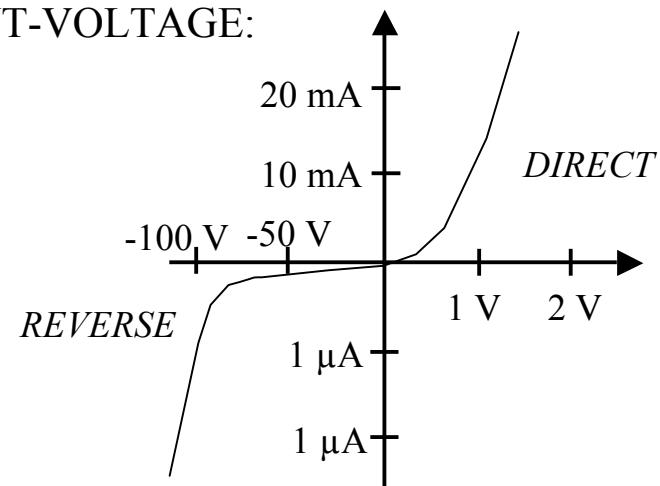
p-n JUNCTION: DIODES



DIRECT AND REVERSE POLARIZATION



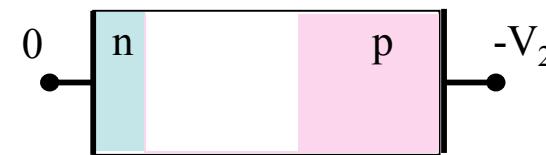
CURRENT-VOLTAGE:



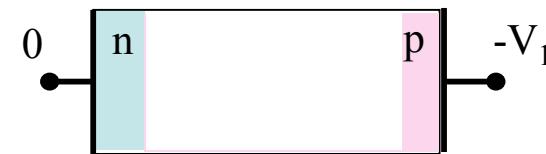
DIODE DETECTORS: REVERSE VOLTAGE
The depletion region increases with voltage until reaching the p-side contact



RECTIFYING CONTACT

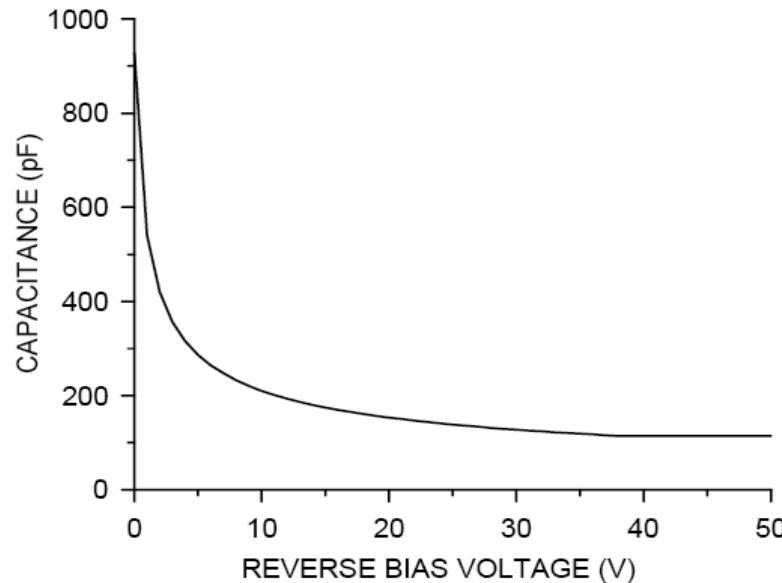


OHMIC CONTACT



JUNCTION CAPACITANCE AND DEPLETION REGION

The diode capacitance decreases with the increase of reverse bias, until the junction is fully depleted



REVERSE LEAKAGE CURRENT

$$I_{INV} = \frac{1}{2} e \frac{n_i}{\tau} W$$

τ : majority carriers lifetime
 W : thickness of depleted region

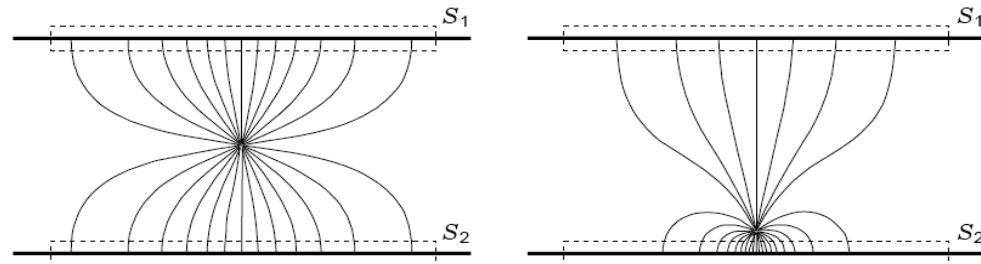
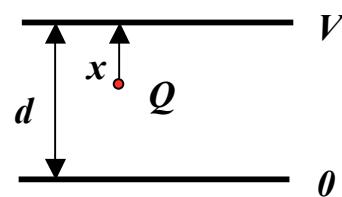
Typical value $I_{INV} \sim 50$ nA

For MIPS in 1 mm Si $I_S \sim 0.6$ μ A

$$\frac{I_S}{I_{INV}} \sim 10$$

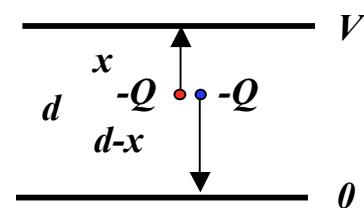
SIGNAL INDUCTION BY MOVING CHARGES

SINGLE CHARGE:

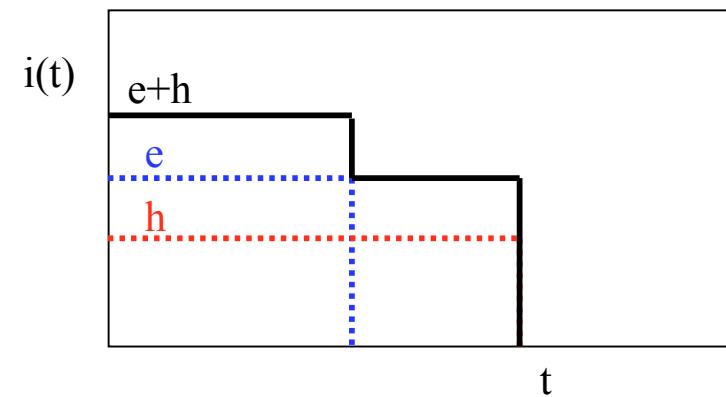


$$dq = Q \frac{dV}{V} = Q \frac{dx}{d} \quad q(x) = \frac{Q}{d} x \quad q(t) = \frac{Q}{d} wt \quad i(t) = \frac{dq}{dt} = \frac{Q}{d} w$$

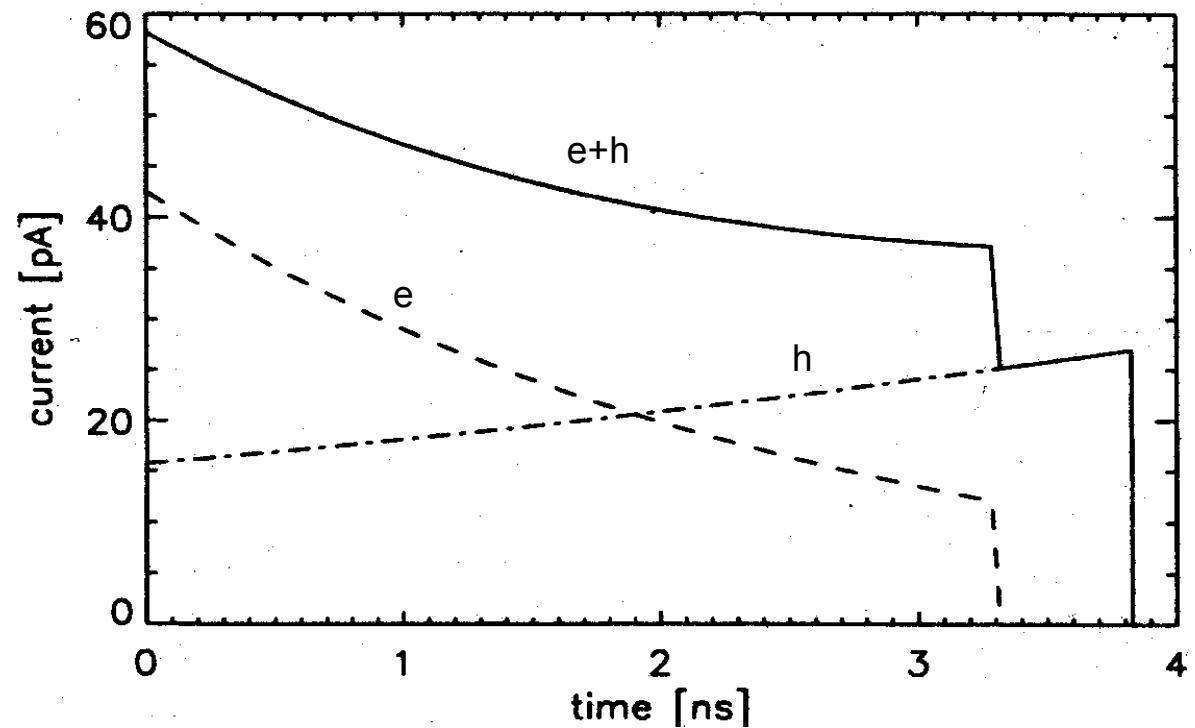
ELECTRONS AND HOLES:



$$i_e(t) = \frac{Q}{d} w_e \quad i_h(t) = \frac{Q}{d} w_h$$

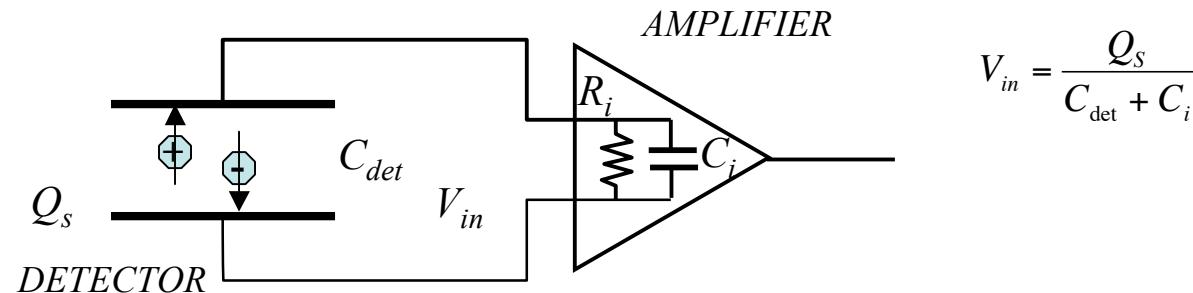


REAL DIODE: NON-UNIFORM ELECTRIC FIELD, PARTLY DEPLETED VOLUME



G. Lutz, *Semiconductor Radiation Detectors* (Springer 1999)

SIGNAL:



NOISE SOURCES:

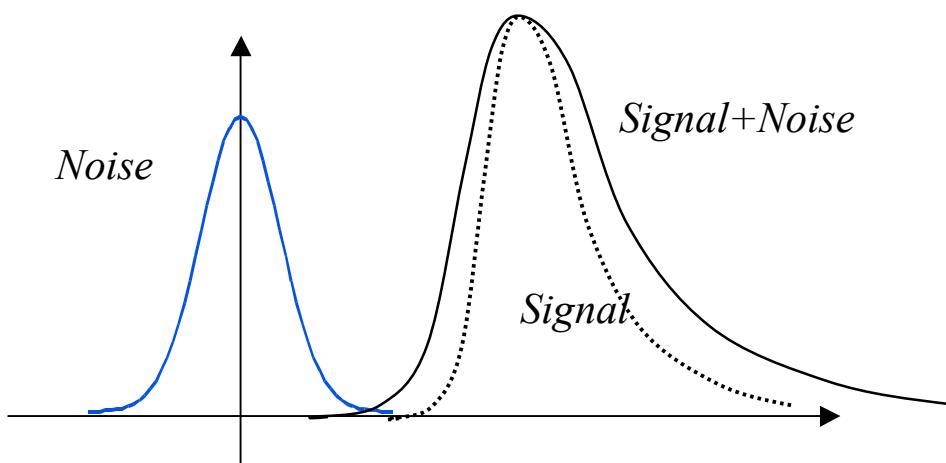
- Thermal noise
- Low frequency voltage noise
- Shot Noise

Equivalent Noise Charge

$$ENC = A + BC_{det}$$

LARGE DETECTOR CAPACITANCE:

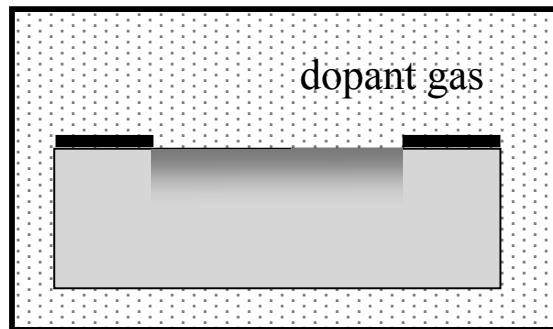
- Smaller signal
- Larger noise



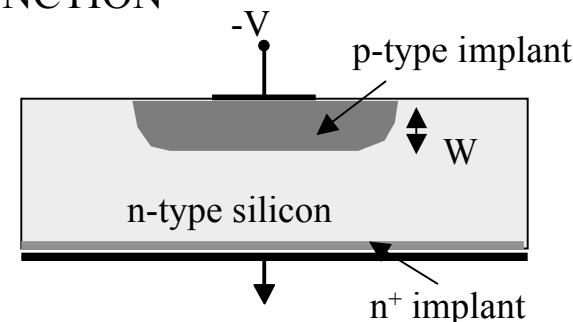
G. Lutz, Semiconductor Radiation Detectors (Springer 1999)

DOPING METHODS

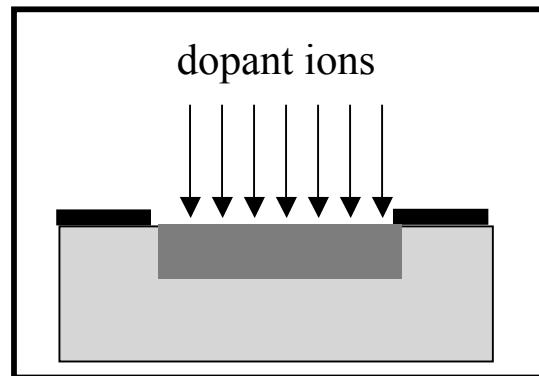
HIGH TEMPERATURE DIFFUSION:



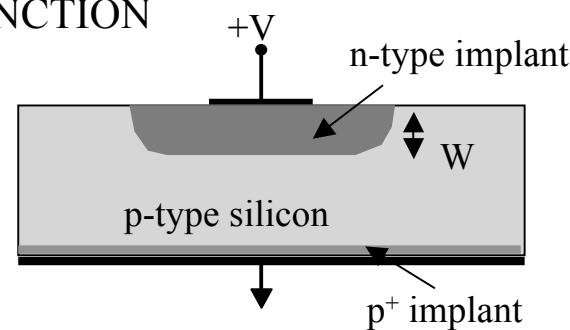
NP JUNCTION



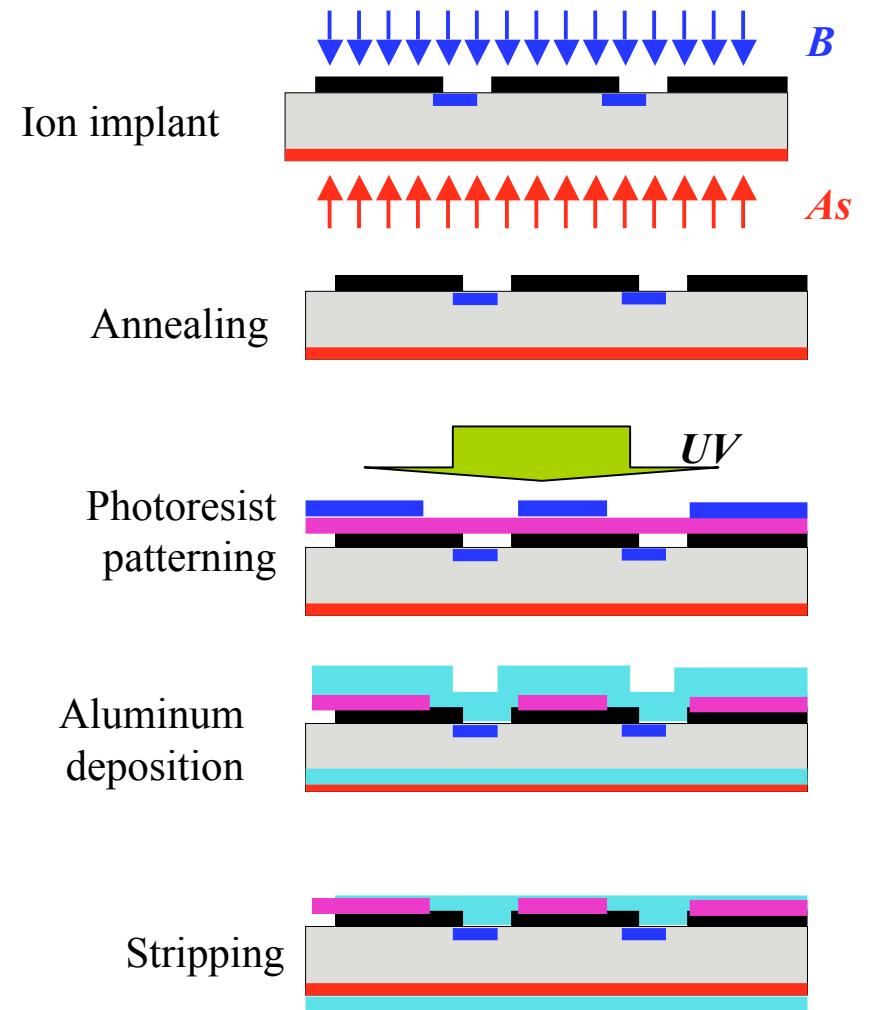
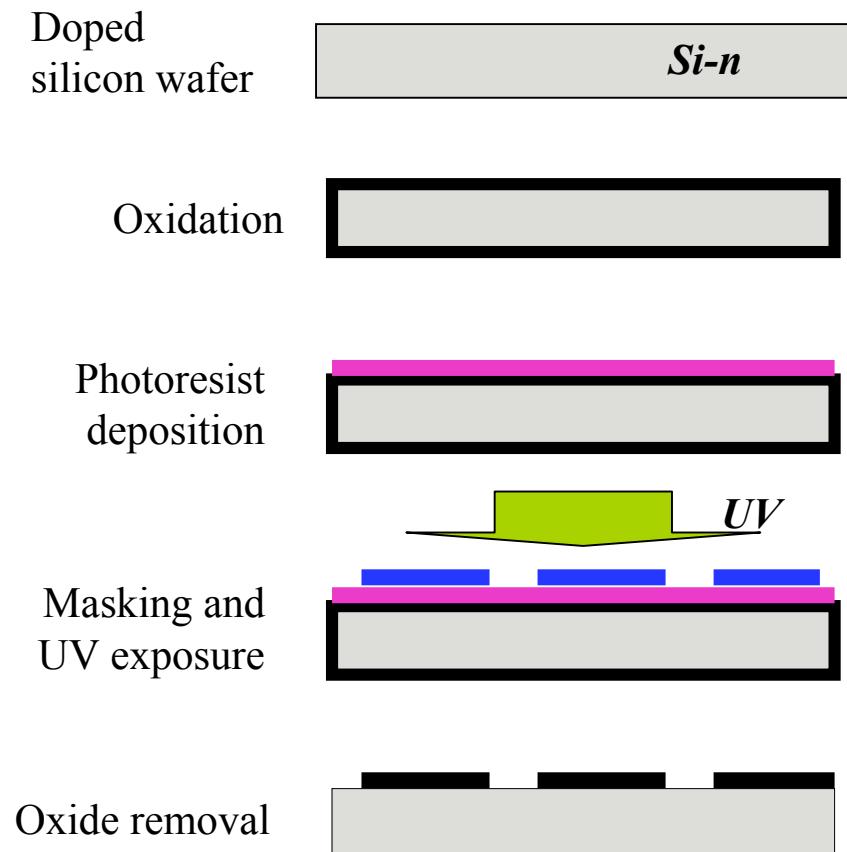
ION IMPLANTATION:



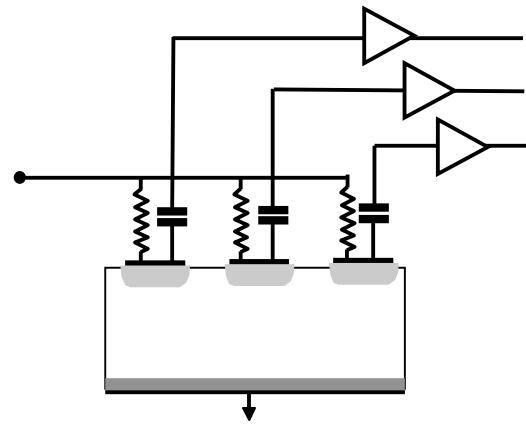
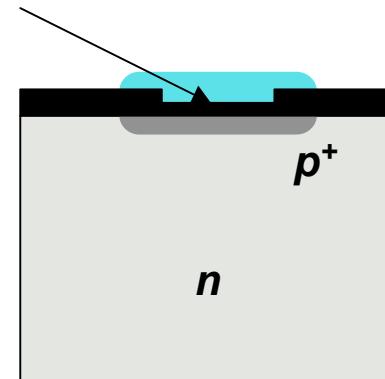
PN JUNCTION



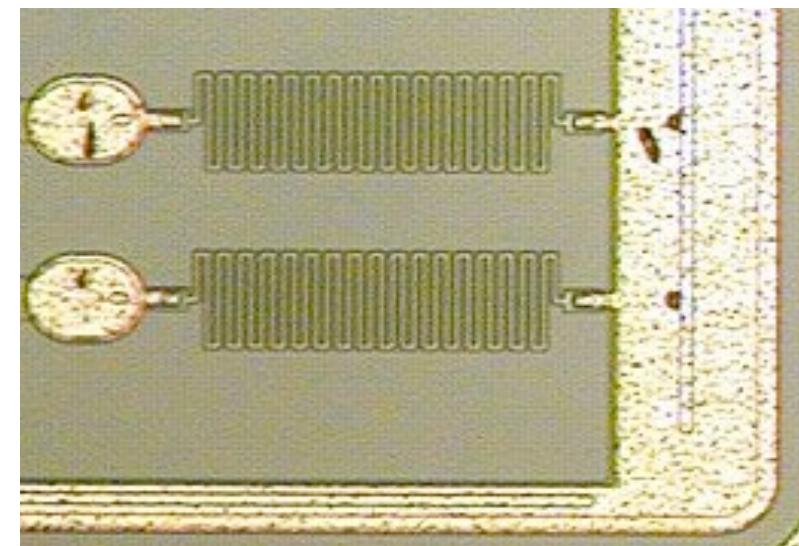
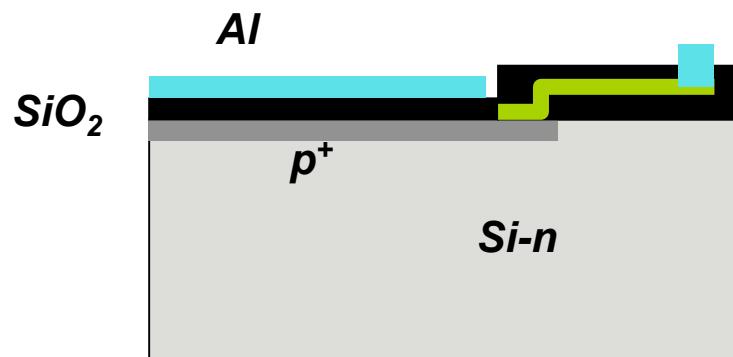
SILICON MICROSTRIPS FABRICATION



STRIPS POWERING AND READOUT

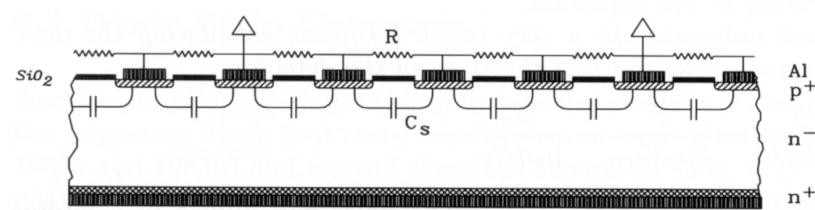
BUILT-IN CAPACITOR
Thin SiO_2 layer ($\sim 0.1 \mu\text{m}$)

POLYCRYSTALLINE SILICON RESISTORS

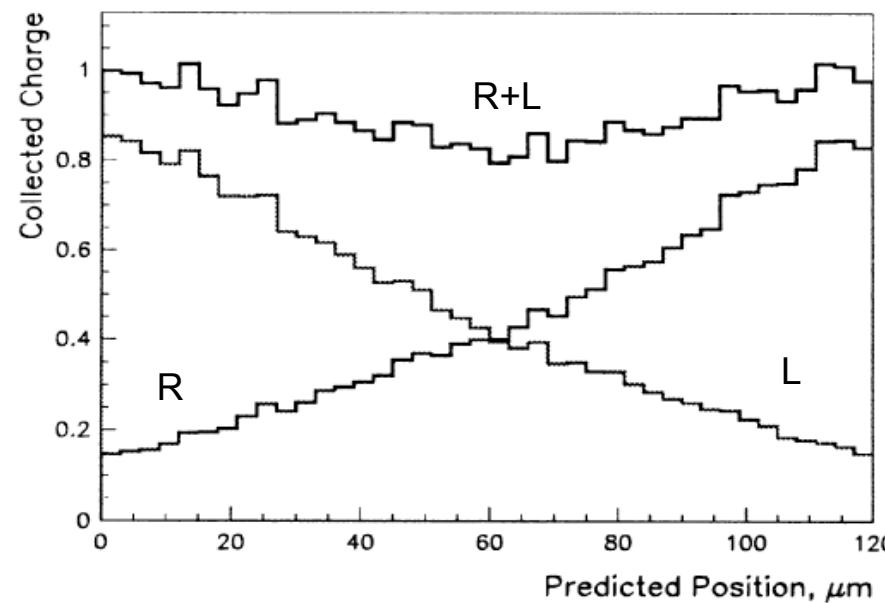


CHARGE SHARING: REDUCE THE NUMBER OF CHANNELS READOUT

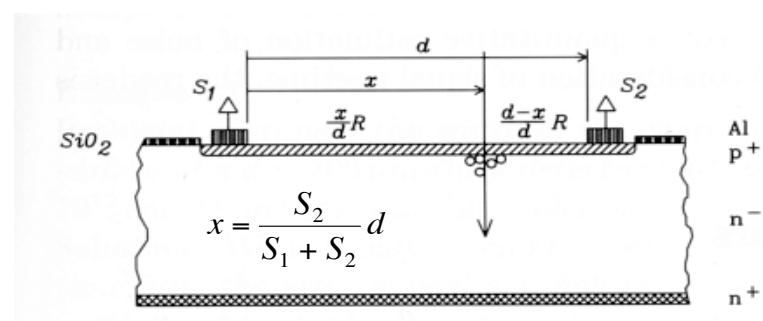
CAPACITIVE



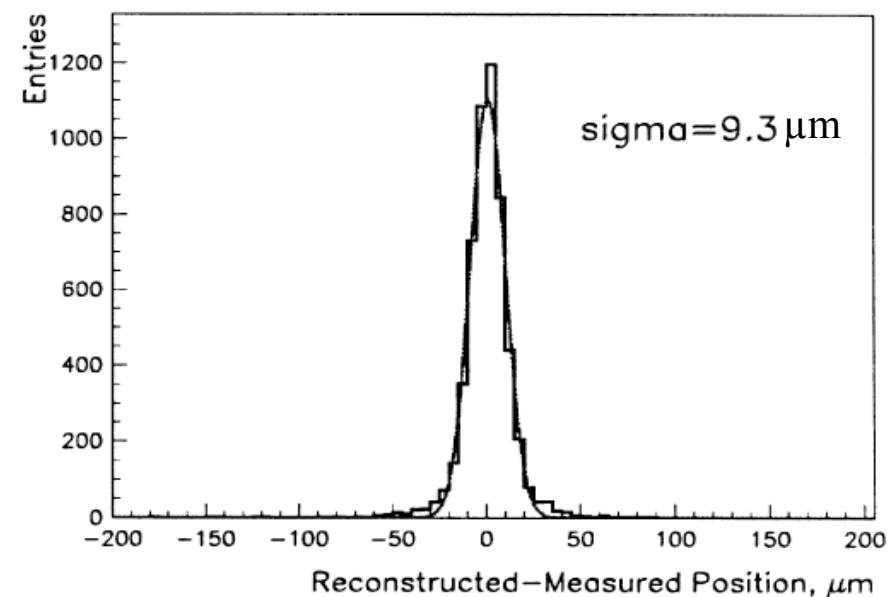
120 μm pitch strips with 5 intermediate strips:



RESISTIVE



LOCALIZATION ACCURACY



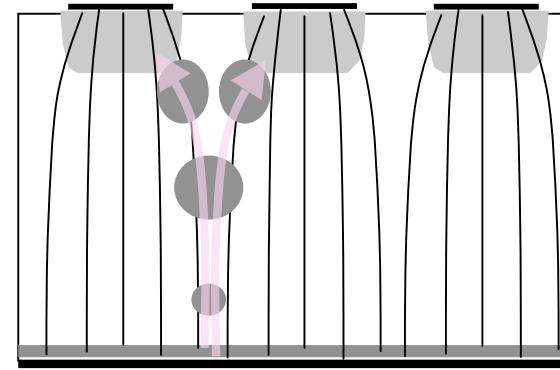
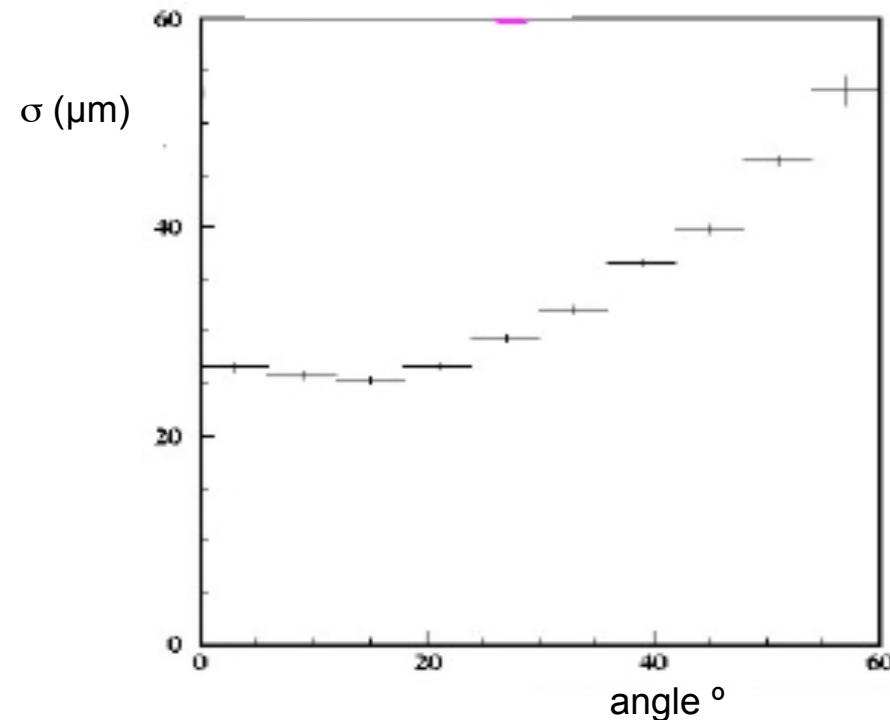
IONIZATION CHARGE COLLECTION AND DIFFUSION

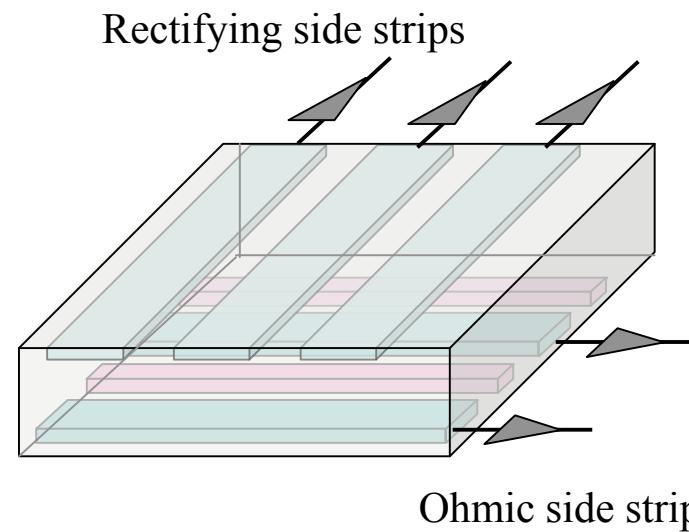
$$\sigma = \sqrt{2Dt} \quad D: \text{diffusion coefficient}$$

$$D = \mu \frac{kT}{e} \quad \text{Einstein's expression}$$

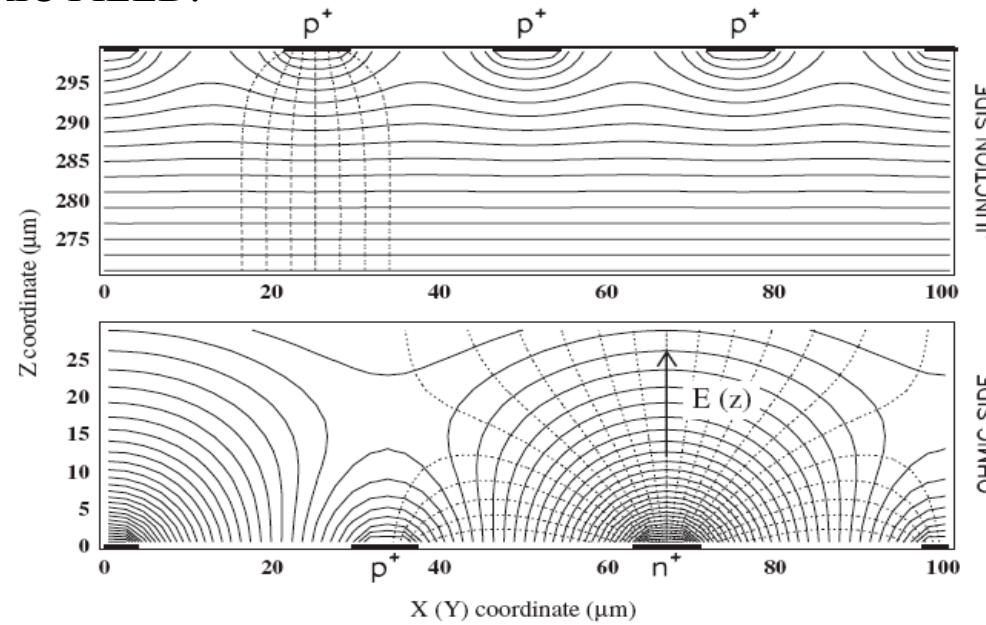
$$\sigma = \sqrt{\frac{2kT}{eE}} s$$

For electrons and holes in 300 μm silicon $\sigma \sim 6 \mu\text{m}$

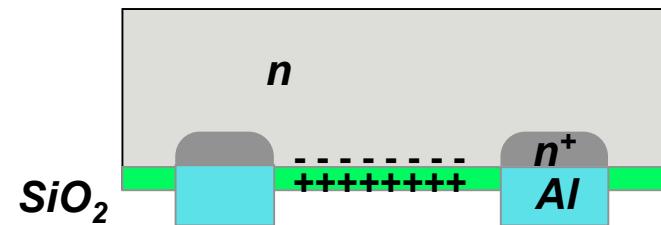
LOCALIZATION ACCURACY vs
ANGLE OF INCIDENCE



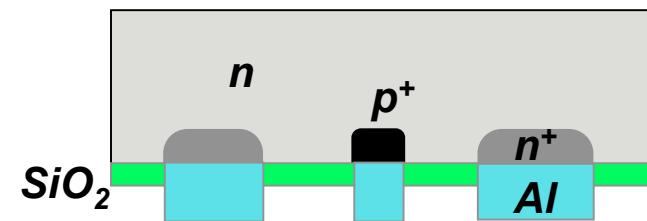
ELECTRIC FIELD:



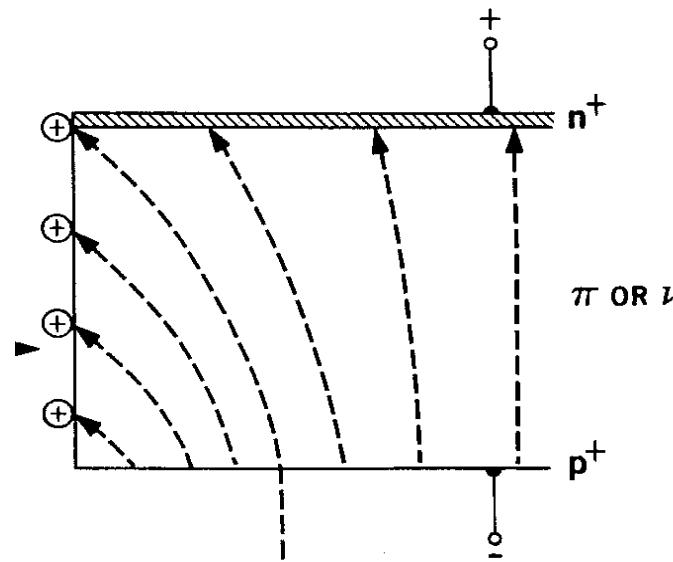
OHMIC SIDE: CHARGE ACCUMULATION



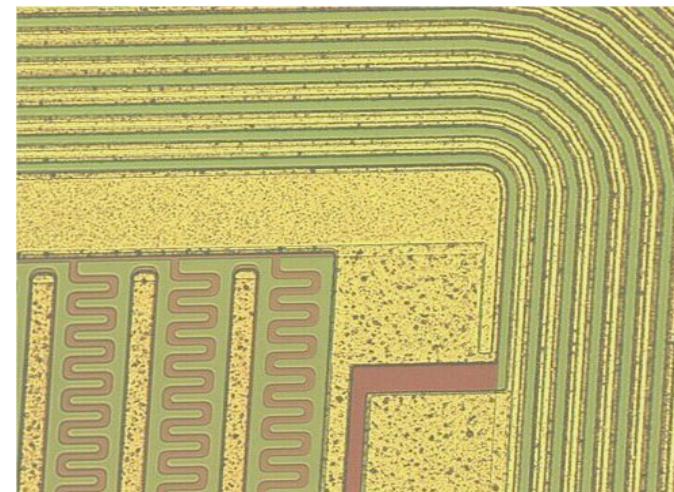
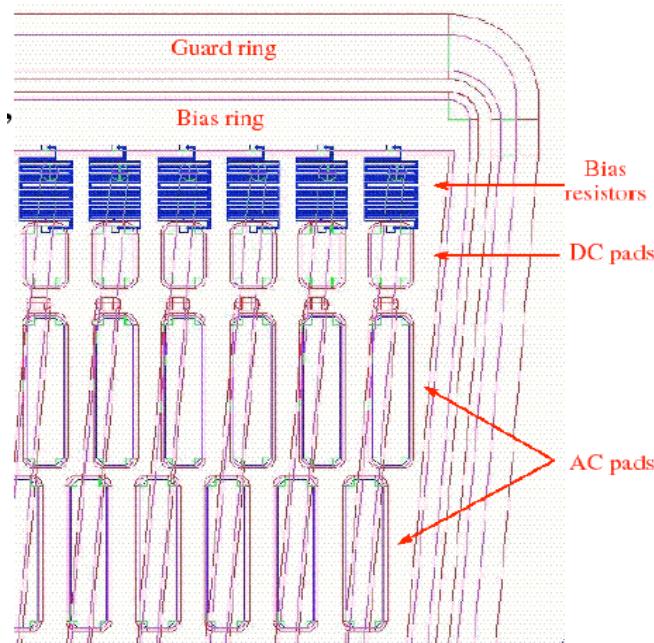
P-STOP STRIPS:



EDGE FIELD DISTORTIONS:
Efficiency and leakage current problems



EDGE GUARD RINGS:



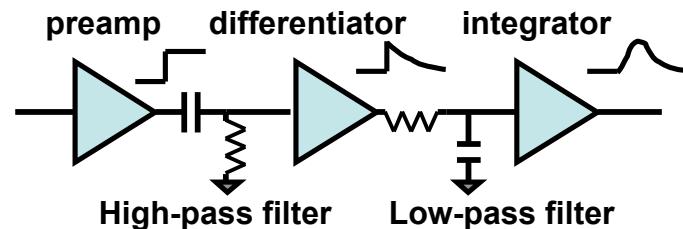
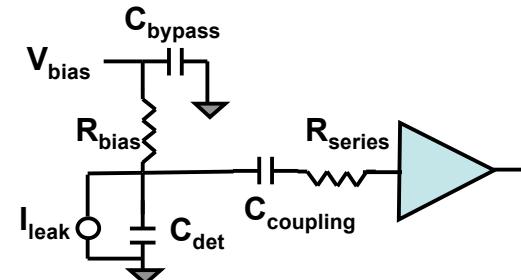
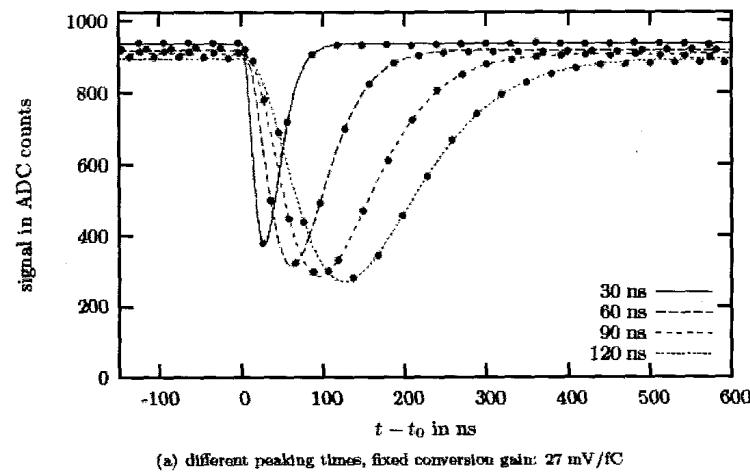
SIGNAL FOR MIPS IN 300 μm SILICON:

$\sim 25,000 \text{ e} (\sim 5 \text{ fC})$

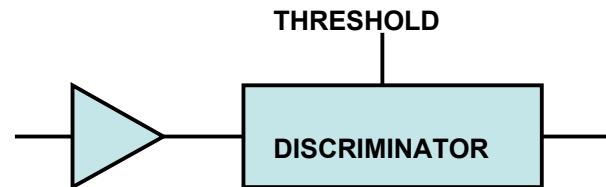
TYPICAL NOISE FOR FAST AMPLIFIERS:

$\sim 1500 \text{ e rms}$

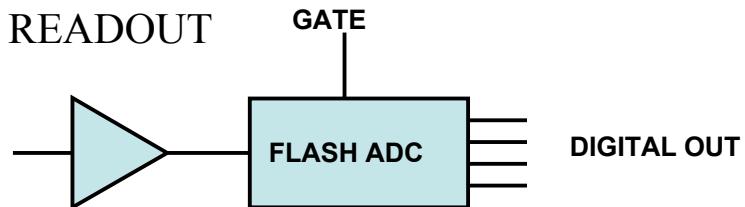
MULTIPLE SHAPING CONSTANTS
FOR FAST RESPONSE



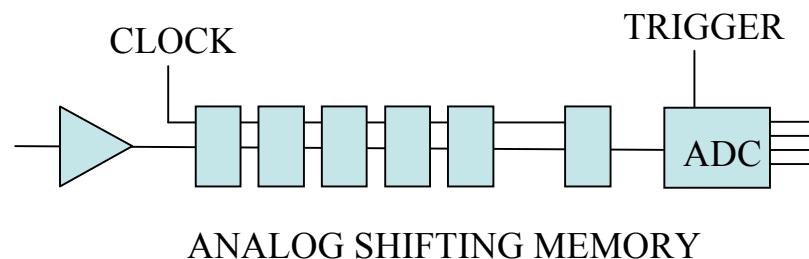
DIGITAL READOUT



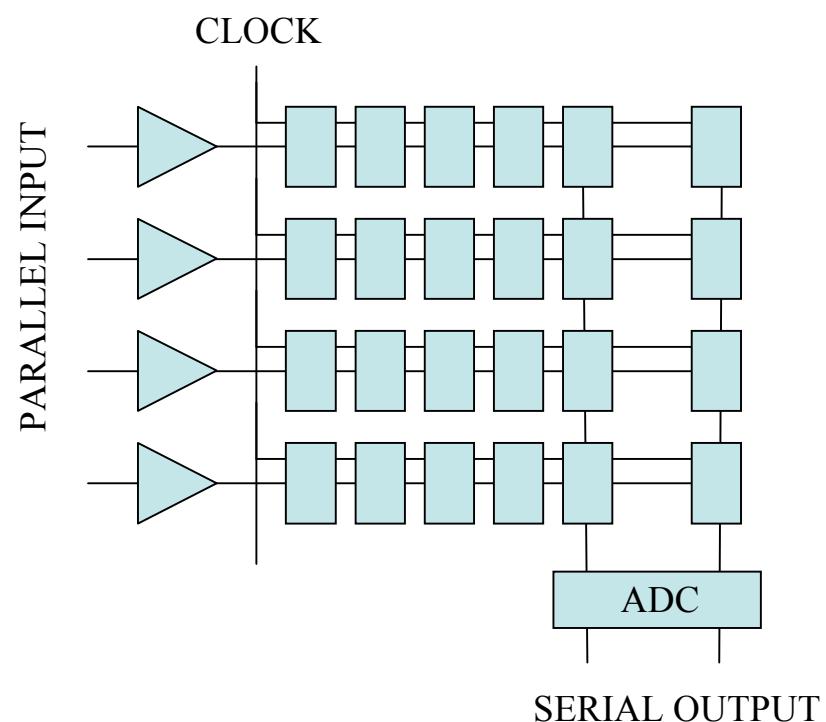
ANALOGUE READOUT



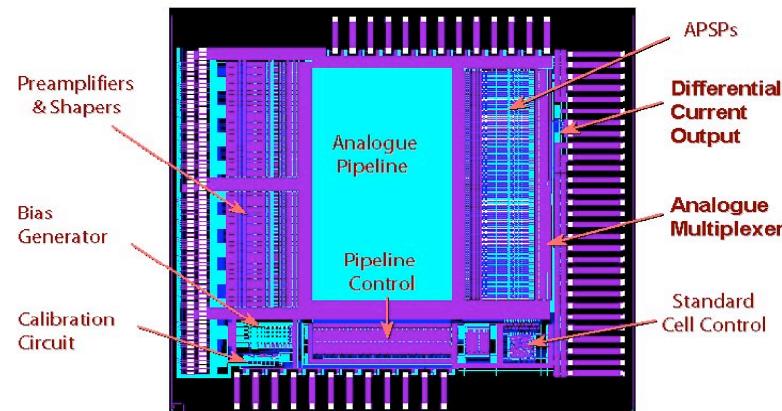
ANALOGUE SHIFT REGISTER: WAITING FOR THE TRIGGER



PARALLEL IN-SERIAL OUT:

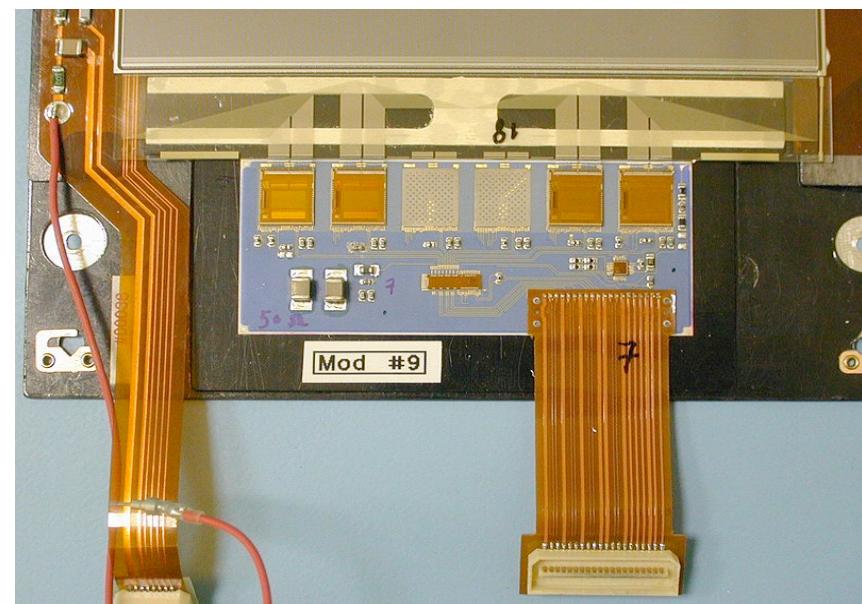
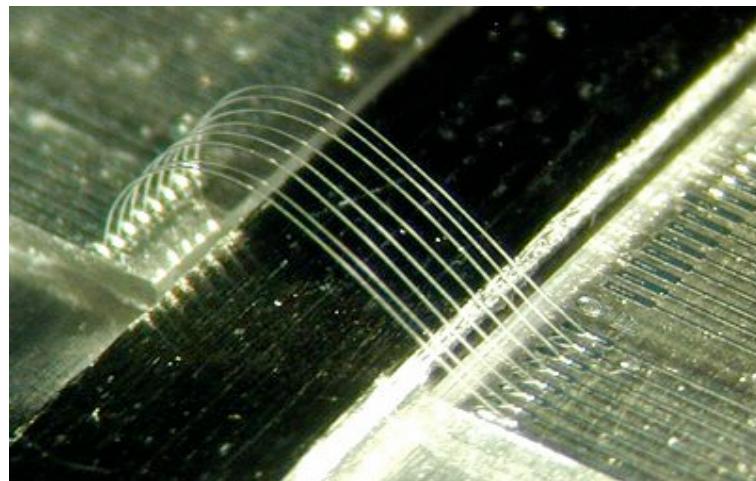
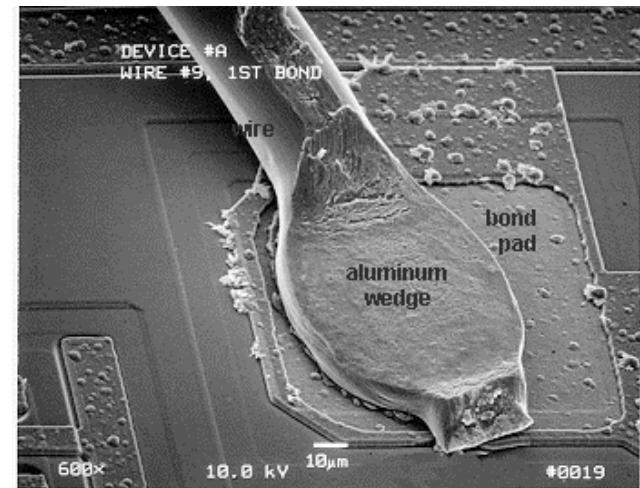
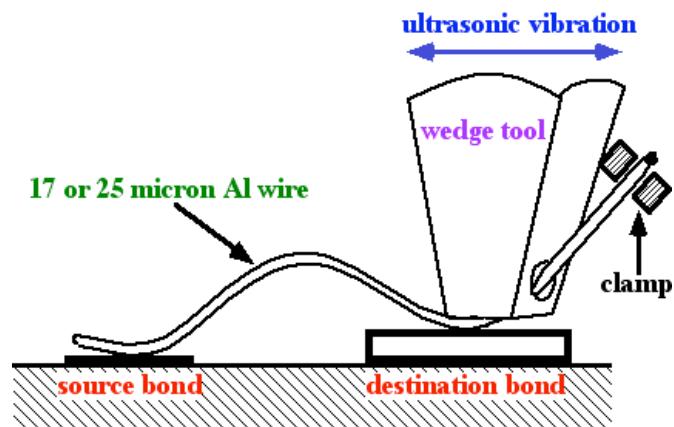


APV25:
128 channels input
196 analogue memory cells (25 ns clock)
serial ADC output (100 kHz)

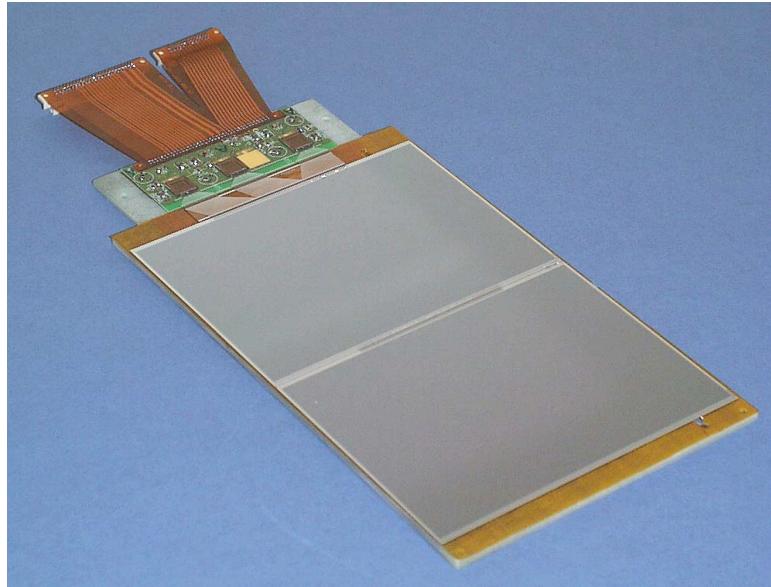


M. French et al, Nucl. Instr. and Meth. A466(2001)359

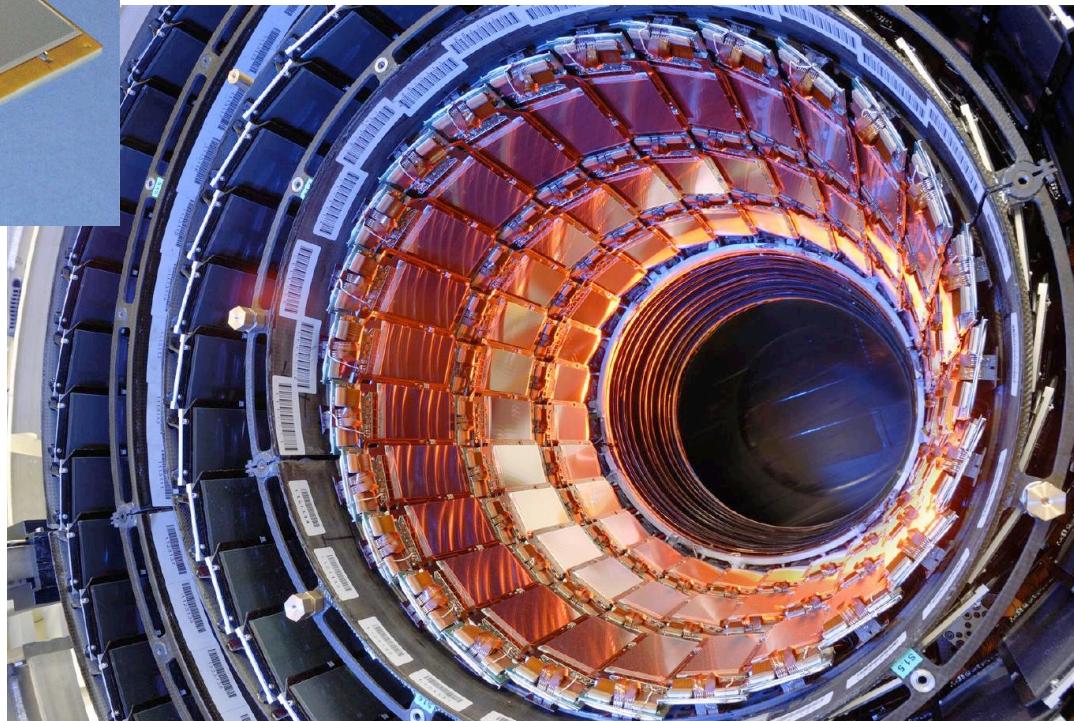
WIRE BONDING

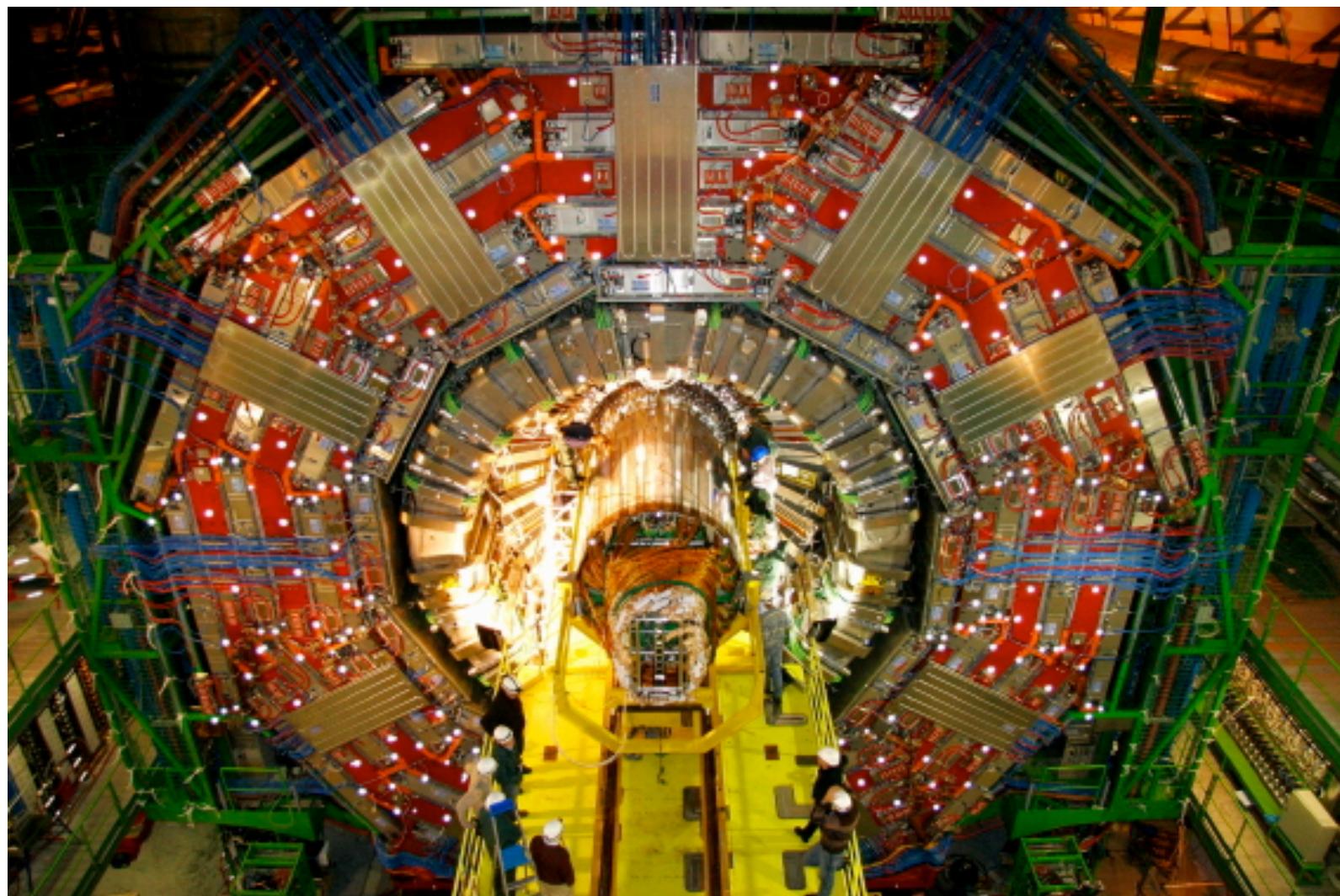


CMS TRACKER

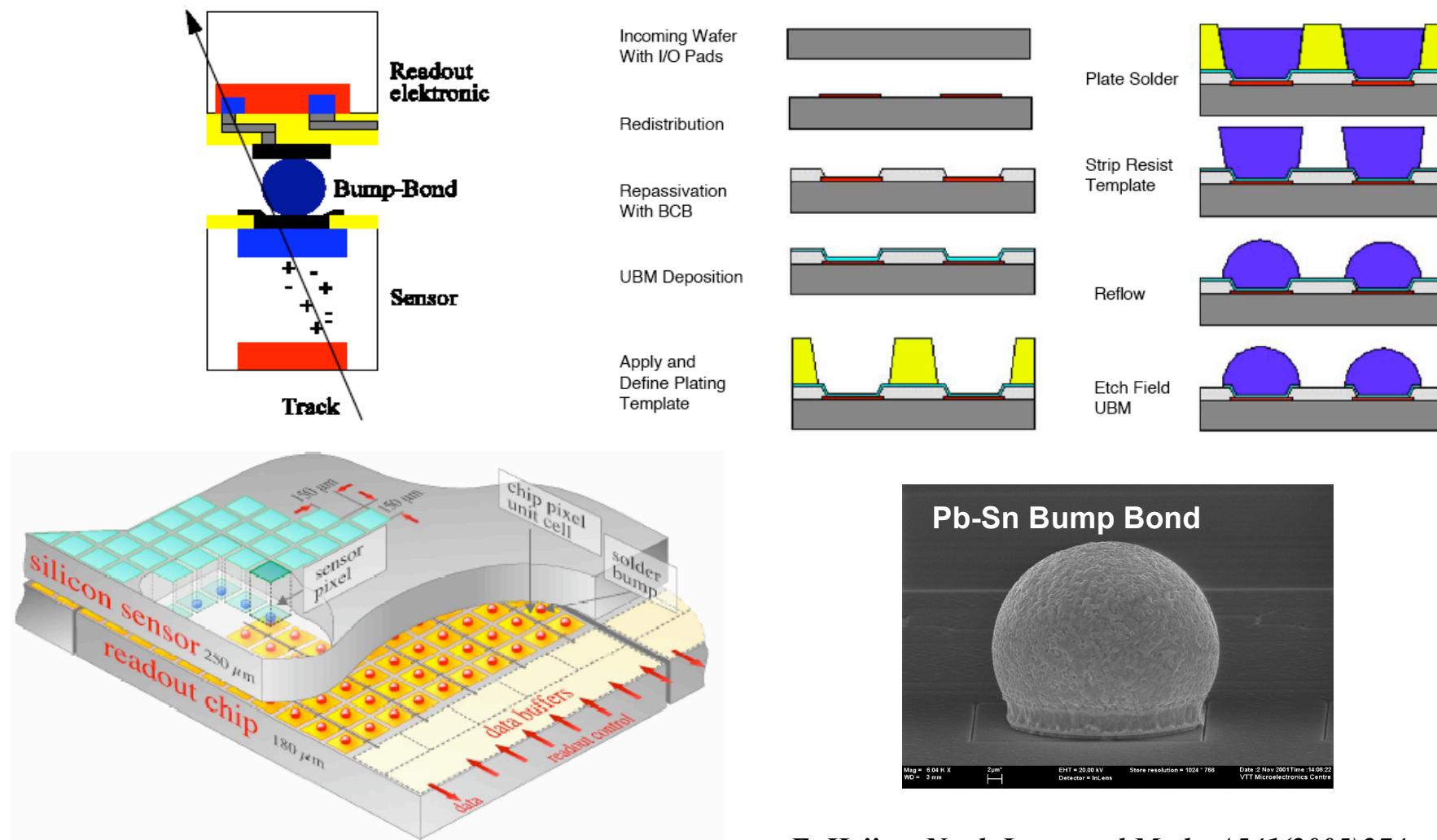


MULTI-LAYER ASSEMBLY



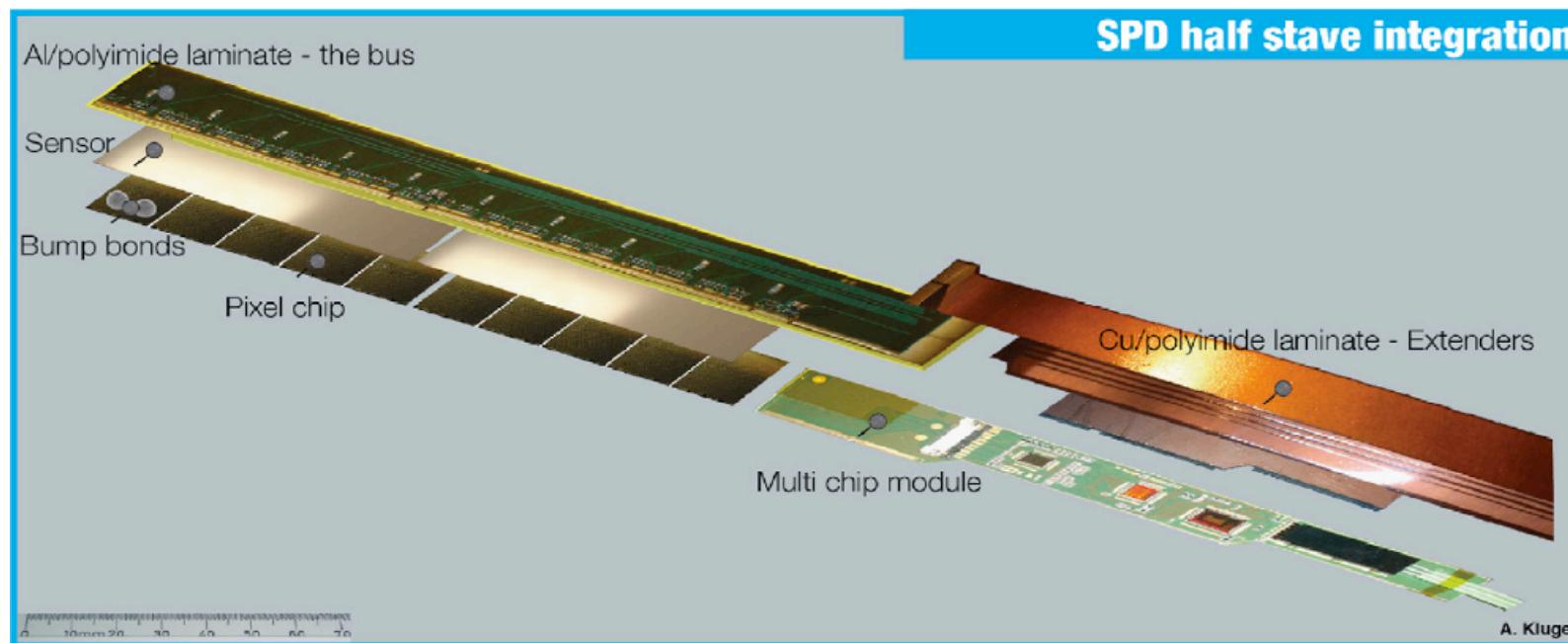
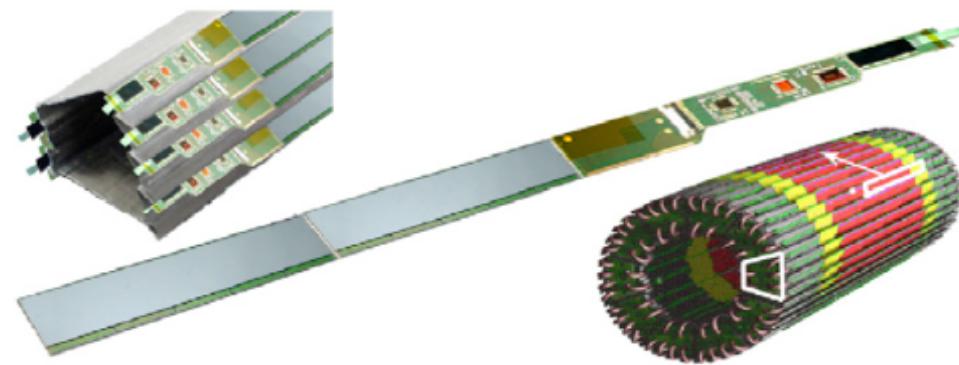


HIGH MULTIPLICITY: SILICON PIXELS DETECTOR BUMP-BONDED TO READOUT ELECTRONICS



E. Heijne, Nucl. Instr. and Meth. A541(2005)274

ALICE SILICON PIXELS DETECTOR

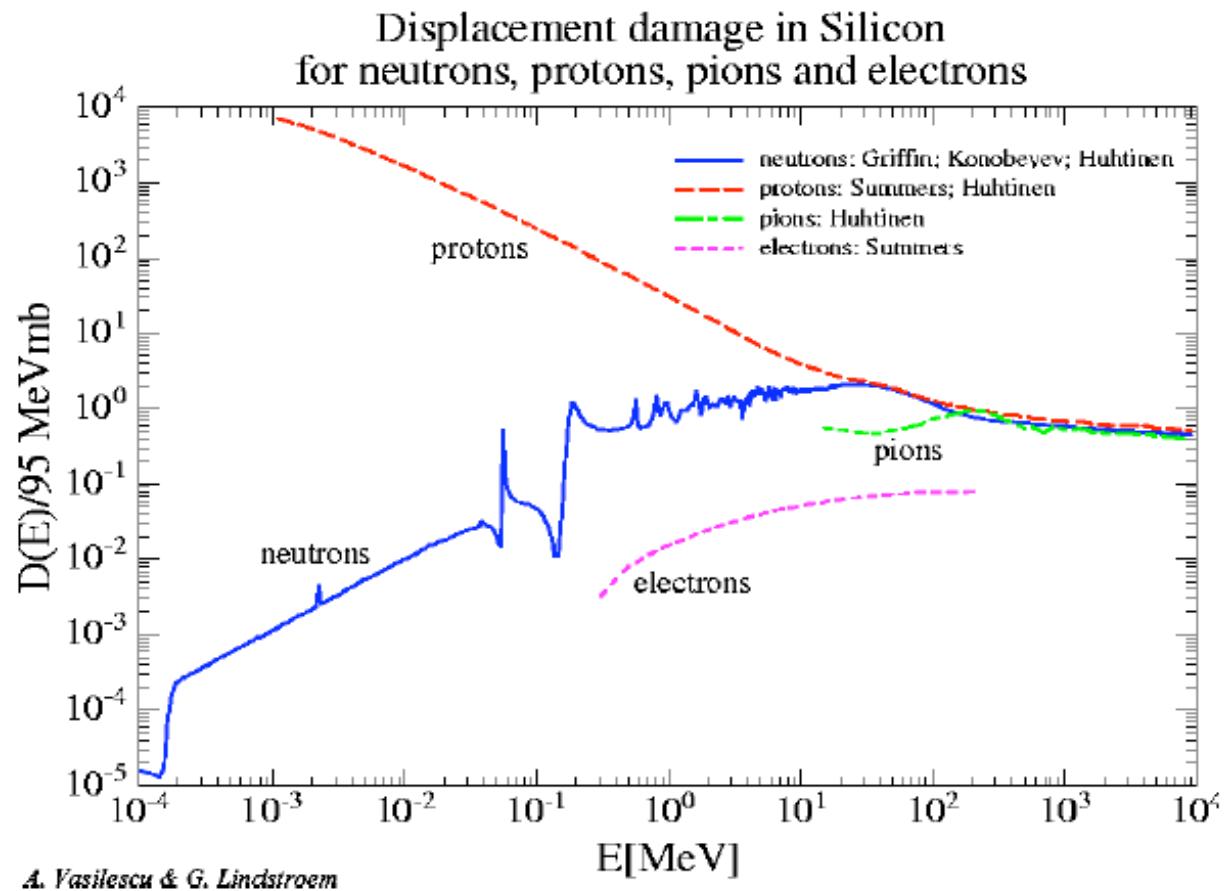


A. Kluge et al, Nucl. Instr. And Meth. A582(2007)728

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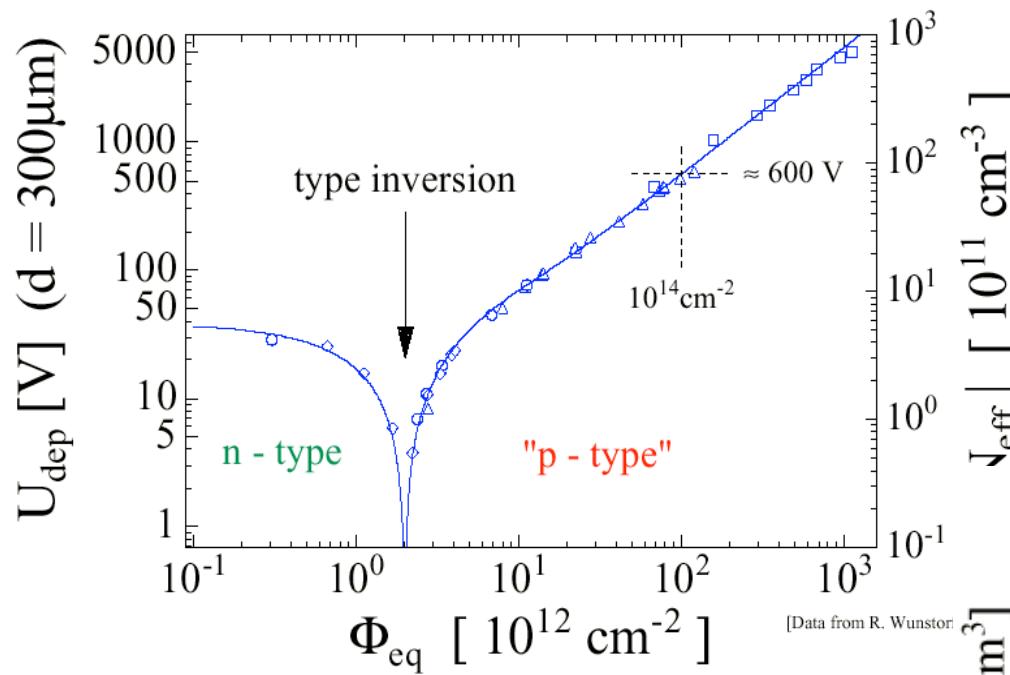
RADIATION DAMAGE IN SILICON

- Creation of recombination and trapping centres
- Change in dopant concentrations
- Increase of leakage current



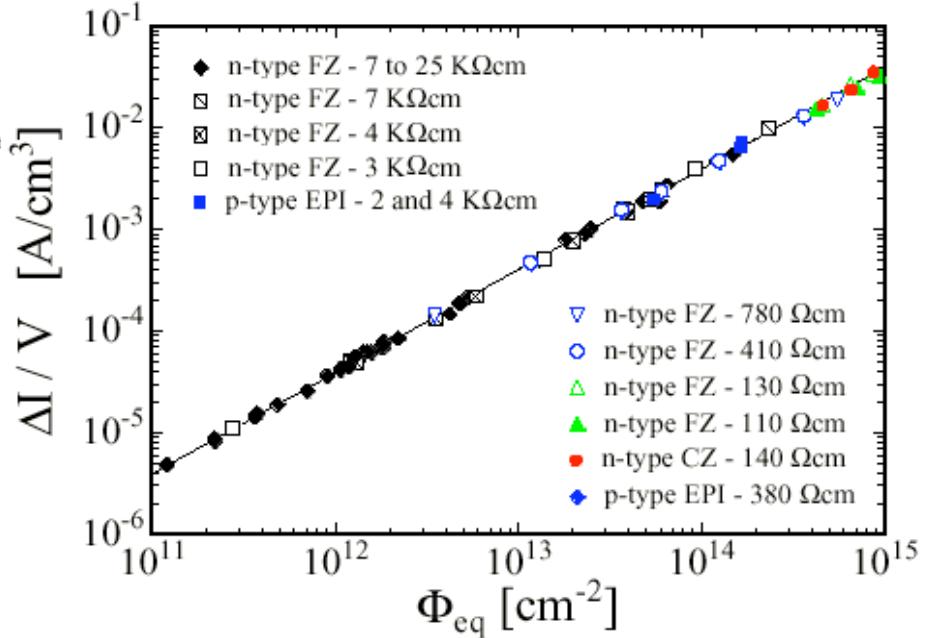
G. Lindström, Nucl. Instr. and Meth. A512(2003)30

DEPLETION VOLTAGE VS RADIATION FLUX:

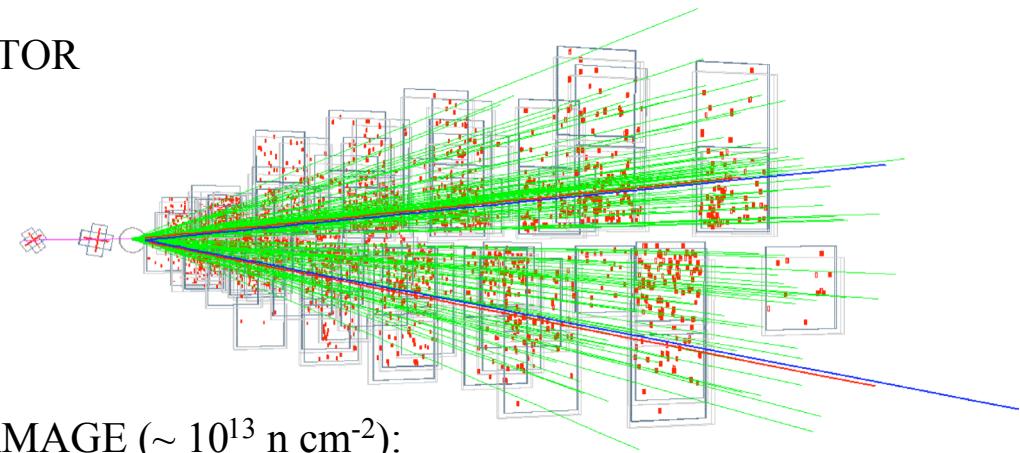
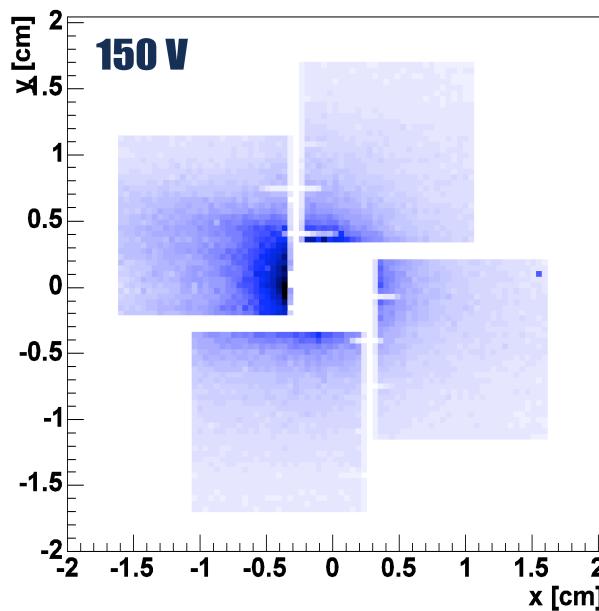
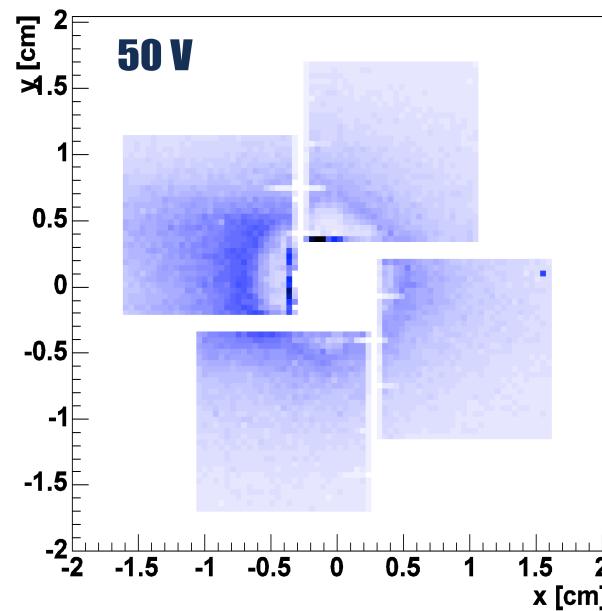


G. Lindström, Nucl. Instr. and Meth. A512(2003)30

INCREASE OF LEAKAGE CURRENT:

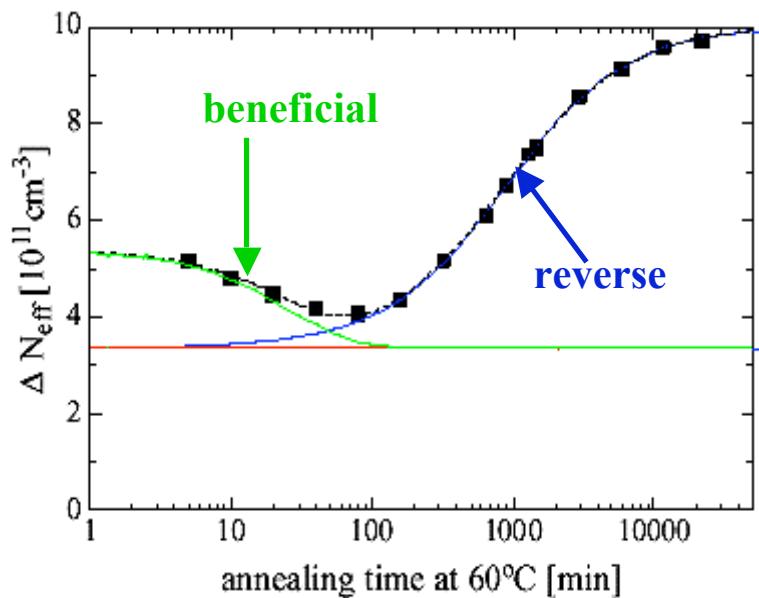


NA60 SILICON PIXELS VERTEX DETECTOR

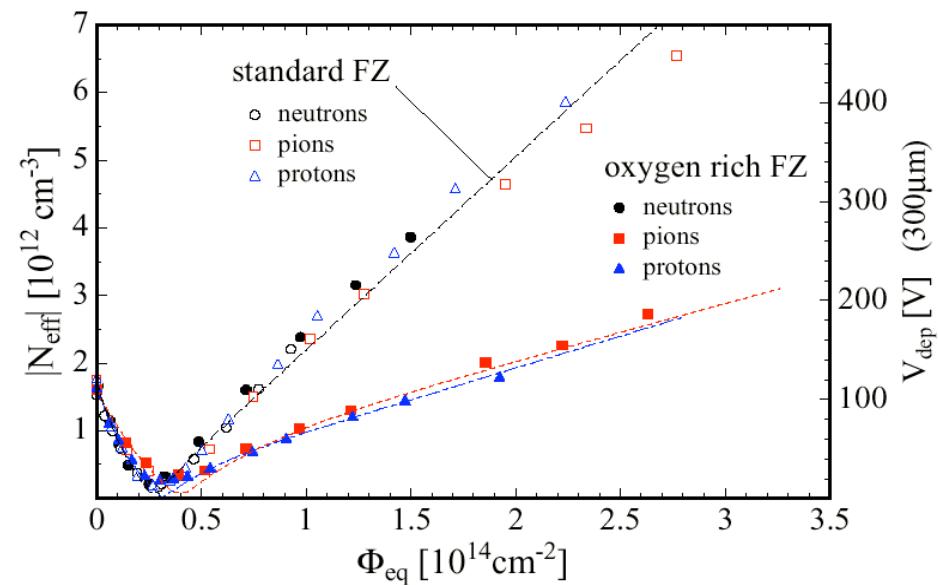
EFFICIENCY AFTER RADIATION DAMAGE ($\sim 10^{13} \text{ n cm}^{-2}$):

J. M. Heuser et al, Nucl. Instr. and Meth. A560(2006)9

THERMAL ANNEALING



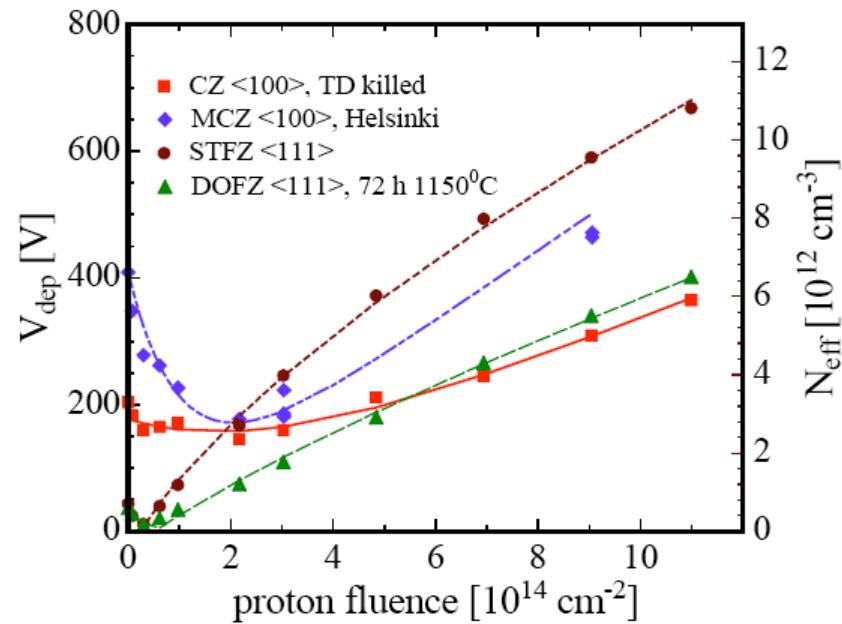
OXYGENATION (RD48):



CZOCHRALSKI METHOD FOR SILICON
MANUFACTURE:
Controlled oxygen impurities

E. Fretwurst, RESMDD04 (Florence, Oct. 10-13, 2004)

Fabio Sauli - CHIPP W



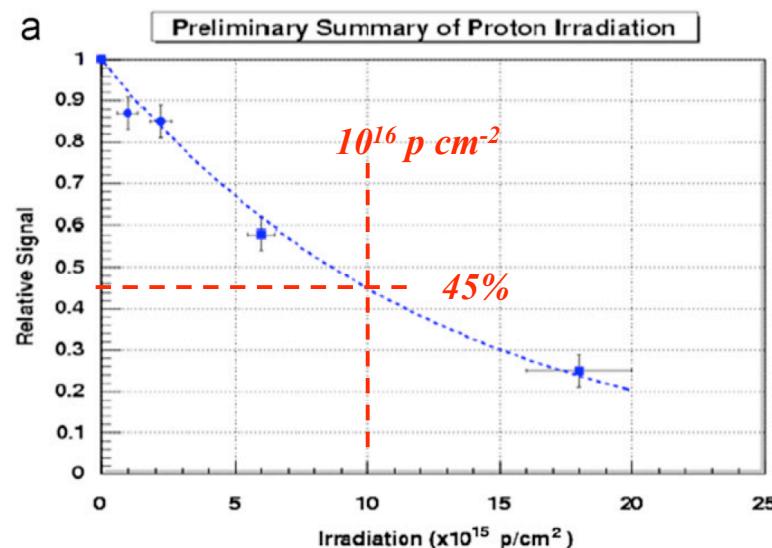
ADVANTAGES OF DIAMOND AS DETECTOR:

- Intrinsic semiconductor
- Large band-gap (5.48 eV) --> low leakage current
- High drift velocity of carriers
- Radiation hard

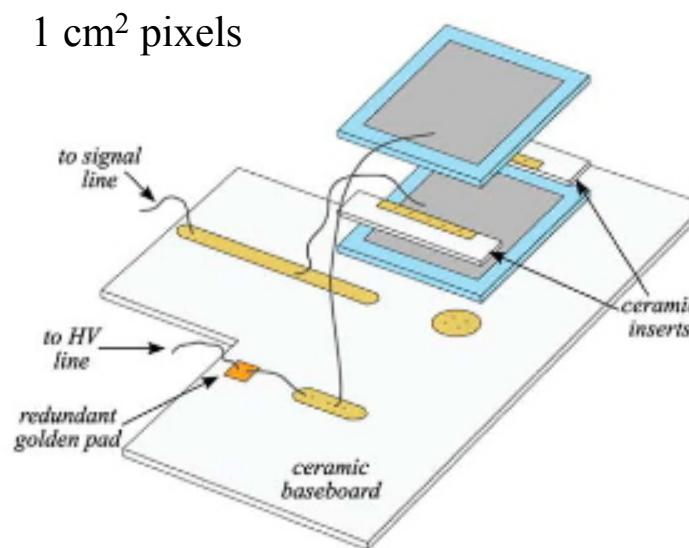
RD42: MANUFACTURED BY CHEMICAL VAPOR DEPOSITION (CVD)

- Large sizes (cm^2)
- Thick (~ mm) --> reasonable signal (8000 e-h for MIPS)

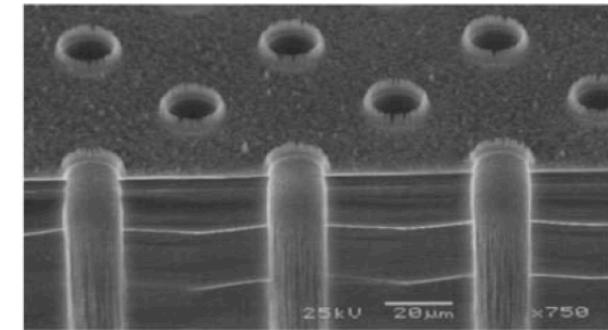
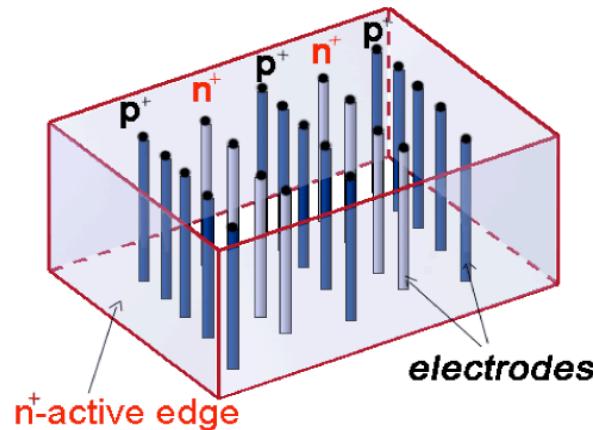
RADIATION TOLERANCE:



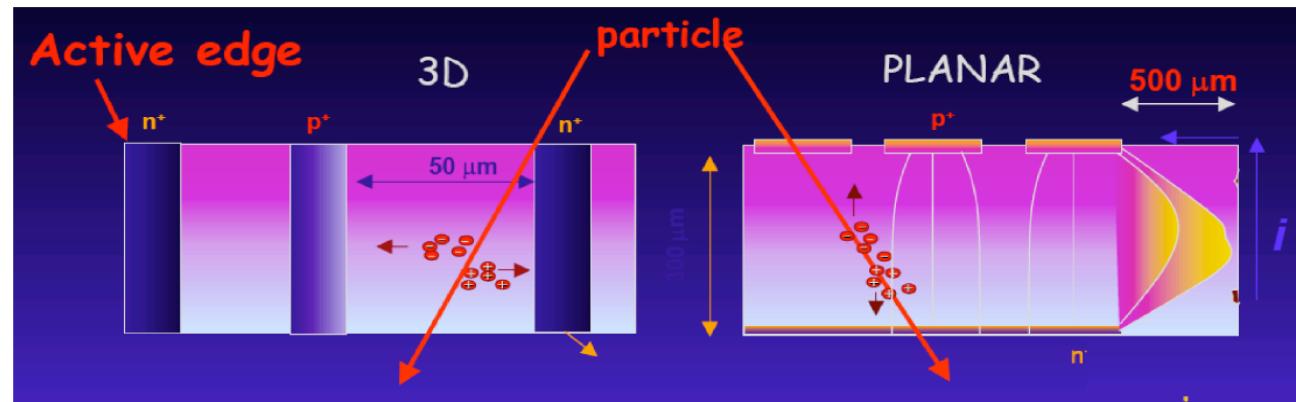
ATLAS BEAM CONDITION MONITOR (BCM):

*A. Gorisek, Nucl. Instr. and Meth. In press (2009)**R. Wallny et al, Nucl. Instr. and Meth. A582(2007)824*

3-D SILICON DETECTORS



Buried channel diodes reduce the charge collection distance, increasing the radiation tolerance

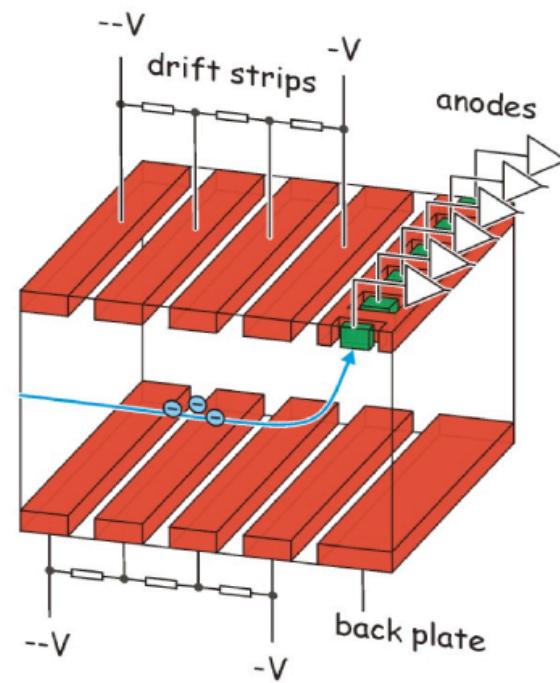
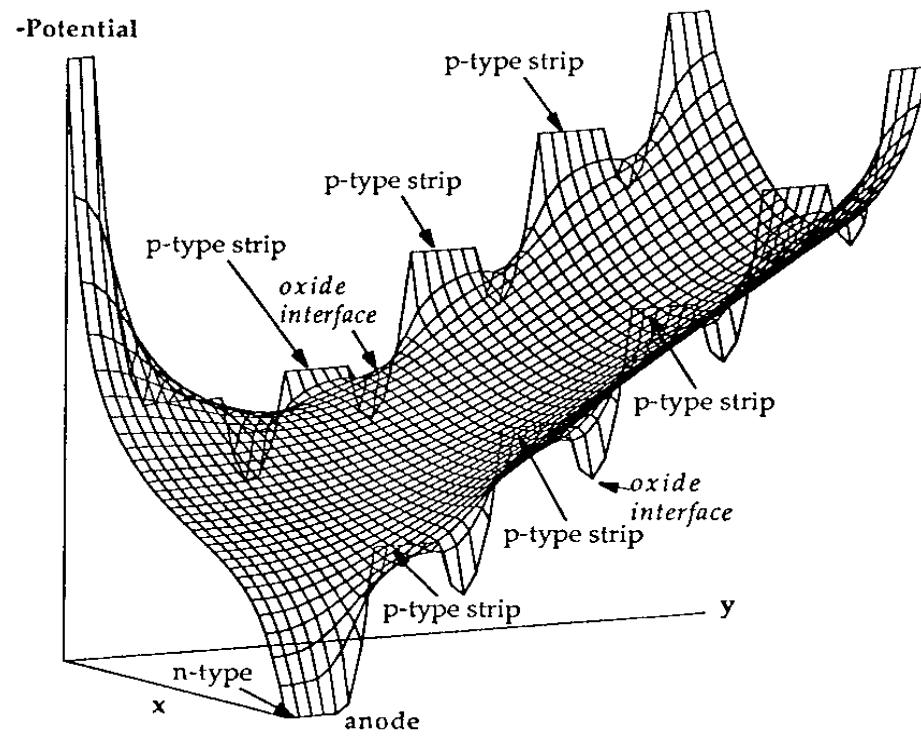
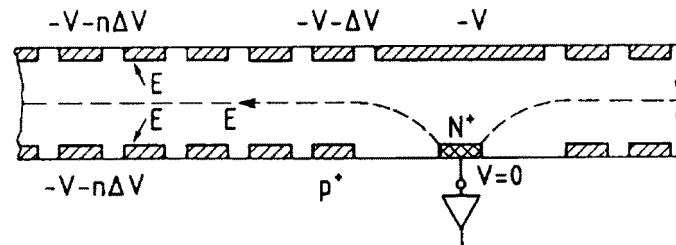


C. Da Via et al, Nucl. Instr. and Meth. A509(2003)86

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THIN SILICON WAFER WITH FIELD-SHAPING P-TYPE STRIPS

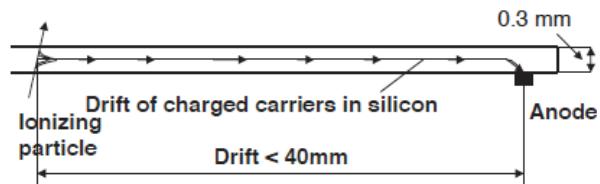
Depleted along drift direction



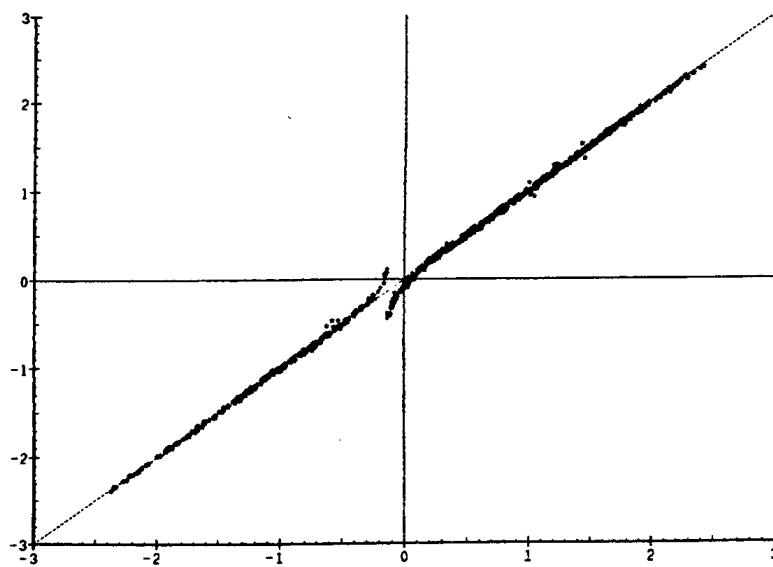
E. Gatti and P. Rehak, Nucl. Instrum. and Meth. 225 (1984) 608

SILICON DRIFT CHAMBERS:

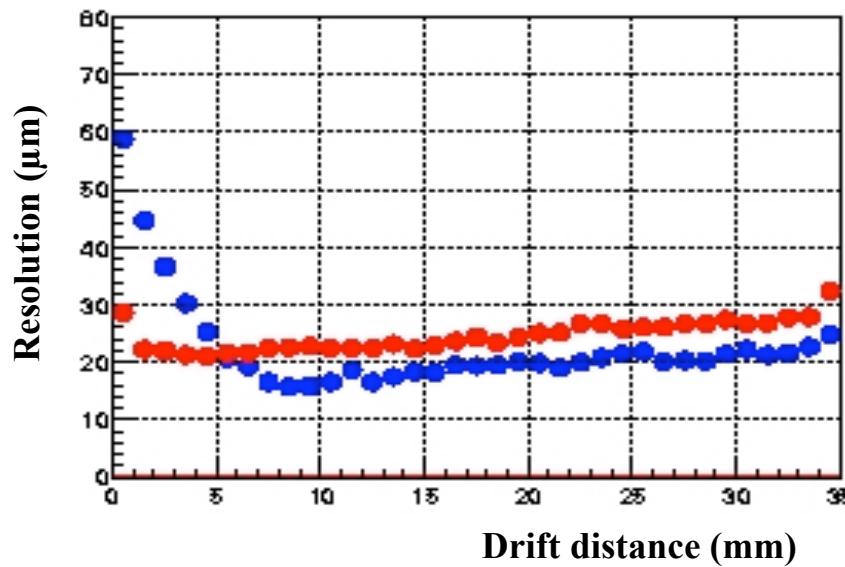
Very good space accuracy
Modest rate capability
(electrons drift velocity $1 \sim \text{cm}/\mu\text{s}$)



SPACE-TIME CORRELATION

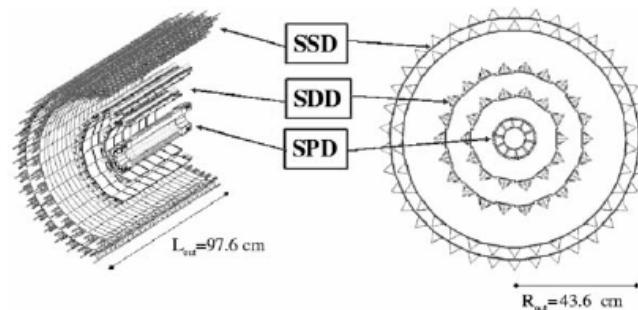


POSITION ACCURACY

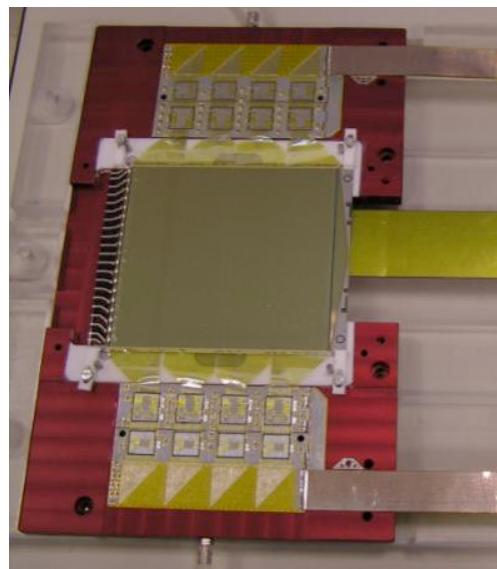


G. Lutz,
Semiconductor Radiation Detectors (Springer 19910

ALICE INNER TRACKING SYSTEM

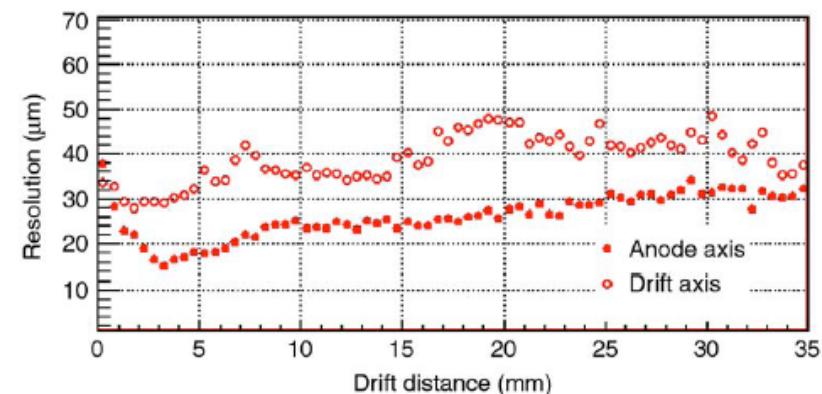
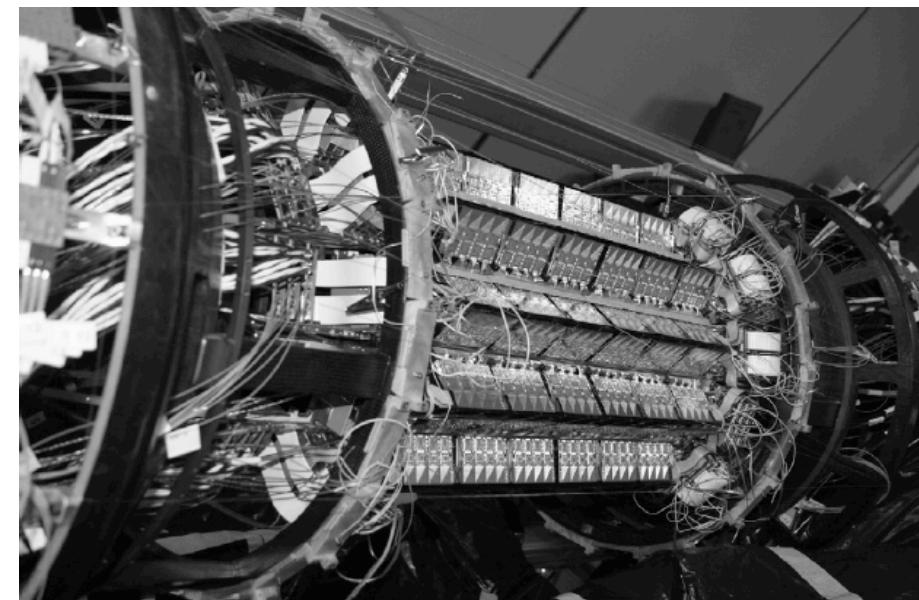


260 modules in two layers
35 mm long, 256 anodes each



F. Antinori, Nucl. Instr. and Meth. A511 (2003)215

SDD LADDER

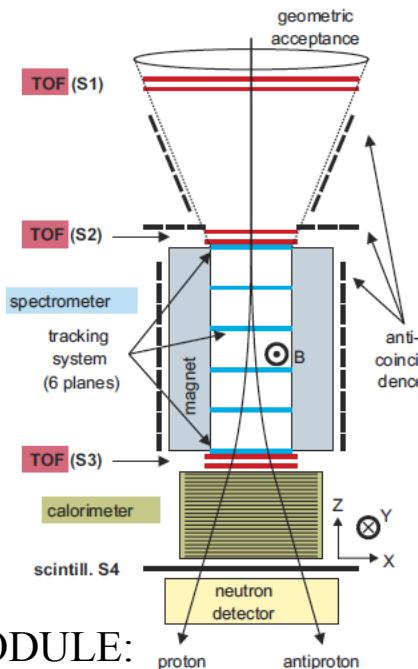


S. Kushpil et al, Nucl. Instr. and Meth. A566(2006)94
Fabio Sauli - CHIPP Winter School 2010

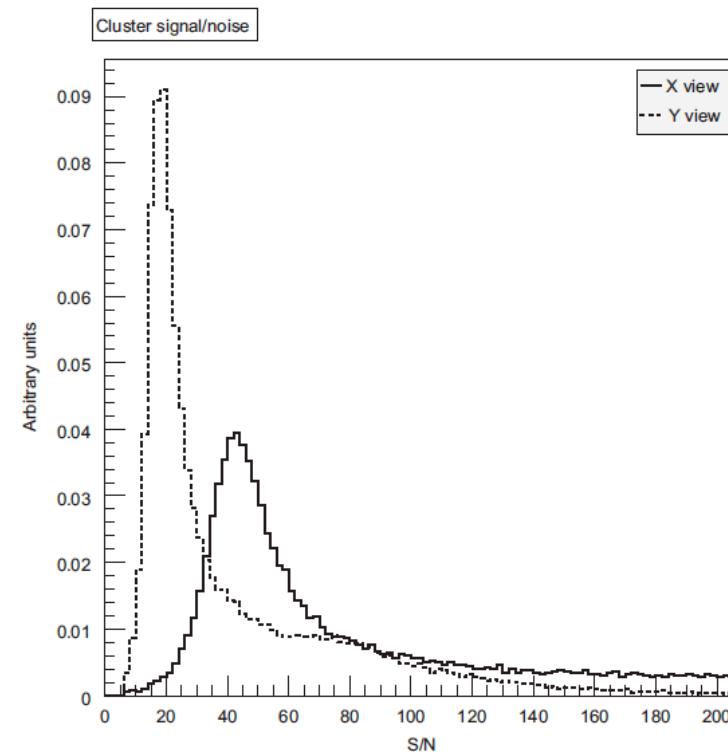
TRACKER FOR THE PAMELA SATELLITE-BORNE EXPERIMENT



SILICON TRACKER MODULE:

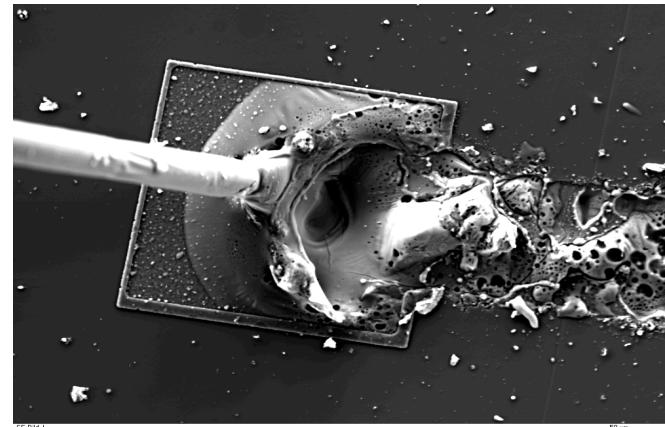
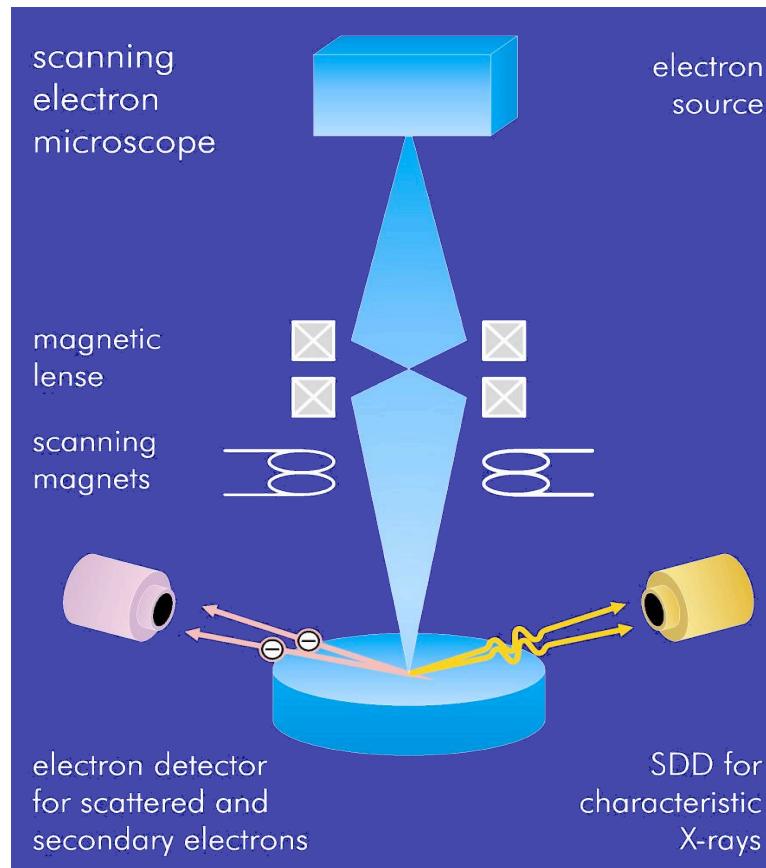


SIGNAL/NOISE FOR X AND Y STRIPS

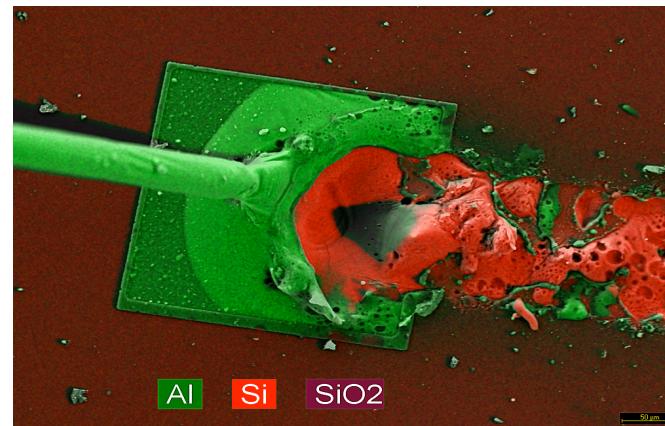


S. Ricciarini, Nucl. Instr. and Meth. A582(2007)892

ELECTRON MICROSCOPY WITH ELEMENT RECOGNITION STANDARD

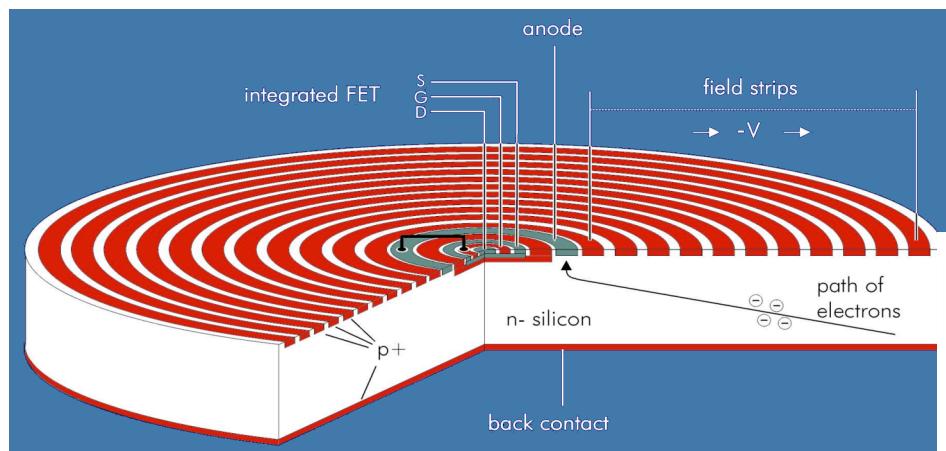


ELEMENTAL ANALYSIS

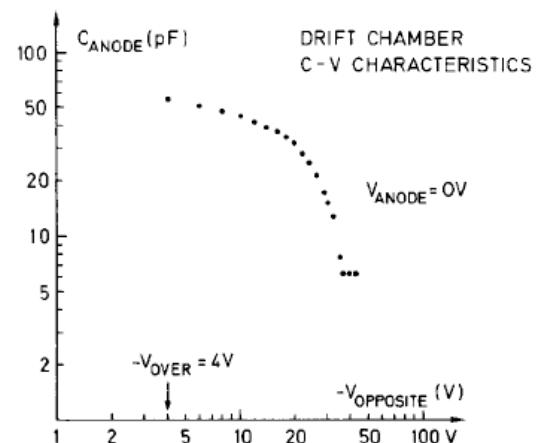


Measurements by RÖNTEC, Berlin

RADIAL DRIFT CHAMBER



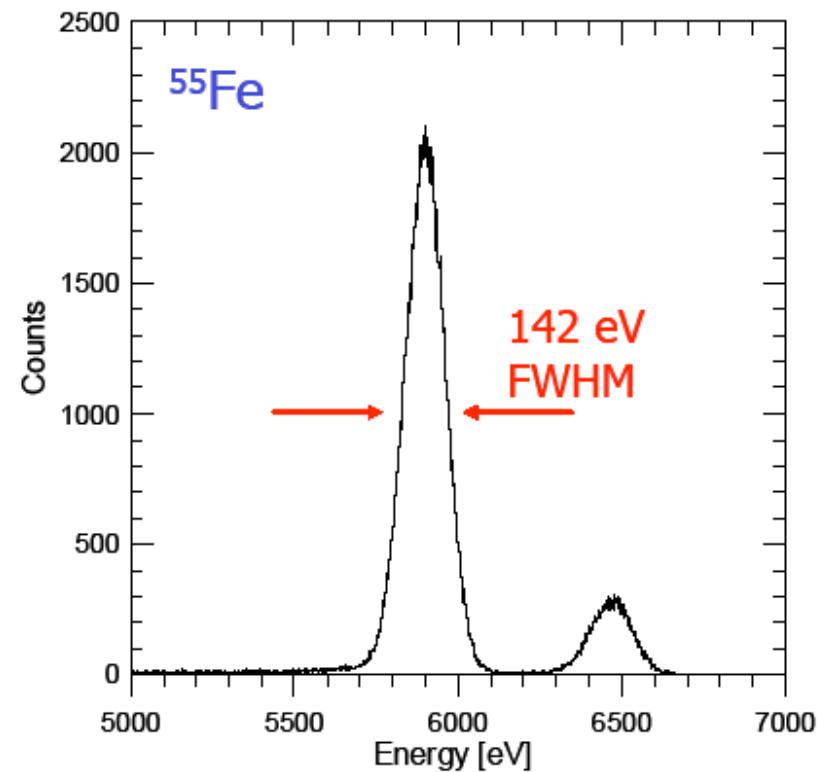
LOW CAPACITANCE:
VERY LOW DETECTOR NOISE



E. Gatti et al, Nucl. Instr. and Meth. 226(1984)129

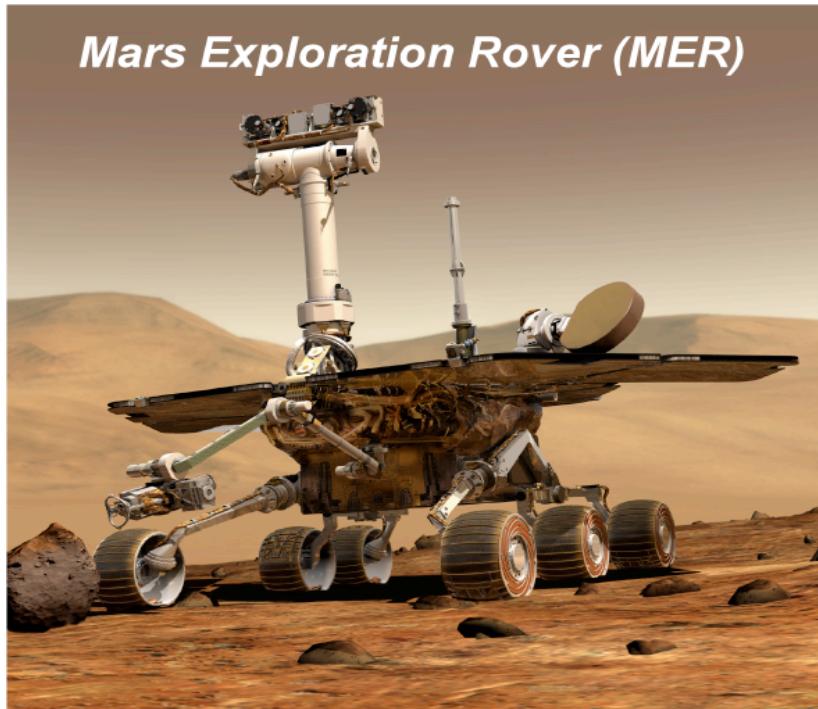
HIGH RESOLUTION X-RAY SPECTROSCOPY

Fe⁵⁵ X-RAY SPECTRUM AT -10 °C
Mn K-a and K-b lines (5.9 and 6. keV)

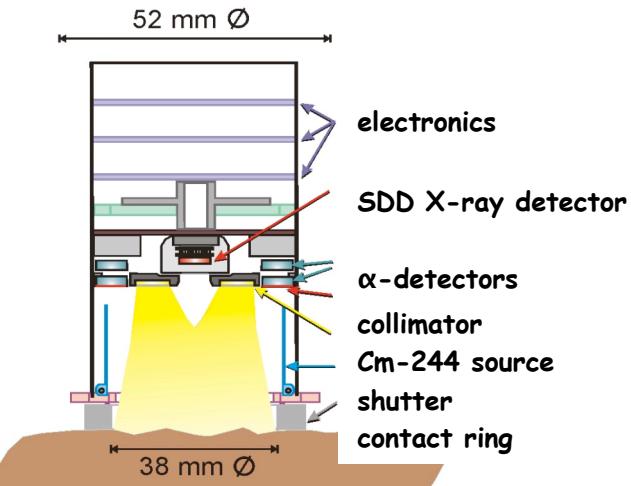
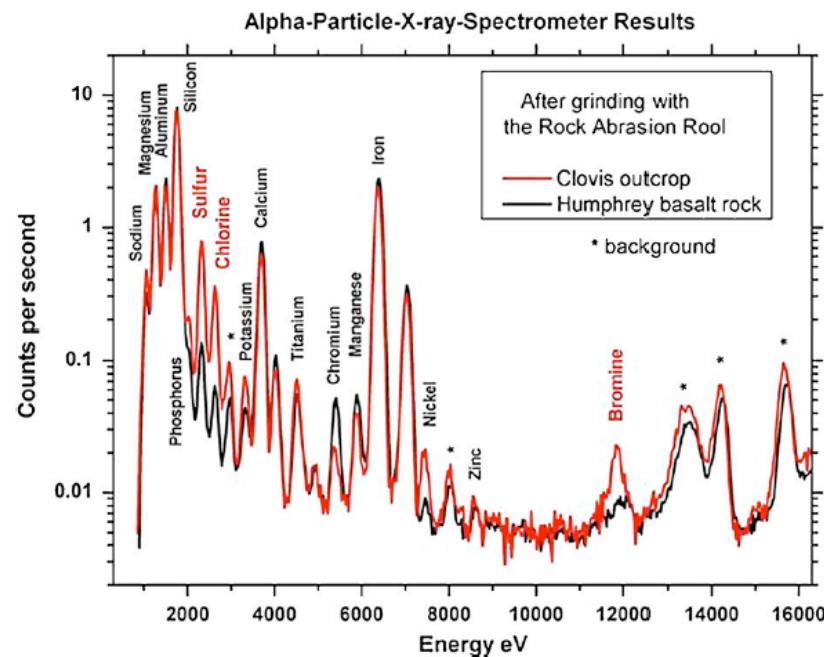


C. Fiorini et al, IEEE Trans. Nucl. Sci. NS52(2005)1165.

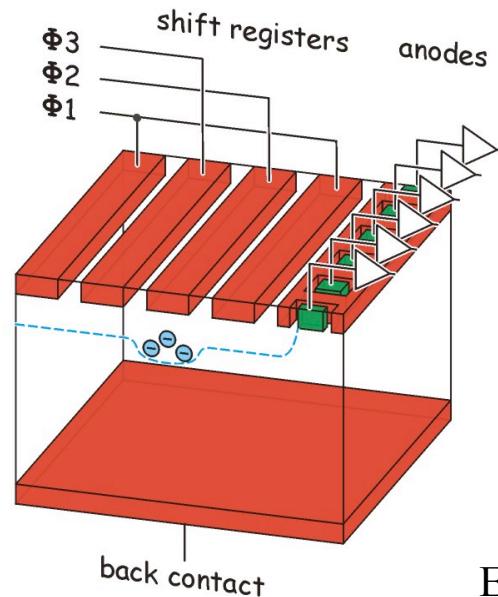
SOIL ANALYSIS BY THE MARS ROVER



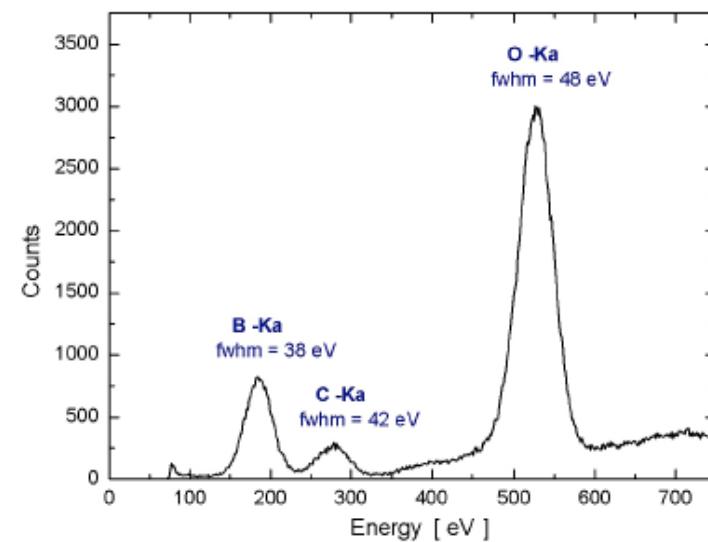
R. Rieder et al, J. Geophys. Res. 108
(E12) (2003) 8066

X-RAY SPECTRUM OF MARS SOIL EXCITED BY α SOURCE:

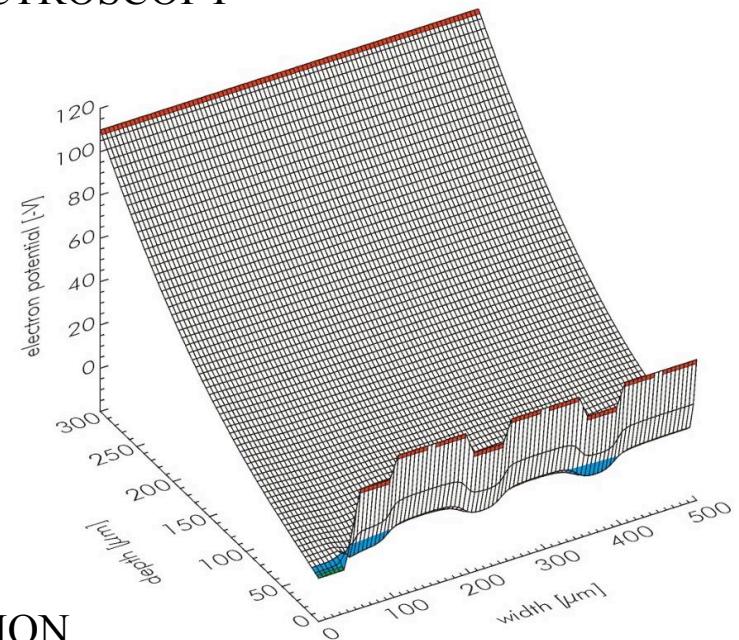
FULLY DEPLETED CCD FOR HIGH RESOLUTION SPECTROSCOPY



ENERGY RESOLUTION



Futaba Saito - CERN Winter School 2010

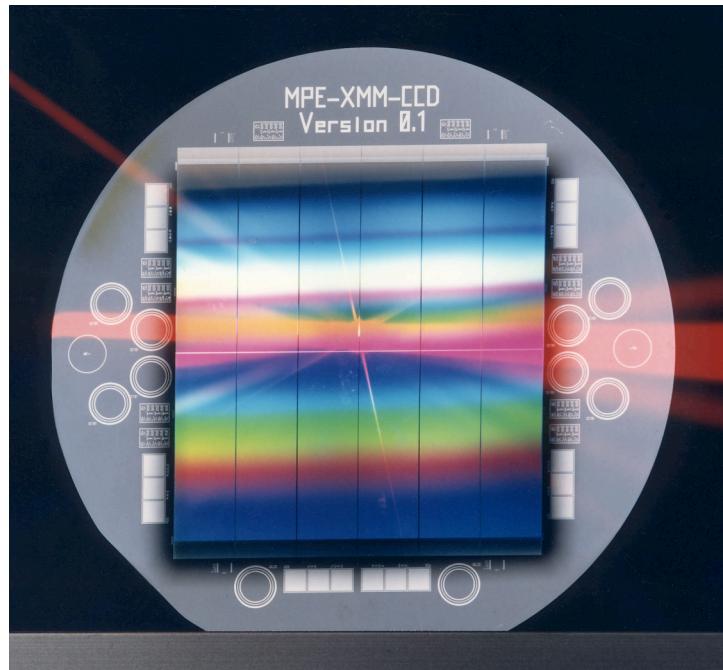


G. Lutz et al,
Nucl. Instr. and Meth. A580(2007)960

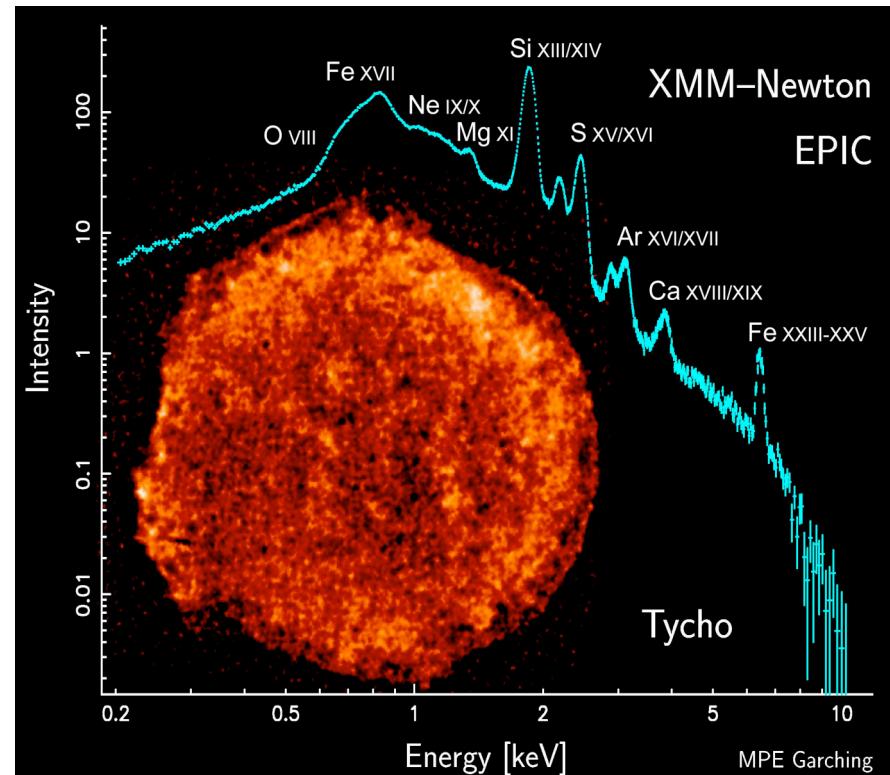
EPIC pnCCDs on EPIC-NEWTON



12 pnCCD array, 200x64 pixels each
150x150 μm



TYCHO SUPERNOVA REMNANTS



GAMMA RAY BURST AFTERGLOW OBSERVATION WITH XMM

