Silicon is to Physics what Carbon is to Life

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Inst. of Experimental and Applied Physics
of the Czech Technical University in Prague
Nikhef       Amsterdam
CMS Silicon Tracker
Inner barrel half-module while under construction

Silicon in LHC

use of silicon in particle physics:
Si-sensors
Si CMOS chips
computing with Si processors

source: CERN- CMS
ATLAS inner Si pixel layer
Increase of area silicon detector systems in LHC experiments and in many others

![Graph showing the increase of area silicon detector systems in LHC experiments and in many others. The graph plots silicon area in square meters (m²) against years from 1970 to 2015. Notable experiments include CMS, ATLAS, LHCb, ALICE, ZEUS, and more. Each experiment is represented by a data point on the graph.](image-url)
Contents

- advantages of miniaturization
- silicon for science and technology = similar to carbon for evolution of life
- silicon for particle physics
- examples of silicon for other science fields
  - 2 using our pixel detectors, 2 others

Science discovery → New technology → Applications
Biology, Medicine, Informatics at quantum level

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Imaging today all electronic

3-dimensional reconstruction

here many tracks + 2 “Jets”

40 million / sec

secondary vertex: particle with short-lifetime is a messenger for new phenomena

blow-up in next slide

source: CERN-ATLAS
ATLAS

details around primary vertex

two secondary vertices: “messengers”

Note scale
1 cm
all this is INSIDE beam pipe ∅ 7 cm

source: CERN-ATLAS
from 2015 also 'inner B pixel layer'

Reconstruction uses the 4 inner pixel layers
Animation of Bunch Crossings and Timing
main advantages silicon sensors in HEP

Segmentation and lithography of sensor cells on Si substrate enables ~µm precision on tracking; pixels → even 2D
mechanically light and stable

Smaller capacitance of sensor cells results in lower noise

Signal ~70 e⁻ charges per µm → in 300µm 20 000 e-h pairs
signal proportional to particle energy deposit

Signal induced by moving electrons and holes
collected with hole velocity ~ 10km/s (e⁻ 3x faster)

Sensitive volume is empty and ready again after ~15ns
40 MHz rate of 'pictures' is possible
Charge carrier transport in Si and GaAs

electron and hole

drift velocity vs electrical field

100km/s

saturation drift velocity vs temp °K

10^7 cm/s = 100 km/s = 3.6 \times 10^5 \text{ km/hr}

NOTE: at RT

thermal velocity: e^- 230 \text{ km/s}
h^+ 165 \text{ km/s}

light velocity ~1000 x faster

mobility $\mu_e$ or $\mu_h$ is a function of doping, temp, field..

semiconductor detectors are INHERENTLY FAST: 5 - 25 ns

from Sze

Physics of semiconductor devices, Wiley
Silicon

would it be possible to integrate sensor and signal processing circuits?

separate silicon substrates/chips preferred due to differences in technology

may become feasible in future developments
Hermetic Si pad detector for UA2 1988

Cylindrical detector array collaboration with Claus Gößling and Alan Clark
U. Dortmund, U. Genève

~5 mm thin CILINDER around beam pipe
ONLY POSSIBLE using "AMPLEX" chip
16-channel circuit design Pierre Jarron

FIRST Si barrel detector in collider experiment
FIRST Si array with IC chip readout

R. Ansari et al. NIMA279(1989) 388

1986 – 1988 also part of LAA microelectronics project
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Silicon Microstrips need CMOS ASICs for readout

silicon MOS technology both for sensors and signal processing

Si sensor connected to ASICs in the “small” LHCb experiment

Barrel of Si sensor modules
ATLAS employs 60m² in 3 layers

source: CERN
from bubble chambers to fully electronic imagers

BEBC 1981
photo every \(~1\)s

LHC 2016
40 million
records per s

Liquid H \rightarrow silicon\text{ for vertexing}\text{ reconstructed, not a full image}

ATLAS experiment 2012
Collision Event at 7 TeV with 2 Pile Up Vertices

ATLAS EXPERIMENT
1988 -> 2013
Chips paved the road to the Higgs boson in LHC

within the LAA project CERN initiated use of self-designed ASICs for particle physics experiments
Custom-design of integrated circuits

Design teams in HEP institutes
initiated ~1985 at CERN, SLAC and LBL, and many more later on

Analog signal processing and logic functions

Optimal matching of readout with the sensors

Radiation hard design methods found at CERN
optimized for use in accelerator experiments

Difficult to follow 'Moore' technology trend
now several generations behind the cutting edge
Worldwide acceptance and chip design efforts for use in particle physics experiments

already many chip design teams ~1994 worked on radhard
Two types of Si sensors exploited

Si Microstrip Detectors
- can cover larger area
- Linear array diodes 2-15 cm
- depleted bulk ~300µm

Si Pixel Detectors
- for highest densities
- 2D pixel matrix with bumps
- diodes 30µm – 500µm
- depleted bulk ~150µm
our 2\textsuperscript{nd} contribution in LAA project
'micropattern' pixel detector

First design in collaboration with EPFL
Krummenacher et al. NIM A288(1990)176
(presented at Munich Symp Feb 1989)

Chip ready
Summer 1989
published at IEEE Nucl Sc Symp 1989

Chip layout Dec 1988
Krummenacher & Enz EPFL

Campbell et al. NIM A290 (1990) 149
results including spectra taken with radioactive sources
TIMEPIX silicon 'emulsion'/portable 'bubble chamber'

H6 120 GeV p/π beam 2007

incident from the right

beam test with help of
John Idarraga / then Montréal

beam test with help of
John Idarraga / then Montréal

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pion interacts with Si,
one secondary pion again, after ~3mm

Trails to the front or to the back?
ambiguity can be solved if
2 adjacent planes are used
-> stack of pixel detectors

FRAME T3-1506
Si Microstrip sensors and CMOS readout chips

- Fully depleted Si Sensor divided in parallel strips: “Microstrip Detector”
- Individual readout chain for each segment
- Signal ~20 000 e-h pairs

Typical signal one particle

Si detector wirebonded to 
READOUT ASIC

p⁺ DIODES
n BULK

~10 cm

n⁺⁺ BACKPLANE
Some of the ASICs in ATLAS

- **FE-I3 pix det**: 28,000 chips, 280 M segments, 1 cm² Si sensor
- **ABCD Si det**: 50,000 chips, 6 M segments, 60 cm² Si sensor
- **ASDBLR TRT det**: 38,000 chips
- **ASD muon det**: 148,000 chips
- **DTMROC TRT det**: 19,000 chips

Total ATLAS: 100 million sensor cells, approx. 800,000 chips, majority ASICs

Chips to scale 1 cm
Some of the ASICs in CMS

- Beam pipe
- Si strip tracker
- Pixel detector
- PSI46 pix det
- 16 800 chips
- 66 M segments
- 1 m² Si sensor
- APV25 Si det
- 110 000 chips
- 9.3 M segments
- 198 m² Si sensor
- QIE8 calorimeter
- 220 400 chips
- MAD muon det
- 181 000 chips
- 25 000 m² gas-filled
- e-CAL
- h-CAL
- Muon chambers

Total CMS
appr. 1 million chips
of which 700 000 ASICs

Chips to scale 1 cm
## Large silicon systems with 1000’s of chips

<table>
<thead>
<tr>
<th>Detector Subsystem</th>
<th>ATLAS Chip-ID</th>
<th>ATLAS #</th>
<th>CMS Chip-ID</th>
<th>CMS #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si Pixel Detector Tracker</td>
<td>FEI</td>
<td>28 000</td>
<td>PS146</td>
<td>16 800</td>
</tr>
<tr>
<td>Control &amp; Monitoring</td>
<td>DORIC</td>
<td>2 700</td>
<td>TBM05</td>
<td>4 690</td>
</tr>
<tr>
<td>Si Microstrip Detector Tracker</td>
<td>ABCD</td>
<td>50 000</td>
<td>APV25</td>
<td>110 000</td>
</tr>
<tr>
<td>Control &amp; Monitoring</td>
<td>DORIC</td>
<td>12 300</td>
<td></td>
<td>52 000</td>
</tr>
<tr>
<td>Gas-filled Tracker</td>
<td>ASDBLR</td>
<td>38 000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control &amp; Monitoring</td>
<td>DTMROC</td>
<td>19 000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calorimeters (different types)</td>
<td></td>
<td>77 300</td>
<td>QIE8</td>
<td>220 400</td>
</tr>
<tr>
<td>Control &amp; Monitoring</td>
<td>37 000</td>
<td></td>
<td>48 000</td>
<td></td>
</tr>
<tr>
<td>Muon Tracker</td>
<td>ASD</td>
<td>148 000</td>
<td>MAD BTI</td>
<td>181 034</td>
</tr>
<tr>
<td>Control &amp; Monitoring</td>
<td>AMT TDC</td>
<td>30 000</td>
<td>RPC</td>
<td>857</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>442 300</strong></td>
<td></td>
<td><strong>633 781</strong></td>
<td></td>
</tr>
</tbody>
</table>
Silicon Si

natural occurrence in many compound materials

atomically pure silicon obtained by electrolysis of quartz

monocrystalline silicon 'wafers' needed for electronics

polycrystalline or amorphous for photovoltaic solar panels

silicon devices now basis for studies in physics / science
physics instruments 15\textsuperscript{th}-19\textsuperscript{th} century

brass, glass, wood in many forms
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Mendeleev <1900

Periodic Table of Elements

COMPOUNDS
also:
Hgl₂
(AgCl)
etc.
elements in the earth crust

mass-abundance:

Si second 28%
after oxygen 46%
carbon only ~ 0.08%
earth all the time
losing volatile elements

source Wikipedia

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Carbon (and water) is basis for life

<table>
<thead>
<tr>
<th>Element</th>
<th>Symbol</th>
<th>Percentage in Body</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>O</td>
<td>65.0</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H</td>
<td>9.5</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N</td>
<td>3.2</td>
</tr>
<tr>
<td>Carbon</td>
<td>C</td>
<td>18.5</td>
</tr>
<tr>
<td>Calcium</td>
<td>Ca</td>
<td>1.5</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>P</td>
<td>1.0</td>
</tr>
<tr>
<td>Potassium</td>
<td>K</td>
<td>0.4</td>
</tr>
<tr>
<td>Sulfur</td>
<td>S</td>
<td>0.3</td>
</tr>
<tr>
<td>Sodium</td>
<td>Na</td>
<td>0.2</td>
</tr>
<tr>
<td>Chlorine</td>
<td>Cl</td>
<td>0.2</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Trace elements include boron (B), chromium (Cr), cobalt (Co), copper (Cu), fluorine (F), iodine (I), iron (Fe), manganese (Mn), molybdenum (Mo), selenium (Se), silicon (Si), tin (Sn), vanadium (V), and zinc (Zn).

carbon abundance by mass 18.5 %
Si single-crystal essential for electron/hole mobility
Silicon single crystal growing

1955-2015

Wafer sizes

Increase of wafer diameter 3/4” - 450mm

max for HEP sensors

slowly being introduced 2018

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CZ Crystal Pullers
(Mitsubishi Materials Silicon)
Si commercial aspects

2017 worldwide Si chip circuits $420 \times 10^9 \text{ US } $ 

> +10% over years

memory chips alone $130 \times 10^9 \text{ US } $

chip import from world into China $134 \times 10^9 \text{ US }$

semiconductor Si crystal area $8 \text{ km}^2 / \text{ year}$

compare with

2015/16 worldwide grain production 

$651 \times 10^9 \text{ US }$

~ +1% over years

rice 235
wheat 184
corn/mais 170
other 62

total metric tonnes $2.43 \times 10^9 \text{ MT}$ (MT=1000kg)

mass-abundance

Si second 28%
after oxygen 46%
Integrated electronics is key: silicon MOS transistor

2 µm TECHNOLOGY
1985

HEP was 2 generations behind industry

0.005 µm
2017

now HEP is 8 generations behind

2 µm TECHNOLOGY
1985

Continuous scaling/miniaturization

2015

same scale

gate length .016 µm

SiO₂ gate thickness 2.75 nm

thin gate usually radhard

2017 development at IBM

gate-all-around

source IBM

not same scale

source IBM
NEW APPLICATIONS NEED MORE ADVANCED nm CMOS

INTEL: IMPROVED LITHOGRAPHY from 45 nm
my seminar in 2009

MINIMAL SRAM CELL

ALSO, SEVERAL CHARACTERISTICS
IMPROVED BEYOND EXPECTATIONS

Mrs Kelin KUHN, IEEE IEDM 2007

90 nm

65 nm

45 nm

32 nm

ISSCC in 2018

'10 nm'

500nm

500nm

Zheng Guo et al. Intel. paper 11.1 ISSCC 2018

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3D Flash memory, program speed characteristic

- Strong dependency on WL layers because the memory-hole size gradually varies from layer to layer.
- Program speed of cells on common WL layers is almost the same.

Hiroshi Maejima et al. Toshiba. paper 20.1
Example of Evolution in HEP: Data Storage

~1985 parallel-serial CCD analog pipeline

1992 analog storage on feedback capacitors

2002 comparator first, binary pipeline storage
iteration “ABCD” actually installed in ATLAS

2004 SRAM allows variable retention times

construction & installation
Silicon devices in many applications

- integrated circuits in computing --> simulations
- integrated circuits in data storage --> servers
- integrated circuits in communication
- sensors in medical and biological applications
- sensors for environmental monitoring
- silicon for scientific experiments
a few scientific silicon device applications outside particle physics

astronomy
DNA lab-on-a-chip

using HEP pixel detectors (Medipix-Timepix)

mass spectroscopy real-time, for surgery
space dosimetry with quantum-identification
silicon CCD in astronomy
Orthogonal Transfer CCD can internally compensate for distortions

5x5 cm OTCCD array with backside incidence
1995-2000 Lincoln Lab MIT

images from Burke et al. - Lincoln Lab Journal 16 (2007) 393-412
silicon CCD in astronomy

CFH Canada-France-Hawaii
CCD array of 12 units, Lincoln Lab
10^8 pixels 15µm --> 228 cm^2
Mauna Kea 1998

Burke et al. - Lincoln Lab Journal 16 (2007) 393-412
silicon for DNA analysis

Crick & Watson used DNA single crystal and X-ray diffraction photography

limited structural analysis

nano CMOS technology using ion-sensitive FET:
now the "lab-on-silicon-chip" changes everything
$1,000 Genome Machine on a Chip

660 Million Sequencing Reactions
-14,000 on the End of a Human Hair

slide J. Rothberg, plenary 1.3 –IEEE-ISSCC 2017
1970 ISFET by P. Bergveld

1973 PhD Thesis
Piet Bergveld
U. Twente NL

detects chemical process
that changes pH of liquid

much more sensitive if
the transistor is very small

then large array possible
with nano-pores

a fragment couples to
known DNA in pore --> H⁺

The Ion Sensitive Transistor

Fig. 3. Schematic representation of MOSFET (a), ISFET (b), and electronic diagram (c).

basic slide J. Rothberg, plenary 1.3 -IEEE-ISSCC 2017
Silicon Timepix for mass spectroscopy

Separation of heavy molecules by Time-of-Flight

figure from J. Jungmann – PhD Thesis Univ Utrecht (2011) p. 96
Timepix for mass spectroscopy

Comparison of mass spectra for different methods and 3 gains in MicroChannelPlate

figures from J. Jungmann – PhD Thesis
Univ Utrecht (2011) p. 97-103
Exploitation of Si systems in space experiments

Large Si telescopes use expertise from HEP experiments

AMS primarily aimed at antimatter
Fermi/GLAST study of energetic photons
gamma bursts

Small Si pixel devices allow radiation studies “in a nutshell”
perfect for pico-satellites

SATRAM (Timepix) on PROBA-V satellite from ESA at ~800km altitude

Dosimetry at the Int Space Station ISS

REM Orbital Dose Rate Map (uGy/min)
D03-W0094 (S/N 1007)

D03-W0094 (S/N 1007): 2014-11-01 → 2015-02-01

University of Houston, IEAP Prague, NASA

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Timepix on ProbaV ‘SATRAM’

Radiation field Earth map spatial distributions measured by Timepix onboard ESA Proba-V satellite LEO orbit 820 km altitude displaying all radiation components integrated over 5.5 months.

South America, Antarctica, South Atlantic Anomaly SAA
particle physics again
The main innovations

A. Segmentation of the sensor area in ever smaller cells
B. Every sensor cell has full own signal processing circuit in parallel
C. Signal processing for single quanta, instead of charge integration
D. Temporary data memory provided on-chip for each signal channel
E. Rectangular sensor design allows 100% active, contiguous array
   - smaller sensor capacitance improves noise level
   - smaller sensor volume has reduced dark current, also improving noise
   - < 10 micrometer precision of particle impact point
   - comparison of analog signals in charge sharing gives even better precision
   - lower noise allows use of thinner sensors for the same signal/noise
   - electrical power for many small cells is lower than for fewer larger cells
     but there is logical processing & transmission overhead
Often thermal noise from the input transistor dominant, in that case:

\[
\frac{S}{N} \sim \frac{Q/C}{\sqrt{gm}} \sim \frac{Q}{C} m^{\sqrt{I}} \sim \frac{Q}{C} m^{\sqrt{P}} \text{ with } 2 \leq m \leq 4
\]

\( m = 2 \) for weak inversion
\( m = 4 \) for strong inversion

For constant S/N:

\[
P \sim \left[ \frac{Q}{C} \right]^{-m} \text{ with } 2 \leq m \leq 4
\]

**smaller capacitance allows larger S/N & lower power**

Collected charge \( Q \) over sensor/input capacitance \( C \) ratio:

- Determinant for analog power consumption
- Very important figure of merit for a particle sensor
- Want SMALL collection electrode for low \( C \)
- Interest of sensor segmentation

**aim at pixel 3x3x3 \( \mu m^3 \) voxel**

**even smaller is possible**

capacitance \(~0.3 fF\)
noise \(<15 e^{-} \text{ rms (?) \( \text{mip signal} \sim 150 e^{-} \)}\)

**fundamentals from Walter Snoeys**

11 million cells/cm\(^2\)
The main innovation
Segmentation of the sensor area into ever smaller cells

Improvement of signal/noise allows thinner sensor: < 100µm
# Miniaturization

<table>
<thead>
<tr>
<th>Type</th>
<th>Sensor Cell Area</th>
<th>Sensor Thickness</th>
<th>Capacitance</th>
<th>Mean Signal</th>
<th>Noise 3xENC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Diode</td>
<td>1x1 cm²</td>
<td>0.3 mm</td>
<td>~30 pF</td>
<td>21 ke⁻</td>
<td>6 ke⁻</td>
</tr>
<tr>
<td>Microstrip 1D</td>
<td>20x0.1 mm²</td>
<td>0.3 mm</td>
<td>~3 pF</td>
<td>&lt;21 ke⁻</td>
<td>4.5 ke⁻</td>
</tr>
<tr>
<td>Pixels 2D</td>
<td>0.05x0.05 mm²</td>
<td>0.1 mm</td>
<td>~0.03 pF</td>
<td>2-7 ke⁻</td>
<td>0.4 ke⁻</td>
</tr>
<tr>
<td>Voxels 3D</td>
<td>0.005x0.005 mm²</td>
<td>0.005 mm</td>
<td>~0.001 pF</td>
<td>300e⁻</td>
<td>50 e⁻</td>
</tr>
</tbody>
</table>

Future development as monolithic detector

Voxel electronics requires advanced technology of a few nanometer dimensions

---

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Stacked imager

Implementation result

- Top chip
- Bottom chip

- Process:
  - Top: 90-nm 1P4M
  - Bottom: 65-nm 1P7M

- Supply Voltage: 2.9 / 1.1 [V]

- Pixels:
  - 1632(H) x 896(V)
  - 1.46M ADCs, 408 Repeaters

- Pixel pitch: 6.9[μm]

- Output interface:
  - 16ch x 4.752 [Gbps/ch]
  - SLVS-EC

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M. Sakakibara et al. Sony; paper 5.1
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Samsung submicron imager with deep-etched separation

'thick' Si: now 4µm instead 2.7µm to improve signal in red
There's plenty of room at the bottom

*Richard P. Feynman 1959, APS at Caltech*
CONCLUSION

Technical innovation essential for physics progress

- silicon replaces liquid and gas;  rates go from Hz to kHz to MHz

Electronics determines sensors and systems

- 'ultra'pixels implemented in advanced nanotechnologies?

Low noise achieved by sensor segmentation

- segmentation is also solution for dark current, even mA

- pixel detectors for multiplicity and precise positions

- Si drift detectors for precise energy spectra, extreme signal/noise

Timing at ps precision next frontier

- silicon not adapted? avalanche layer?  light is faster than electrons

Other technologies?

- stacking of active layers  integrated cooling  real μm imaging
Future experiments will rely on newest electronics need timely R&D efforts, expertise and resources worldwide collaboration & tens of millions to do it right

Thank You
The progress of science has always followed the development of the experimental arts, and this has been as true in nuclear physics as it has been in astronomy, chemistry and biology. One has only to mention the ionization counter, the cloud chamber, the scaling circuit, nuclear emulsions, magnetic spectrometers, the modern scintillators, and the bubble chamber to bring to mind the historical framework of experimental nuclear physics. To this distinguished lineage we may now have to add the semi-conductor detector. [Its characteristics] place it in a class by itself, and [as such it] is likely to go a long way.

Arthur H. Snell
Chairman, Subcommittee on Instruments and Techniques
USA National Academy of Sciences

Proceedings Conference Semiconductor Nuclear Particle Detectors
Asheville NC, USA, 28-30 September 1960
NAS-NRC Pub 871