Silicon is for physics what carbon is for life

Erik H.M. Heijne

Inst. of Experimental and Applied Physics of the Czech Technical University in Prague
CERN EP Department Geneva
1990 in RD19 we started with both monolithic and hybrid, but hybrid proved much easier for quick results and ~1995 we abandoned monolithic today, monolithic may fulfill even ATLAS needs, if pixels can be made sufficiently small

but note that consumer imagers move to hybrid ...!!!

BSI on CMOS is expensive
STREAM Summer School

Advanced radiation detectors + long-term reliability

Why semiconductors? Why silicon? Historical perspectives

The sensor and the associated signal+information processing

From 0- to 1- to 2-D Now towards 3D detection with Si existed already in gas or liquid detectors

Monolithic/3D CMOS detectors with fully integrated processing

Reliability & radiation hardness of sensors & integrated circuits

First thing: what is going on elsewhere, and where best to look?
STREAM Summer School

Measurement is the basis for understanding at least since Galilei and van Leeuwenhoek

Technology is the basis for measurement

Instead of evolutionary, progress may be disruptive

Reconsider prejudices: your own, and those of others

What was impossible 5 years ago, may have become feasible

Thousands of scientists work in all corners of the planet

My own activities were guided by visits at other labs, conferences by IEEE (NSS, NSREC, IEDM, ISSCC,..) and workshops Many visits and personal contacts in industry
Some potentially controversial points

note that I am semiconductor, not particle physicist

UPGRADE SHOULD BE AMBITIOUS

NO TRIGGER, READ ALL ?? as intended by LHCb

INVESTIGATE VECTOR DETECTOR

SEMICONDUCTOR or GASEOUS after all

INTEGRATE TRACKING and CALORIMETRY

FLOW APPROACH, FULLY RESOLVE JETs

USE INDUSTRY TRENDS in Si towards '3D'

THICK Si TRACKing & IMAGING

R&D MUST INCLUDE SYSTEM ASPECTS

HARDWARE but also SOFTWARE & ANALYSIS TIME
on earth silicon is more abundant but carbon has been more successful versatility and lower binding energies
**Mendeleev <1900**

**Periodic Table of Elements**

<table>
<thead>
<tr>
<th>Period</th>
<th>Group</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IA</td>
<td>H</td>
</tr>
<tr>
<td>2</td>
<td>IIA</td>
<td>Li, Be</td>
</tr>
<tr>
<td>3</td>
<td>IIIA</td>
<td>Na, Mg</td>
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<tr>
<td>4</td>
<td>IIIB</td>
<td>K, Ca</td>
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<tr>
<td>5</td>
<td>IIIC</td>
<td>Sc, Ti</td>
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<tr>
<td>6</td>
<td>IIID</td>
<td>V, Cr</td>
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<tr>
<td>7</td>
<td>IIIE</td>
<td>Mn, Fe</td>
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<tr>
<td>8</td>
<td>IIIF</td>
<td>Co, Ni</td>
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<tr>
<td>9</td>
<td>IIIG</td>
<td>Cu, Zn</td>
</tr>
<tr>
<td>10</td>
<td>IIIV</td>
<td>Ga, Ge</td>
</tr>
<tr>
<td>11</td>
<td>IIIV</td>
<td>As, Se</td>
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<tr>
<td>12</td>
<td>IIIV</td>
<td>Br, Kr</td>
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<tr>
<td>13</td>
<td>IIIV</td>
<td>Rb, Sr</td>
</tr>
<tr>
<td>14</td>
<td>IIIV</td>
<td>Y, Zr</td>
</tr>
<tr>
<td>15</td>
<td>IIIV</td>
<td>Nb, Mo</td>
</tr>
<tr>
<td>16</td>
<td>IIIV</td>
<td>Ta, W</td>
</tr>
<tr>
<td>17</td>
<td>IIIV</td>
<td>Re, Os</td>
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<tr>
<td>18</td>
<td>IIIV</td>
<td>Ir, Pt</td>
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<tr>
<td>19</td>
<td>IIIV</td>
<td>Au, Ag</td>
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<tr>
<td>20</td>
<td>IIIV</td>
<td>Hg, Tl</td>
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<tr>
<td>21</td>
<td>IIIV</td>
<td>Pb, Bi</td>
</tr>
<tr>
<td>22</td>
<td>IIIV</td>
<td>Po, At</td>
</tr>
<tr>
<td>23</td>
<td>IIIV</td>
<td>Rn, Fr</td>
</tr>
</tbody>
</table>

**COMPOUNDS**

- also: Hgl₂ (AgCl) etc.

---

**Legend - click to find out more...**

- H - gas
- Li - solid
- Br - liquid
- Tc - synthetic

- Non-Metals
- Transition Metals
- Rare Earth Metals
- Halogens
- Alkali Metals
- Alkali Earth Metals
- Other Metals
- Inert Elements
Mono-crystalline semiconductors

- sensitive to visible light (CCD, CMOS camera)
- also all other sorts of radiation (>1.12 eV bandgap)
  LOW Z, not efficient for $\gamma > 10$keV
- conductivity adjustable over 10 orders ($10^{10}$-$10^{20}$)
- surface oxide provides high impedance isolation

~1955 Bell, 1959 Planar (Hoerni-Fairchild), 1970 LOCOS (Kooi, Philips)
Ionization energy of atoms

- Ionization energy of isolated Si atom: 8.15 eV
- Noble gases have the highest ionization energies: 15-25 eV
- But electrons can move relatively free in gases.
Semiconducting single crystal is different

Overlapping electron waves:

Electrons are shared throughout whole crystal...

Ionization:
8.15 eV $\rightarrow$ 1.12 eV

e-h pair 3.64 eV

Exclusion principle applies to a whole crystal
$\rightarrow$ filling of energy bands
silicon is 2\textsuperscript{nd} most common element (28\%) in earth crust quartz (SiO\textsubscript{2})

sand - mostly SiO\textsubscript{2}
Silicon single crystal growing

1955-2017

Wafer sizes

Increase of wafer diameter 3/4” - 450mm

diameter 450 mm
area 1590 cm²
coming 2018?

CZ Crystal Pullers
(Mitsubishi Materials Silicon)
Very large silicon single crystal $\Phi$ 45 cm

450mm still not widely accepted as next standard.
CMOS foundries worldwide use $\Phi$ 30 cm
Some approximate economics, just to get a feel:

Worldwide production of Si wafers 2015 was $67 \times 10^9 \text{ cm}^2$ (6.7 km$^2$) corresponds to 96 million wafers of 300mm diameter (700 cm$^2$) Revenue in Si was only 7.2 B$, amounts to average of 10.7 cents per cm$^2$ or 75$ for a polished 300mm wafer

High resistivity Si much more expensive, available up to Ø150mm (200mm?)

Typical wafers processed in major foundry: some thousands/day, 1M/year

Worldwide sales of semiconductor devices in 2015 revenue 333.7 B$ if all Si area were used --> 5$ per cm$^2$

the raw Si enters for only 2.1% in the cost of the devices

expected revenue in 2017 378 B$ with growth 12% to 2016

data from SEMI website
Plans for Si particle tracking systems

1960

~1959 proposal of diode array suggested at Hughes Aircraft by Friedmann and Mayer reported by Bromley in Asheville

1998

1998 artistic concept in CMS Technical Design Report for the inner Si tracker
The 1980 revolution in Si detectors

In 1980 several ‘revolutionary’ innovations took place, that were to shape silicon detectors for future applications in particle physics and other fields

1. Segmented surface barrier detector, 19 strips, pitch 0.6mm made in Pisa. NIM 176 (1980) 457, Amendolia et al. (Menzione, Bosisio,..) readout 2-ch, in beam at CERN

2. Si microstrip detectors, 100 strips, pitch 0.2mm, Heijne, Burger, Jarron, CERN made at Enertec, Strasbourg; tested May at CERN, with full readout and a first vertex reconstruction by Jos Vermeulen and Andrew Wylie: NIM 178


Charmed particle 2\textsuperscript{nd} vertex recognition

\textbf{NA11 CHARM EXP}

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

Invariant mass distribution of Lambda with wirechamber spectrometer only in spite of large statistics, ‘NO’ selectivity

using new technology: Si microstrip detectors + CCD  
2D helps much more  
CCD by Damerell cs.

much less background events  
much improved sensitivity  
NA11 can run at reduced beam intensity

DRAMATIC IMPROVEMENT!
Segmented silicon detectors

- **~1965**
  - PHILIPS-Amsterdam
  - 100 x 1370µm x 1370µm
  - Ammerlaan, van Dantzig, Visschers

- **1980 CERN / ENERTEC Strasbourg**
  - 100 x 4000µm x 200µm
  - Jarron, Burger, CSEM, Kemmer

- **1989-2000**
  - Pixel detectors developed at CERN
  - Smallest pixel side ~50µm
  - Campbell, Snoeys, LAA, IMEC, ETHZ, EPFL, RD19, Omega, Medipix
Early <1990 readout chips for segmented Si detectors

SLAC/(DELPHI)
Microplex 1983
Walker, Parker, Hyams, Shapiro
NIM A226 (1984) 200

RAL/DELPHI
MX1 MX2 1987
Seller, Allport, Tyndel
IEEE TNS 35(1988) 176

CAMEX64/ALEPH-MPI
Buttler, Lutz, Hosticka
Becker et al. IEEE TNS 36(1989) 246

CDF-SVX Kleinfelder 1988
Kleinfelder et al. IEEE TNS 35(1988) 171

AMPLEX (UA2)
Pierre Jarron 1987
classical, continuous feedback
actually the first in a collider:1988
Beuville et al. NIM A288 (1990) 157

Chips NOT to scale
Hermetic Si pad detector for UA2

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

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

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

R. Ansari et al. NIMA279(1989) 388

1986 – 1988 in LAA microelectronics project
Hermetic Si pad detector for UA2

2015 Inner-B-Layer ATLAS IBL

2nd Generation Insertion

Figure 1: Picture of IBL insertion into the ATLAS detector.
from Bubble Chambers to fully Electronic Silicon Imagers

BEBC 1981
photo every ~1s

LHC 2016
40 million records per s

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

Liquid H$_2$O silicon for vertexing (but full image information is lost)
Imaging Now
All Electronic
with 3-D
Reconstruction

Many Tracks
+ here 2 “Jets”

40 million / sec

Second Vertex:
a short-lifetime
particle is a
messenger for
new phenomena

next: blow-up

source: CERN-ATLAS
ATLAS

Details around Primary Vertex

Two Secondary Vertices: “messengers”

Note scale
1cm
all this is INSIDE beam pipe $\varnothing$ 7cm

source: CERN-ATLAS
Collision Event at 7 TeV with 2 Pile Up Vertices

Reconstruction needs 3 inner pixel layers

10cm

7cm

vacuum beam pipe

source: CERN - ATLAS


source: CERN- ATLAS
Increase of the size of silicon detector systems in all LHC experiments and in many others
Radiation effects in equipment have been an issue for spacecraft since Telstar.

Dose levels even much higher inside collider experiments: krad -> Mrad. 
~1988 only ‘iron-ball’ experiment looked possible, what to do?

Understanding of the particle interactions in Si and Si-oxide + beam testing.

The 3 main radiation effects require 3 main solutions:
- Oxide threshold shift disappears due to tunneling, if oxide <5nm, suggestion based on work Nelson Saks, NRL Washington.
- Edge leakage current under thick oxide avoided by enclosed layout, solution implemented ~1978 at RCA Princeton by Ron Smeltzer.
- Single event effects (upset, burnout,..) avoided by triplication, standard approach in avionics, visit by Eugene Normand Boeing.

These ‘innovations’ allowed financially acceptable radiation hard chips.

A serious situation avoided by learning from specialists 1984-1997.

Radiation hardness improvement of sensors has also been achieved. Segmentation helps for dark current and signal loss.
Integrated electronics is key: silicon MOS transistor

2 µm TECHNOLOGY
1985

HEP was 2 generations behind industry

SiO$_2$ gate thickness 2.75 nm

gate length .016 µm

continuous scaling/miniaturization

2015

Erik HEIJNE IEAP-CTU & CERN EP Department

STREAM School CERN 6 November 2017
Integrated electronics is key: silicon MOS transistor

2 \mu m TECHNOLOGY

1985

HEP was 2 generations behind industry

0.016 \mu m

2015

now HEP is 8 generations behind

SiO$_2$ gate 2.75 nm
thin gate is radhard

ongoing miniaturization

on the same scale
Integrated electronics is key: silicon MOS transistor

**Continuous scaling/miniaturization**

- **2015**
  - Same scale
  - Gate length: 0.016 µm
  - SiO₂ gate thickness: 2.75 nm
  - Thin gate usually radhard

- **2017 development at IBM**
  - Gate-all-around
  - Source: IBM
  - Not same scale

**2 µm TECHNOLOGY**

- **1985**
  - HEP was 2 generations behind industry

**0.005 µm**

- **2017**
  - Now HEP is 8 generations behind
Ever more advanced (smaller) nm CMOS

INTEL: large improvement in lithography ≤45 nm

example: minimal SRAM cell

Several characteristics also have been improved, well beyond expectations

linear scale 4x smaller; area 10.8 x smaller

Mrs Kelin KUHN
IEEE IEDM 2007 & 2010
SAMSUNG: Trend in NAND memory cell 1996-2008

FLASH UNIT CELL 0.00375 um² → 260 cells/um²
Microelectronics essential for experiments vice versa: CMOS chips impossible without accelerators

major tools for CMOS manufacturing:
- ion implanters
- analysis equipment: X-ray, RBS, fluorescence, e-beam scanning SEM/TEM

ION IMPLANTATION FOR SEMICONDUCTOR DEVICES: THE LARGEST USE OF INDUSTRIAL ACCELERATORS

S.B. Felch, Susan Felch Consulting, Los Altos Hills, CA 94022, USA
M.L. Current, Current Scientific, San Jose, CA 95124, USA
M.C. Taylor, Taylor Consulting, Lake Oswego, OR 97034, USA

~300/year
Silicon 2D pixel detectors from 1989 can handle hundreds of simultaneous particles. Smaller cells allow improved signal/noise S/N. Example: Timepix development, now prototype for LHCb Velopix vertex upgrade.
TIMEPIX original cell layout

design by
Xavier Llopart
and colleagues
PhD Thesis p. 107
CERN 2007

1. PREAMPLIFIER CSA
2. THRESHOLD, 4-BIT TUNING
3. 8-BIT CONFIG REGISTER
4. REF_CLK & SYNCHR LOGIC
5. 14-BIT COUNTER

includes Time-Over-Threshold signal amplitude digitizer in each pixel
Hybrid Pixel Detector - Basic Circuit

Timepix can easily distinguish Fe\textsuperscript{55} line used for energy calibration in-pixel ToT → imaging free of noise
Timepix Pixel Operation Modes

Particle counting

Open shutter Close shutter

Arrival Time*

Open shutter Close shutter

Time over threshold

Open shutter Close shutter

* originally implemented at the request of the EUDet Collaboration for use in gas-TPC
TIMEPIX silicon 'emulsion'/portable 'bubble chamber'

H6 120 GeV p/π beam 2007

incident from the right

Beam

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
or: see hereafter, new Timepix3

beam test with help of
John Idarraga / then Montréal
Timepix3 track entry point & direction

carrier drift time in z-coordinate is always recorded in each pixel: 0 to ~15ns
currently with 1.2ns precision
future chip intends to achieve well below 1 ns

ambiguity is resolved and entry point is precisely known

useful for high-energy electrons at ~low intensity in microscope
500µm thick sensor can stop electrons ~350keV; little radiation damage
Timepix3 3D track reconstruction

120 GeV $\pi$

60 deg
p+ in n Si sensor
500$\mu$m thick
$V_{bias} = 130$V
Colour (and diameter) indicate charge
Measured z resolution $\sim 50\mu$m

Slide courtesy of B. Bergmann, S. Pospisil, IEAP, CTU, Prague
Photosensitive Emulsion, a slow 3D Detector

Thick gelatine film with AgBr

3D, sub µm precision

CHARM DECAY
Photon exp. WA59 ~ 1985

Successive ionizing energy transfers (~5keV) to grains create latent image

50 µm

500 µm
Particle Physics Old Times (2m Chamber CERN)
Typical Muon Trails in Timepix ...

T3-1500

bubble in BEBC

T3-1504

T3-1507
Arguments for imaging detector

Tracking with many pixels (15-30) improves precision
  allows to exclude points corrupted by a d-ray
  possible to reach precision <0.1µm

Reduction of ambiguities in reconstruction process
  recent 2-point stubs design helps, imaging goes further

Additional information on type of particle: improved dE/dx

Specific features help to identify energetic leptons (e, µ)
  transverse momentum, delta rays, lateral scattering

Sensitivity for exotic things
  e.g. clusters from neutrals, interactions at very low energy
Towards 3D voxel/vector detector
5µm x 5µm x 5µm
monolithic, stacked
The main innovation
Segmentation of the sensor area into ever smaller cells

Improvement of signal/noise allows thinner sensor: < 100µm
Voxel electronics requires advanced technology of a few nanometer dimensions. The table below compares different detector technologies:

<table>
<thead>
<tr>
<th>Technology</th>
<th>Area</th>
<th>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.

S/N 13

S/N 35

S/N 15
Matrix with smaller cells performs better in noise and power:

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

or

\[
P \sim \left\{ \frac{S}{N} \right\}^m
\]

with \(2 \leq m \leq 4\).

For constant S/N:

\[
P \sim \left[ \frac{Q}{C} \right]^{-m}
\]

with \(2 \leq m \leq 4\).

Signal charge/detector capacitance \((Q/C)\) is the figure of merit for the sensor determining the analog performance/power consumption.

\(m = 2\) for weak inversion up to \(4\) for strong inversion.
small changes all

mosquito 5 mg

$5 \times 10^{-3} \times 6 \times 10^{23} \sim 3 \times 10^{21}$ nucleons

walks upside down as well
represents same energy as LHC proton, but not concentrated
3-D Stacked Si for flash memory
256 Gb 48 layers -- 2016

now in 2017 64 layers, 512 Gb

Samsung Electronics, Korea

can store 3 bits per cell

how to access this for science???
‘old’ example of 3D memory stacking; 48 layers in 2016

16 Chip Stacking Technology

- Pad Relocation using WLI
- 30 um Wafer Thinning
- Laser Sawing
- Damage-less Die Pick-up
- 250um Overhang
- 50um Loop Height

SAMSUNG at ISSCC 2007
3D Stacked Pixel Imaging Unit

Spacer to achieve circle

ELECTRICAL CONNECTIONS + READOUT

periphery 0.44mm
64 pixels 2.56mm
total 3 mm

20.5 mm
512 pixels
40x40µm

Spacer to achieve circle

READOUT CHIP
25 µm 30 µm

COOLING SHEET
DIAMOND?

COOLING and SUPPORT

200µm
Speculative design for a thick tracker

Full Pixel System of 20 rings, 40cm long:
- Number of chips 20x200x4 = 16 000
- 16 000 x 32768 = 525 000 000 pixels

Overall layer structure:
- Basic Unit has 4x512 pixels of 200µmx40µm
- Coverage is 200 x 2064 = 400 000 pixels per layer
- Occupancy ~1% for 1000 interactions/average multiplicity 40
- 20% Insensitive area from readout chips and spacers, remedy could be to incline basic units
- 64 layers deep along the radius

Operational:
- Ultra-LHC 1000 collisions/crossing
- 40 000 tracks x 64 pixels generate 1010 carriers/10ns
  - Continuous signal current ~0.1A
  - Dark current ~equal 16 000 x 10µA = 0.16 A

Highly speculative indeed, many mechanical and electrical issues....
What could be physics gains for such a system?
silicon is catching up on carbon scientific applications abound
carried by high volume in consumer field
disruptive and new applications
a few scientific silicon device applications outside particle physics
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:
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
DNA sequencing in USB device

single molecule analysis
  e.g. protein or DNA
via ‘nano’ hole in polymer foil
on top of a Si readout chip

see
https://www.nanoporetech.com/
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

0.2 µm pores
4µm

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

Heather and Chain, Genomics 107 (2016)

The Ion Sensitive Transistor

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

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basic slide J. Rothberg, plenary 1.3 – IEEE-ISSCC 2017
silicon imagers in astronomy

photographic recording in astronomy has nearly completely disappeared since the introduction of high quality silicon imagers

long exposures now can be made in separate steps

various on-line processing methods

electronic processing of spectra into (false) colors
silicon CCD in astronomy

Orthogonal Transfer CCD can internally compensate for distortions

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

part of M71 star cluster

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

Erik HEIJNE IEAP-CTU & CERN EP Department
STREAM School CERN 6 November 2017
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 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 the mass spectra by 3 different methods and 3 gains in MicroChannelPlate

Timepix spectrum less noise
better resolution
+ image of sample

Radiation imagers for schools and amateurs
with educational kit

IEAP/CTU, Prague

IEAP/CTU, Prague

Jablotron &
IEAP/CTU, Prague

AdvaCam &
IEAP/CTU, Prague

CERN Timepix imager inside

http://ardent.web.cern.ch/ardent/ardent.php

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Timepix for dosimetry in Int Space Station ISS

AMS largest space experiment.... Pixel chip maybe smallest
Timepix SATRAM on PROBA V at 820km

Space Application Timepix Radiation Monitor

Launched 7 March 2013
Altitude ~820km (Low Earth Orbit)

Carlos Granja
from talk EPS Ravenna Workshop

Erik HEIJNE IEAP-CTU & CERN EP Department
4s Timepix exposure taken in ISS passing over South China Sea
Timepix dosimetry at the Int Space Station ISS

4s Timepix exposure taken in ISS passing through SAA South America Anomaly

various types of quanta can be identified and accounted for in personal dosimetry
Timepix dosimetry at the Int Space Station ISS

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

University of Houston, IEAP Prague, NASA
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.
Observe exotic phenomena already in space?

Clusters observed with Timepix pixel detector at 850km altitude in ESA Proba V mission SATRAM experiment 2013-2014

Most of these clusters (from several frames) can be explained as energetic heavy ions sometimes come from nuclear interaction in upstream material.
STON Age

IRON AGE

SILICON AGE

BRONZE AGE
Main points

how to innovate

silicon for science and technology =
  = similar to carbon for evolution of life

sensor design depends closely on signal circuits

silicon is disruptive in society and in science

miniaturization basis for better measurements

examples of silicon in other science fields
  using our pixel detectors or other

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

........
End of the beginning
Find alternatives to enable triggers in Ultra-LHC (1000 collisions/crossing) if muons and calorimetry run out.

2025-2035 Horizon

increase of intensity probably the main option for long-term operation of LHC

as long as radiation levels can be supportable

hints for TeV-energy physics may be found in space

virtual particles in high-precision LHCb?
Physics experiments should exploit recent industrial Si technology (<20nm) and achieve:

- lower power for same functions
- ps timing
- more on-chip memory
- multilayer information processing
- economy of scale
- ....
- higher rates, better data
- new physics?
CMOS readout circuits in 32nm, 14nm,..via & 3D stacking

More recent nanoCMOS technology also for sensors

Monolithic detector chips in CMOS instead of hybrid ......

more on-chip memory

Smaller pixel capacitance: 100 e\(^{-}\) on 0.1 fF -> 160mV

ultrapixels of ~2x2\(\mu\)m\(^2\) need charge from ~3\(\mu\)m Si ---> 32nm CMOS +fast

Larger wafersize can be used if smaller pixels

Faster signals allow timestamps ‘inside-crossing’ <20ps?
Moore’s uncertain future

saturation since 2000
still more transistors
power improves

slide by
Michael Campbell
from Economist article

Sources: Intel; press reports; Bob Colwell; Linley Group; IB Consulting; The Economist

* Maximum safe power consumption
End
Silicon for Science

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Future HEP experiments will rely on newest electronics need timely R&D efforts, expertise and resources worldwide collaboration & tens of millions to do it right