The History of Silicon Detectors for Particle and X-ray Physics

Table of Content

1. Prehistory – on the way to:
2. Strip Detectors
3. Pixel Detectors (CCDs and Hybrid Detectors)
4. Drift Devices and their Descendants
5. Outlook and Summary
The Very Early Days of Solid State Detectors

Idea of solid state ionization chamber and first successful realisations:
- 1943: P.J. von Heerden, Utrecht (AgCl)
- 1949: K.G. McKay, Bell (Ge – pn junction)
- 1955 – 1965: Si mono-crystals available → surface barrier detectors at several labs. Oak Ridge, Chalk River, CEA, ... main motivation nuclear particle spectrometers
- 1961: G. Dearnaley, Harwell :first segmented detector a pixel detector!
- 1970: first strip detectors – Argonne, Fermilab, Karlsruhe, Southampton; for nuclear physics and nuclear medicine
- 1970: W.S. Boyle and G.E. Smith, Bell CCD

Several companies in the US and Europe for detector fabrication (> 7 in 1975)

Typical values for Si:
- voltage: 50 – 500 V
- thickness: 0.05 – 1 mm
- signal: 1e/h-pair/3.6 eV → mip 25000 charges/0.3 mm
- collection time: 5-50 ns
- diffusion: few μm
- sensitive to light < ~1 μm, x-rays 0.2–~20keV, charged part.
Si-detectors can also be used to detect minimum ionizing particles!

(J.E. Bateman, NIM 71(1969)256)

The Very Early Days

- surface barrier detector
- area: 2 cm²
- thickness: 500 µm
- resistivity: 8 kΩ·cm
- voltage: 400 V
- noise: ~ 4000 e (rms)
Early Realization of Double Sided Strip Detector

S.M. Gruner BSC-thesis (1972):

- (0.6x0.6) mm² x 50 μm n-type Si
- B-diffused (+Al): p⁺n-junction
- Au strips: np-junction
- test with ⁹⁰Sr source + amplifier + scope

The feasibility of initiating the fabrication of a large area integrated circuit semiconductor detector following our basic design has been demonstrated both conceptually and experimentally. The initial fabrication of a small test device has shown that the construction problems can be overcome. Further, testing of the small device has yielded attractive resolution in space and time (20 microns; 10 nano-seconds) and has done so with a signal to noise ratio which allows digital logic handling.
Surface barriers: a “mystic” art
- reliability not guaranteed
- but successful experiments and great potential
→ limited use

This changed in 1974 with
- discovery of J/ψ
- paper by Gaillard, Lee und Rosner on charmed particles
- discovery of charm (1975) (lifetime \( c\tau \sim 100 \mu m \))
- discovery of \( \tau \)-lepton
- discovery of beauty

→ Hunt for high position resolution electronic detectors
(a friendly competition between gaseous and solid state approach)
But there are 3 reasons why the development of high position resolution Si-detectors took off in the late seventies:

- discovery of short-lived particles; lifetime $\tau \sim 100 \mu m$ defines required resolution
- highly developed Si-technology for electronics (crystals + the planar process)
- development of miniaturized electronics (thick film hybrids $\rightarrow$ VLSI) generally available

$\rightarrow$ Several hep groups started to learn the art of silicon sensors and $\mu$-electronics (in close collaboration with industry)
Still surface barrier technology:

**PISA group** (Amendolia et al. 1980) →
Si-strip sensor with 600 µm pitch

**CERN group** (Hyams et al. 1980)
Si-strip sensor with 300 µm pitch
- demonstrate vertex reconstruction (within the NA-11 experiment)
- demonstrate capacitive charge division (thanks to broken channels)
Transfer of the Planar Process to Detector Fabrication

Kemmer 1979, TU-München, transferred the highly developed Si-technology for electronics to detector fabrication + industry (P. Burger – Enertec/Canberra)

Getting Organized

1983: 3rd European Symposium on Semiconductor Detectors at Munich
NA-11/32 experiment:
- spectrometer for the study of hadronic reactions eg $\pi$Be->charm+X
- 1981: 6 planes Si-strip detectors
  * 24x36mm$^2$, 1200 strips/sensor
  * strip pitch 20 $\mu$m, 280 $\mu$m thick
  * 60 $\mu$m readout $\rightarrow$ $\sigma=5.4$ $\mu$m
  * 120 $\mu$m readout $\rightarrow$ $\sigma=7.8$ $\mu$m
  * total <2000 channels
  * 100% efficiency

B. Hyams et al., NIM 205(1983)99
Results from the NA11 Experiment

NA-11/32: Charm physics results
- lifetimes $D^+$, $D^0$, $D_S$, $\Lambda_c$, ...
- observation and mass of $D_S$
- hadronic production of charm particles (QCD)

Impact of NA11/32:
- demonstrated excellent performance of Si-strip detectors
- demonstrated excellent performance of pixel detectors ($\rightarrow$ CCDs have been added in NA32)
- testing ground for new ideas and concepts ($\rightarrow$ Si drift ch.)
- learning- + communication-environment for junior and senior Si-experts
(R.Horisberger, D.Dorfan, S.Parker, U.Kötz, V.Lüth, E.Gatti, P.Rehak + many more)
Si Vertex Detector for e⁺e⁻: SVD at Mark-II at SLC

Parallel to Si-detectors → development of VLSI readout chips
(CAMEX: G.Lutz et al., MPI; Microplex: Hyams, Walker, Shapiro; ...)

Sept. 1985: Proposal to add SVD to Mark-II (Adolphsen et al.)

Layout: "Coke Can"

Impact parameter resolution ~20 µm

Prototype "Ladder" ready for beam test

Fig. 40. The impact parameter measurement relative to the single-event vertex, for tracks with transverse momenta above 3.5 GeV/c. The points represent the measured tracks, the histogram shows the results of a detailed Monte Carlo simulation.
Following the pioneering success of MarkII → Si vertex detectors for all 4 LEP-detectors, TeVatron, B-factories, HERA, RHIC and → LHC

Example: **CMS Tracker** the largest Si tracker ever built!
precision tracking in the harsh LHC environment for |η| < 2.5

**Strip detectors:**
- 9.3 M channels
- 210 m² sensor area
- 10 barrel layers
- 9 (+3) endcap disks

**(Hybrid) Pixel detectors:**
- 66 M channels
- ~1.1 m² sensor area
- 3 barrel layers
- 2 endcap disks
- innermost layer at r=4.3 cm

Tracker is running with **97.8 % strips** and **96.5 % pixels** operating at design resolutions and efficiencies
CMS Tracker

The building blocks of the **Si-strip modules** and **Si-pixel modules**

**Quasi-industrial assembly (quality control!)**
CMS Tracker – “The non-sleeping Beauty”

View of the CMS Tracker during installation in 2007
CMS Tracker: Producing Physics Results

$\mu\mu$-mass spectrum
$\sqrt{s} = 7$TeV; $L_{\text{int}} = 40\text{pb}^{-1}$

Some of the challenges:
- events with many interactions/bunch crossing (@ 25 ns)
- Particle densities in heavy ion interactions
- radiation damage

LHC machine + experiments:
- verified Standard Model,
- ready for New Physics

13 interactions within 1 bunch crossing!
Silicon Detectors in hep and Space Experiments

Silicon detector area [m²] in different experiments: 1981 - now

- ~5 orders of magnitude since 1981
- Si detectors are used in (practically) all hep- and in many space-experiments
Si-Strip Detectors for X-ray Science

Just one example: **MYTHEN** (PSI)

Si-strip sensors: 320 μm thickness  
1280 8 mm long strips with 50 μm pitch  
- counting rate: > 2×10⁶ per strip  
- max. no counts 24 bits (16,777,216)  
- energy range 5keV (90%) – 30 keV (8%)  
- frame rate: 25Hz (24bit) – 500Hz (4bit)

A highly successful example:

- reduction of measurement time for powder diffraction by ~10,000  
→ acquire data before radiation damage  
→ time resolved measurements possible

Pixel Detectors: Invention and Principle of CCD

2009 Nobel prize: W.S. Boyle and G.E. Smith

Invention Charged Coupled Device, the first (practical) solid state imaging device

Test device 1 week after idea! (1970)

Picturephone + CCD inventors

Principle of charge shift

Shift pattern for 2-d CCD
Use of CCDs for imaging pioneered by **astrophysics**
- high sensitivity compared to film
- low noise (few electrons when cooled)

**For X-rays:** external scintillator $\rightarrow$ record image

**Starting point:** scintillator $\rightarrow$ X-ray film

Gain in sensitivity (measurement time) by **many orders of magnitude** and in data quality (PSF - Point Spread Function)

*S.M. Gruner, Transaction ACA 34(1999)11*
CCDs as Precision Position Detectors in hep

\[ \Lambda_c \rightarrow p K^- \pi^+ \]

→ superior pattern recognition convincingly demonstrated

→ C. Damerell et al. join SLD@SLC to build the best vertex detector built so far (with respect to resolution and material budget)

C. Damerell et al.,
NIM 185(1981)33,
NIMA 541(2005)178
CCDs: VXD3 Vertex Detector for SLD@SLC

VXD3@SLD
- installed in 1995
- 307 MPixels (ATLAS: 80Mpixels !)
- 0.4% $X_0$ (multiple scattering)
- 1st layer < 3cm from beam)

By far most performing vertex detector in terms of resolution → reference point for ILC vertex detectors

8$\mu$m impact parameter resolution
Hybrid Pixel Detectors

Idea: separate sensor and electronic → flexibility but additional material

Concept:

Special features:
- read-out chip directly mounted on top of detector by bump bonding
- every pixel has its own electronics
- technology for electronics and sensor can be chosen separately (eg high-Z sensor + Si readout; optimize for radiation hardness,...)

Limitations:
- amount of material for precision vertex detector (multiple scattering!) also power dissipation - cooling
- read-out speed and dynamic range (in particular for X-ray science)

Hep experiments using hybrid pixels:
- CMS (66 Mpixels of 150×100 μm²)
- ATLAS (80 Mpixels of 40×400 μm²)
- ALICE, PHENIX (BNL), FAIR-expts. (PANDA, CBM, ...) ...
Early Hybrid Pixel Detector for X-rays

First Ge pixel detector in 1961
G. Dearnaley

S. Gaalema at 1984 IEEE-NSS

Performance:
- 600×600 pixels (20 μm)$^2$
- 50 e (rms) noise
- random access to every pixel
- average power 1 μW/pixel (for 1kHz readout)

was used to read out Si and Ge detectors

**Charge Integrating Hybrid Pixel Detector for X-rays**

**Task:** Fast time resolved imaging with \( \mu \)s frame rate → counting not an option → integrating readout

**Application:**
μs time-resolved x-ray radiography of multi-phase, direct-injection gasoline fuel spray → Verify fluid dynamics simulations

**Specifications and performance:**
- Si: 92×100 pixels, \((150 \mu m)^2\); 300 \( \mu \)m thick
- 8 storage cells; min. integration time 1 \( \mu \)s
- capacity: 17,000 8.9keV X-rays
- non-linearity <0.2% (full range)
- noise: \(~20 \text{ keV (X-rays)}\)
- 1.2\( \mu \)m HP process; GEC-Marconi bump bond
- 100 \( \mu W \) power/pixel
- limited radiation hardness

Supersonic jet of Diesel fuel spray in 1atm SF\(_6\)
- image area \((61.7\times7.5) \text{ mm}^2\) [built-up from images \((13.5\times2.5) \text{ mm}^2\)]
- shockwave: increase in gas density \(~15\%\)


MacPhee et al., Science 295(2002)1261
Several examples: Medipix1, Medipix2, Medipix3, PILATUS1, PILATUS2, ADSC, development chains $\rightarrow$ continuous improvements + profit from technology advance

Example: PILATUS (PSI)- specifications and performance:
- pixelsize: $(172 \, \mu m)^2$
- max. rate: 1.5 MHz/pixel
- dynamic range: 20 bits $(1,048,576)$ no noise!
- read-out time: 5 ms
- frame rate: 10-100 Hz

B. Henrich et al., NIM-A607(2009)247

1st generation PILATUS module
1st generation PILATUS 1M
PILATUS 6M
X-ray Counting Hybrid Pixel Detector(s)

Example of an early measurement with PILATUS1

Electron density map of Thaumatin

Swiss Economic Award to DECTRIS
**Pixel Detectors in hep**

**Hybrid-Pixels** in use in hep since 1995  
needs micro-electronics because of large no. of channels!  
- pioneered in fixed target heavy ion expts. at CERN  
- $e^+e^-$ colliders (DELPHI)  
- pp- and ion-collider; in particular ATLAS,CMS,ALICE

**CMS Pixel Detector:** 66 Mio. pixels  
- 3 barrel layers at 4.3, 7.2, 11.0 cm  
- 2 forward disks

**Performance from data:** position resolution $\sigma_x = (12.8 \pm 0.9) \mu m$; $\sigma_y = (32.2 \pm 1.4) \mu m$  
→ design specifications achieved  
→ highly efficient b-tagging / secondary vertex recognition in complex environment  
→ essential tool to search for New Physics at the LHC
For hep: inactive material + sensor thickness → interactions + multiple scattering → degradation of performance (in particular for $e^+e^-$) → monolithic sensor - readout and thinning of substrate


MAPS: Monolithic Active Pixels

- standard VLSI technology
- small (>10 μm) pixels
- low power
- low noise (5e rms)
- thinned down to 50 μm
- random access
State of the art: MIMOSA-26 (EUDET-telescope)

- 0.35\,\mu m CMOS OPTO process
- 572\times 1152 pixels of (18.4\,\mu m)^2 \rightarrow 10\,\text{mm}\times21\,\text{mm}
- 80 MHz read-out: zero suppressed, binary with data sparsification \rightarrow reduction of data volume by factor 10–1000 (depending on occupancy)
- 112\,\mu s integration time

Position resolution (CERN beam test)
\[ \Delta x \sim \Delta y \sim 2.7\,\mu m \]
Drift Detectors: The Principle of Sideward Depletion

planar pad diode

- n-type substrate
- n+ ohmic contact (V=0V)

sideward depletion

- p+ rectifying junction (V=-80V)
- n+ ohmic contact (V=0V)

E.Gatti, P.Rehak
NIMA226(1984)608
below full depletion

- parallel plates
  $\rightarrow C \sim \text{area}$

above full depletion

- line (or point) - plate
  $\rightarrow C \sim \ln(\text{area})$

$\rightarrow$ collect charge from a large area with minimal capacitance
$\rightarrow$ large area low noise detectors feasible

impact on anode capacitance

Fig. 12. Capacitance versus voltage plots of two of the test devices provided on the wafer for monitoring its doping uniformity.

P. Rehak et al., NIMA235(1985)224

full depletion
Si Drift Detector as 2-D Tracking Detector

- Cathode strips $\rightarrow$ drift field
- segmented anode $\rightarrow$ transverse position - time-of-flight $\rightarrow$ longitudinal pos.

achieved performance: 2 $\mu$m in lab (laser light)
10 $\mu$m in test beam
18 $\mu$m in actual experiment
Emilio Gatti and Pavel Rehak: Silicon Drift Detector SDD
SDD with integrated JFET → Low Noise X-ray Detector

Mars Exploration Rover (MER)

L. Strüder, IEEE-NSS Rome 2004, R. Rieder, MPI für Chemie, Mainz
The Family of Detectors Based on Sideward Depletion

**Silicon drift detector**

- Integrated FET
- Field strip
- Anode
- Back contact/Field stoppers

**Fully depleted pnCCD**

- Control-drift detector
- DePMOS

- Intrinsic FET
- Gate
- Source
- Drain
- Drift region
- Depleted silicon bulk
- Incident radiation
- Signal electrons at internal gate
- p+ back contact (-1.15V)

Robert Klanner - Univ. of Hamburg - Joint Detector Seminar - 2.9.2011
Fully Depleted pn-CCD (eg EPIC on XMM-N, CAMP,...)

- charge from entire thickness collected and stored in potential trough (below $\Phi_2$)
- by modulating potentials $\Phi_i \rightarrow$ transfer charges until they reach read-out electrode(s)
- channel stops prevent that charges spill to neighbouring rows (eg from n $\rightarrow$ n±1)
  $\rightarrow$ high quantum efficiency for X-rays due to full depletion (CMOS CCDs ~ 20 $\mu$m thick !)
  $\rightarrow$ backside illumination allows for thin entrance window (min. detectable X-ray energy !)
  $\rightarrow$ high transfer efficiency (uniform response)
  $\rightarrow$ pixel size down to $\sim$30 $\mu$m
  $\rightarrow$ good radiation hardness because of pn junctions (no potential steering through oxide)
 pn CCDs in Heaven

elemental analysis of TYCHO supernova remnant:

L. Strüder, IEEE-NSS 2004
Detectors at the LCLS and other FELs

Experiments at FELs → unprecedented requirements for detectors:
- energy resolution and dynamic range (0 → 10^5 photons)
- segmentation and readout-speed
- charge densities and radiation dose (1 GGy @ EXFEL)

Beautiful instruments existing + under developments → iWoRID13

Example for a running detector: CAMP (CFEL ASG MultiPurpose) detector
Example: CAMP@LCLS

- Most macromolecules cannot be grown to crystals of sufficient size for conventional crystallography*)

- X-ray dose required to study crystals will destroy them

- Can fs pulses at FELs produce diffraction pattern before damage occurred?

- Experiment with CAMP at LCLS: $10^{12}$ 1.8keV γ/pulse of 10, 70 and 200 ns, focussed to 7 μm (FWHM) → 70 MJ!

  record 3M diffraction patterns of 0.2–2 μm nanocrystals of photosystem I (structure known)

*) so far only 300 unique structures of membrane proteins deciphered!

Single shot femtosecond nanocrystallography demonstrated!

→ excellent Si detectors were necessary for this success
→ further developments are required and under way to meet the challenges of the new X-ray sources - one of the main themes of IWORID13
Looking back on more than half a century of development of solid state sensor and detector systems:

- an exciting story of fascinating developments
- solid state detectors enabled important discoveries and precision measurements
- the developments have major impact on industry and science outside of physics
- frequently there has been amazingly little exchange between groups
- the close collaboration between academia and industry has been important

Looking forward:

- rapidly developing technologies bring new opportunities - they will help solving the many challenges posed by the new science ideas and the new experimental facilities, like Free-Electron Lasers, the High-Luminosity LHC, the International Linear Collider, and many more
- I also hope that there will also be completely new ideas, like in the past the CCD, the concept of sideway depletion, the DepFET and more

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