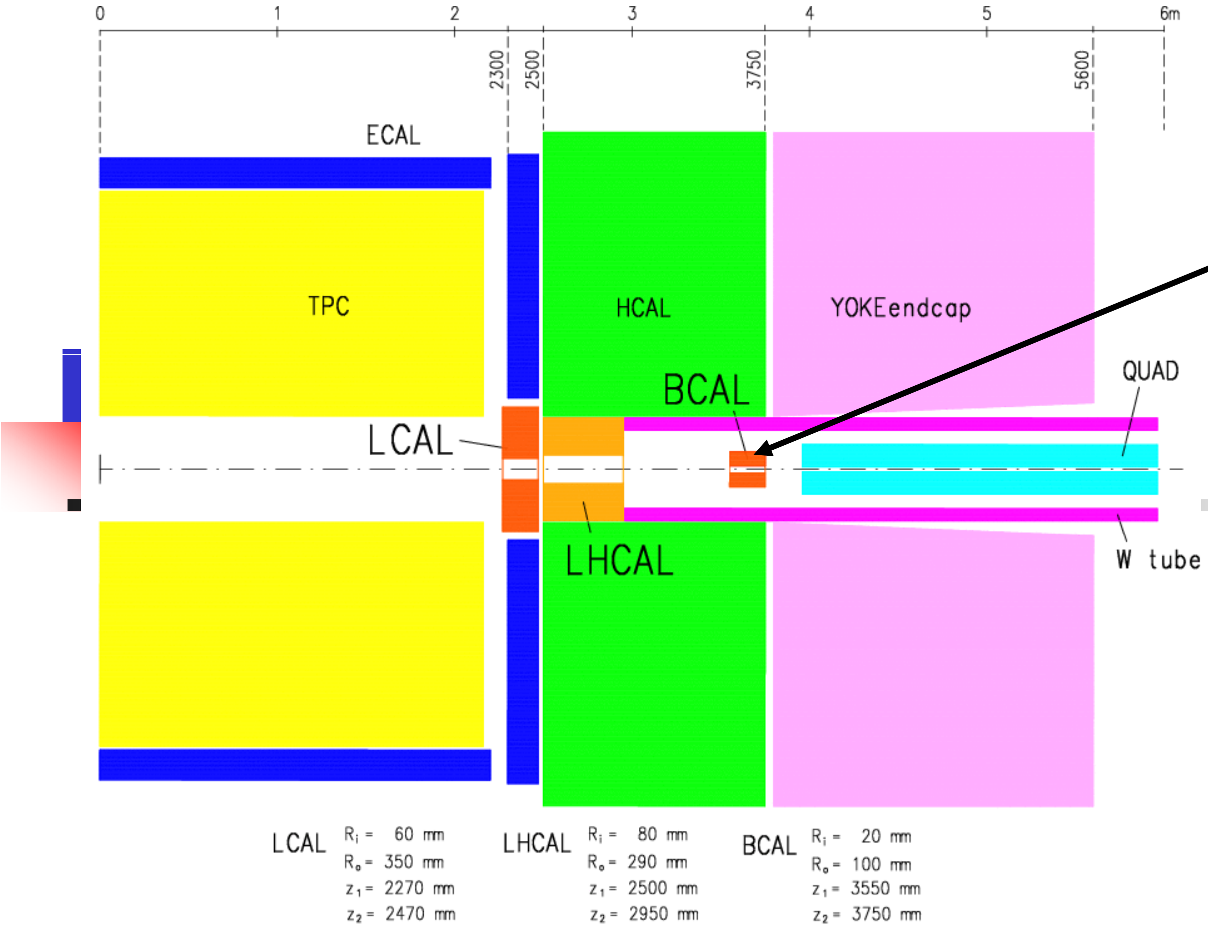
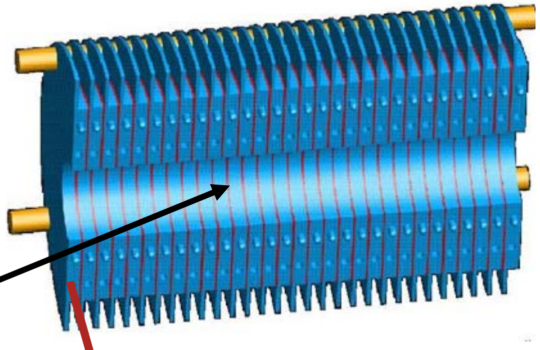
MOTIVATION FOR RADHARD SENSORS





BeamCal

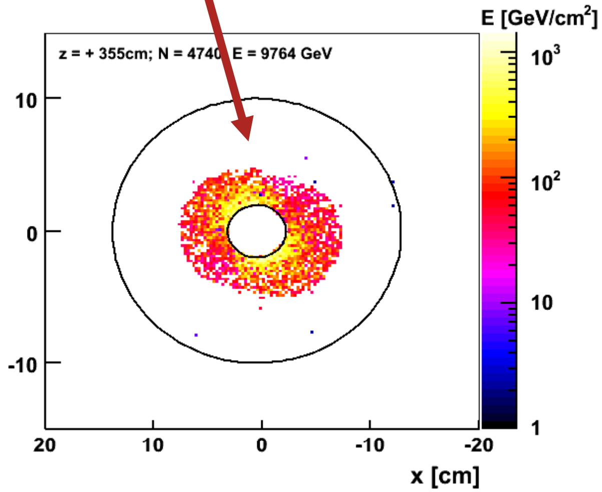
30 layers of

W / CVD diamond (?)

5 < ***ANGLE*** < 28 mrad

Energy deposition from beamstrahlung pairs in BeamCal:

Dose of up to 10 MGy/a ==1Grad



QuickTime™ and a Graphics decompressor are needed to see this picture.

potential candidates?

- Silicon (various type, Cz, Dofz, MCz,EPi)
- Silicon Carbide
- Diamond
- GaAs

Look for best performances in terms of :

- Signal yield
- stability , long-term behavior
- charge collection efficiency
- charge collection distance
- radiation hardness
-Easy industrial procurement
- budget

Status des matériaux durcis candidats

Property	**Si**	**Diamond**	**Diamond**	**4H SiC**
Material Quality	**Cz, FZ, epi**	**Polycrystalline**	**single crystal**	**epitaxial**
E_g [eV]	**1.12**	**5.5**	**5.5**	**3.3**
$E_{breakdown}$ [V/cm]	**$3 \cdot 10^5$**	**10^7**	**10^7**	**$2.2 \cdot 10^6$**
μ_e [cm^2/Vs]	**1450**	**1800**	**>1800**	**800**
μ_h [cm^2/Vs]	**450**	**1200**	**>1200**	**115**
v_{sat} [cm/s]	**$0.8 \cdot 10^7$**	**$2.2 \cdot 10^7$**	**$2.2 \cdot 10^7$**	**$2 \cdot 10^7$**
Z	**14**	**6**	**6**	**14/6**
ε_r	**11.9**	**5.7**	**5.7**	**9.7**
e-h energy [eV]	**3.6**	**13**	**13**	**7.6**
Density [g/cm3]	**2.33**	**3.515**	**3.515**	**3.22**
Displacem. [eV]	**13-20**	**43**	**43**	**25**
e-h/μm for mips	**89**	**36**	**36**	**55**
Max initial ccd [μm]	**>500**	**280**	**550**	**40 (= thickness)**
Max wafer ϕ tested	**6”**	**6”**	**6mm**	**2”**
Producer	**Several**	**Element-Six**	**Element-Six**	**Cree-Alenia, IKZ**
Max fluence[cm^{-2}]	**$7x10^{15}$ 24GeV p**	**$2x10^{15}$ n, π, p**	**Not reported**	**10^{16} in progress**
CERN R&Ds	**RD50, RD39**	**RD42**	**RD42**	**RD50**

Material sensors

Property	**Diamand**	**GaN**	**4H SiC**	**Si**
E_g [eV]	**5.5**	**3.39**	**3.26**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4\cdot10^6$	$2.2\cdot10^6$	$3\cdot10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2\cdot10^7$	-	$2\cdot10^7$	$0.8\cdot10^7$
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/cm3]	3.515	6.15	3.22	2.33
Displacem. [eV]	**43**	**≥15**	**25**	**13-20**

- **Zone interdite bandgap (3.3eV)**

⇒ **Courant de fuite plus faible que le silicium**

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

⇒ Plus de charges que le diamand

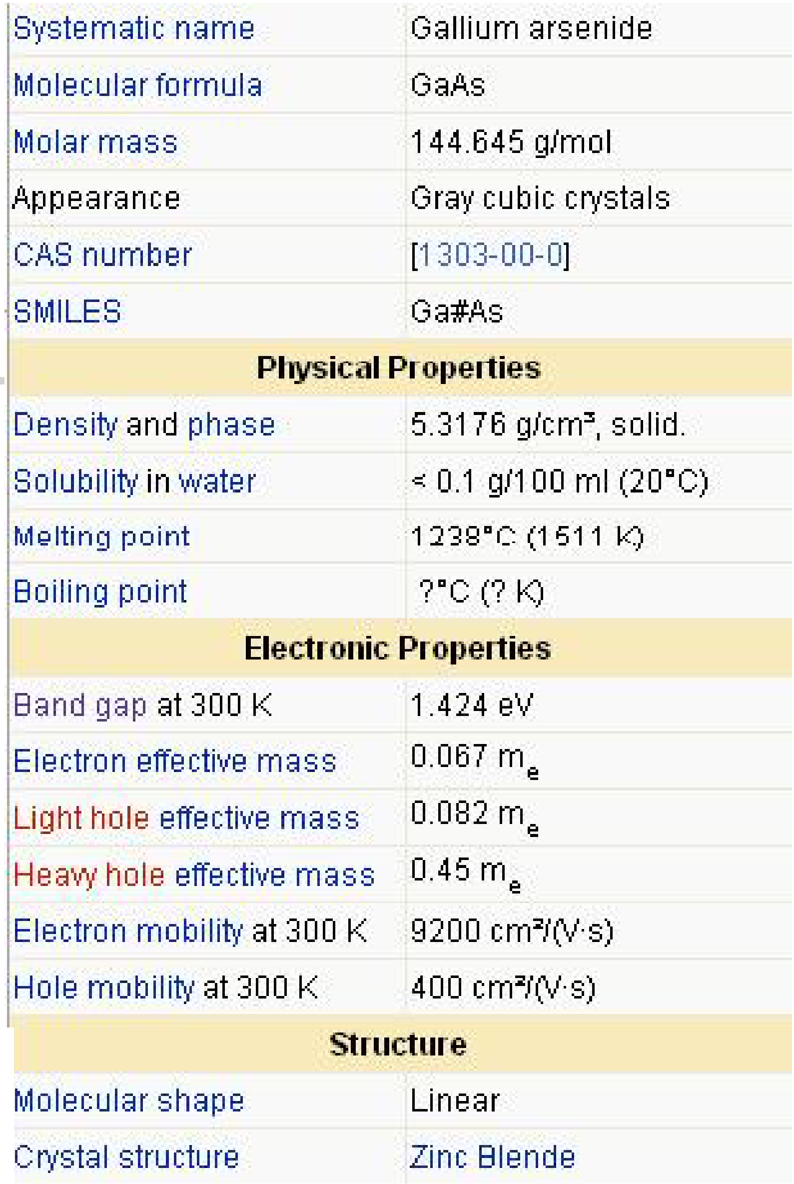
- Seuil de déplacement plus elevé que pour le Si

⇒ Meilleure tenue aux radiation que le Si

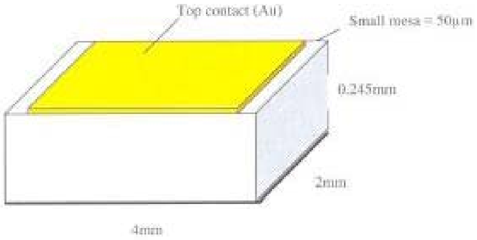
R&D on diamond detectors:
RD42 – Collaboration
http://cern.ch/rd42/

Recent review: P.J.Sellin and J.Vaitkus on behalf of RD50 “New materials for radiation hard semiconductor detectors”

AsGa



Systematic name	Gallium arsenide
Molecular formula	GaAs
Molar mass	144.645 g/mol
Appearance	Gray cubic crystals
CAS number	[1303-00-0]
SMILES	Ga#As
Physical Properties	
Density and phase	5.3176 g/cm³, solid.
Solubility in water	< 0.1 g/100 ml (20°C)
Melting point	1238°C (1511 K)
Boiling point	?°C (? K)
Electronic Properties	
Band gap at 300 K	1.424 eV
Electron effective mass	0.067 m_e
Light hole effective mass	0.082 m_e
Heavy hole effective mass	0.45 m_e
Electron mobility at 300 K	9200 cm²/(V·s)
Hole mobility at 300 K	400 cm²/(V·s)
Structure	
Molecular shape	Linear
Crystal structure	Zinc Blende



Dommages dûs à l'irradiation des Senseurs au Si

- **Deux types de dommages aux irradiations aux matériaux des détecteurs**
  - **dommages substrat Bulk (Crystal) dus à perte d'énergie non ionisante (NIEL)**
    Non Ionizing Energy Loss (IEL)

    → **déplacements , défauts dans le crystal ....**

    I. **Changement de la concentration effective du dopage (tension de désertion plus élevée, sous-desertion)**

    II. **Augmentation du courant de fuite (augmentation du bruit de grenaille, bruits thermiques..)**

    III. **Augmentation du taux de piégeage de porteurs de charge (perte de charges)**
  - **dommages de Surface dûs à la perte d'énergie ionisante Ionizing Energy Loss (IEL)**

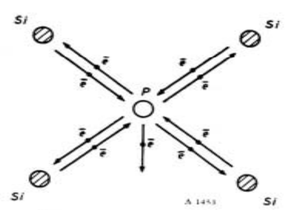
    - accumulation de charges positives dans oxide (SiO_2) et entre interface Si/SiO_2

    - affecte: capacités interpistes (bruit), claquages, ...
- **Ceci a un impact direct sur la performance et l'efficacité de collection de charge**

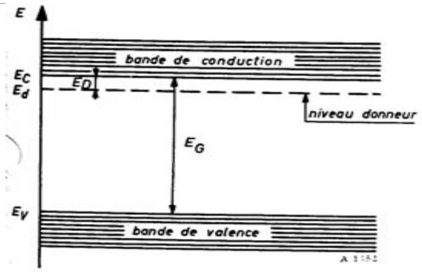
→ conséquence sur le rapport signal/bruit !

Irradiations sévères

- Semiconducteurs extrinsèques du type N

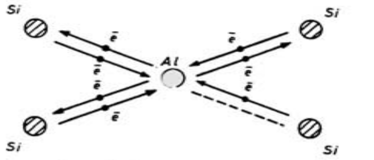


— Atome pentavalent en position interstitielle dans un cristal de silicium.

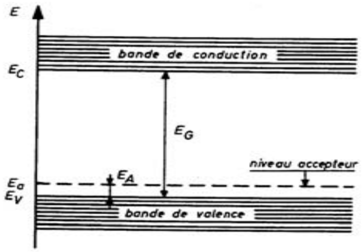


— Schéma d'énergie d'un solide cristallin de type N.

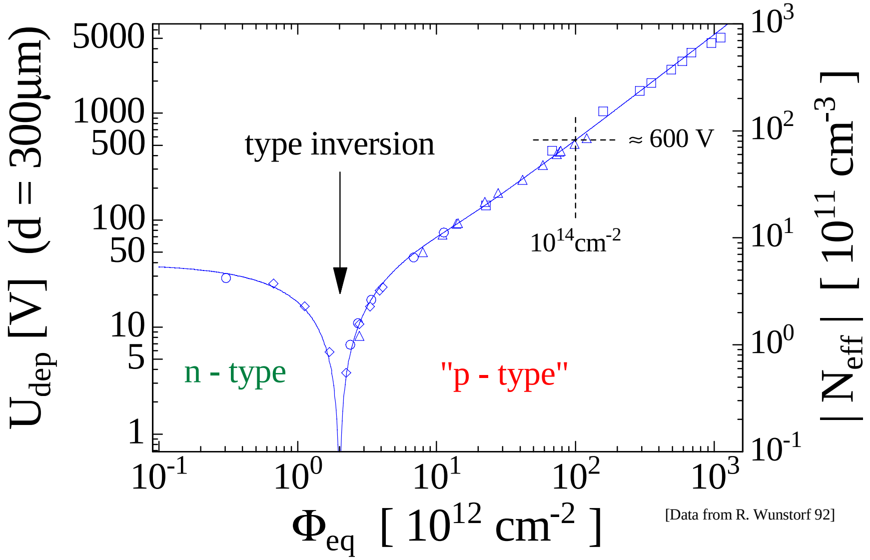
Semiconducteurs extrinsèques de type P



Atome trivalent en position interstitielle dans un cristal de silicium.

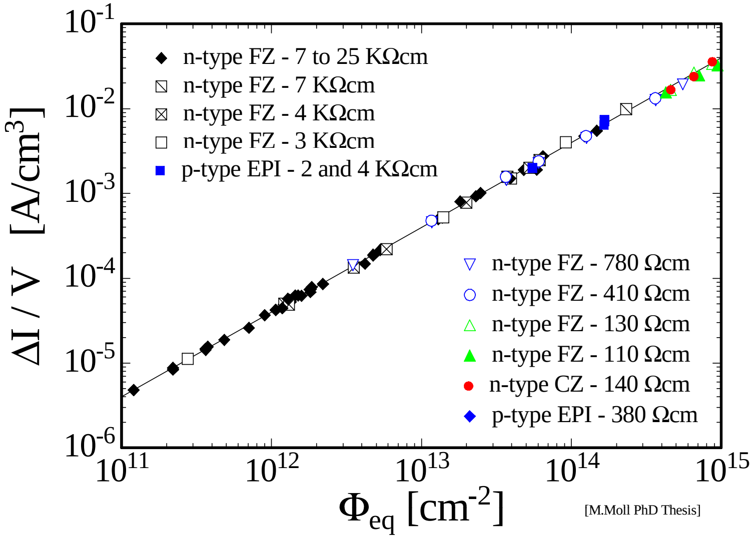


— Schéma d'énergie d'un solide cristallin de type P.



[Data from R. Wunstorf 92]

tension désertion, N_{eff}



[M.Moll PhD Thesis]

Courants de fuites

Charge collection efficiency

Limitations →

- **partial depletion**
- **deep trapping levels**
- **type inversion**

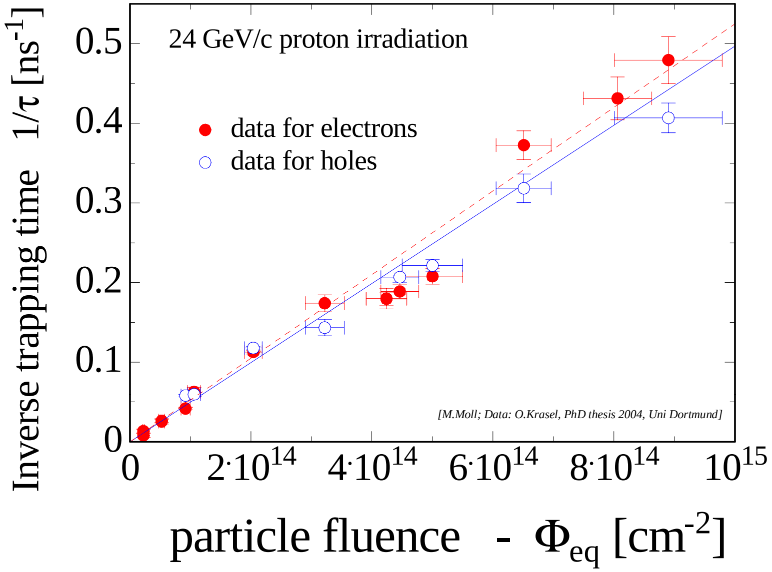
Charge collected:

$$Q = Q_o \cdot \varepsilon_{dep} \cdot \varepsilon_{trap}$$

$$\varepsilon_{dep} = \frac{d}{W} \qquad \varepsilon_{trap} = e^{-\frac{\tau_c}{\tau_t}}$$

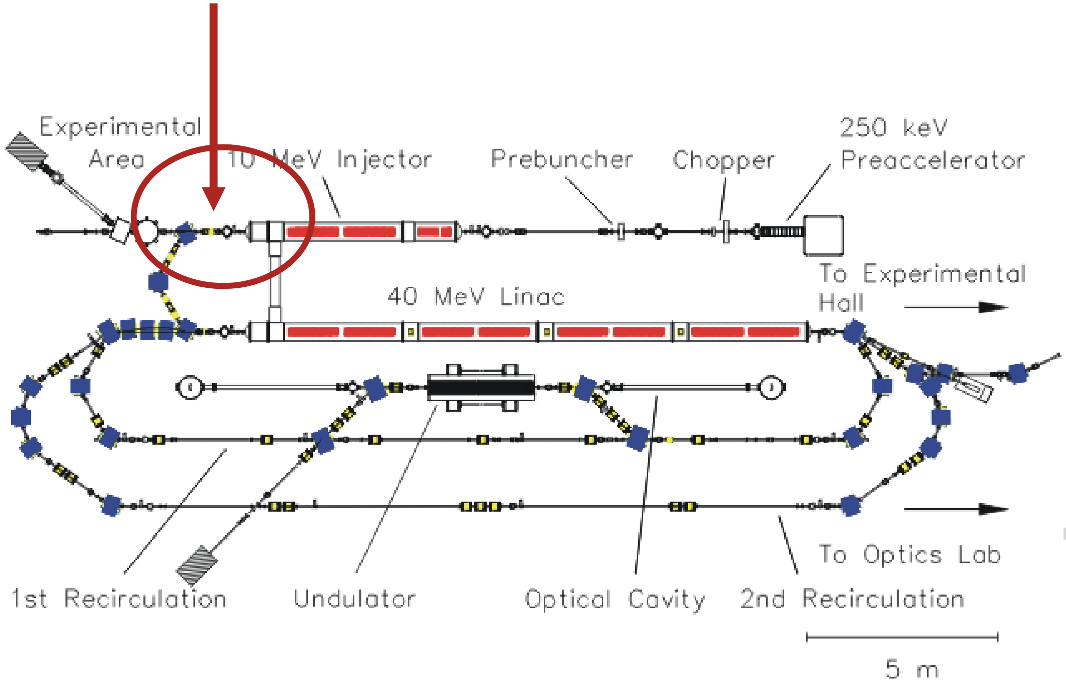
$1/\tau_{trap}$ increase with fluence :
Krasel et al. (RD50)

W: total thickness
d: active thickness
τ_c : Collection time
τ_t : trapping time



[M.Moll; Data: O.Krasel, PhD thesis 2004, Uni Dortmund]

TEST BEAM @ S-DALINAC



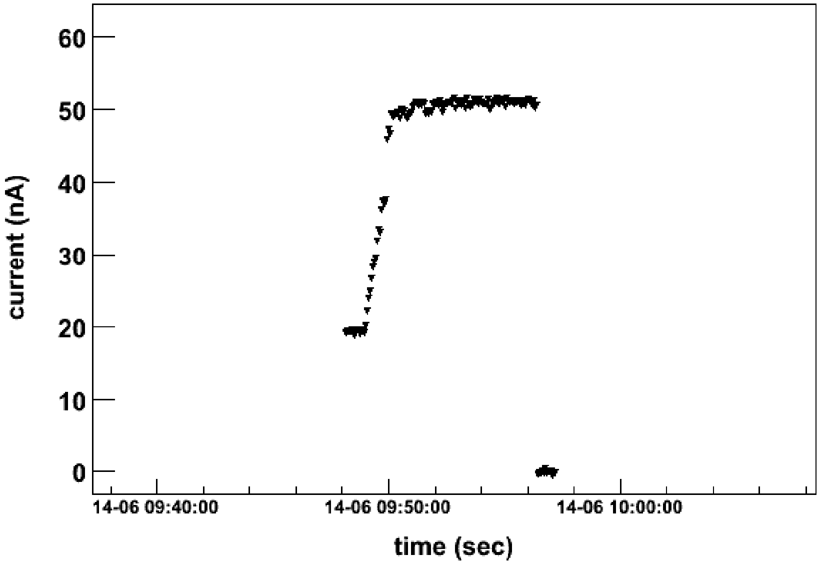
Superconducting **DA**rmstadt **LIN**ear **AC**celerator
Institut für Kernphysik, TU Darmstadt

Using the injector line of the S-DALINAC:

10 ± 0.015 MeV and possible beam currents from ***1nA to 50µA***

Beam current

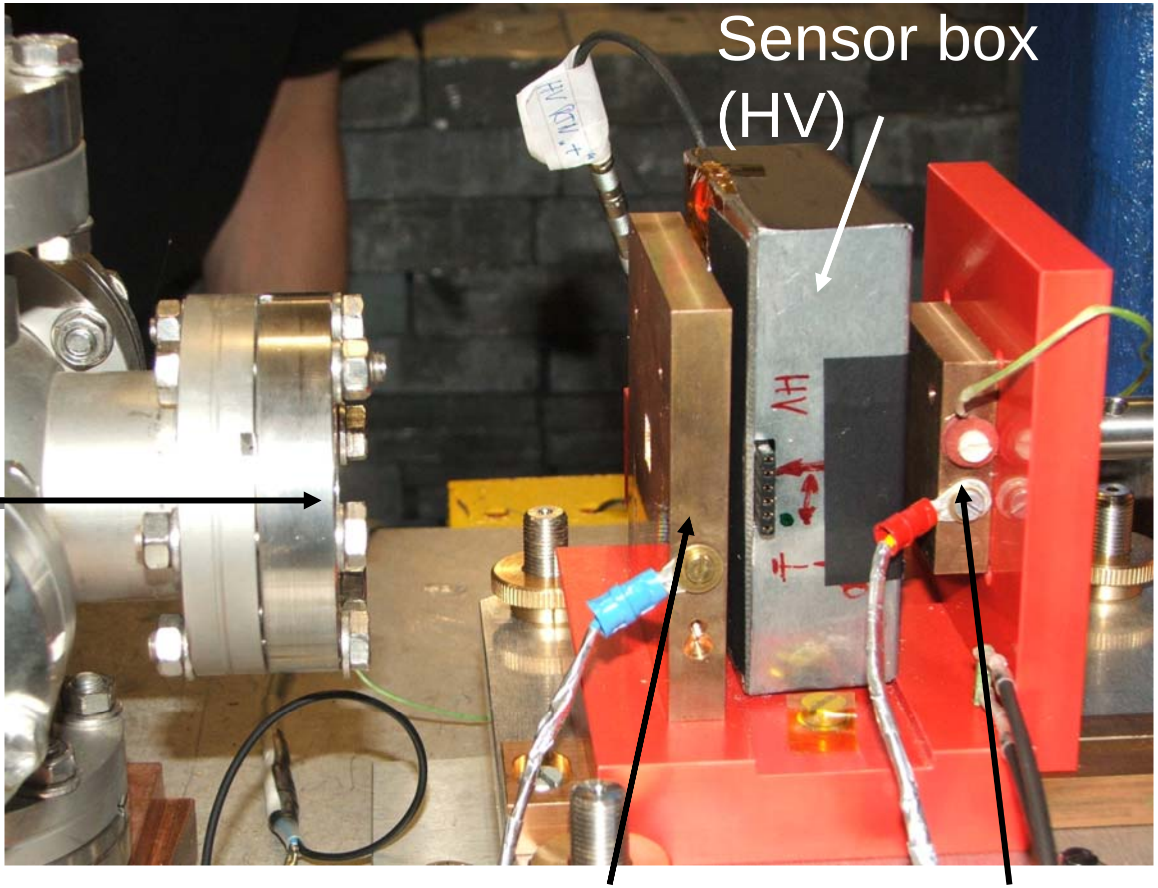
- Tuned the beam to currents in the Faraday cup of:
  - 10, 20, 50 and 100 nA
- This corresponds to dose rates of:
  - 59, 118, 295 and 590 kGy/h
- Dose controlled by beam current
- Error assumed ~ 10%



setup

Beam area:

Beam exit window



Sensor box (HV)

Collimator (I_{Coll})

Faraday cup (I_{FC}, T_{FC})

sensors

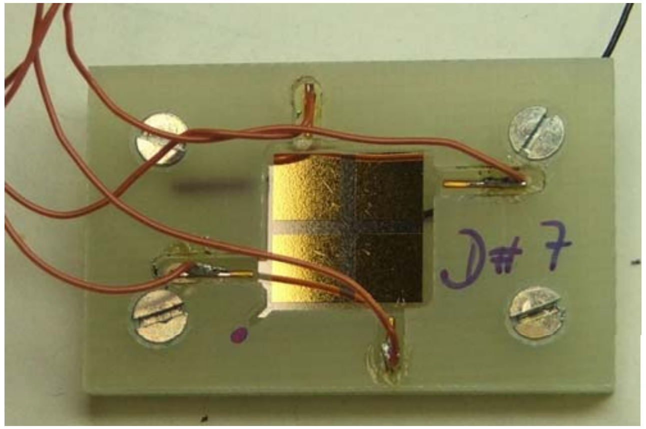
Investigate:

☐ diamond

- samples from E6 (pCVD)
  - 1 MGy
  - 5 MGy
- samples from IAF Freiburg (pCVD)
  - 1 MGy
  - 5 MGy

☐ Si

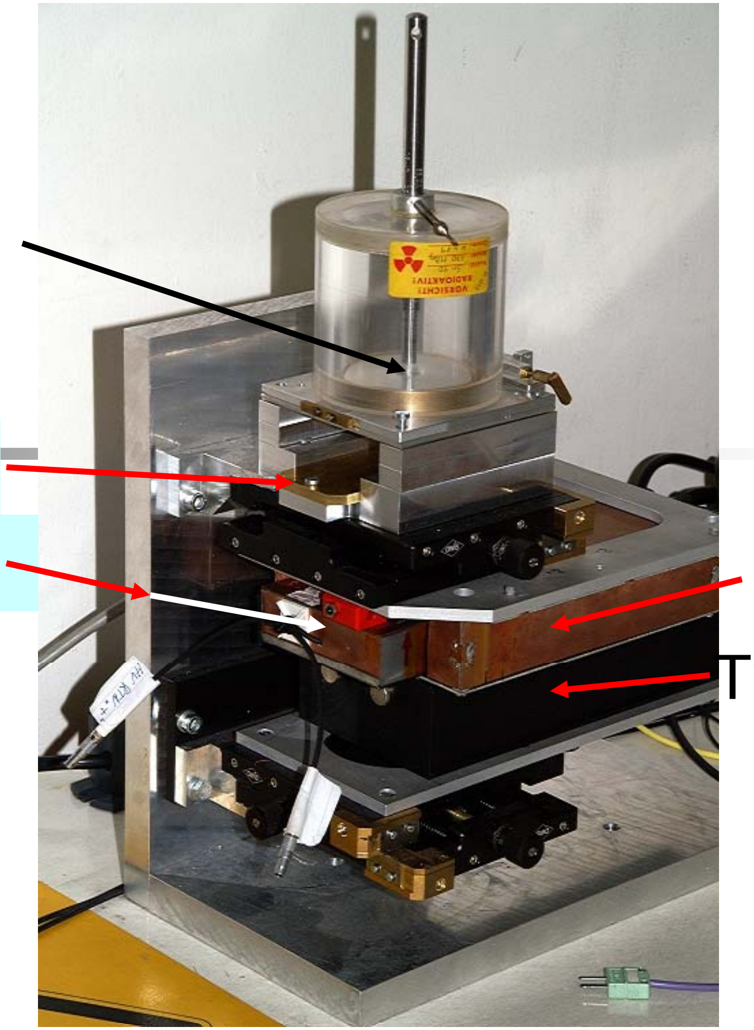
- samples (Micron Ltd. UK)



IAF fraunhofer, Freiburg
E6 Element six

SOURCE CALIBRATION

measurement:



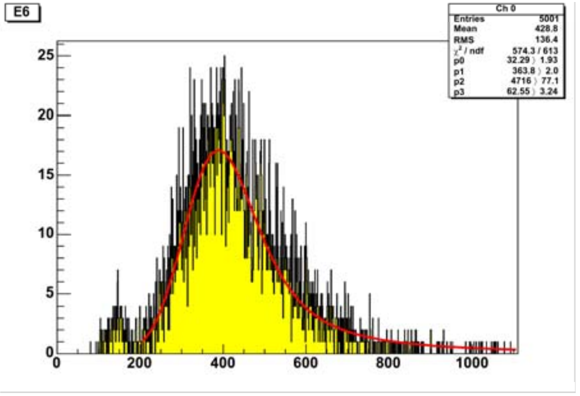
Source (Sr 90)

collimator

Sensor box

preamp

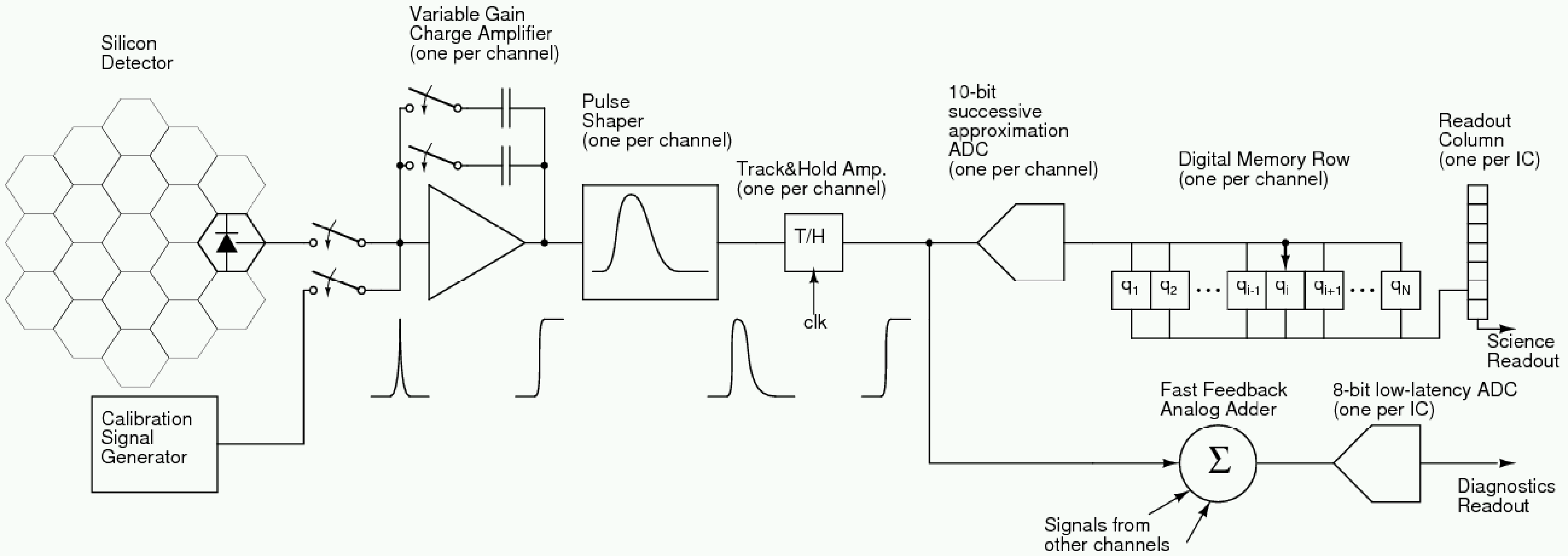
Trigger box



programme

- S/N
- S/N for high irradiation doses
- Comparison between different sensors
- Power dissipation
- Longterm behavior I(t)
- Electronics : Asic study (next step)

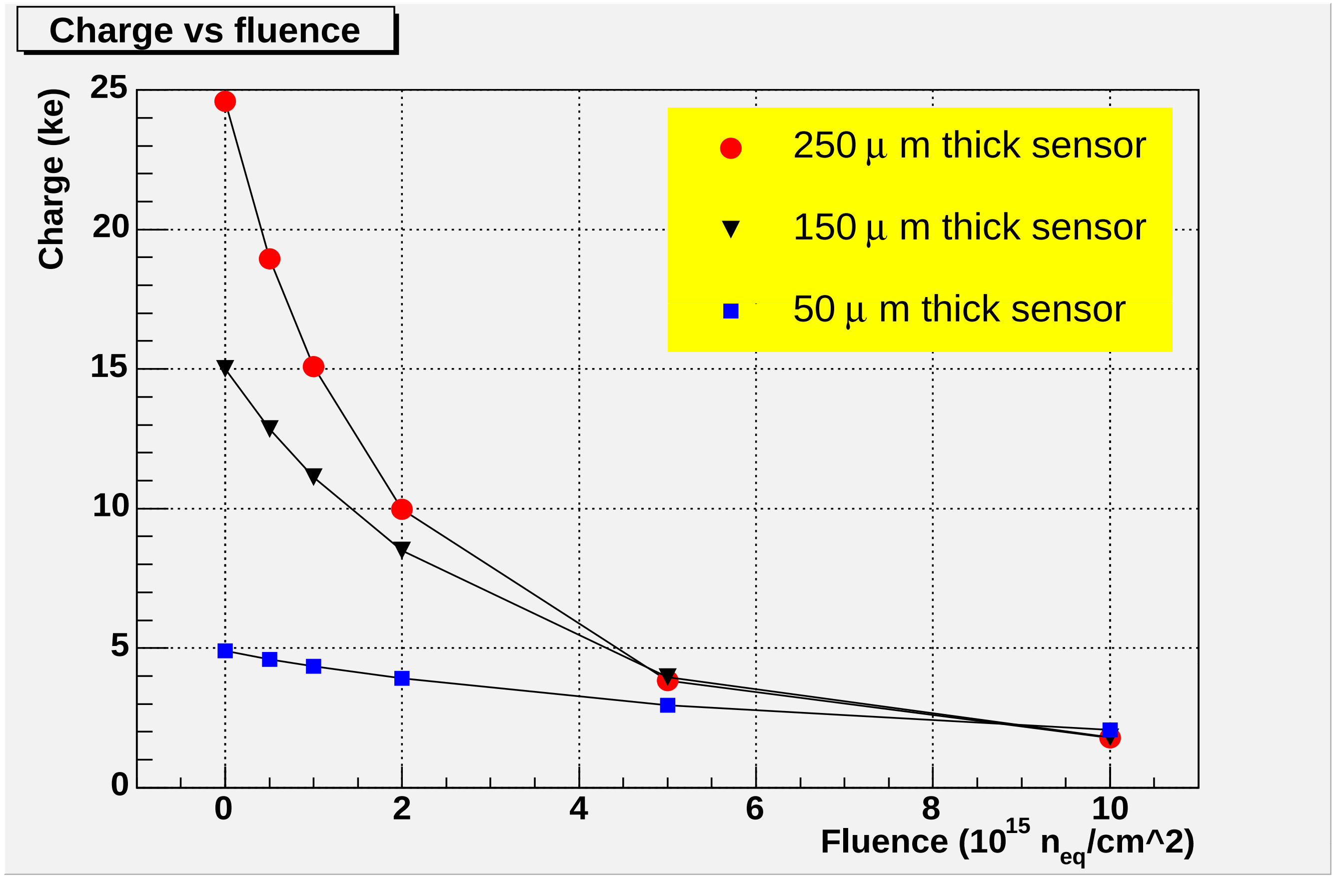
BeamCal electronics operation



- Dual-gain front-end electronics: charge amplifier, pulse shaper and T/H circuit
- Successive approximation ADC, one per channel
- Digital memory, 2820 (10 bits + parity) words per channel
- Analog addition of 32 channel outputs for fast feedback; low-latency ADC

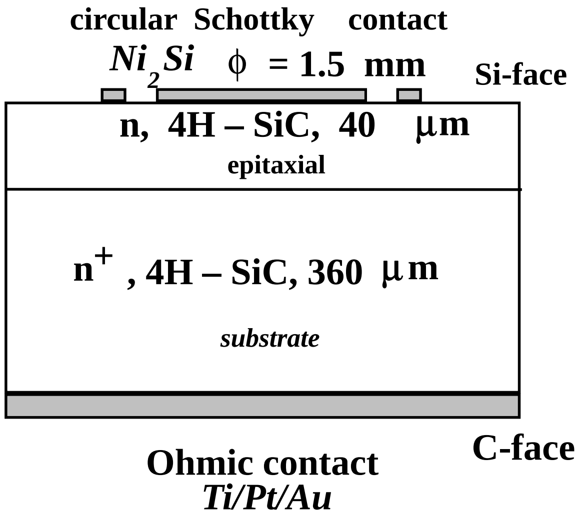
FIN

Why thin detectors ?



- **Simulation**

silicium epitaxial



circular Schottky contact

Ni_2Si ϕ = 1.5 mm

Si-face

n, 4H – SiC, 40 μm

epitaxial

n^+, 4H – SiC, 360 μm

substrate

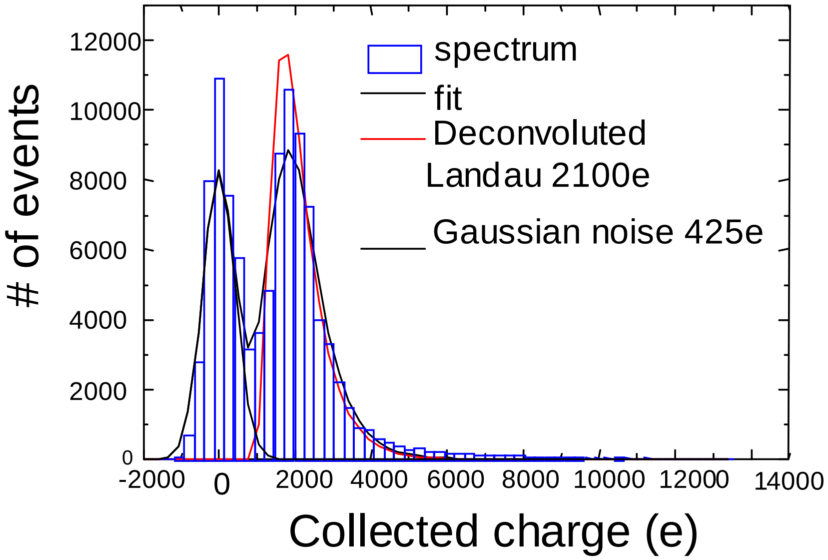
C-face

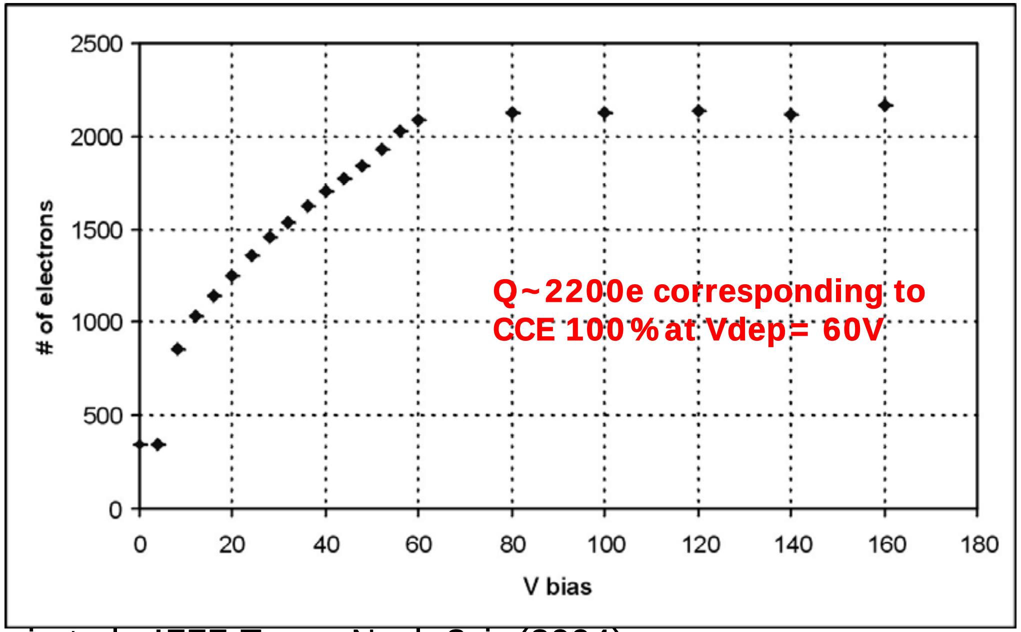
Ohmic contact

Ti/Pt/Au

Modena& alenia systems
Italy

RD 50



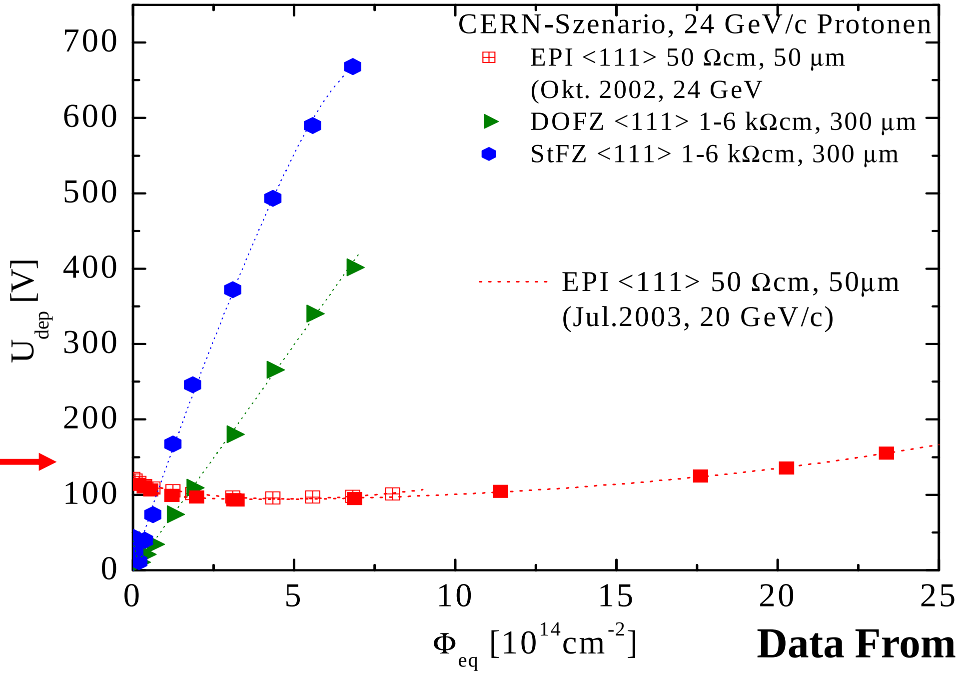


Q~2200e corresponding to
CCE 100% at Vdep= 60V

Data from F. Nava, S. Sciortino, M. Bruzzi et al., IEEE Trans. Nucl. Sci, (2004)

Silicium épitaxial

Utilisation de détecteurs fins (50-100 µm) avec une basse resistivité épitaxiale **Si 50µm, 50Ωcm on CZ Si**



120 V →

← **160 V**

Data From G.Lindstrom et al.

Pixels Hybrides

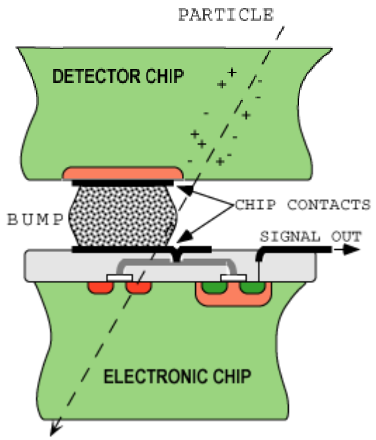
Hybrid Pixels Sensors: Détecteur soudé sur son électronique

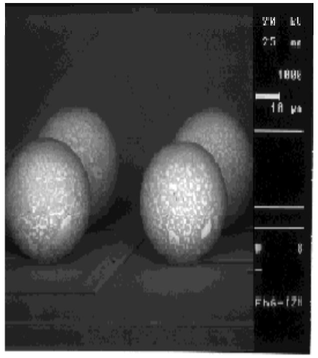
Détecteur: Silicium de haute résistivité

système: Silicium + “électronique” au dessus du détecteur

Micro-Soudure par billes d’Indium ou SnPb

Résolution:	*pixels 100 μm, résolution ~15 μm*
Très bonne tenue aux radiations:	*$10^{15}\ n_{eq}/cm^2$ 60 Mrad @ -6°C*
Transparence:	*0.2-0.4% X_0*

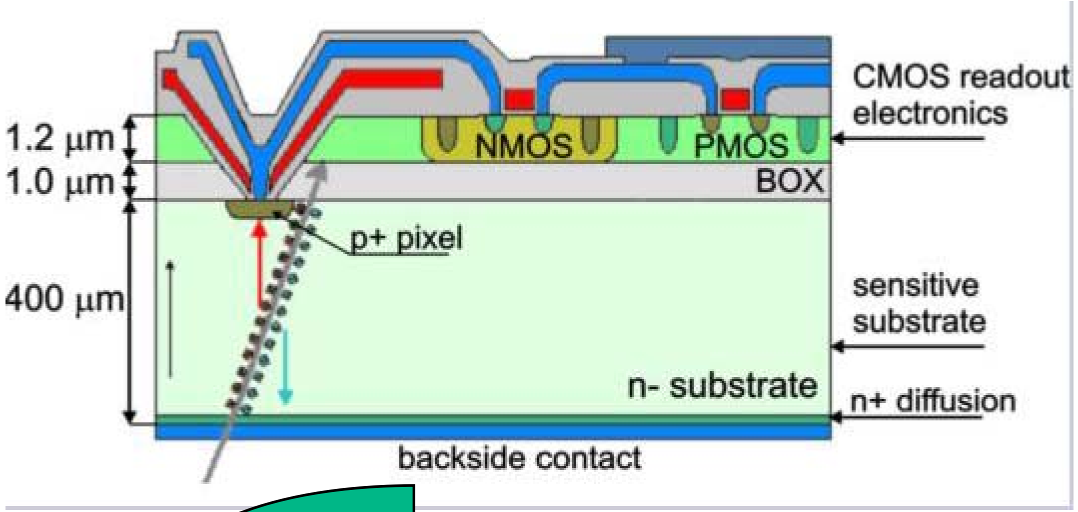




courtesy IZM, Berlin

bumps: 50 µm pitch
PbSn or In
6-20 µm high

Silicium sur Oxyde : une voie d'avenir ?

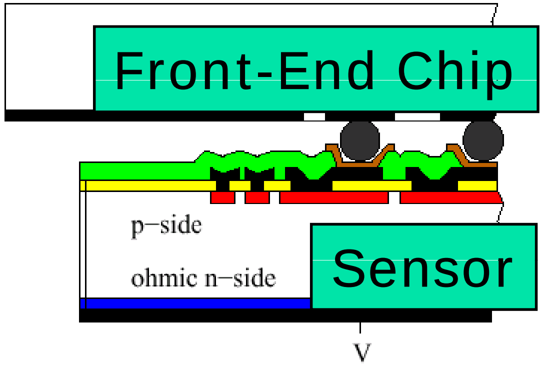


<u>Avantages :</u>
- **Monolithique**
- **épaisseur totale réduite**
- **évite les problèmes de bondings**

(réduit la capa, le bruit..)

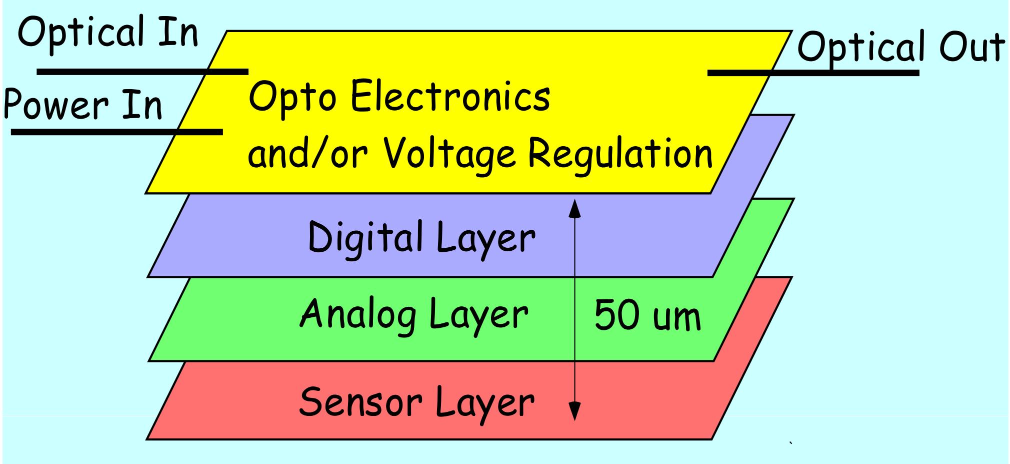
<u>A condition de :</u>
- **Réduire l'épaisseur du substrat**
- **incorporer une électronique discriminante et amplificatrice**

(aller dans le sens la techno 130 nm ou plus ?)

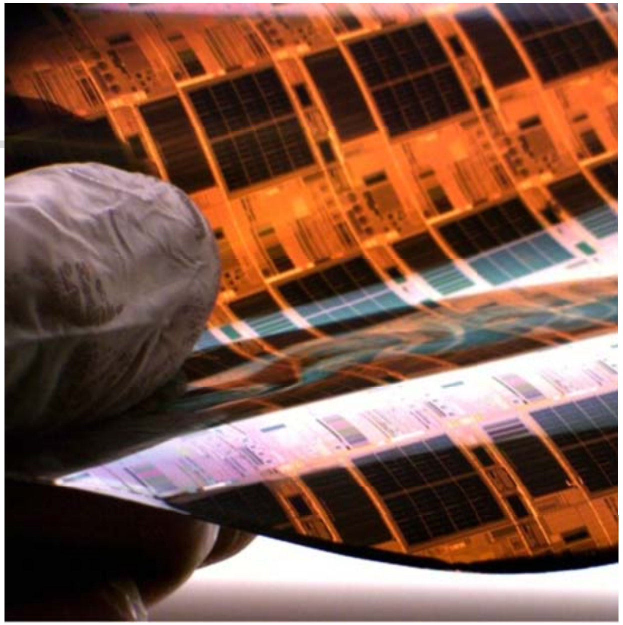

Front-End Chip
p–side
ohmic n–side
Sensor
V

Vertical Scale Integration (3D)

Le principe : empilement de couches fines dotées de fonctionnalités spécifiques et indépendantes pouvant être conçues en technos variées.



Physicist's Dream



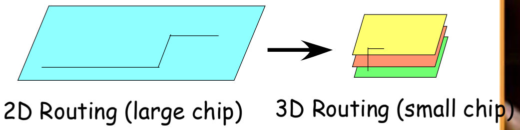
Avantages:

Réduction de R,L, C

Moins de pad entrées/sorties sur les puces (I/O pads)

Réduction des consommations et des diaphonies

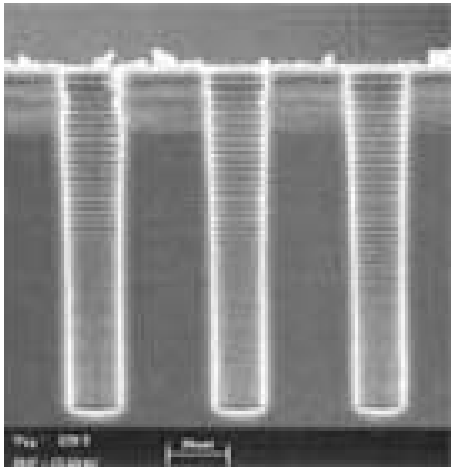
Augmentation des fonctionnalités (signal/bruit)



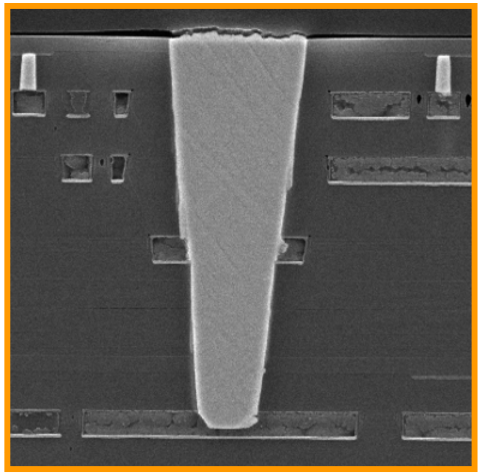
Remarque : industry driven

Key Technologies

SEM of 3 vias using Bosch process[8]



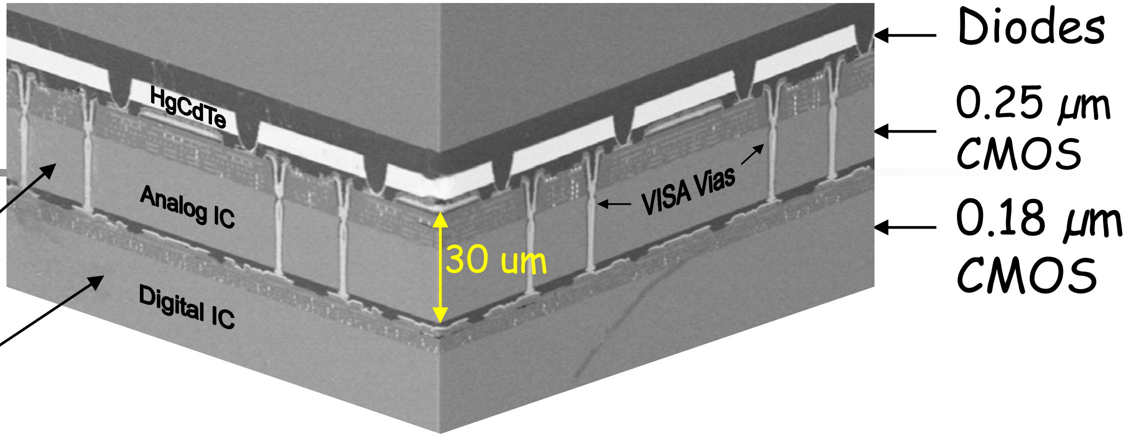
Via using oxide etch process (Lincoln Labs)



Typical diameters are 1-2 microns

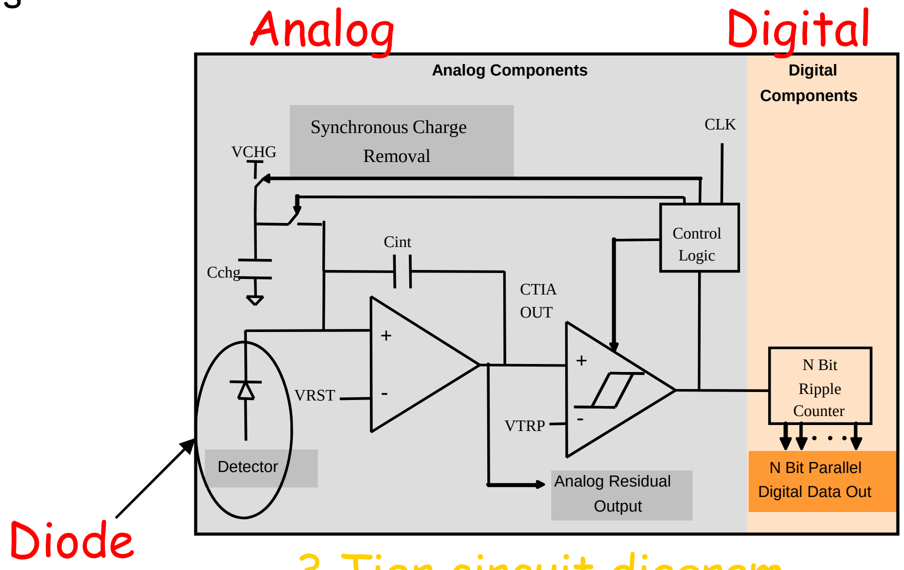
RTI 3D Infrared Focal Plane Array

- 256 x 256 array with 30 µm pixels
- 3 Tiers
  - HgCdTe (sensor)
  - 0.25 µm CMOS (analog)
  - 0.18 µm CMOS (digital)
- Die to wafer stacking
- Polymer adhesive bonding
- Bosch process vias (4 µm) with insulated side walls
- 99.98% good pixels
- High diode fill factor



Array cross section

Infrared image



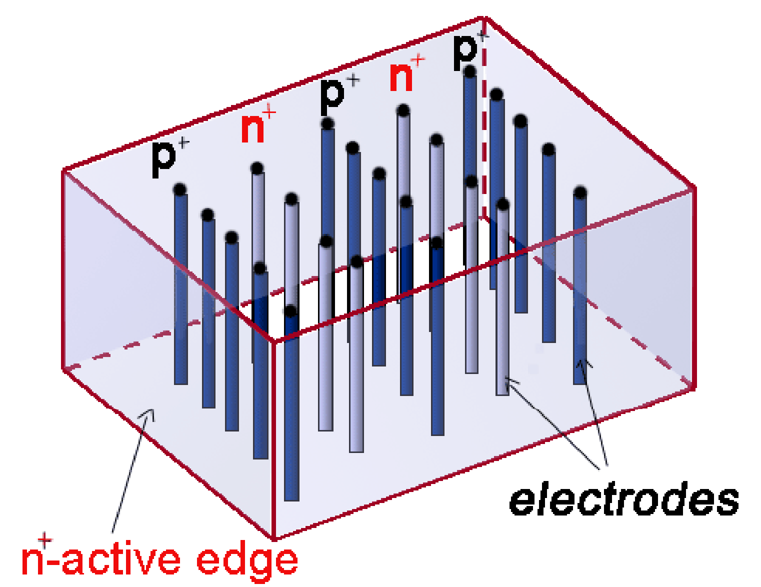
3 Tier circuit diagram

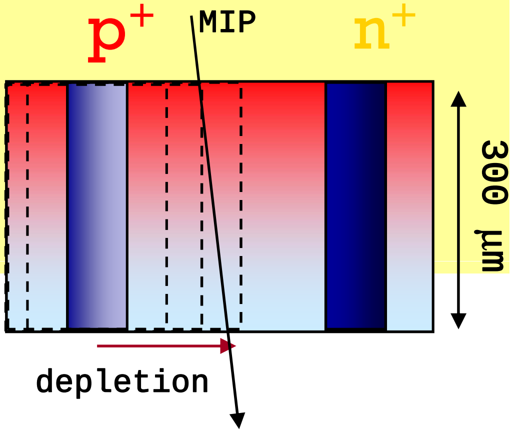
détecteurs -3D -

- Bords actifs, peu de zones mortes (sensitibilité aux bords < 10µm)
- courte distance de collection
  - V depletion petit (~10V)

$$V_{depletion} = \frac{q_0}{2\varepsilon\varepsilon_0}\left|N_{eff}\right|d^2$$

- rapide collection de charges(1 – 2 ns)
- épaisseur reste à 300 µm (signal)
- Durcissement aux radiations





- S.I. Parker C.J. Kenney and J. Segal, NIMA 395 (1997) 328

3D are currently processed at the Stanford Nanofabrication Facility