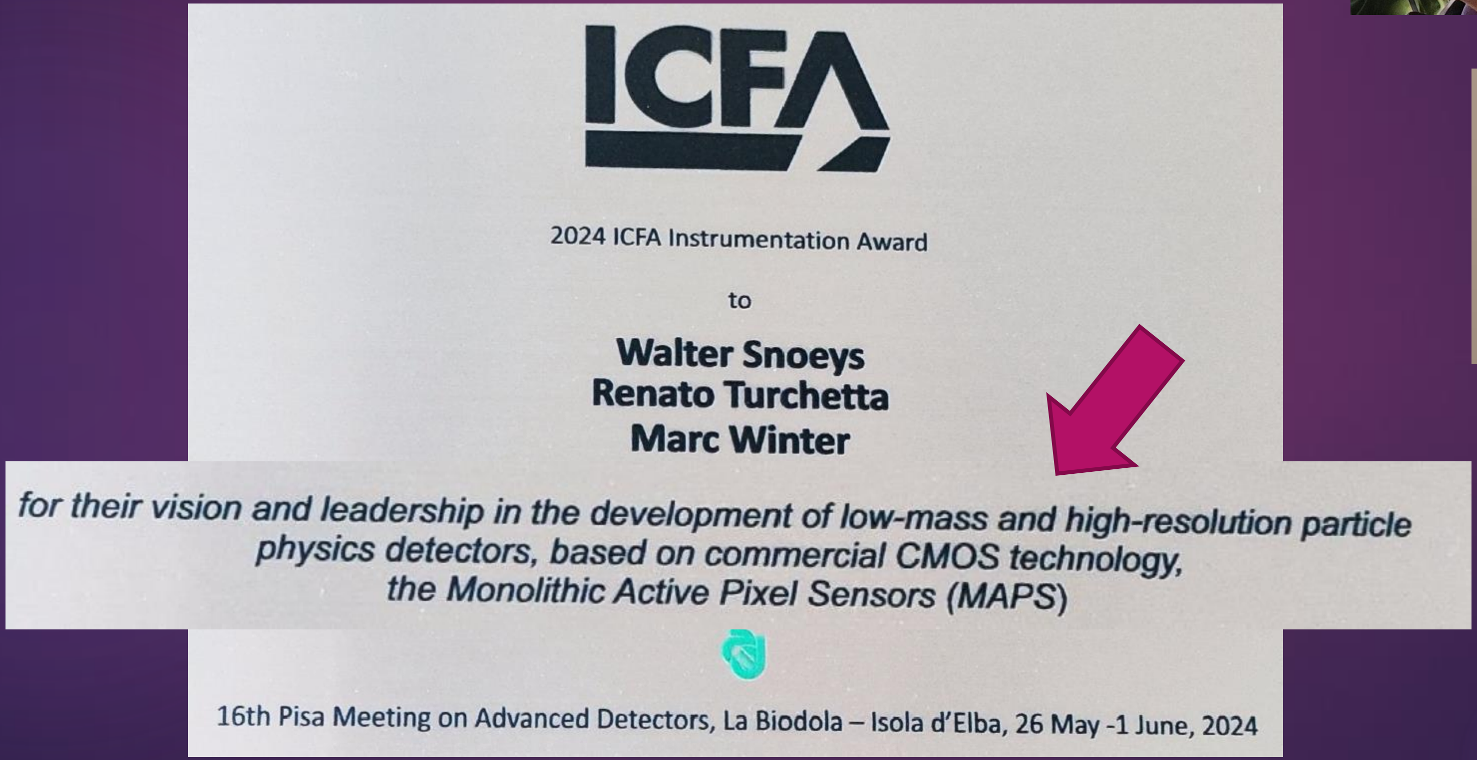
From Novel Imaging Sensors to Advanced Tracking Devices

IJCLab 10/02/2025

FROM DELPHI AT LEP TO MIMOSIS AT FAIR AND BEYOND

Marc WINTER -- IJClab (CNRS), Orsay, France
(20 years of R&D with the PICSEL team of IPHC-Strasbourg)


ICFA

2024 ICFA Instrumentation Award

to

Walter Snoeys
Renato Turchetta
Marc Winter

for their vision and leadership in the development of low-mass and high-resolution particle physics detectors, based on commercial CMOS technology, the Monolithic Active Pixel Sensors (MAPS)

16th Pisa Meeting on Advanced Detectors, La Biodola – Isola d'Elba, 26 May -1 June, 2024

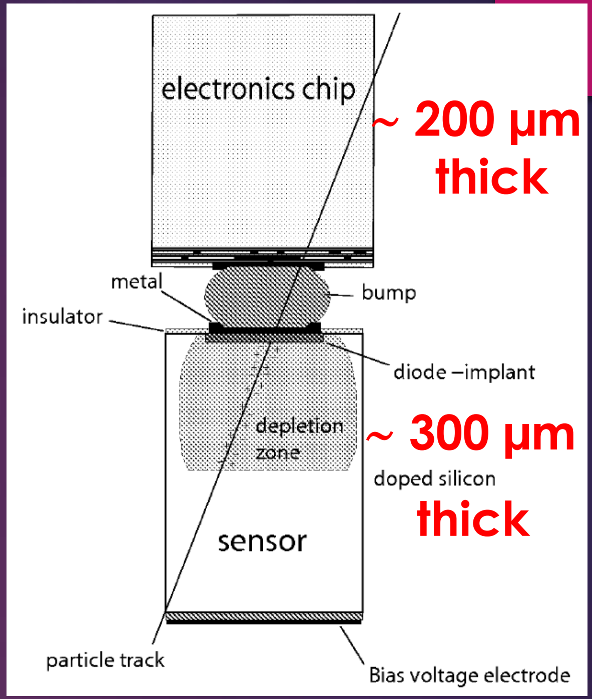
Monolithic CMOS pixel sensors for charged particle detection

CONTENT

- Introductory remarks on Semi-Conductor Pixel sensors
- The **proof of principle**: efficient detection of charged particles
- Establishing **charged particle tracking**
- **1st CMOS sensor based vertex detector** in a collider experiment
- Follow-ups: **ALICE-ITS2** at CERN-LHC and **CBM-MVD** at FAIR/GSI
- Kernel actors of > 20 years of CMOS sensors developpement
- Conclusion - Outlook

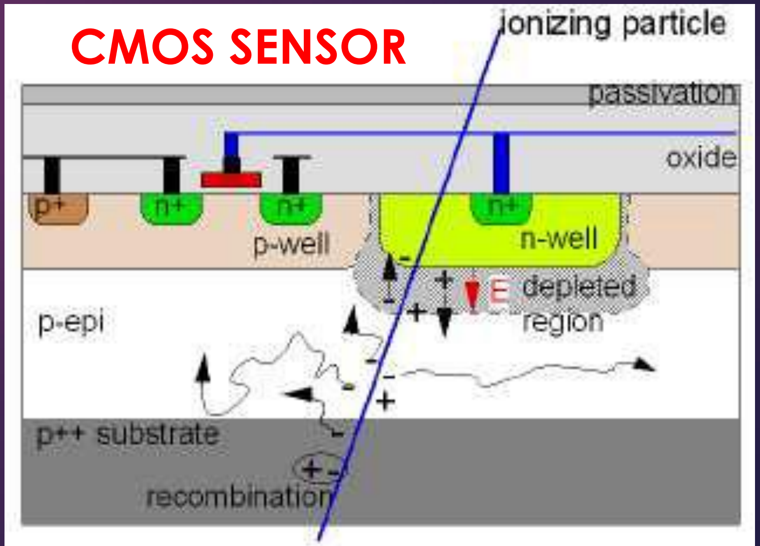
FROM HYBRID TO MONOLITHIC SENSORS

- **Limitations of Hybrid Pixel Sensors**
  - **Bump bonding** is expensive and is subject to industrial fabrication yield shortcomings (it is moreover fragile)
  - Signal processing electronics is enough **power** consuming to require active cooling
    → **cooling pipes** on the way of particles to detect
  - Electronics chips introduces substantial passive material on the way of the particles to detect
  - Sensor is relatively thick
    → **material budget** (multiple scattering issue)
  - **Pixels need to be relatively large** because of bump bonding and of read-out μ-circuit dimensions (e.g. in-pixel threshold dispersion correction)



→ **HPS are not suited to high the precision physics programme anticipated at a future lepton collider**

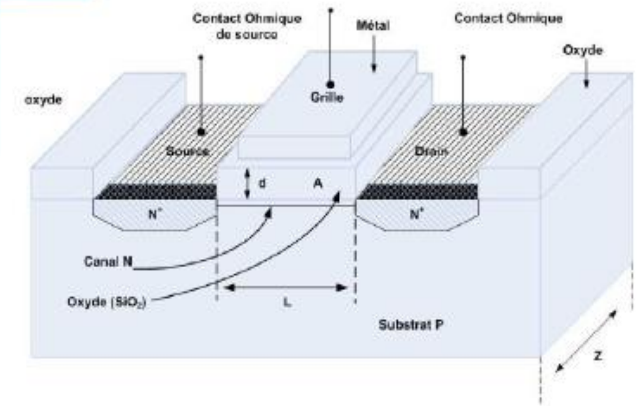
→ **SEARCH FOR MORE COMPACT AND TRANSPARENT PIXELATED STRUCTURE**



➡ CDD too slow, needing cooling, radiation soft, …

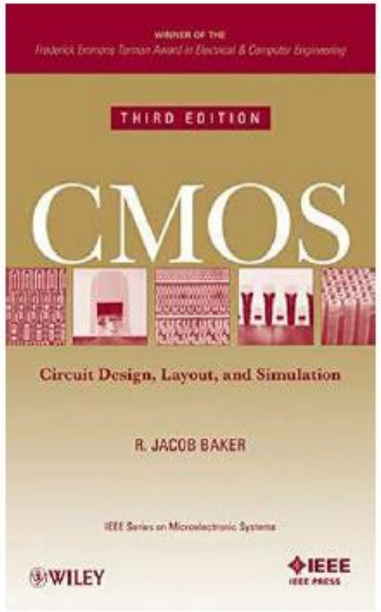
Semi-Conductor Detectors: Origin of (Monolithic) CMOS Pixel Sensors

- **CMOS Pixel Sensors are derived from ASICS**
  - **$\equiv$ Application-Specific Integrated Circuits**
  - ASICs populate every day's life: e.g. credit cards, PC, cell-phones, cars, washing machines, ...
    - $\Rightarrow$ industrial mass production item (world revenue $\sim$ several 100 billions USD/year)
  - key element: MOSFET transistors & conductive traces printed in **Silicon** (usually)



Substrat type P pour MOSFET canal N
Substrat type N pour MOSFET canal P

- **C.M.O.S. $\equiv$ Complementary Metal Oxyde Semi-conductor**
  - widespread technology for constructing integrated circuits used in microprocessors, microcontrollers, memories, etc.



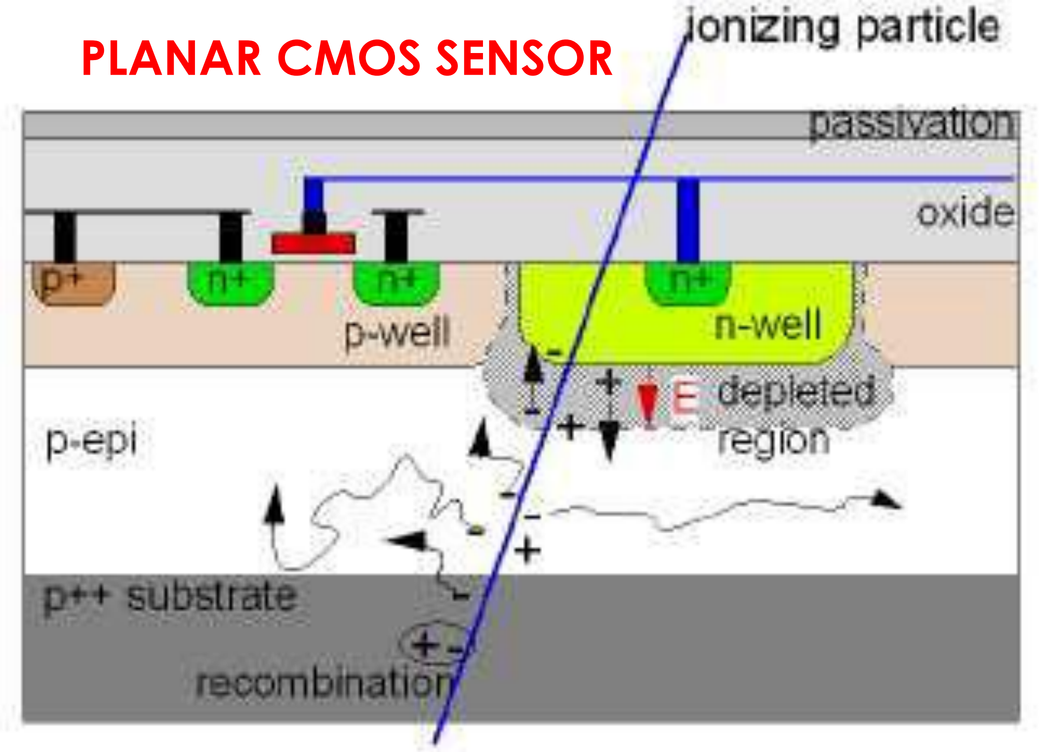
EMERGENCE AND RISE OF MAPS

Industrial Monolithic CMOS Sensors: Constraints

- First use of ASICs (Application Specific Integrated Circuits) for detection pionnered in the 1990's for light imaging (e.g. Eric Fossum et al. at NASA Jet Propulsion Lab)

- Industrial CMOS technology is not suited to particle detection by default:
  - Most commercial processes don't feature low doping epitaxial layer (= sensitive volume)
  - Thinning to ~ 50 µm (default chip thickness is typically 700 µm)

- First industrial CMOS process investigated: **AMS-0.6**
  - Feature size (0.6 µm) ≡ precision of lithography
    → dictates the transistor gate dimension
    → restricts the density of µ-circuits inside pixels
  - Planar process: only NMOS transistors may be integrated inside pixels since PMOS transistors would require dedicated n-wells, which would act as parasitic charge sensing nodes
    → restricted µ-circuitry inside pixels
  - EPI: 14 µm thick → ~ 1000 e- signal charge
    low resistivity → thermal diffusion of signal e-



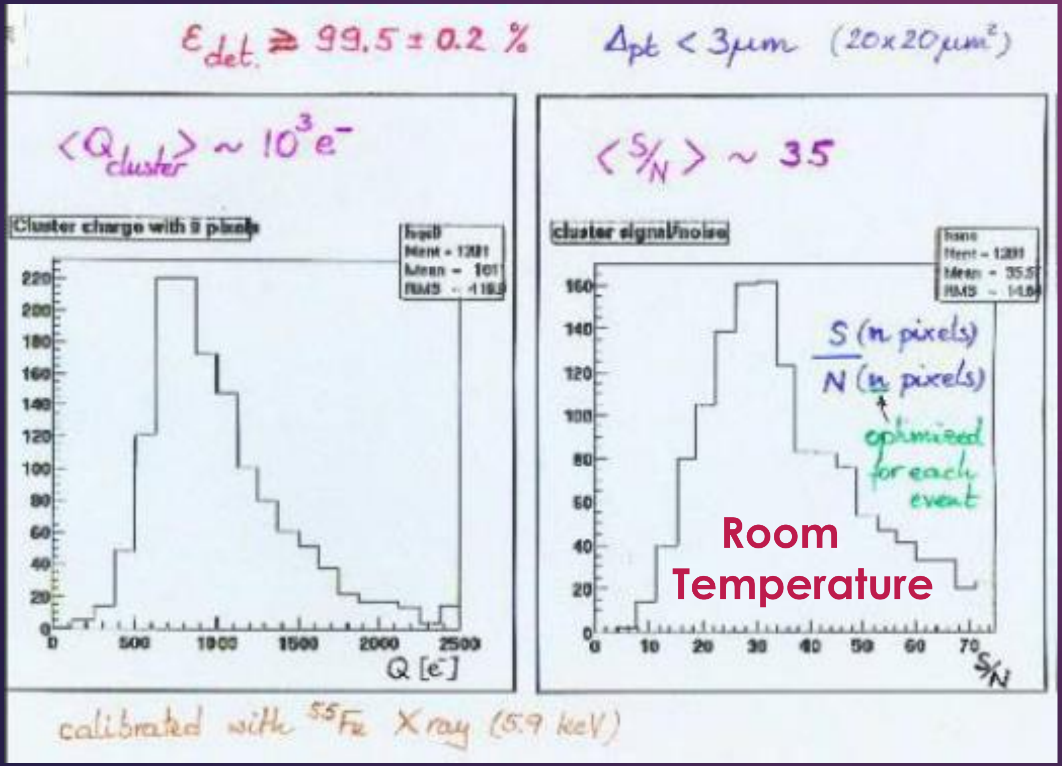
ESTABLISHING A PROOF OF PRINCIPLE

LEP/e+e- coll./HF tagging with HAPS:
Delphi: 200x200 μm²; > 1% X0, > 1 W/cm²

> join TESLA collider project on VD (F.Richard)
> contact LEPSI-Strasbourg: **Renato Turchetta**

March '99: 1st talk on MAPS for a VD at ECFA-LC workshop in Oxford

MIMOSA-1: fabricated in **2000** with AMS-0.6 μm commercial CMOS process



A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI technology, **NIM A458 (11 Feb. 2001), pp 677-689**


Simulation and Measurements of Charge Collection in Monolithic Active Pixel Sensors

MIMOSA I (Minimum Ionising particle MOS Active pixel detector)

Goal of fabrication:

- feasibility study
- understanding/tests
  - standard 0.6μm CMOS (tox=12.7nm)
  - 14μm thick EPI layer (10¹⁴cm⁻³)
  - 4 arrays 64x64 pixels
  - pixel pitch 20x20μm
  - diode (nwell/pepi) size 3x3μm - 3.1fF
  - readout clock f<10MHz
  - readout - serial analog
  - die size 3.6x4.2mm²

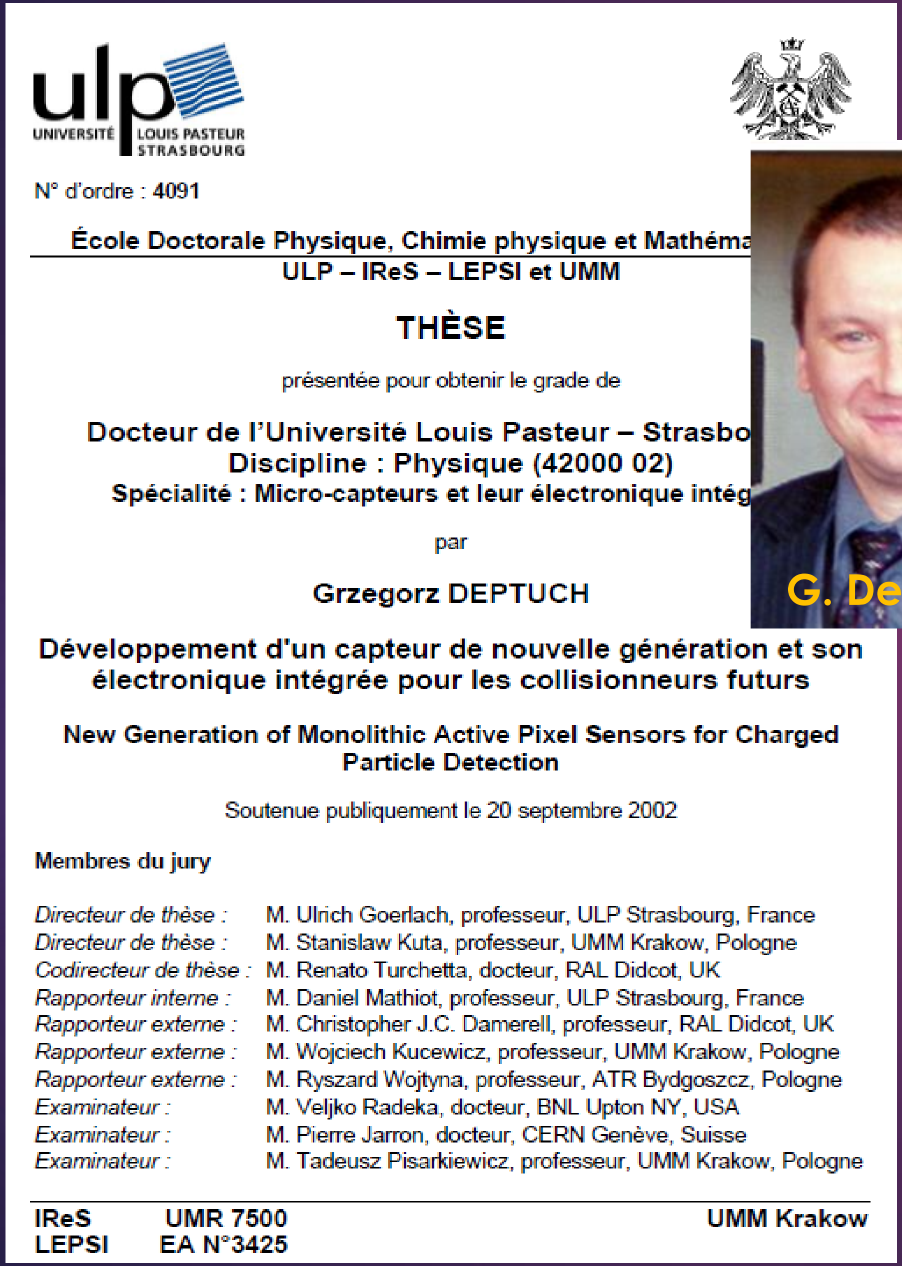
"visible light photography with MIMOSA"

- 5 -

G. Deptuch
1st PhD

W. Dulinski
† '14

ESTABLISHING A PROOF OF PRINCIPLE


N° d'ordre : 4091

École Doctorale Physique, Chimie physique et Mathéma

ULP – IReS – LEPSI et UMM

THÈSE

présentée pour obtenir le grade de

Docteur de l'Université Louis Pasteur – Strasbo

Discipline : Physique (42000 02)

Spécialité : Micro-capteurs et leur électronique intég

par

Grzegorz DEPTUCH

Développement d'un capteur de nouvelle génération et son électronique intégrée pour les collisionneurs futurs

New Generation of Monolithic Active Pixel Sensors for Charged Particle Detection

Soutenue publiquement le 20 septembre 2002

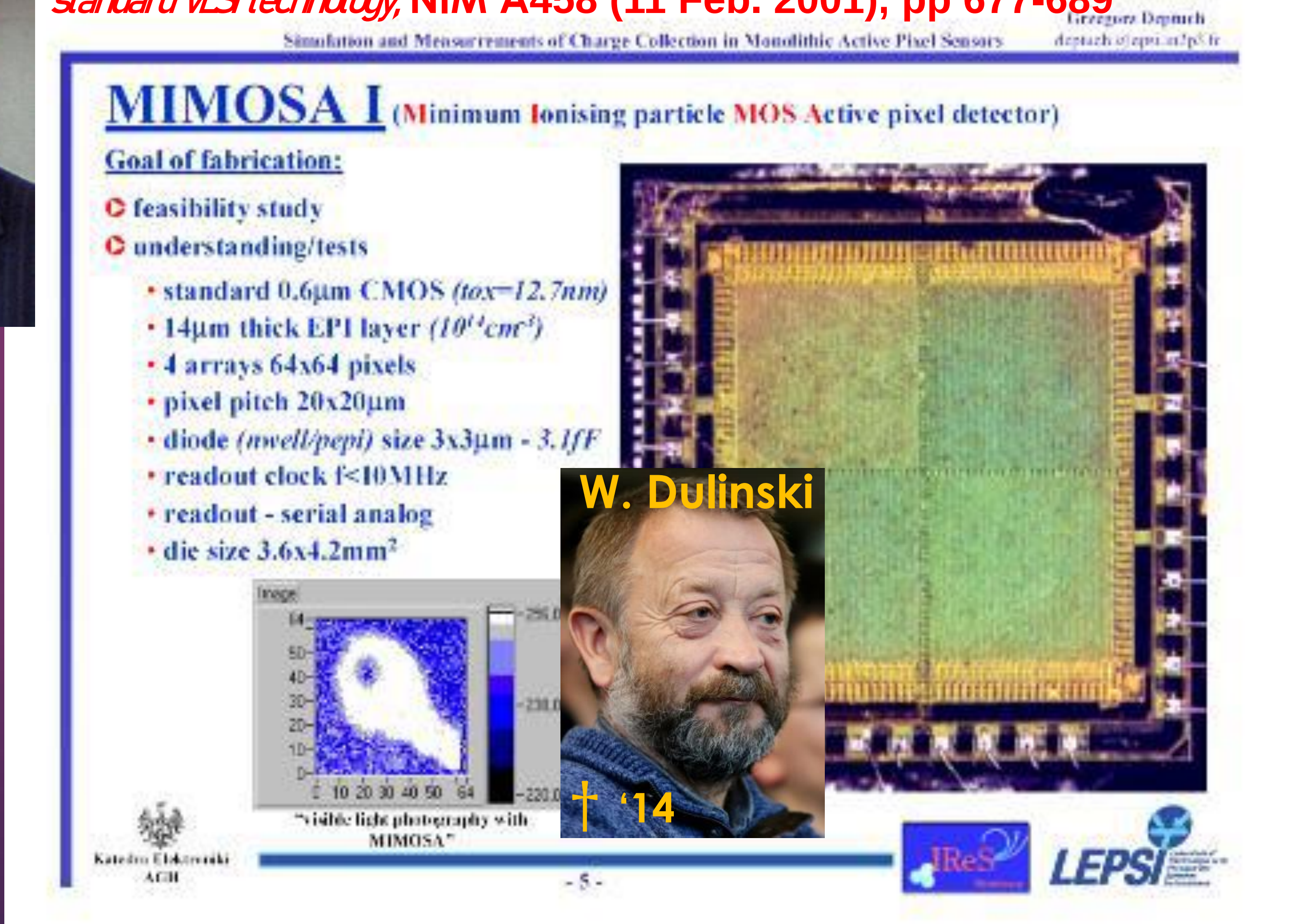
Membres du jury

Directeur de thèse :	M. Ulrich Goerlach, professeur, ULP Strasbourg, France
Directeur de thèse :	M. Stanislaw Kuta, professeur, UMM Krakow, Pologne
Codirecteur de thèse :	M. Renato Turchetta, docteur, RAL Didcot, UK
Rapporteur interne :	M. Daniel Mathiot, professeur, ULP Strasbourg, France
Rapporteur externe :	M. Christopher J.C. Damerell, professeur, RAL Didcot, UK
Rapporteur externe :	M. Wojciech Kucewicz, professeur, UMM Krakow, Pologne
Rapporteur externe :	M. Ryszard Wojtyna, professeur, ATR Bydgoszcz, Pologne
Examinateur :	M. Veljko Radeka, docteur, BNL Upton NY, USA
Examinateur :	M. Pierre Jarron, docteur, CERN Genève, Suisse
Examinateur :	M. Tadeusz Pisarkiewicz, professeur, UMM Krakow, Pologne

IReS UMR 7500 **UMM Krakow**

LEPSI EA N°3425

A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI technology, **NIM A458 (11 Feb. 2001), pp 677-689**



ESTABLISHING A PROOF OF PRINCIPLE

SUCIMA
EU-FP5 project

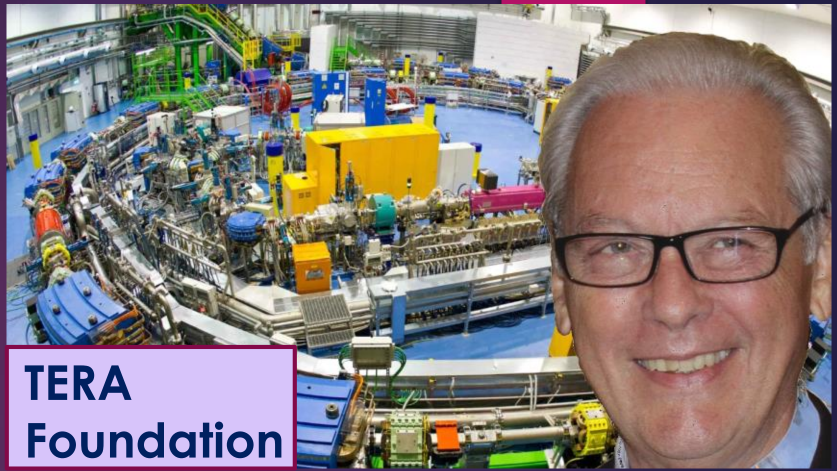
MIMOSA-5
Fab. In 2003

P.I. M. Caccia

SUCIMA for TERA: Hadrontherapy

MIMOSA-5 = proton beam monitor

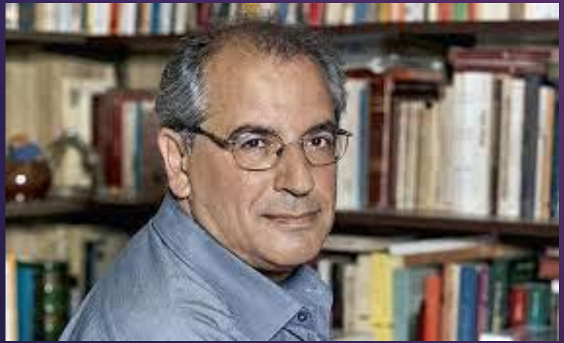
CMOS technology:
- **AMS 0.6 µm feature size**
- **14 µm thin sensitive volume**
- **planar: only NMOS T inside pixels**



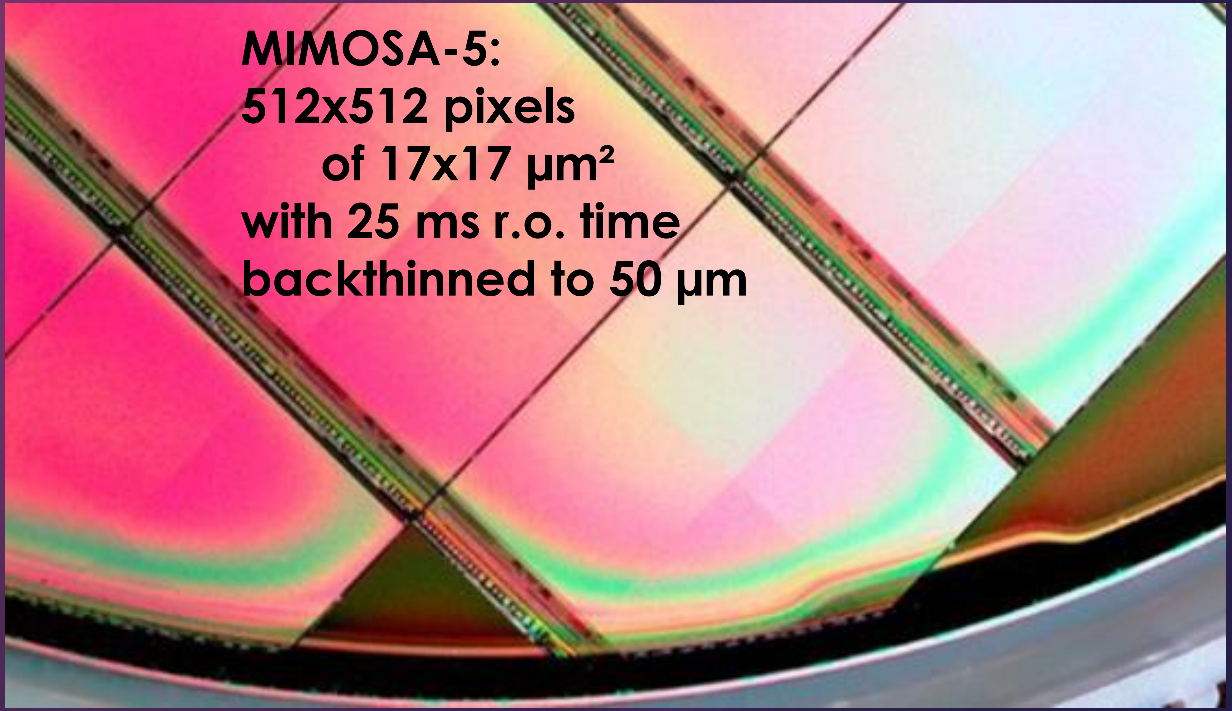
TERA Foundation

Numerous spin-off applications

S. Katsanevas † '22



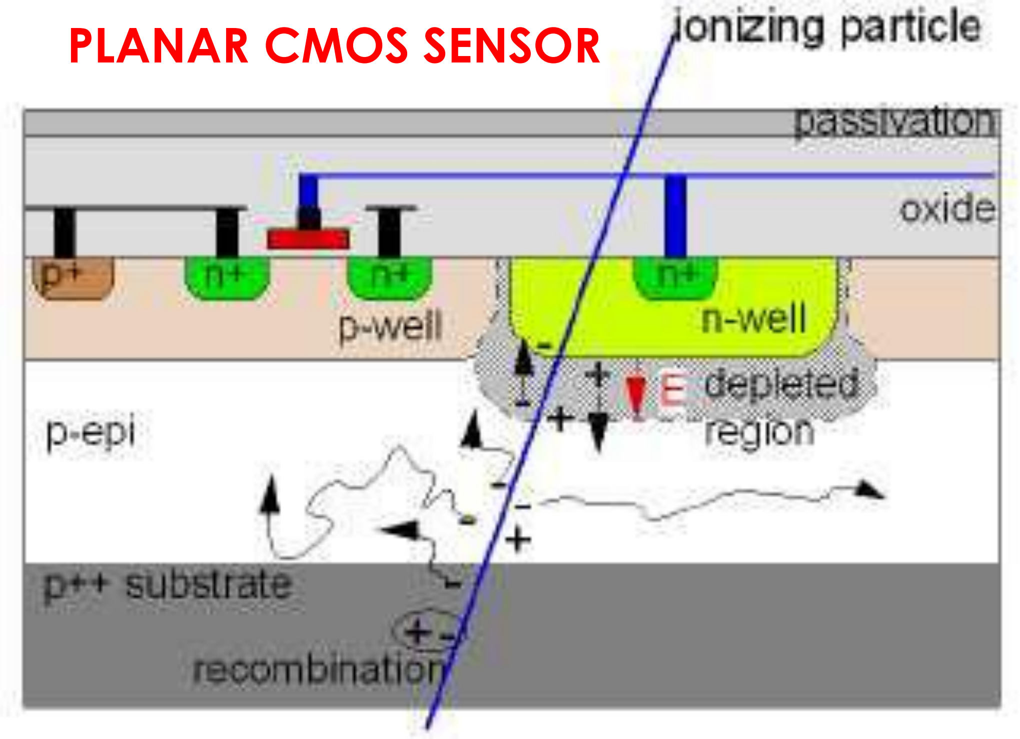
MIMOSA-5 in HPD
Photonis / Antares



MIMOSA-5:
512x512 pixels of 17x17 µm²
with 25 ms r.o. time
backthinned to 50 µm

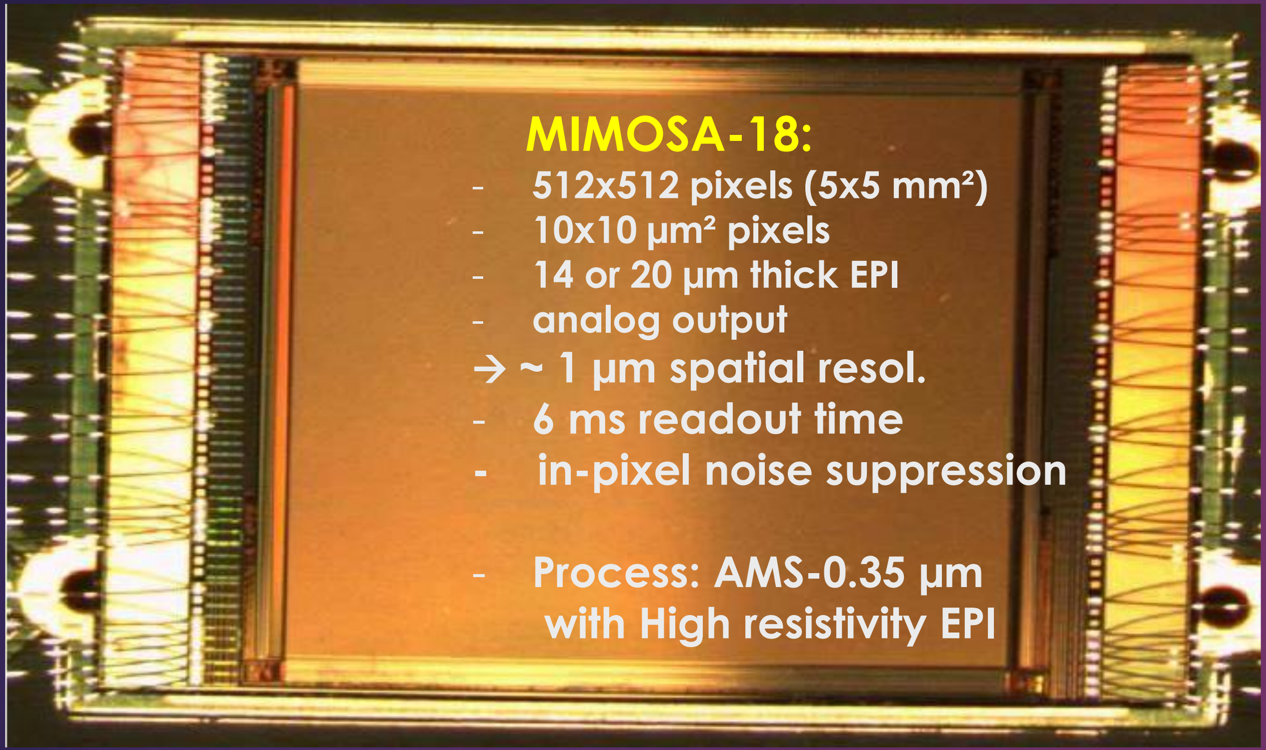
Industrial Monolithic CMOS Sensors: 2nd Generation

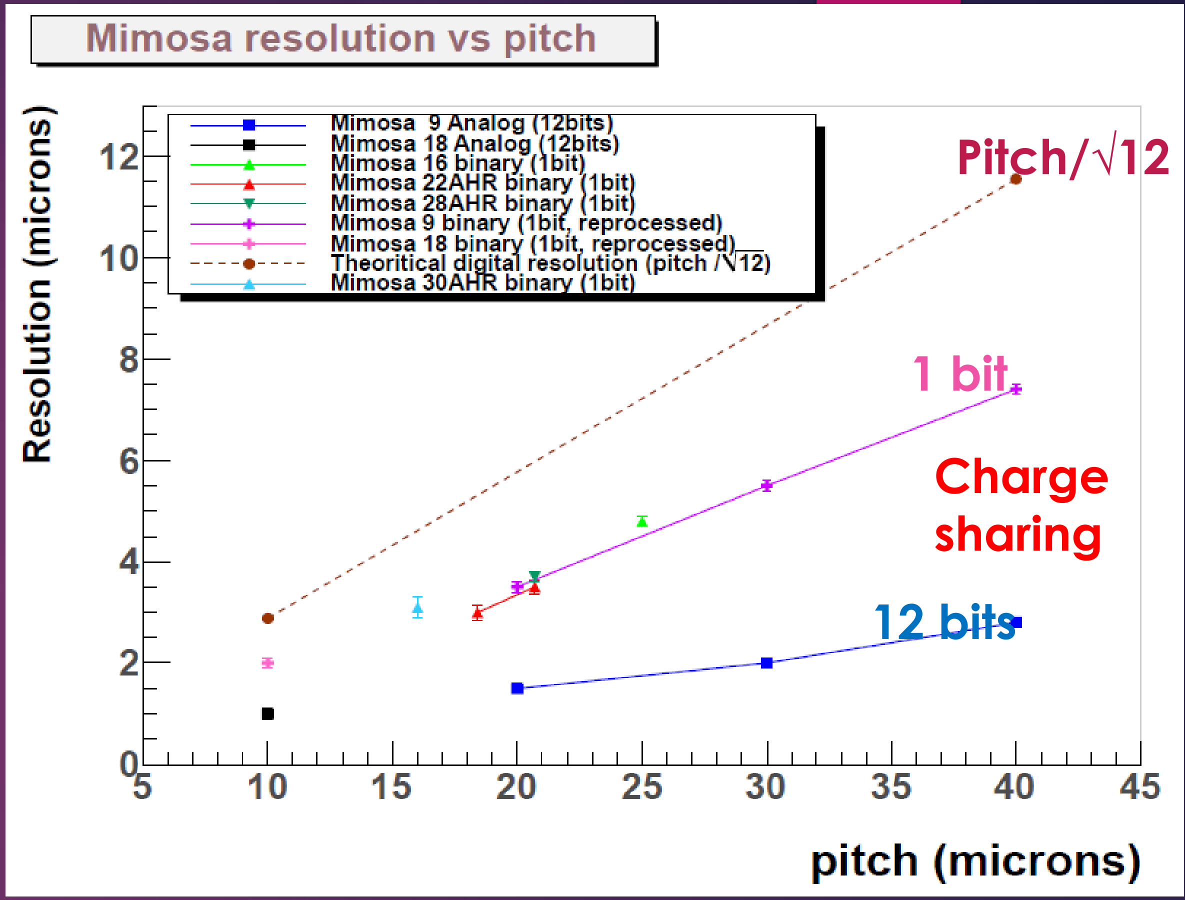
- Second industrial CMOS process used: **AMS-0.35**
  - Still a planar process
  - Feature size (0.35 μm) allowed to integrate noise-suppression μ-circuits inside pixels
    → correlated double-sampling
  - EPI: 12 & 15 μm thick → $\sim 10^3$ e- signal charge
    low resistivity → thermal diffusion of signal e-



ESTABLISHING CHARGED PARTICLE TRACKING

Achieving micron level spatial resolution





O(1) µm resolution exploiting charge sharing with read-out time > 1 ms (4 sub-arrays read out in //)

But a Higgs-Factory Vertex Detector requires < 10 µs

→ much more // read-out necessary

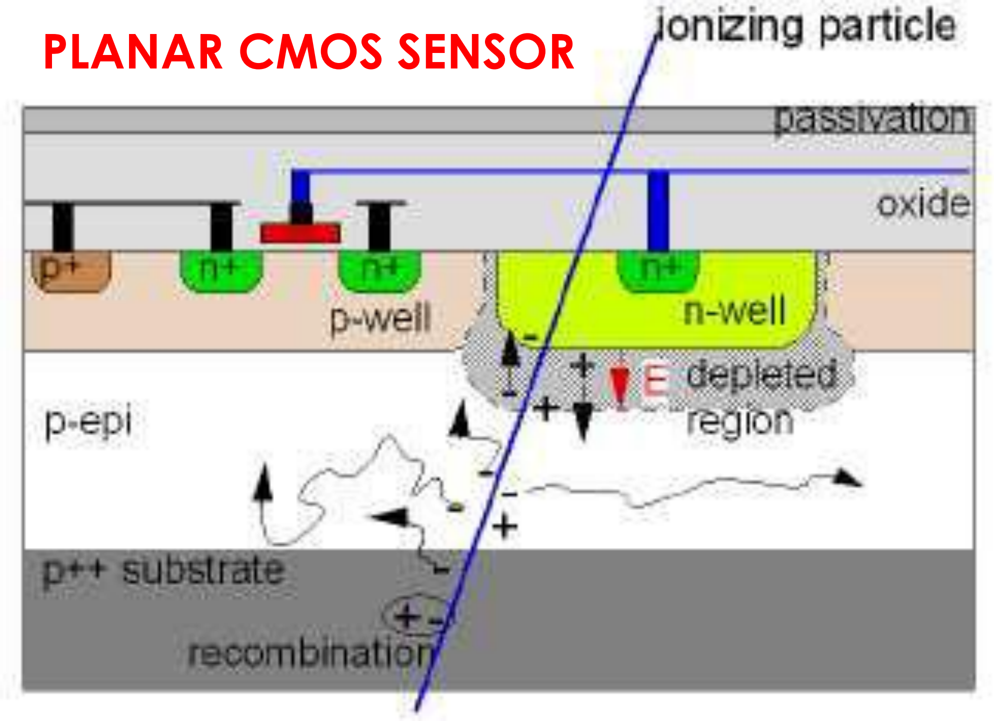
→ less bits for charge encoding mandatory

INDUSTRIAL MONOLITHIC CMOS SENSORS: 3rd GENERATION

- Second industrial CMOS process used: **AMS-0.35**
  - Still the same planar process
  - Same integrated μ-circuitry as previously
  - EPI: 12 & 15 μm thick → $\sim 10^3$ e- signal charge

high resistivity → part of signal e- collected by drift → enhanced seed pixel signal
→ improved radiation tolerance
→ improved cluster multiplicity

400 – 800 Ω·cm ➡



ESTABLISHING CHARGED PARTICLE TRACKING

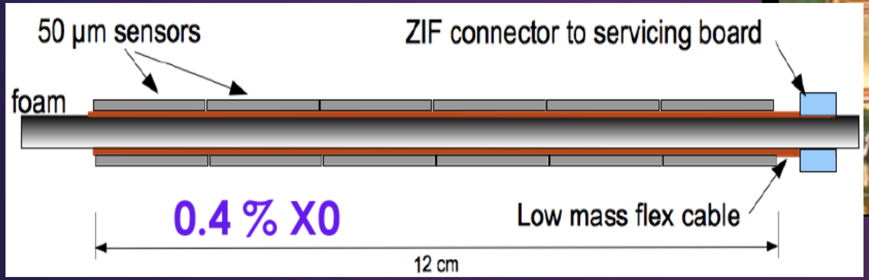
EUDET: 6th Framework Programme of E.U.: MAPS for Beam Telescope

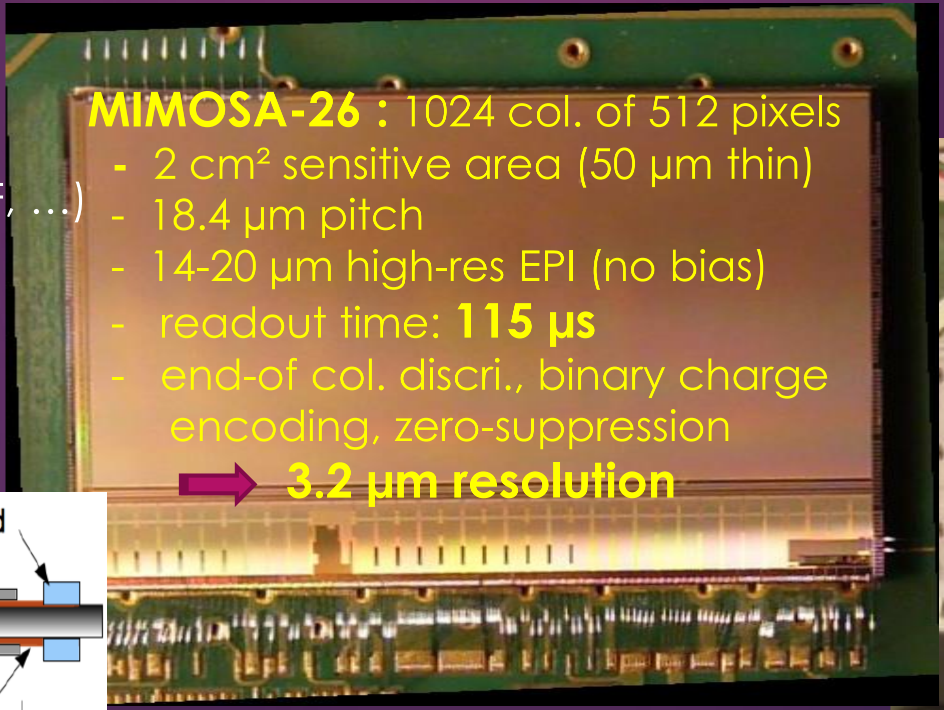
Introducing on-chip signal discrimination & 1 bit charge encoding

MIMOSA-8 proto. (TSMC-0.25): **2004/5** end of col. discri. (Yavuz Degerli/Irfu)
→ **MIMOSA-16/22** proto. (AMS-0.35 OPTO)
→ **MIMOSA-26** final sensor (EUDET-FP6): High resolution beam telescope

MIMOSA-18:
- 512x512 pixels (5x5 mm²)
- 10x10 µm² pixels
- 14 or 20 µm thick EPI
- analog output
- ~ 1 µm spatial resol.
- 6 ms readout time

Numerous applications:
- > 10 BT (DESY, CERN, SLAC, TRIUMF, …)
- Fixed target expts (NA61, …)
- Hadrontherapy
- Industrial imager
- Research in biology
- PLUME 2-sided ladder





MIMOSA-26 : 1024 col. of 512 pixels
- 2 cm² sensitive area (50 µm thin)
- 18.4 µm pitch
- 14-20 µm high-res EPI (no bias)
- readout time: **115 µs**
- end-of col. discri., binary charge encoding, zero-suppression

→ **3.2 µm resolution**

EUDET Beam Telescope - 2008

MIMOSA-26/-28 GEOGRAPHICAL DISTRIBUTION

APPLICATION TO A VERTEX DETECTOR COMPOSING A COLLIDER EXPERIMENT

STAR
AMS-0.35

A new Inner Vertex Detector for STAR

H. Wieman
Vertex 2000

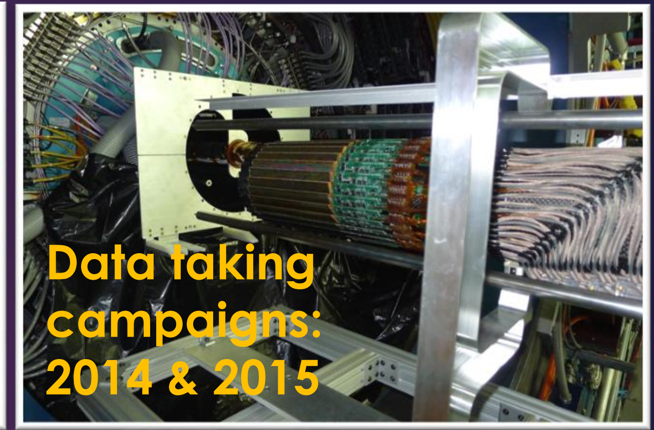
1

11.09.00

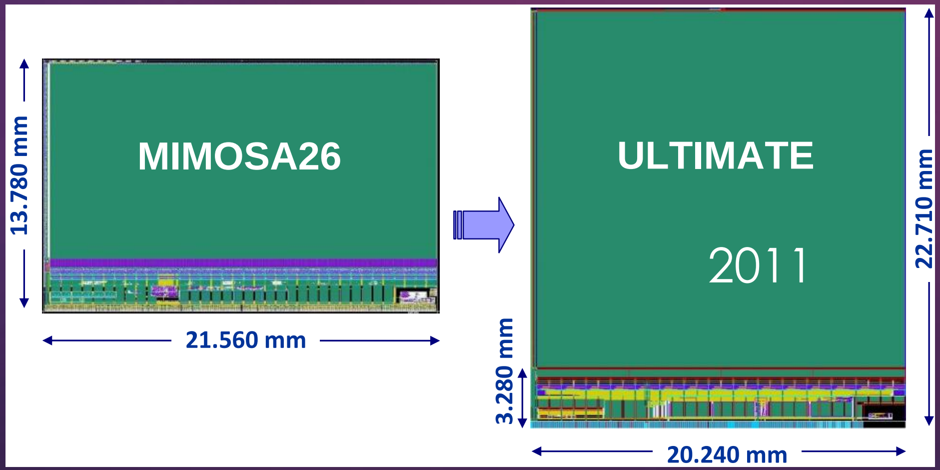
MONOLITHIC ACTIVE PIXEL SENSORS FOR A LINEAR COLLIDER

(Marc WINTER - IReS (Strasbourg))
on behalf of IReS+LEPSI coll.

- Physics Motivations
- Principle of Operation of M.A.P.S.
- Characteristics of 1st MAPS prototype
- Beam test Results (preliminary)
- Outlook



STAR-PXL: 2 layers (~ 0.4 % X0/layer),
400 ULTIMATE sensors (1600 cm²),
back-thinned to 50 µm
170 mW/cm2, air-cooled (10 m/s)



AMS-0.35 OPTO (twin-well process)

Customised EPI: 15 µm, **High Res.**

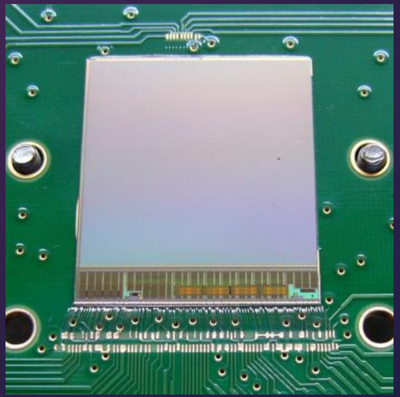
960 x 928 pixels (pitch = 20.7 µm)

Spatial resolution < 4 µm

Readout time: 185 µs

In-pixel Amp. & Corr. Dble Sampling

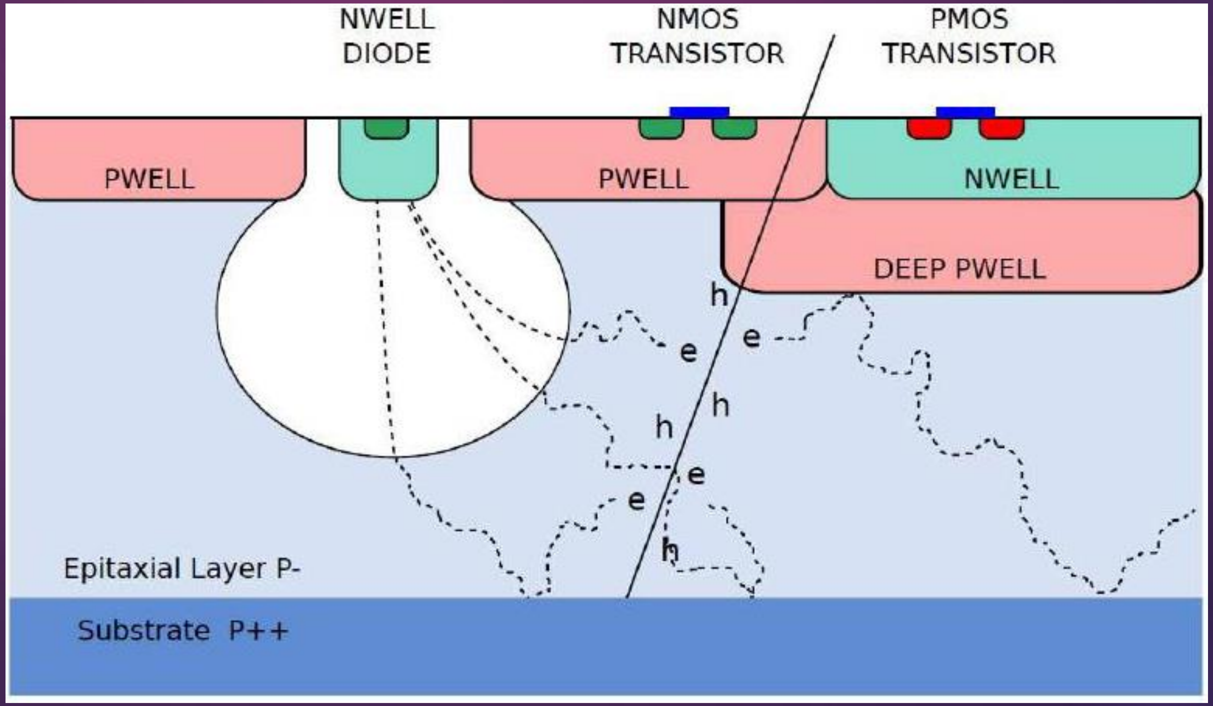
Deep Reactive Ion Etching (DRIE)



INDUSTRIAL MONOLITHIC CMOS SENSORS: 4th GENERATION

- Third industrial CMOS process used: **TSMC-0.18** (Tower-Jazz CIS)
  - INMAPS process pioneered by Renato Turchetta at RAL
  - Quadruple well technology → in-pixel N-MOS and P-MOS transistors
    → more in-pixel funtionnalities or smaller pixels will less μ-circuits
  - EPI: thickness of 18/25/30/40 μm → up to $2.5 \cdot 10^3$ e- signal charge
    high resistivity → **substantial part of signal** e- collected by drift
    → fast charge collection, enhanced radiation tolerance
    → reduced cluster multiplicity → degraded spatial resolution

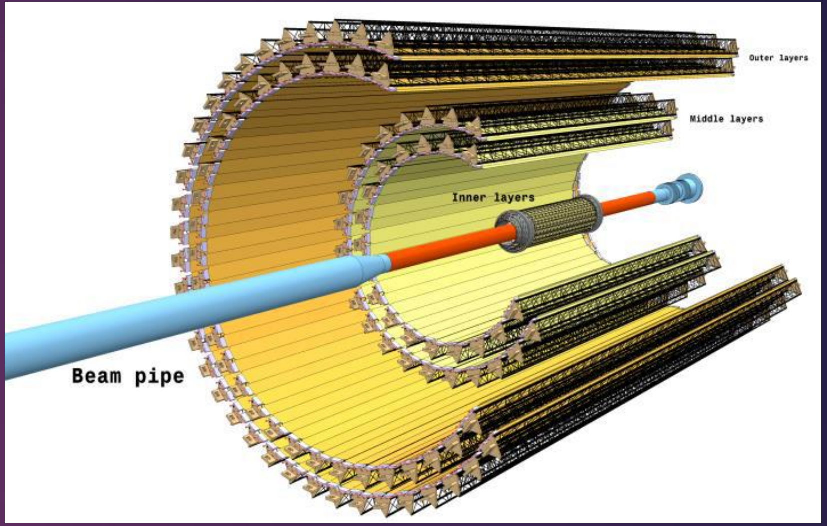
> 1 kΩ·cm →



APPLICATION TO AN INNER TRACKER COMPOSING A COLLIDER EXPERIMENT

ALICE
TJsc-0.18

2010/11: proposal to consider CMOS pixel sensors fo the upgrade of the ALICE vertex detector, based on the same readout architecture (**rolling shutter**) as MIMOSA-26/-28, customised for the ALICE physics goal & more demanding running conditions



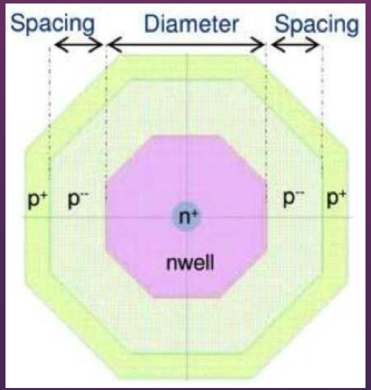
ALICE coll. approved the proposal in 2011/12, promoted by Luciano Musa, who extended the concept to the whole ITS (10 m²)

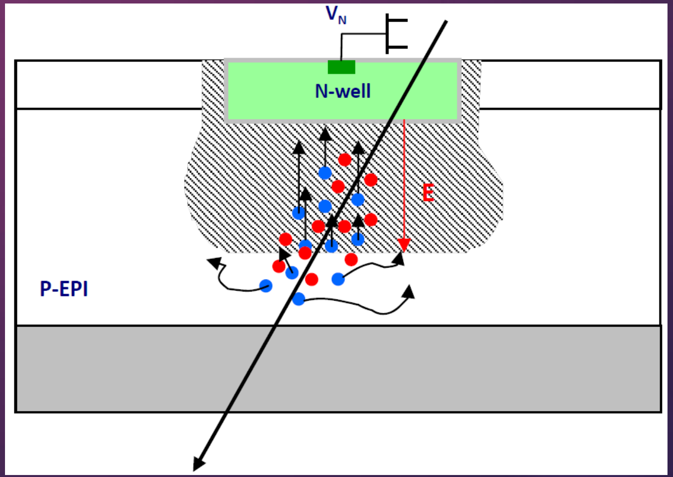
PICSEL Team (IPHC-Strasbourg):

- extensive study of the techno. charge collection & sensing node characteristics
- find out an **optimal sensing system** (EPI, diode, etc.)
- MISTRAL (ASTRAL):
  - rolling shutter, column // read-out
  - end-of-column discriminators

  → 30 (15 ?) μs read-out time, power ≤ 200 mW/cm²

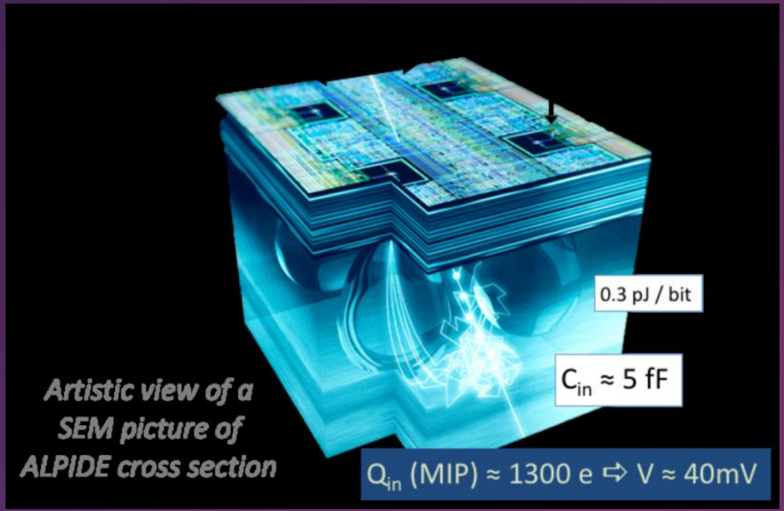
AIDA – FP6 EU support

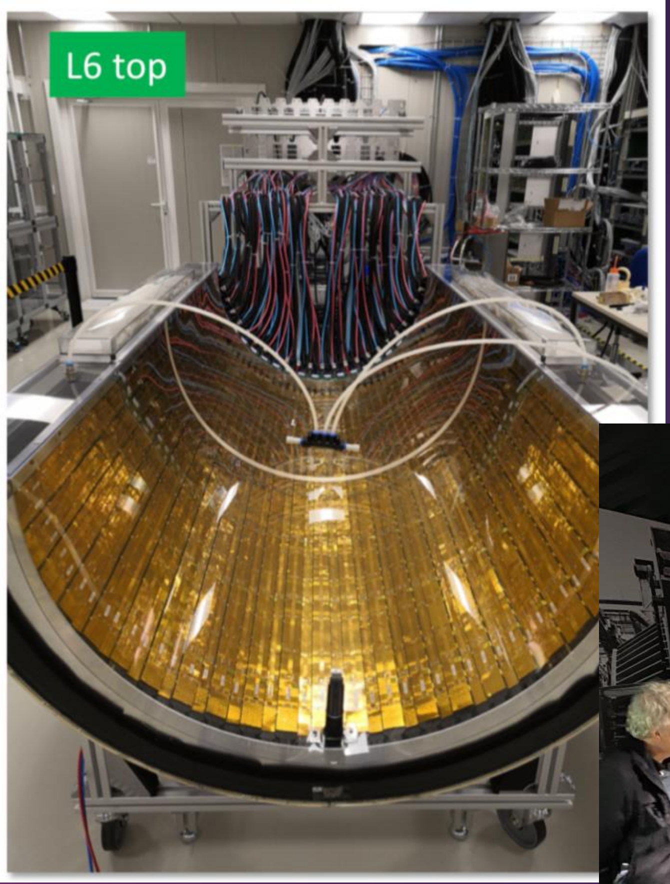


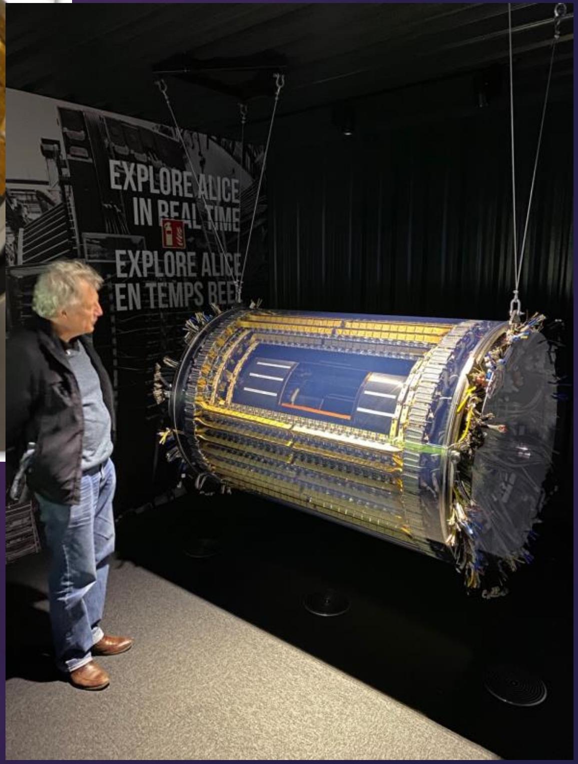


APPLICATION TO AN INNER TRACKER COMPOSING A COLLIDER EXPERIMENT

ALICE
TJsc-0.18







CERN Team (Walter Snoeys & coll.): ALPIDE sensor

- design based on hybrid pixel sensor read-out architecture
  → in-pixel discriminator, priority encoding, active EPI depletion
- advantage:
  - suppressed power consumption : ≤ 50 mW/cm²
  - faster read-out : ≤ 10 µs
  - improved radiation tolerance
  - less periphery (insensitive) area devoted µ-cricuits
  - …

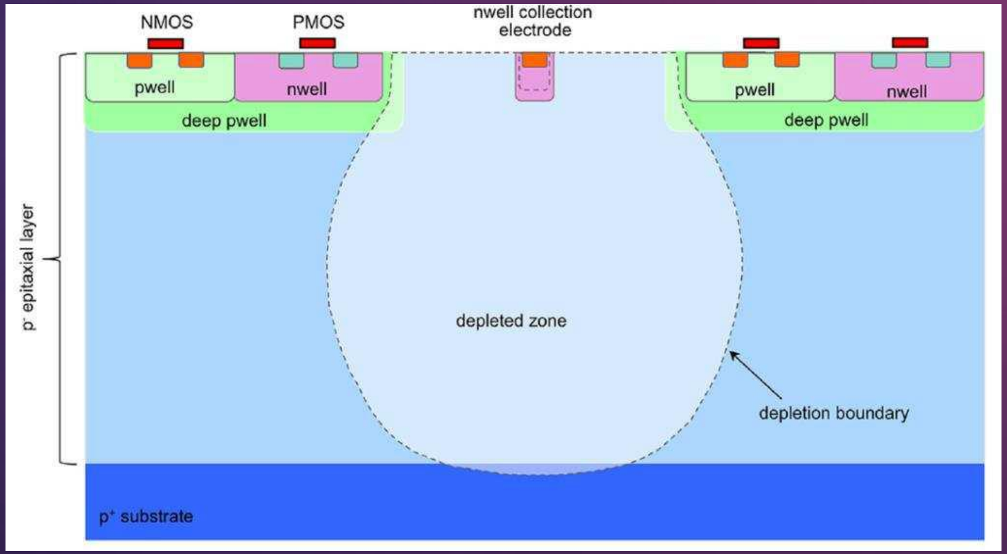
↳ 24120 sensors (~12.5 Gpixels) equipping ~ 10 m²

INDUSTRIAL MONOLITHIC CMOS SENSORS: 5th GENERATION

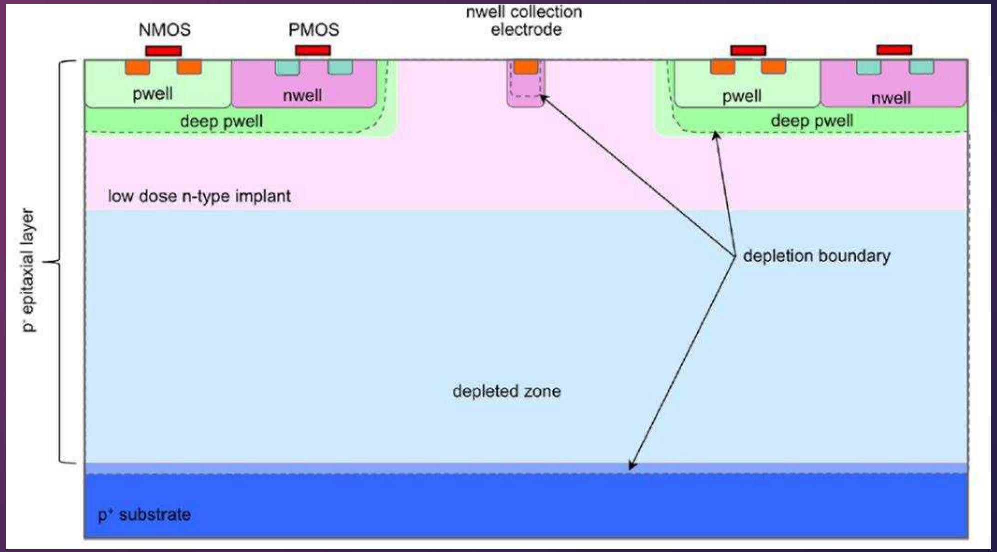
- Third industrial CMOS process used: **TSMC-0.18** (Tower-Jazz CIS)

- EPI: **foundry accepted to modify the doping profile** (film of n-type dopant introduced on top of EPI)
  - → drift field extended laterally underneath sensing nodes
  - → benefit: faster charge collection, enhanced radiation tolerance
  - → drawback: reduced cluster multiplicity → somewhat degraded spatial resolution

Standard EPI



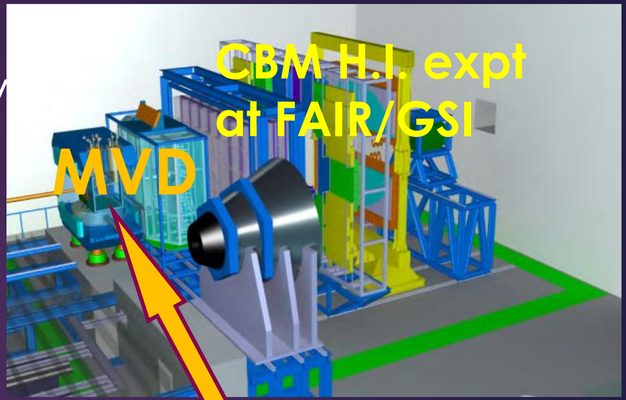
Modified EPI profile
(introduced by **Walter S.)**



APPLICATION TO A VERTEX DETECTOR COMPOSING A FIXED TARGET EXPERIMENT

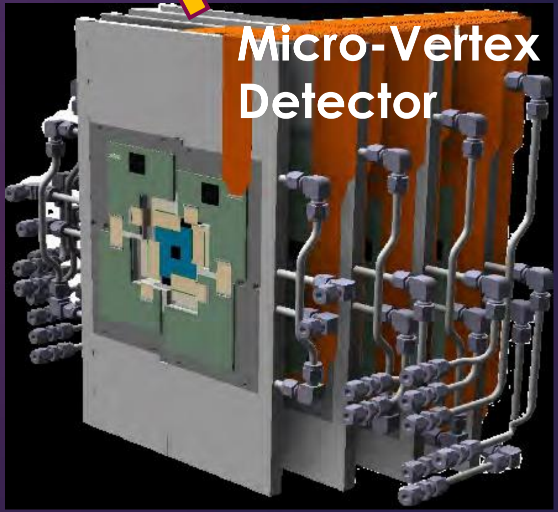
CBM
TJsc-0.18 modified

March 2003:1st seminar on CMOS pixel sensors at GSI (invited by H. Gutbrod)
CBM ≡ H.I. fixed target expt ➡ Micro-Vertex Detector faces very high hit density
➡ more demanding running conditions than ALICE-ITS2



Stretched timeline allowed to benefit from evolution of CMOS industry (Tower-Jazz 180 nm) and progress on CMOS sensor design (ALPIDE, mod. EPI)

Priority encoder & pixel design derived from ALPIDE EPI layer doping profile modified for improved radiation tolerance



20 yrs of steady support and trust from GSI / Darmstadt & Univ. Goethe / Frankfurt, with highly appreciated collaborators

EXTENSICE STUDY OF KEY PARAMETRES RULING CHARGED PARTICLE DETECTION

PICSEL:
Physics with **I**ntegrated **C**mos **S**ensors and **EL**ectron machines

Support from IN2P3/CNRS Dir.:
→ PICSEL & CMOS sensor devt:
- ≈ 10 engineer positions created
- ≥ 6 post-docs, 2 phys. positions
- funding: foundry submissions, test equipment

& Support from IPHC-Strasbourg

Strasbourg **PICSEL** team (≤ 25 FTE):
3-5 physicists, O(10) ASIC designers,
4-5 electroniciens, ≤ 5 PhD students
> 20 PhDs on CMOS sensor R&D

Essential Partners *(incomplete)*:
- Irfu-CEA (Y.Degerli): end-of-col. discri. (MIMOSA-8)
- DESY/Univ.Hamburg (I.Gregor): EUDET Beam Tel., AIDA
- STAR coll. (Berkeley, BNL): STAR-PXL/HFT
- Univ. Frankfurt (J.Stroth), GSI: CBM-MVD, Hadron-Physics-2
- ALICE-ITS2/CERN (L.Musa): → ALPIDE (Walter S.)

Charge collection & signal sensing:
- EPI: thickness, resistivity doping profile
- junction: dimensions, insulation
- depletion: top vs back vs field amplitude
- impact of/on pixel dimensions
- ISE/TCAD simulations

In-pixel signal processing:
- pre-amp T: size & shape vs gain & RTS
- noise suppression: double-corr. sampling, …
- junction to preamp: DC vs AC

Read-out architecture:
- charge encoding: binary, ADC (4-5 bits, …)
- zero-suppression, elastic buffering, …)

Particle detection performance assessment:
- lab tests: noise, steering param. , threshold dispersion, …
- beam test: det. eff., cluster characteristics, spatial resol.
- radiation tolerance assessment: TID, NIEL, SEE, …

Determination of requirements:
- ILC vertex detector and inner tracke
- optimisation of conflicting design param.
- investigate charge coll. system variants

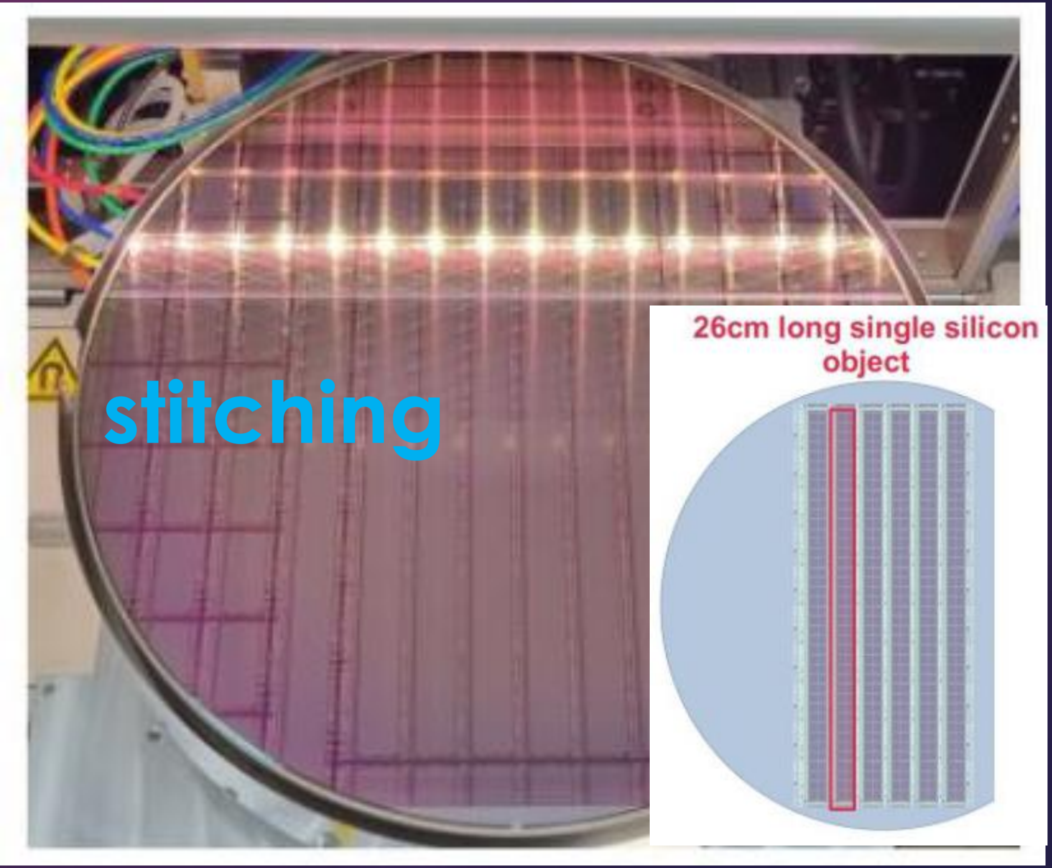
Comparaison of CMOS processes:
- impact of feature size, design rules, IP µcircuits
- planar vs triple-well vs quadruple-well
- nb of ML
- intrinsic radiation tolerance

INDUSTRIAL MONOLITHIC CMOS SENSORS: 6th GENERATION

- Fourth industrial CMOS process used: **TPSco-65**
  - Access based on close contact between CERN (Walter Snoeys) and Tower-Jazz foundry
  - Feature size : 65 nm (Vref = 1.2 V)
  - Quadruple well technology → in-pixel N-MOS and P-MOS transistors
    → feature size: 65 nm
  - EPI thickness: less than with previous CMOS processes → **modest (< 1000 e-) signal charge**

    high resistivity → **nearly all signal** e- collected by drift
    → fast charge collection, enhanced radiation tol.
    → BUT smallest cluster multiplicity
    → degraded spatial resolution
    → partially recovered with smaller pixels ?

New step toward passive material suppression → **stitching**

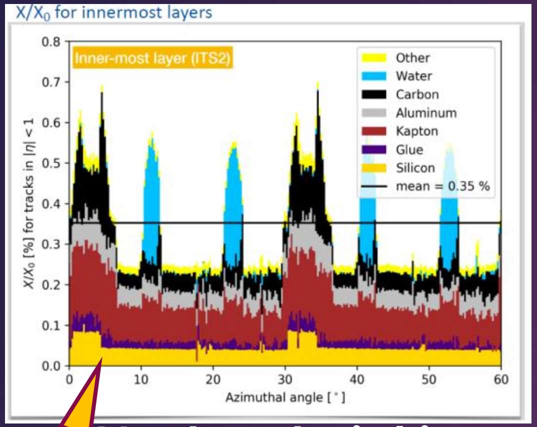


Flagship: ALICE-ITS3 Vertex Detector

FLAGSHIP PROJECTS BASED ON CMOS SENSORS

FUTURE
TPSco 65 ?

ALICE-ITS2 material budget.

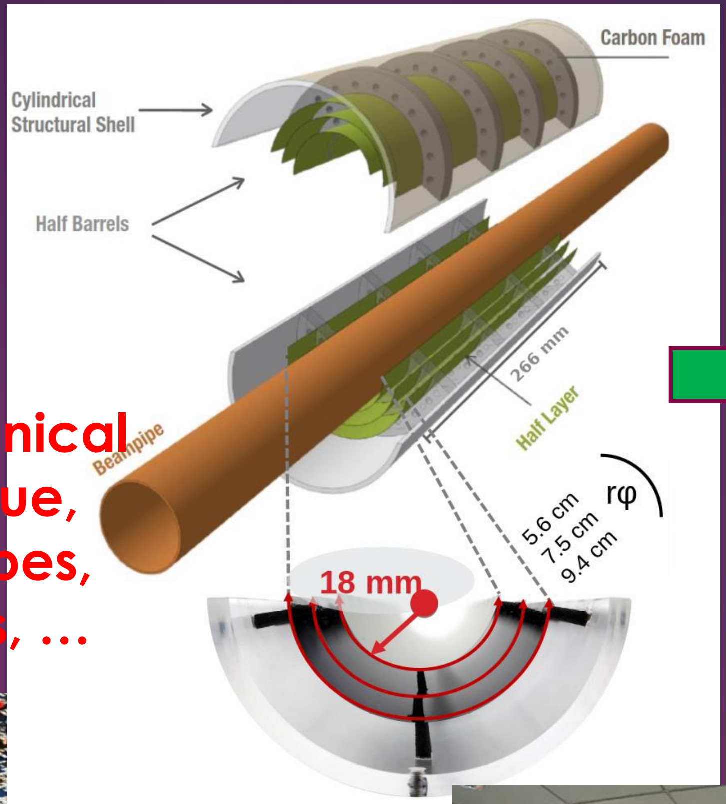


Most material is passive (services)

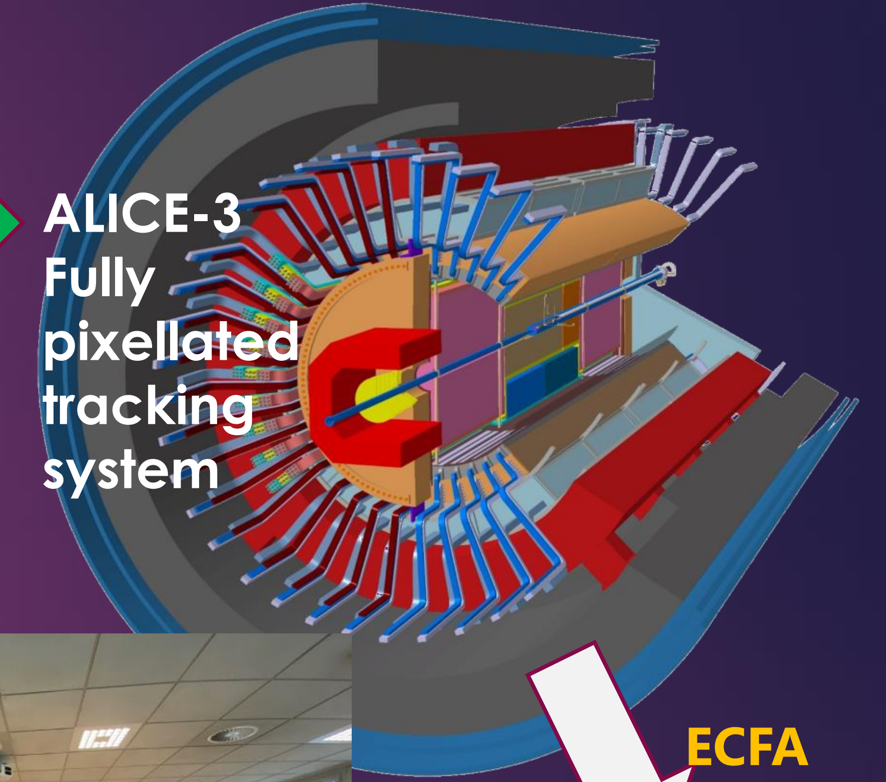
Si

ITS3

NO mechanical support, glue, cooling,pipes, flex cables, …



ALICE-3 Fully pixellated tracking system



ECFA DRD-3

Expts at a future lepton collider

CONCLUSION & OUTLOOK

My involvement in the birth and devt of CMOS pixel sensors for charged particle tracking stems from an **idea proposed by Renato T.** and benefited from **R&D realised/supervised by Walter S.**

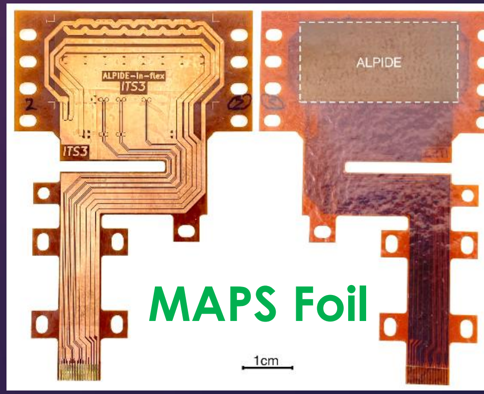
Monolithic CMOS Pixel Sensors for charged particle tracking are born 25 years ago. They have evolved in numerous aspects, relying on an industrial market which was not anticipated to preserve characteristics essential for charged particle detection

Toward a future (e+ e-) Higgs Factory:

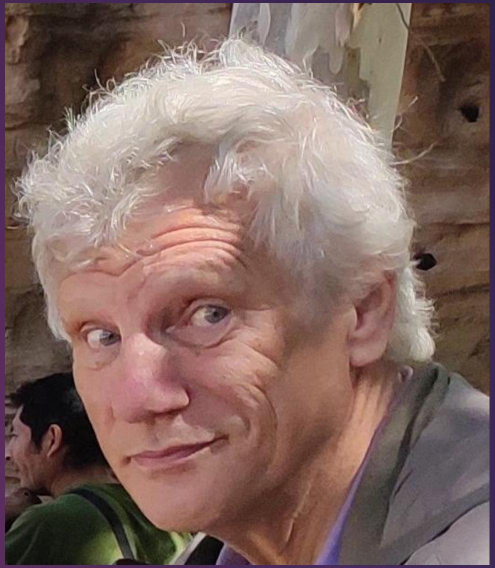
- the challenge is still to concentrate in a single, thin, low power sensor the ambitionned spatial and time resolution
- on-going & emerging projects pave a promissing path:
  CBM-MVD (& STS upgrade), ALICE-ITS3 (& eIC expts), Belle-II ?, ALICE-3
- …..

Numerous pending questions:

- which CMOS technology: TPSCo 65 nm ?, XXX 28 nm ? … or TJsc 180 nm ?
- with/without stitching (e.g. what about sensors embedded in mylar foils ?)
- why restricting to processes featuring an EPI layer ?
- what about stacked sensors ?
- etc.



Thank You for Your Attention !



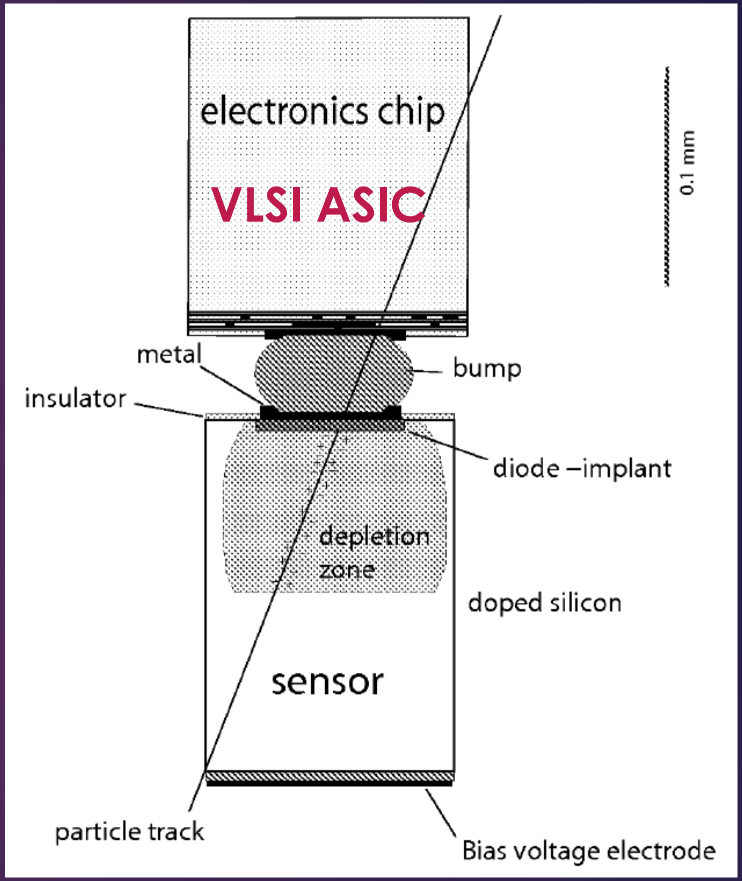
THE TRIGGER FOR CMOS PIXEL SENSORS: HYBRID PIXEL SENSORS

VOCABULARY:

- **PIXEL:** short term for **PICT**ure **El**ement
- **PIXEL DETECTOR**: device able to detect an image with a resolution power expressing the size of the pixels
- **PIXEL DETECTOR FOR PARTICLE PHYSICS**:
  1. an image is generated in a semi-conductor by ionisation,
  2. the charge generated is converted in an electronic signal,
  3. which is processed electronically (VLSI: Very Large System Integration)
  4. the resulting signals are read out and transfered to the DAS
- 1st generation of pixel detectors with on-pixel electronics **Hybrid Pixel Sensors,** first used at CERN in DELPHI/LEP and in the WA-97 Heavy Ion fixed target expt (1996/97)

→ **Hybrid:** sensing element & read-out μ-circuits are fabricated separately and interconnected via bump-bonding

Hybrid Pixel Device

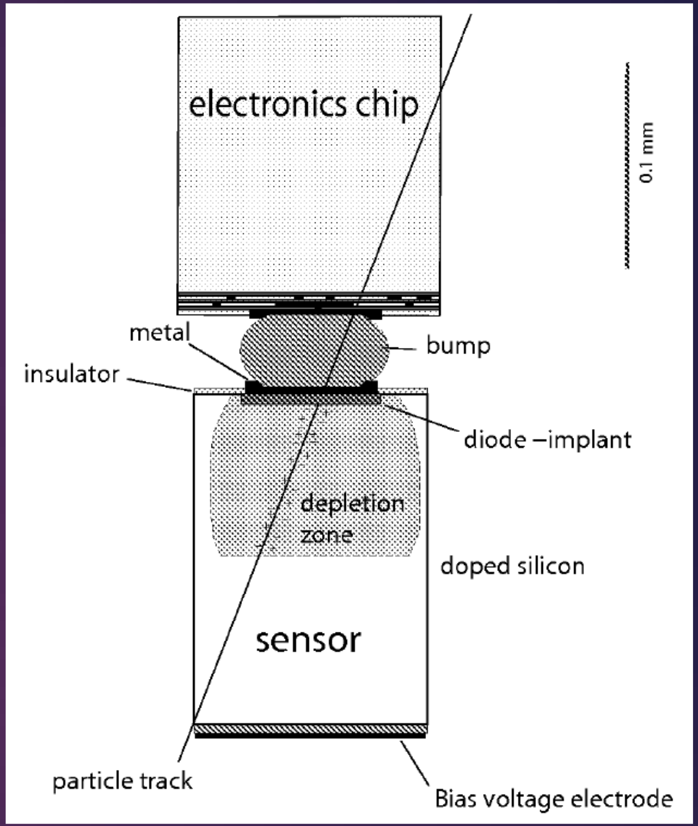


SEMI-CONDUCTOR DETECTORS: HYBRID PIXEL SENSORS

FUNCTIONNING:

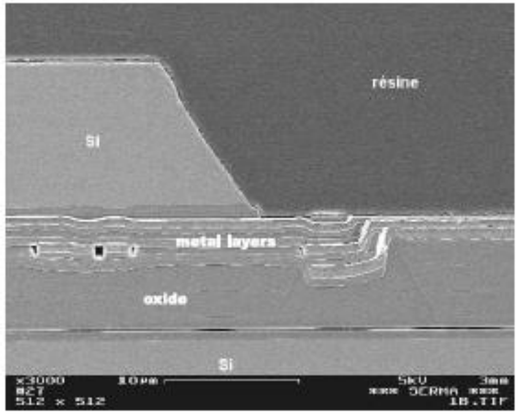
- When a charged particle crosses the sensor, it liberates about 70 eh pairs/μm (3.6 eV / eh pair) → Landau fluctuations !
- The ionisation electrons and holes diffuse thermally (by default)
- Sensor material: usually P-type silicon (dopant with 3 electrons populating valence band, while Si has 4 valence electrons)
- The dopant is integrated into the lattice structure of the semiconductor crystal, the number of outer electrons defining the type of doping: Elements with 3 valence electrons (e.g. Bo, In) are used for p-type doping, while 5-valued elements (e.g. P) are used for for n-doping. The conductivity of a deliberately contaminated silicon crystal can be increased by a factor of 10^6.

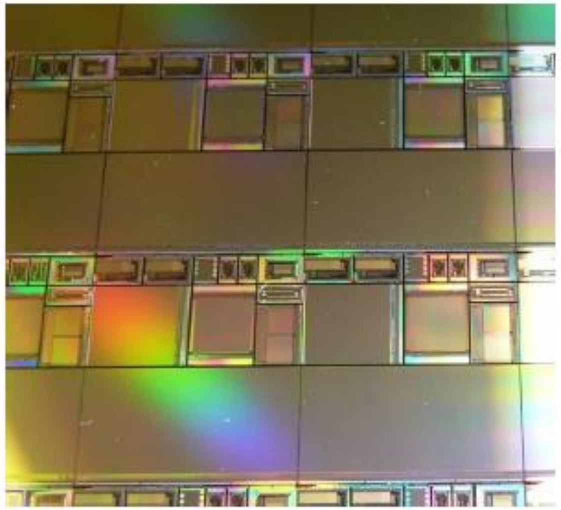
Hybrid Pixel Device

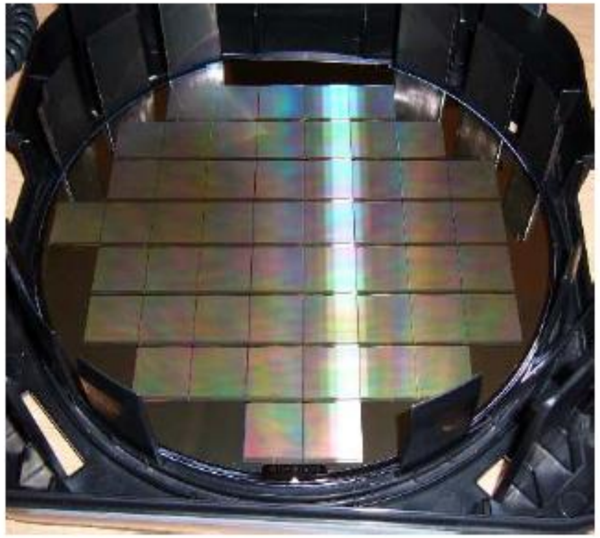


Semi-Conductor Detectors: CMOS Technology

- **CMOS fabrication mode :**
  - μcircuit lithography on a substrate sliced from a crystal ingot (or *boule*)
  - proceeds through reticules (e.g. 21x23 or 25x32 mm^2) organised in wafers

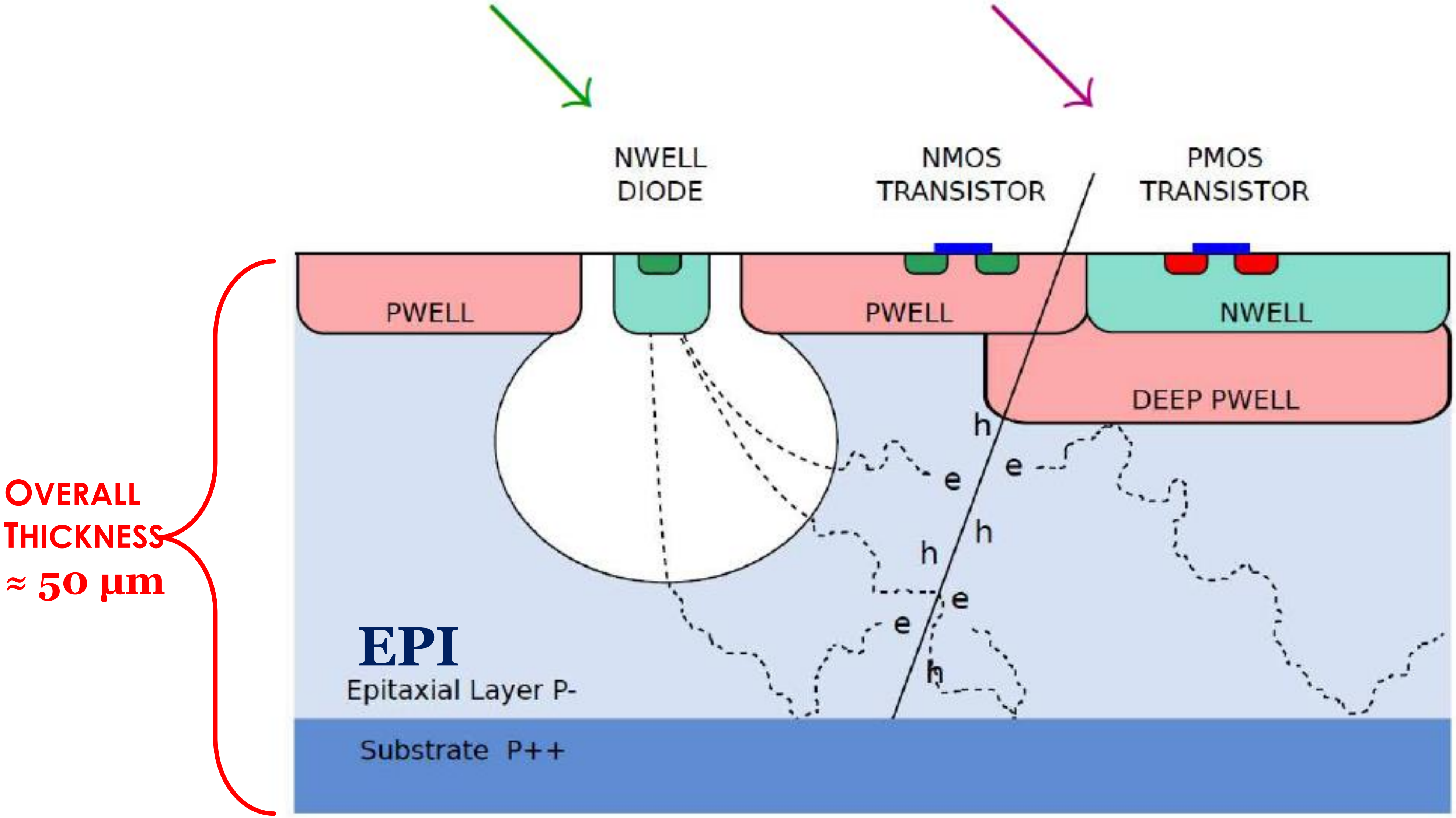






Semi-Conductor Detectors: CMOS Technology

- CMOS Pixel Sensors ≡ **Detector** ⊕ **Front-End Electronics** in same die



Semi-Conductor Detectors: CMOS Technology

- R&D addresses **Sensing Element** ⊕ **Read-Out μcircuitry**