The silicon crystal

Diamond structure (tetrahedron)
Unit cell has 8 atoms

Shared electrons in covalent bond

110

100
Silicon wafers as you can buy

Integrated Circuits (IC) on a Silicon wafer

4” (10-cm) silicon wafer processed at BNL
Two great materials: Silicon vs Steel

Max Zorin: “For centuries alchemists tried to make gold from base metals. Today, we make microchips from silicon, which is common sand, but far better than gold”
Two great materials: Silicon vs Steel

Shockley, Bardeen, Brattain 1950

Moore, Noyce, Grove at Intel 1978

Falcata (4th century BC)
Electrons and holes

Doping in Semiconductors

Array of Si atoms

n-type semiconductor

p-type semiconductor

Silicon

Electron

Phosphorus

Boron

Doped semiconductor
In forward bias, high currents flow.
In reverse bias, the current is blocked, so the Voltage must fall in a region with $\rho \neq 0$:
Electrons (holes) are swept away from $n$- ($p$-) type silicon leaving a net positive (negative) charge,

\[ \frac{dE}{dx} = -\frac{\rho}{\varepsilon} \]

Since charge neutrality holds ($\rho = 0$),
$E = \text{constant} = V/\text{thickness}$
Diode in integrated circuits

From the top

Diode as a sensor unit

Section

- N+ implant
- P+ implant
- n-well
- P substrate

< 1μm

lightly doped n-substrate

E

< 1μm

~500μm

n+ implant
Mechanism of radiation detection

Ionizing radiation (photons or charged particles) creates free charges in the bulk. Electrons and holes drift in opposite directions, following the electric field lines, creating current pulses at the electrodes.
Why sensors made of silicon?

- Very well developed technology (simplified version of IC’s)
- Fair signals created, “easily” detected (3.6 eV for the creation of an electron/hole pair)
- Operation close to Room Temperature (RT)
- Possibility to finely segment the electrodes down to few tens of μm
Absorption of photons in Silicon

If $N_0$ photons enter the silicon, after a distance $L$, the number of photons which have not been absorbed by silicon is: $N = N_0 \exp(-L/l)$, where $l$ is the attenuation length.

- Silicon detects with good efficiency above 20 eV and below 20 keV.
- Visible photons create just one couple e⁻/h⁺.
Interaction of charged particles with silicon: the Bethe Block formula

In most practical cases, we are here, i.e. at the minimum of energy loss. Still, a m.i.p. (minimum ionizing particle) produces 80 pairs/μm in Silicon (for 300 μm → 24k electrons)

Landau distribution

Signal distribution in 300μm silicon

- Peak = 23512.3
- FWHM = 49.8%

Not-relativistic particles

relativistic particles

- $dE/dx$ (MeV g$^{-1}$ cm$^{-2}$)
- $\beta\gamma = p/Mc$
- Muon momentum (GeV/c)
- Pion momentum (GeV/c)
- Proton momentum (GeV/c)
Read-out chain

- Can be made by separate blocks
- Modern trend: integrate everything in a IC

ASIC: Application Specific Integrated Circuit, designed in house but fabricated in TSMC, IBM, AMS, ST, …
The common trend is to fabricate the CSA in CMOS technology: smaller, good electrical properties, cheap. For example, state-of-the-art is CUBE ~1x1x1 mm$^3$. 

Charge Sensitive Pre-Amplifier

Input transistor

feedback

Double source-follower stage

Charge preamp ©Radeka 68
Filtering in the frequency domain = Shaping in the time domain
- Limit the bandwidth to limit the noise
- Noise depends on shaping time
- Modern trend: to go from analog to digital shaping
Peak detection

# electron/hole pairs ~ amplitude of CSA output ~ amplitude of shaper output.

Stored for a short period of time, then fed to Analog-to-Digital Converter. Then sent out for processing.

Low-activity X-ray-emitting radioactive materials are used as calibration sources.
Noise in a detection system

\[ \text{ENC}^2_{\text{parallel}} \sim I \text{ leakage } \tau \]

\[ \text{ENC}^2_{\text{series}} \sim C^2 / \tau \]

\[ \text{ENC}_{\text{flicker}} \sim \text{constant} \]

\[ \text{ENC}^2_{\text{total}} = \text{ENC}^2_{\text{parallel}} + \text{ENC}^2_{\text{series}} + \text{ENC}^2_{\text{flicker}} \]
**Patterning the electrodes**

It gives information about the position of the incident radiation

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Pixels, pads, strip are possible, in a large variety of dimensions, ranging from few μm to mm, depending on the application.
Pad sensor
Array of ~ 400 square pads at a pitch of 1 mm

MAIA microprobe detector for elemental analysis in synchrotrons
Microstrip sensors

Long narrow electrodes give position just in direction normal to the strips:
Two planes to reconstruct the 2D position

Used in trackers in physics experiments, and in few other applications that need just 1D
Hybrid pixel = sensor + readout

Price to pay? $N^2$ channel w.r.t. $2*N$ of strip sensor
Bump bonding is difficult and expensive → go for a pixel sensor on a chip!!

The sensor is integrated in the same substrate of the electronics.

Drawback: the active region is thin (not a problem for mip, problem for X-rays)

Modern trend: Inner tracking system in physics experiment are made of MAPS

← STAR tracker
ATLAS inner tracking system

- Barrel semiconductor tracker
- Pixel detectors
- Barrel transition radiation tracker
- End-cap transition radiation tracker
- End-cap semiconductor tracker

Dimensions:
- 6.2m
- 2.1m
CMOS Cameras

- Array of many small pixels (~ M), for visible light detection
- Fabricated in CMOS technology
- Pushed by digital photography

“three-transistor read-out” in each pixel
Charge Coupled Devices

Willard S. Boyle and George E. Smith developed the charge-coupled device in 1969 while working at Bell Laboratories.
Silicon Drift Detectors

Invented at BNL in 1984

It is possible to deplete the substrate by means of a point-like anode. Anode connected to ROIC, while voltages applied to the cathodes create an electric field following which the electrons drift to and are collected by the anode. No matter how large the area is, the anode is small and so the capacitance and the noise.

V_D = 50 V
d = 300 µm

Electrostatic potential

\[ p^+ \quad n^+ \quad n^- \]
Large area silicon drift detectors used in the tracker of ALICE at CERN
Silicon Drift Detectors as X-ray spectroscopy detectors
Due to the low capacitance, they have the lowest noise: can detect lowest-energy X-rays

Electrostatic Potential

Entrance window

cathodes

anode

X-rays enter from the uniform entrance window
Silicon PhotoMultiplier (SiPM)

Visible photons create just one e-/h+ pair, beyond detection. But, if one electron crosses a high-electric field region, it triggers an avalanche. Microcells (single Avalanche Photo-Diodes) work above the breakdown voltage.

Alternative to vacuum photomultipliers tubes for the detection of single visible photons

**Pros:** smaller, insensitive to magnetic fields, low V, cheap

**Cons:** high dark count rate
Single Photon Detection

A signal is induced by just one electron, but it is made by ~1M electrons (i.e. huge gain)