Silicon Detectors
part 1

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EDIT school 2023

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U.S. DEPARTMENT OF ENERGY

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Why sensors made of silicon?

- Silicon is a semiconductor sensitive to photons and charged particles
  Fair signals created, “easily” detected
  No need of multiplication (in most applications)

- Silica (SiO_2) everywhere
  “easy” to make silicon crystals

- Very well-developed technology (simplified version of Integrated Circuits - IC)
  - Silicon dioxide excellent insulator
  - Possibility to finely segment the electrodes down to few tens of μm

- Operation close to Room Temperature (RT)

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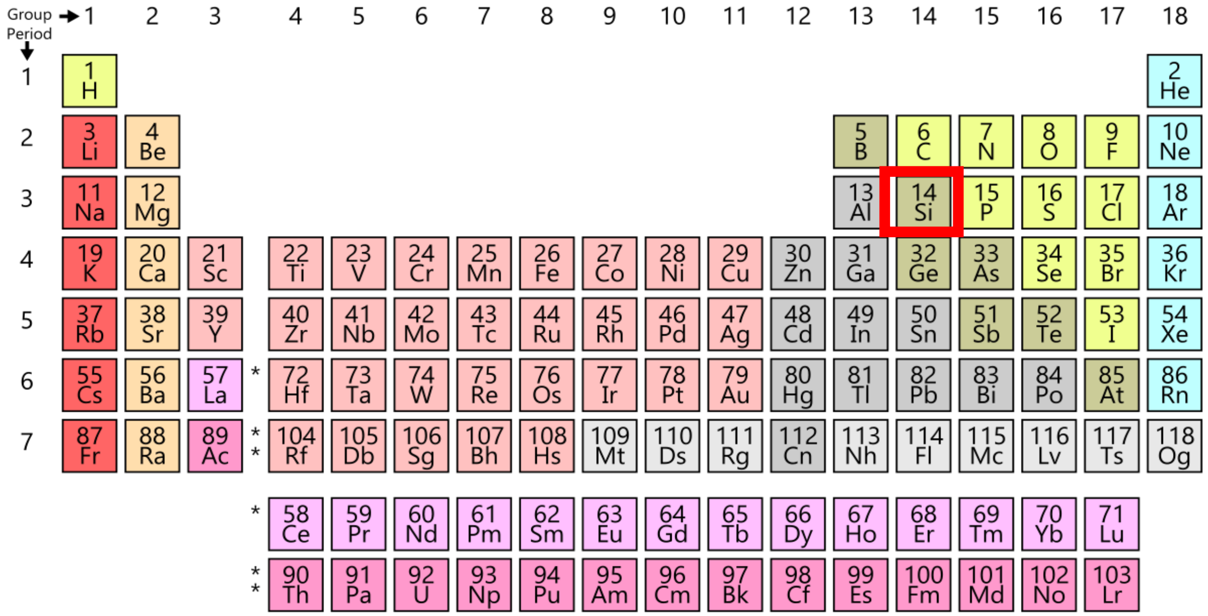
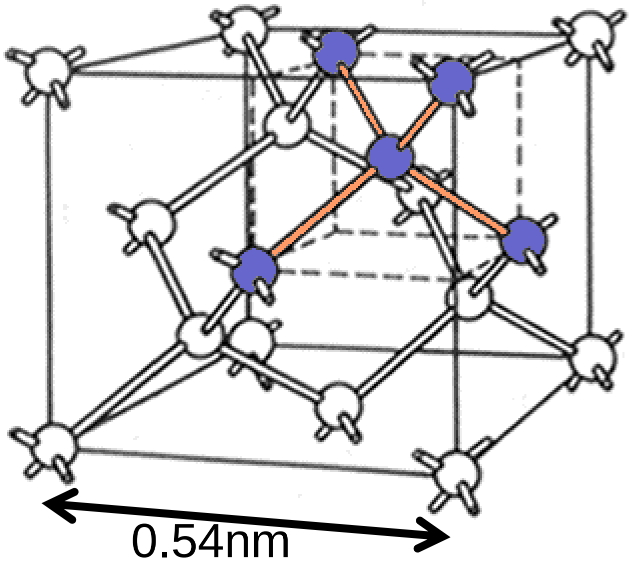
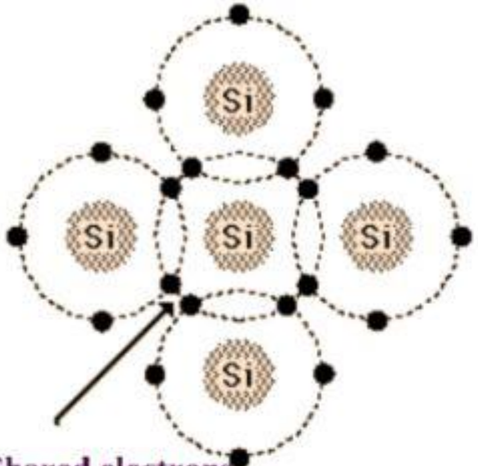
The silicon crystal

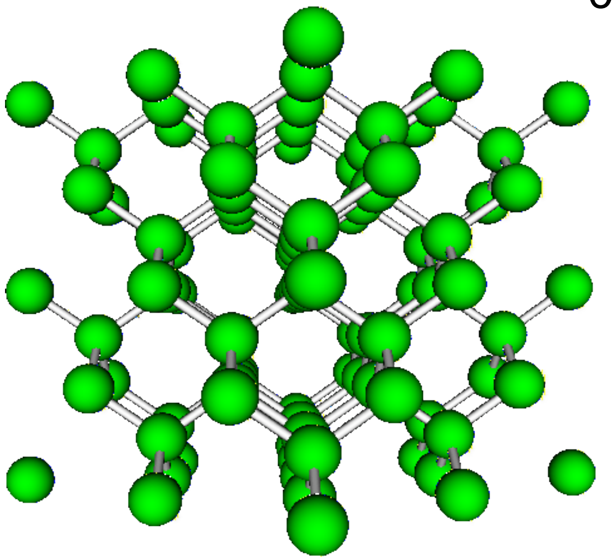


Diamond structure (tetrahedron)
Unit cell has 8 atoms

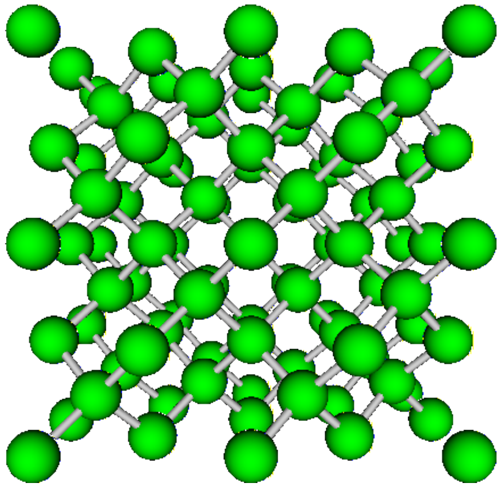




Shared electrons in covalent bond

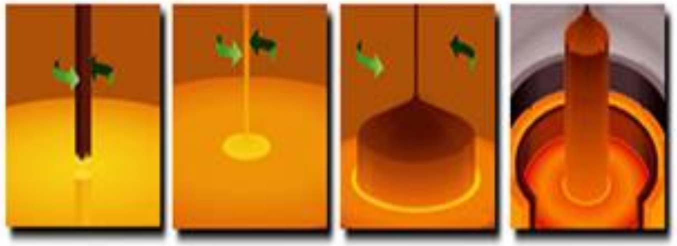


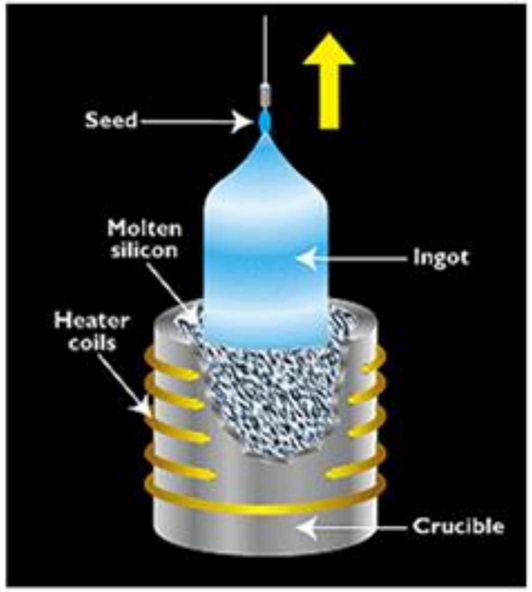
110

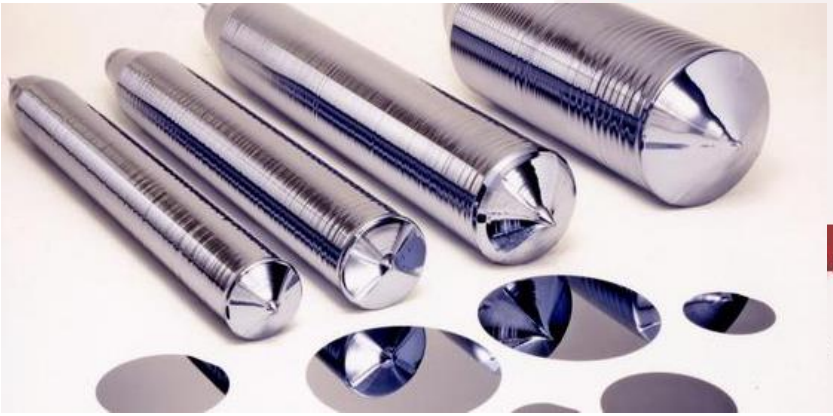


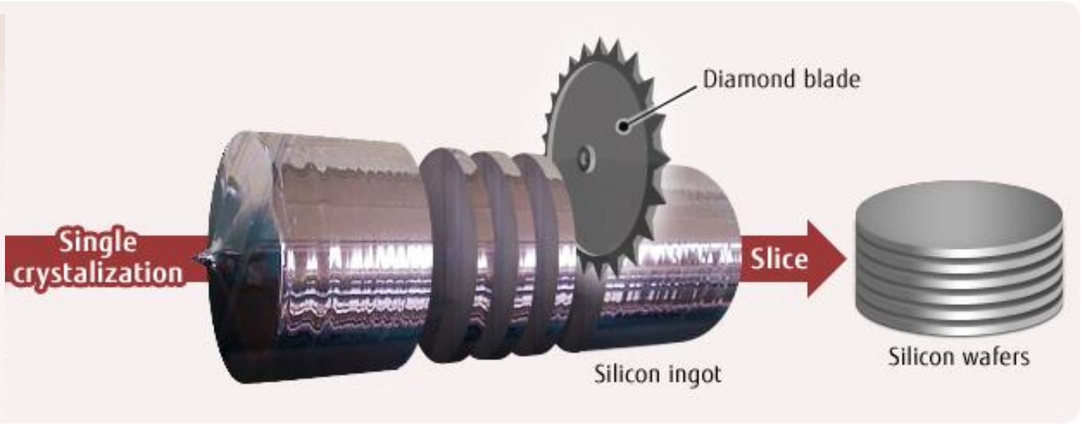
100

Czochralski method









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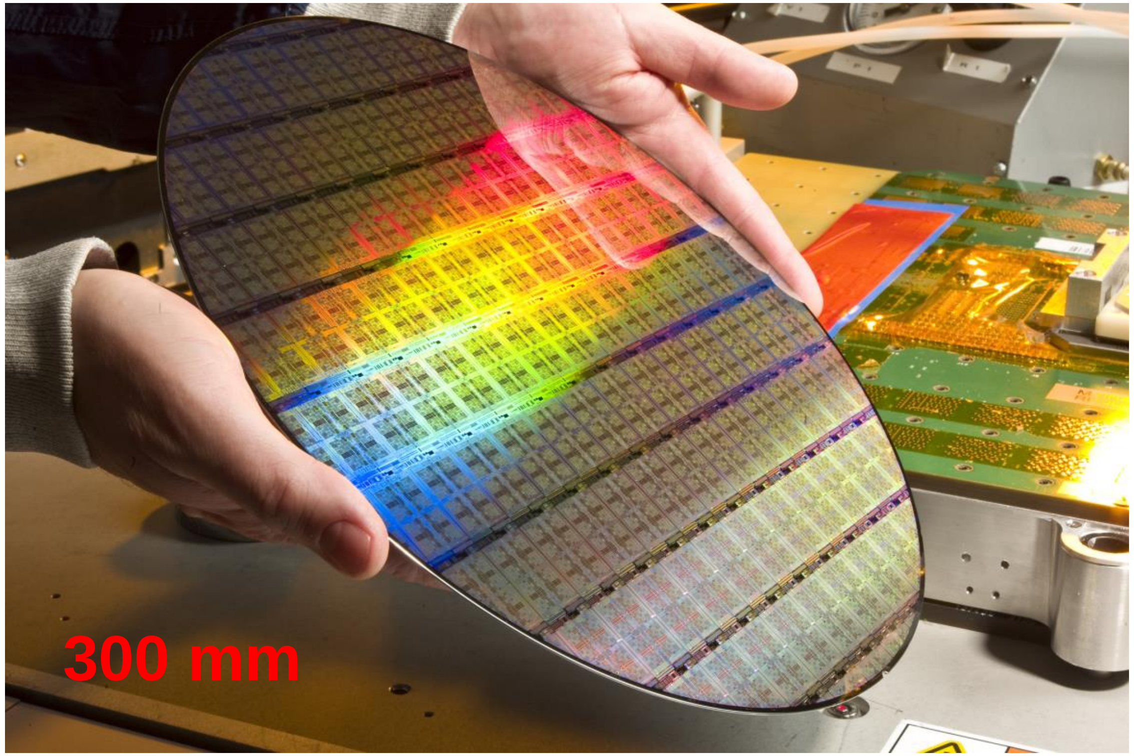
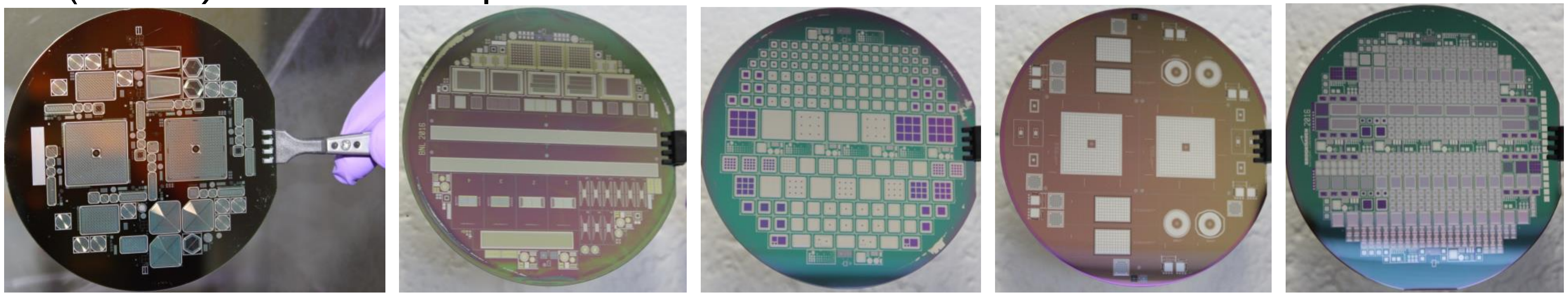
Silicon wafers as you can buy

Integrated Circuits (IC) on a Silicon wafer



4” (10-cm) silicon wafer processed at BNL

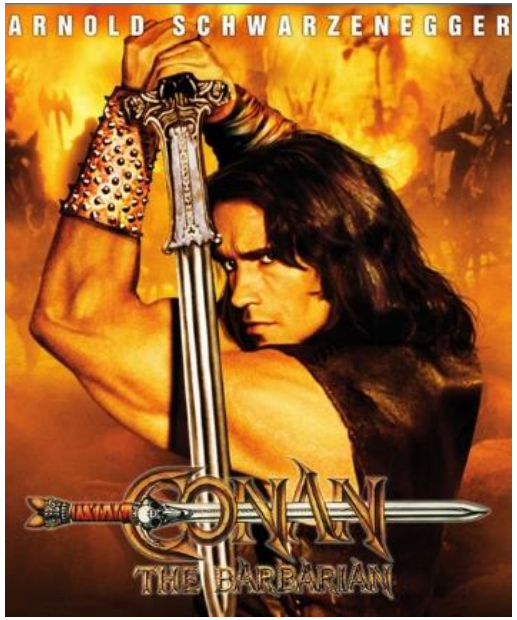


Two great materials: Silicon vs Steel

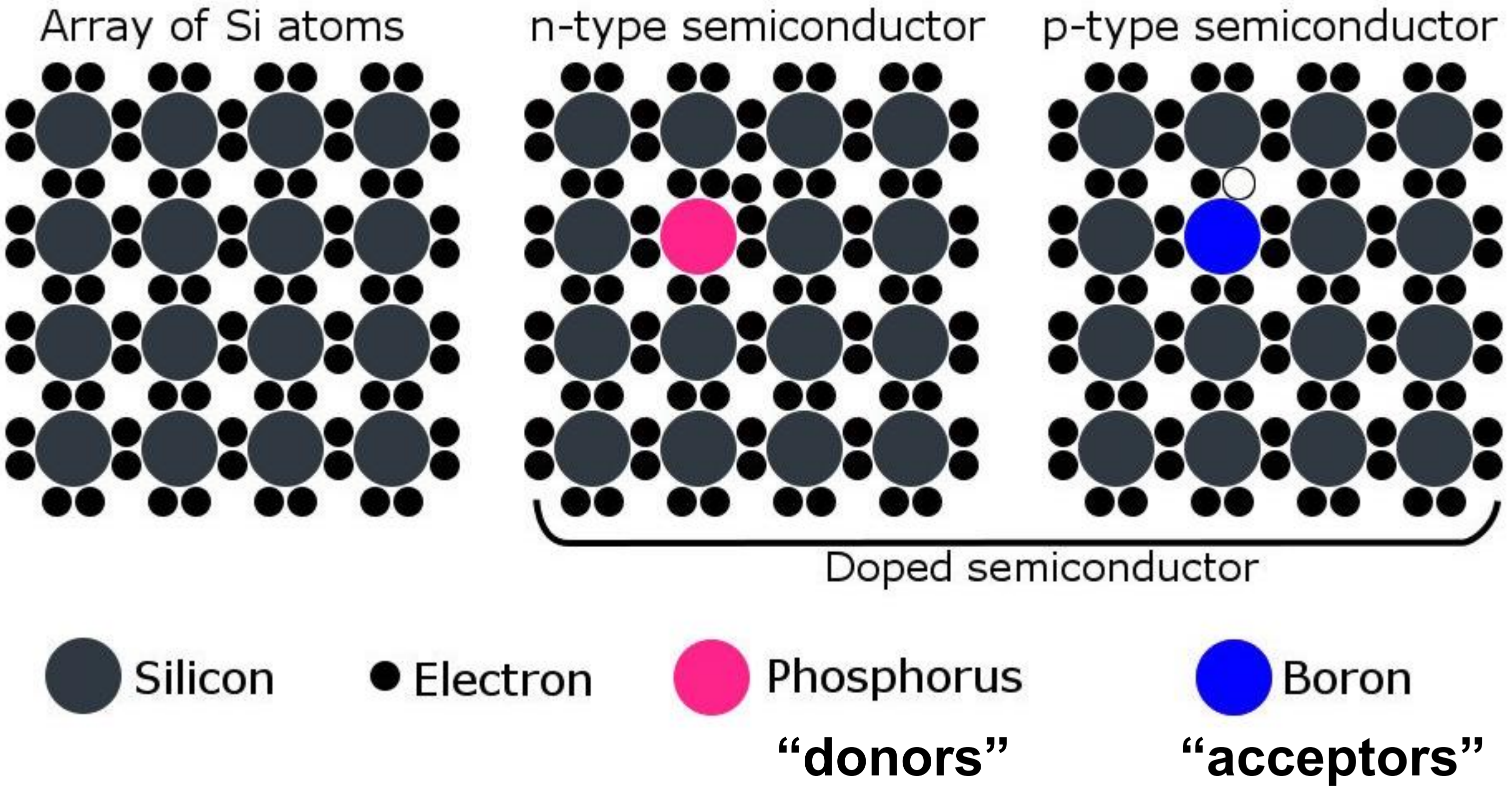
Shockley,
Bardeen,
Brattain 1950

Moore,
Noyce ,
Grove
at Intel 1978

Falcata
(4th century BC)



Electrons and holes in semiconductors



~10^{22} atoms of Si/cm^3

High doping of B/P if their concentration is > ~ 10^{19} cm^{-2} (low resistivity)

Low doping of B/P if their concentration is < 10^{12} cm^{-2} (high resistivity)

Electron and holes can be treated as “free” particles, negatively and positively charged.
If tied on their atom, charge neutrality holds; if freed from the atom, a net charge develops.

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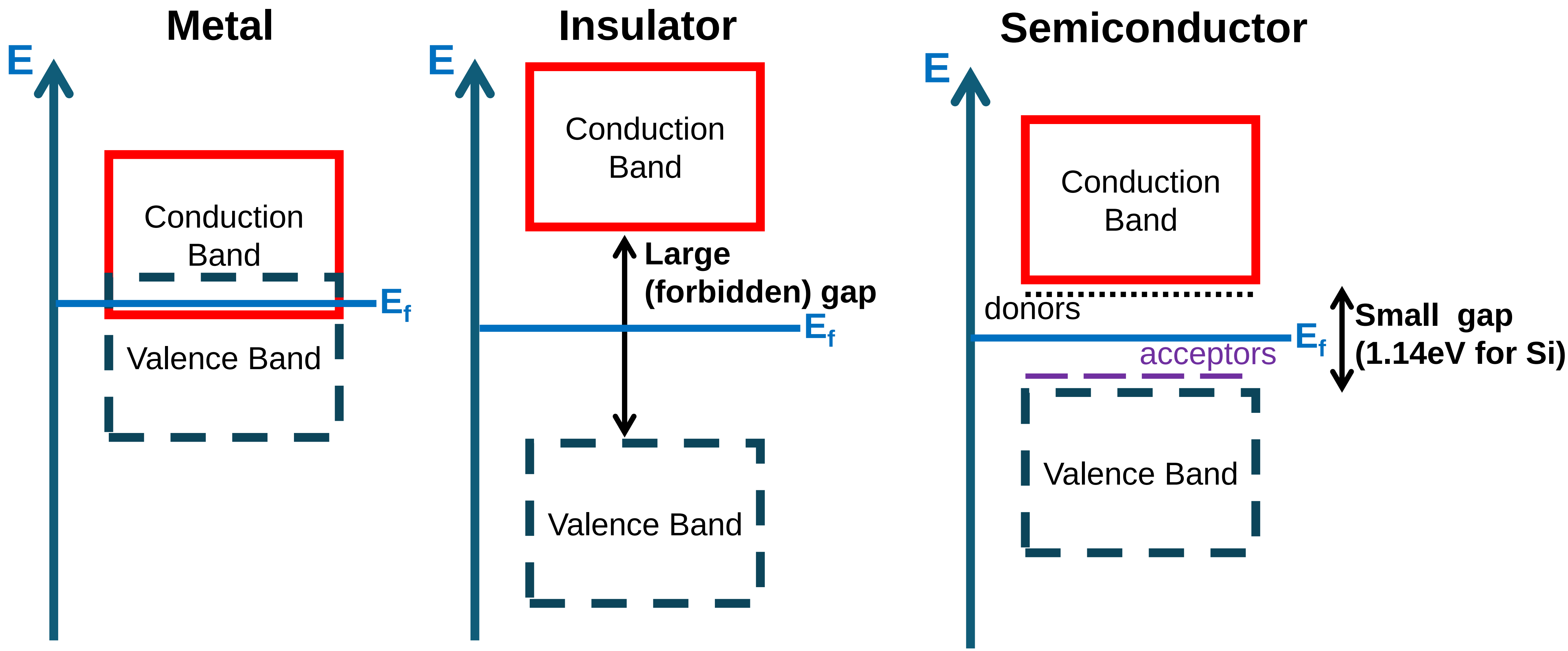
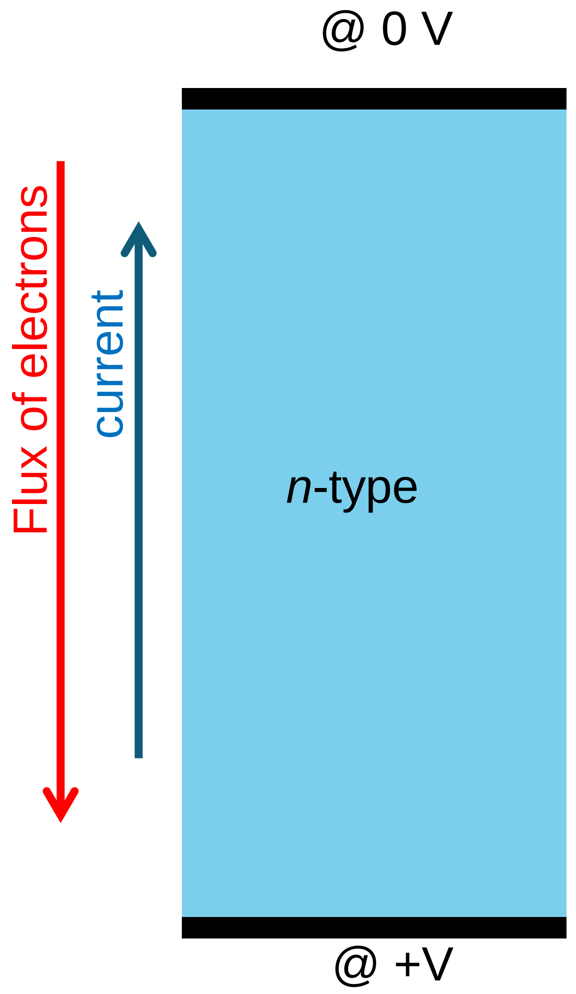
Band Structure



A slab of (n-type) silicon



Upon application of a Voltage V, free electrons and holes distribute as to satisfy Maxwell Equations.

Gauss Law (in 1D) : d**E**/dx = ρ/ε

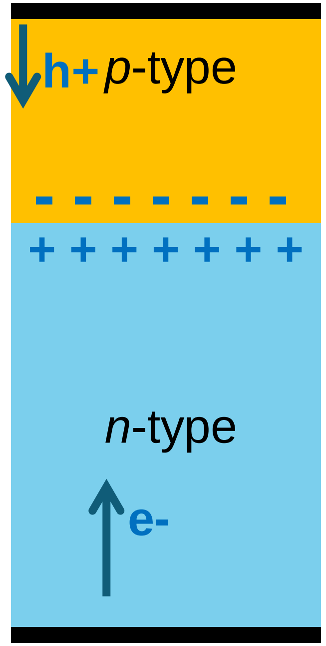
N-type has negligible holes.
Since charge neutrality holds, ρ=0.

→ **E** = constant= V/thickness

Electrons are emitted by electrode at 0V and drift to electrode at +V.
Current is given by Ohm's law

This device is actually an interesting optoelectronic device: it is called a photoconductor. It exhibits gain, but it is very slow. Surpassed by Junction Diodes.

Two slabs face-to-face: n-type + p-type
The junction Diode (forward bias)

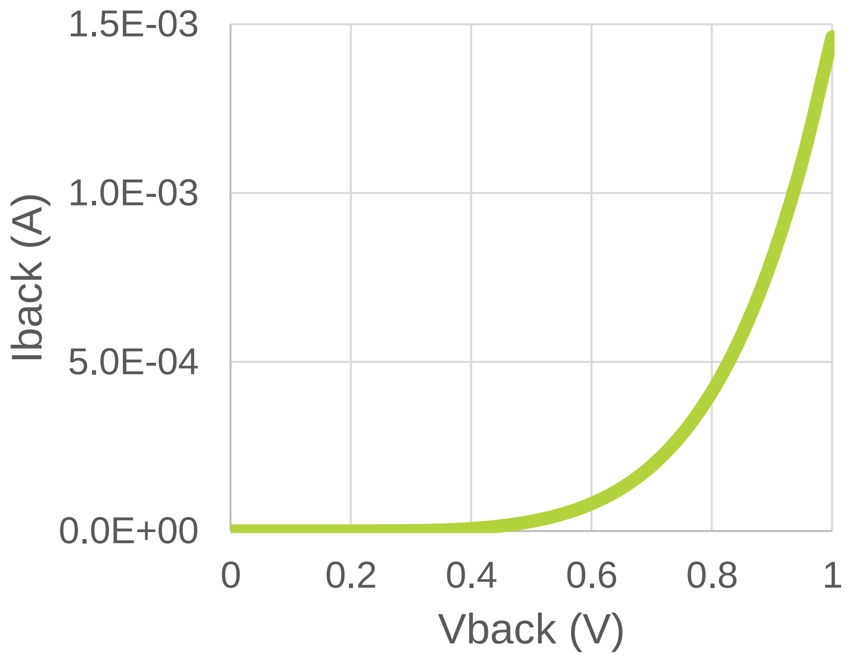


Holes on the p-side diffuse to the n-side, leaving ionized (negative) Boron behind. Electrons on n-side diffuse to the p-side, leaving ionized (positive) Phosphorus behind.

Charge density builds up and so electric fields (Maxwell equation) (or, a potential barrier) which counteracts the diffusion process.

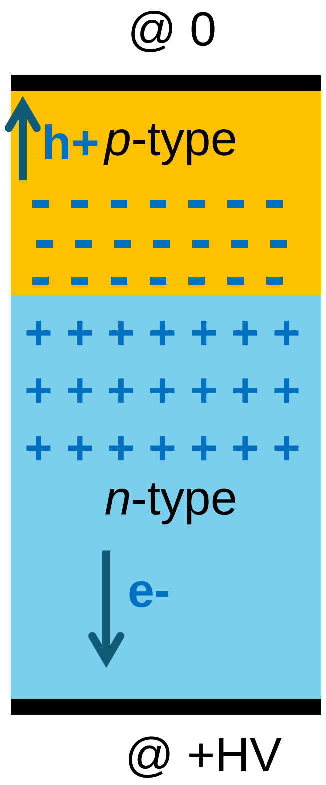
At the junction, a charge region exists (even at zero bias) → built-in voltage.

If we lower the potential barrier by applying an external voltage, more electrons and holes can diffuse on the other side of the junction
→ Forward bias.



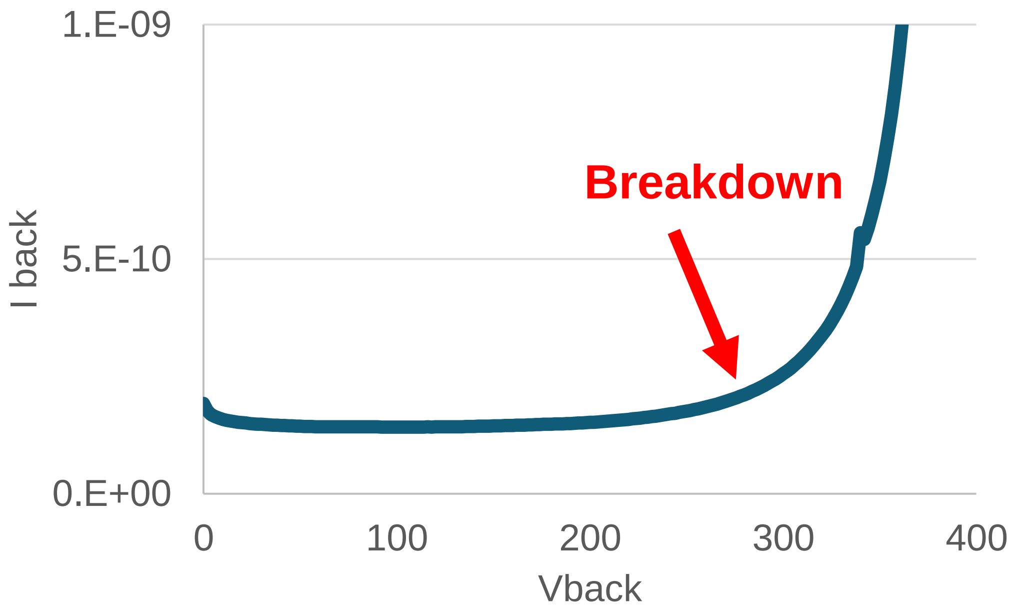
Two slabs face-to-face: n-type + p-type
The junction Diode (reverse bias)

If we increase the potential barrier by applying an external voltage, the flow of electrons and holes is inhibited: no current!!



But Gauss law still holds:
If we have a voltage across the junction, a net charge must develop across the junction:
Electrons and holes are swept away from the n and p-type regions, leaving behind a charged volume, made by ionized donors and acceptors.
We speak of **Depleted** (from electrons and holes) **Region**.

Current is thermally generated in the depleted volume by SRH process. (**leakage current, or dark current**)
Max Voltage that can be applied is limited (breakdown will occur if electric field is too high, ~ 3e5 V/cm in silicon)



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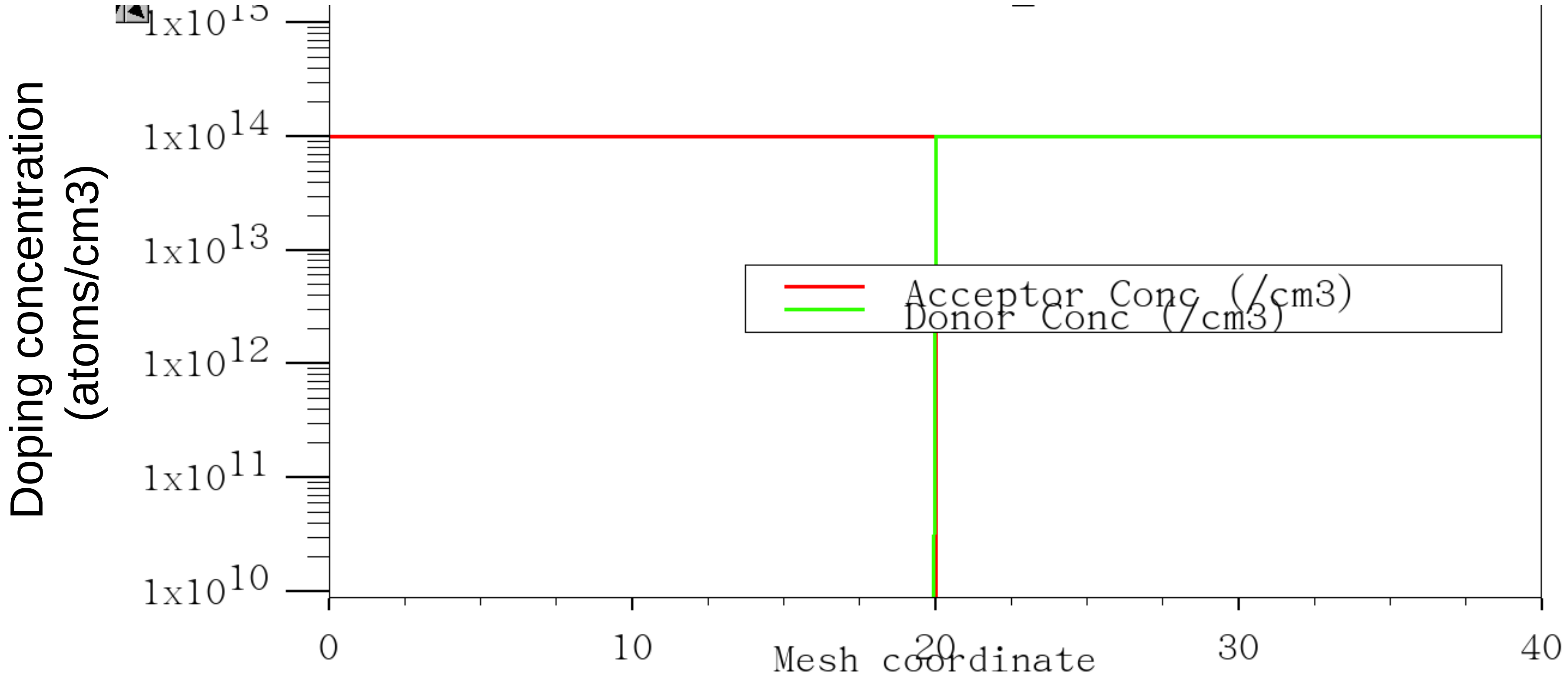
The depletion region - 1

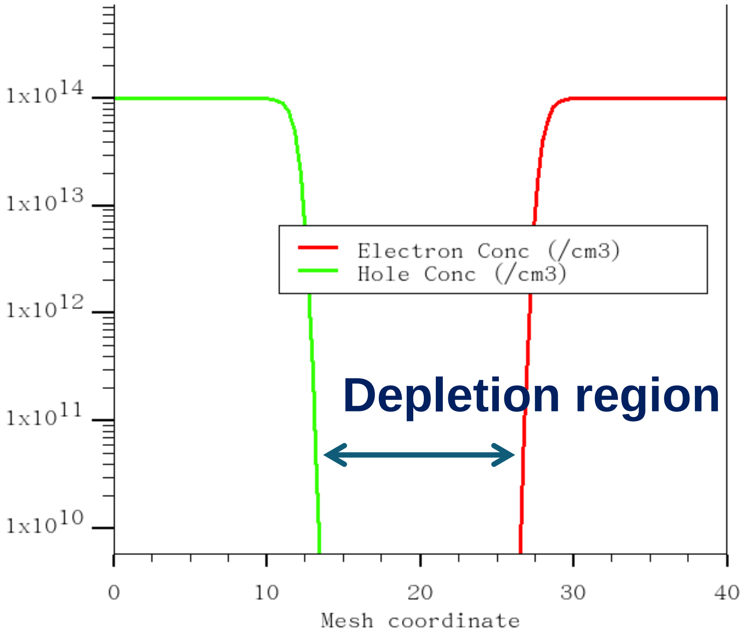
Let's take a 1D diode, 40 um thick, with symmetric doping:
20 um of p-type silicon in contact with 20 um of n-type silicon.
Let's apply 10V at the n-type silicon.

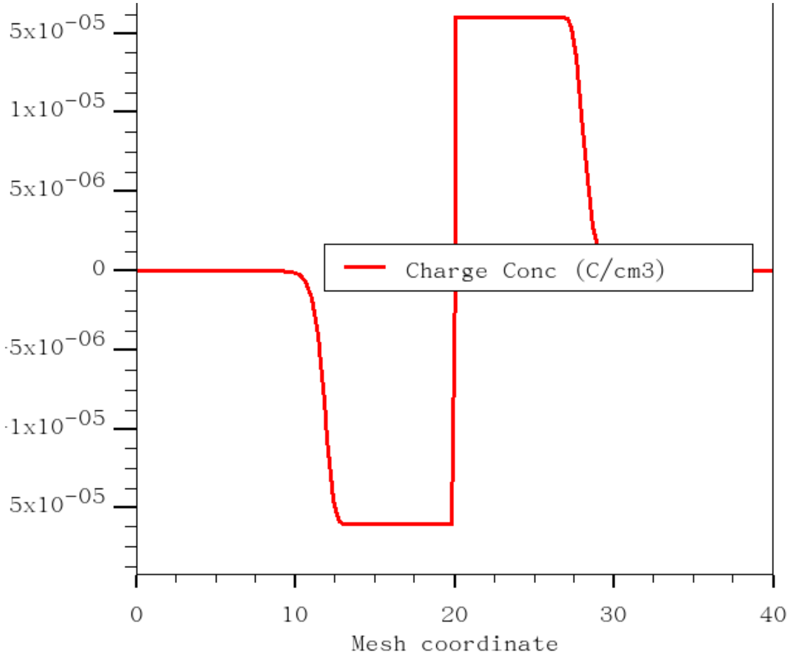


The depletion region - 2

In the depletion region:

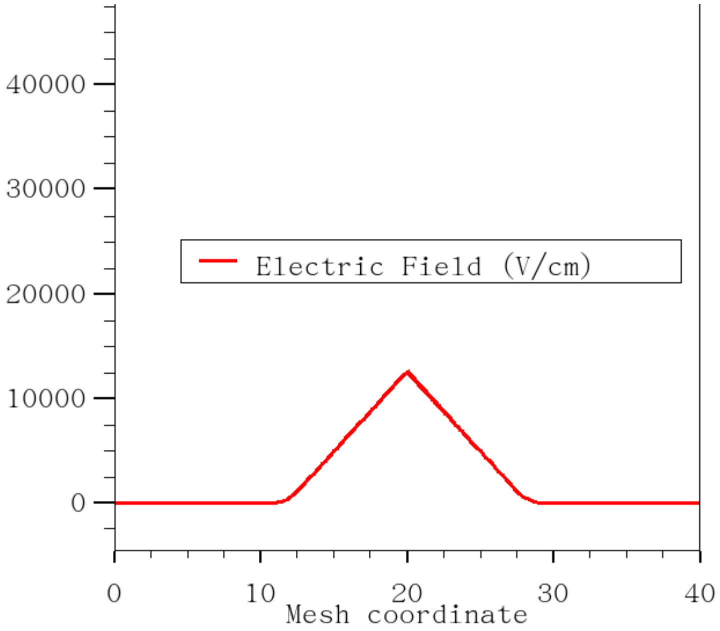
- No electrons or holes
- Charge ≠ 0
- Electric field ≠ 0
- Potential barrier

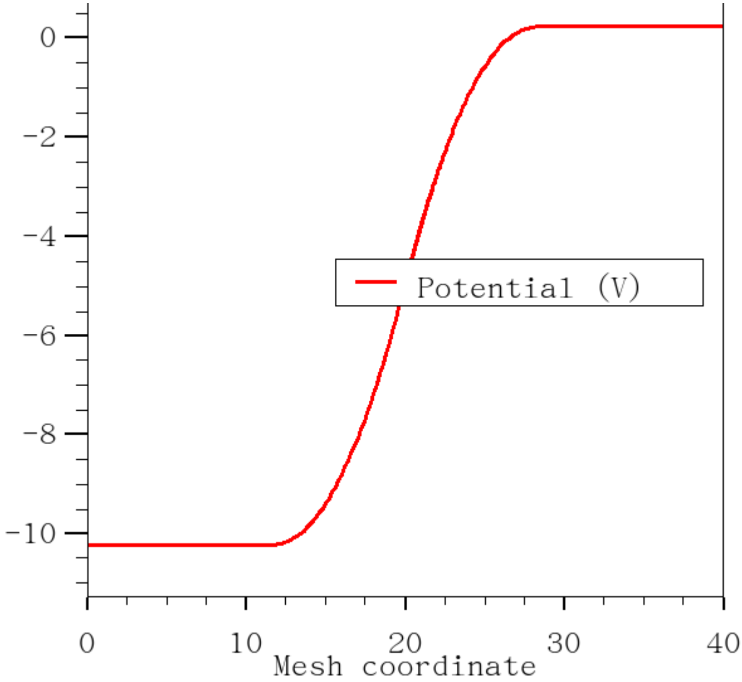




Outside of the depletion region:

- electrons or holes = doping
- Charge = 0
- Electric field = 0
- equipotential





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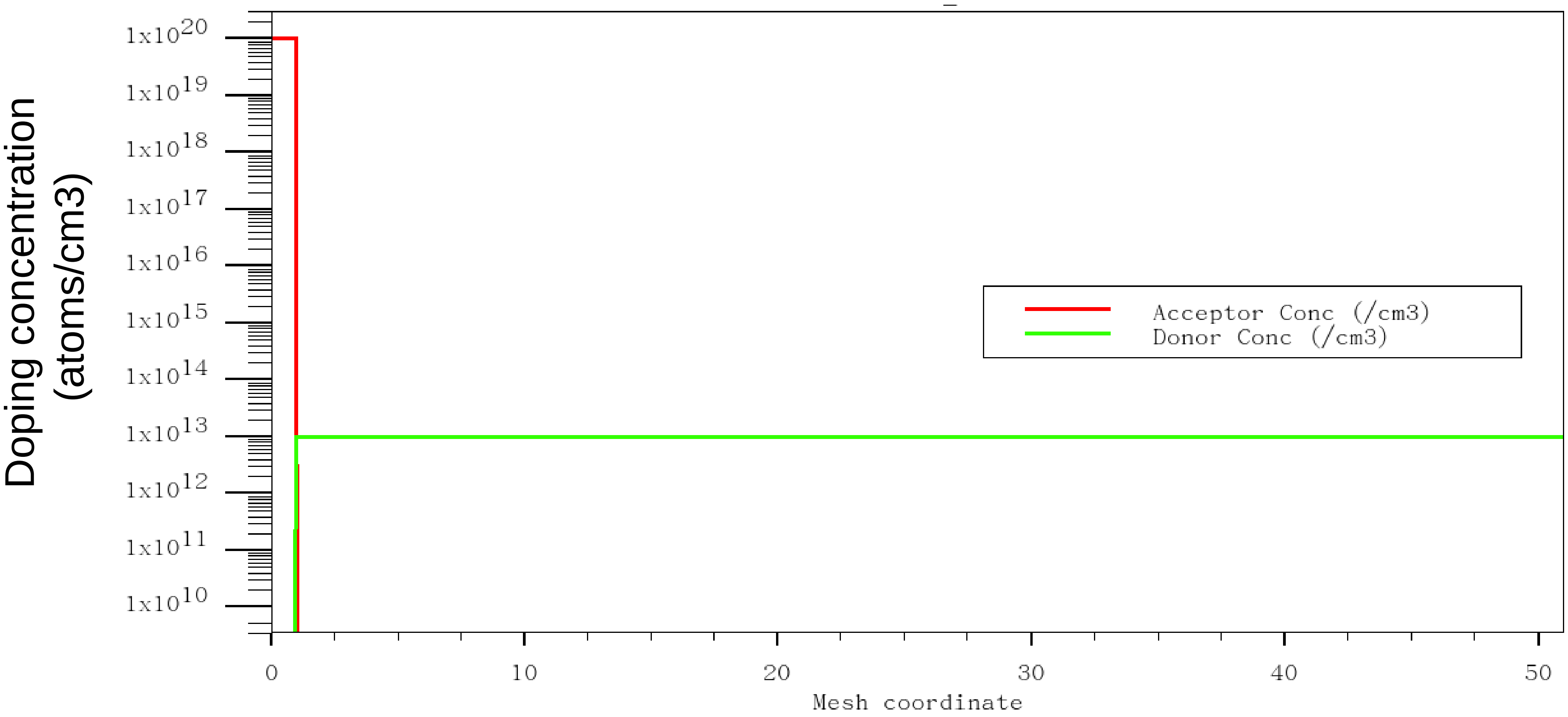
The depletion region - 3

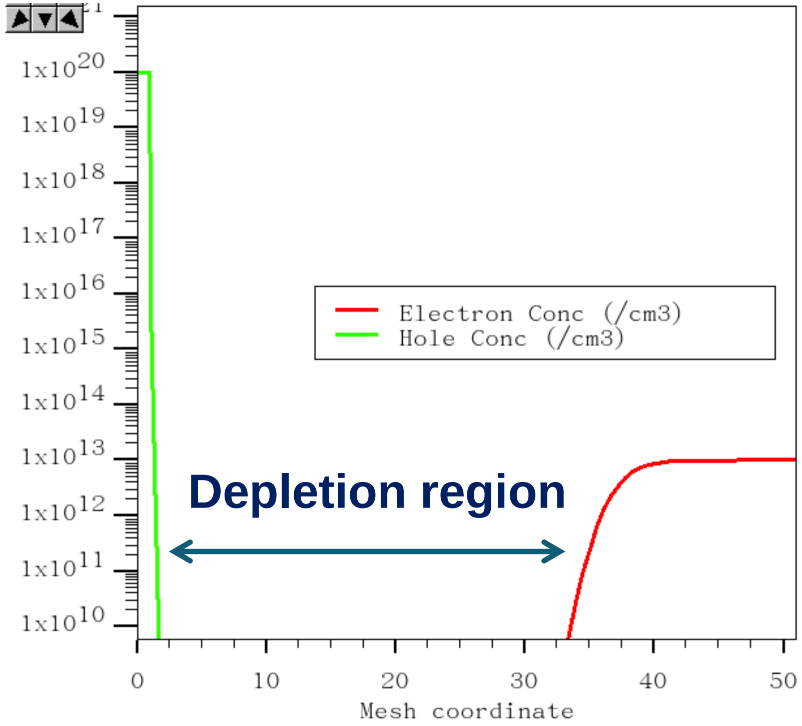
Let's take a 1D diode, 50 um thick, asymmetric doping:
Shallow heavily doped p-type silicon in contact with 50 um of lightly doped n-type silicon.
Let's apply 10V at the n-type silicon.

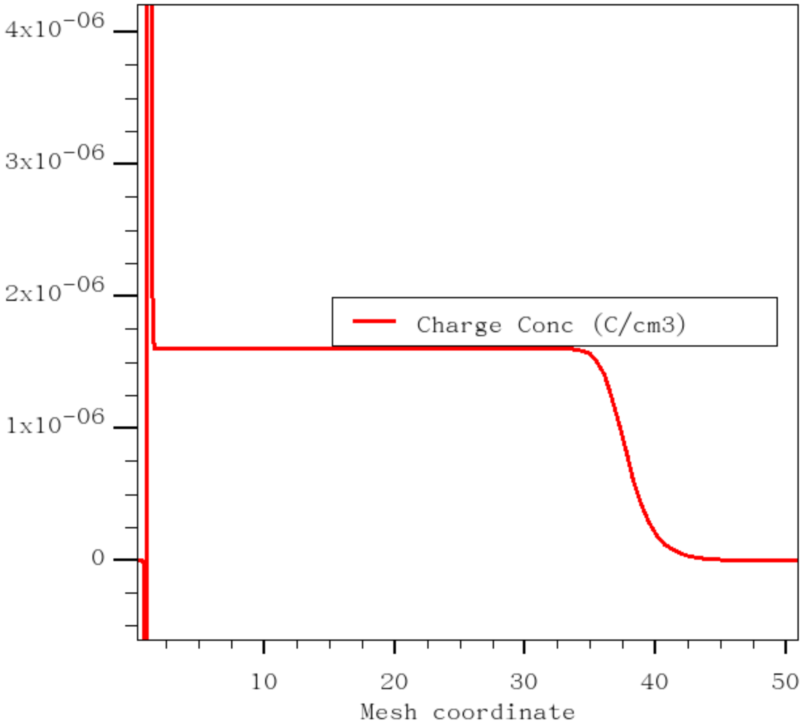


The depletion region - 4

Again,
in the depletion region:

- No electrons or holes
- Charge ≠ 0
- Electric field ≠ 0
- Potential barrier

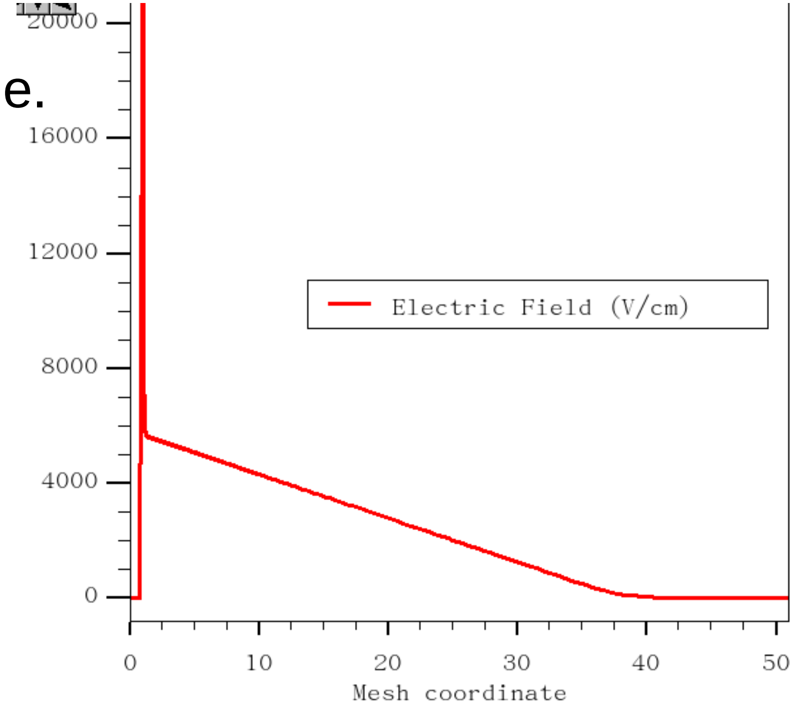


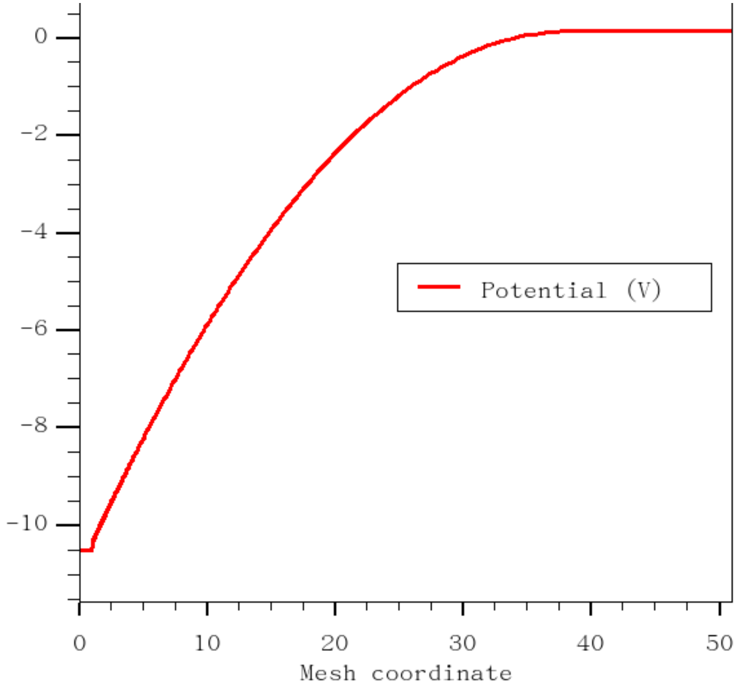


But this time the depletion region extends only on the lowest doped side.

The n-side is almost fully depleted.
Sensors operate in full-depletion regime.

VFD ~ Thickness² * N$_{doping}$





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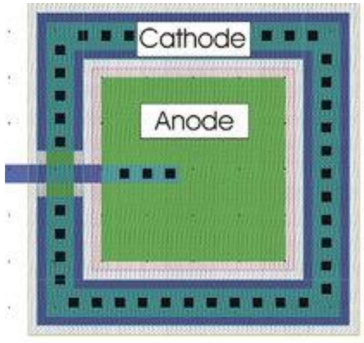
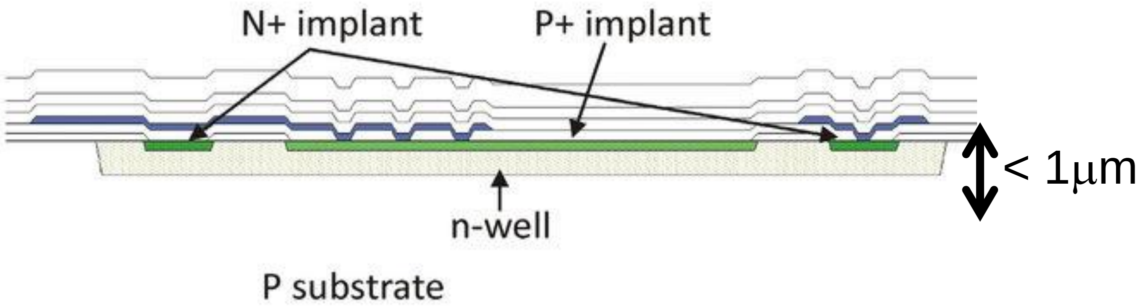
Diode in integrated circuits

Highly doped, small depletion region

From the top



Section

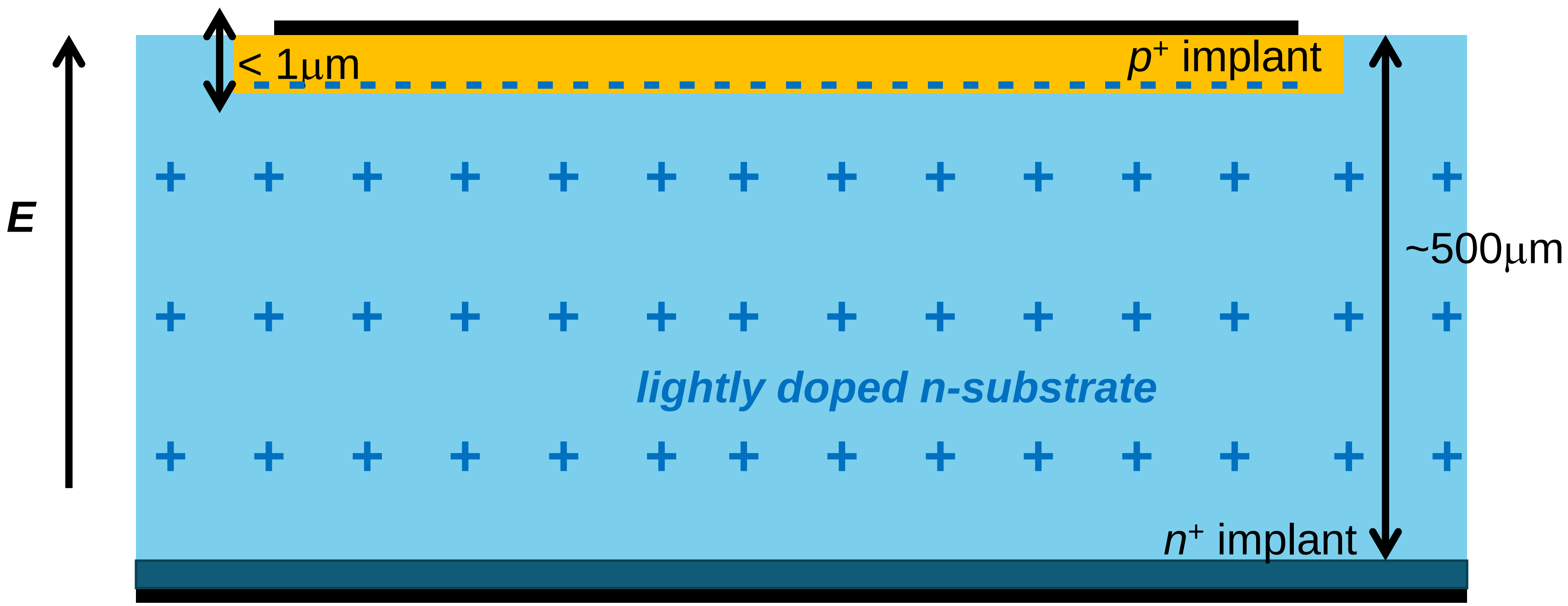


Diode as a sensor unit

Substrate lightly doped

depletion region = substrate thickness

$V_{full\text{-}depletion}$ ~ 100V, depending on thickness, application,…



KETEK

SDD ⌄ DOCUMENTATION ⌄ NEWS ⌄ COMPANY ⌄

Company

ABOUT US MANAGEMENT COMPANY FOUNDER SALES TEAM

Silicon sensors by planar process since 1980

COMPANY FOUNDER

Dr. Josef Kemmer

FOUNDER and SENIOR PRESIDENT
* 1938 – † 2007

NUCLEAR INSTRUMENTS AND METHODS 169 (1980) 499-502; © NORTH-HOLLAND PUBLISHING CO.

FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS

J. KEMMER

Fachbereich Physik der Technischen Universität München, 8046 Garching, Germany

Received 30 July 1979 and in revised form 22 October 1979

Dedicated to Prof. Dr. H.-J. Born on the occasion of his 70th birthday

By applying the well known techniques of the planar process: oxide passivation, photo engraving and ion implantation, Si pn-junction detectors were fabricated with leakage currents of less than 1 nA cm^{-2}/100 μm at room temperature. Best values for the energy resolution were 10.0 keV for the 5.486 MeV alphas of ^{241}Am at 22 °C using 5×5 mm^2 detector chips.

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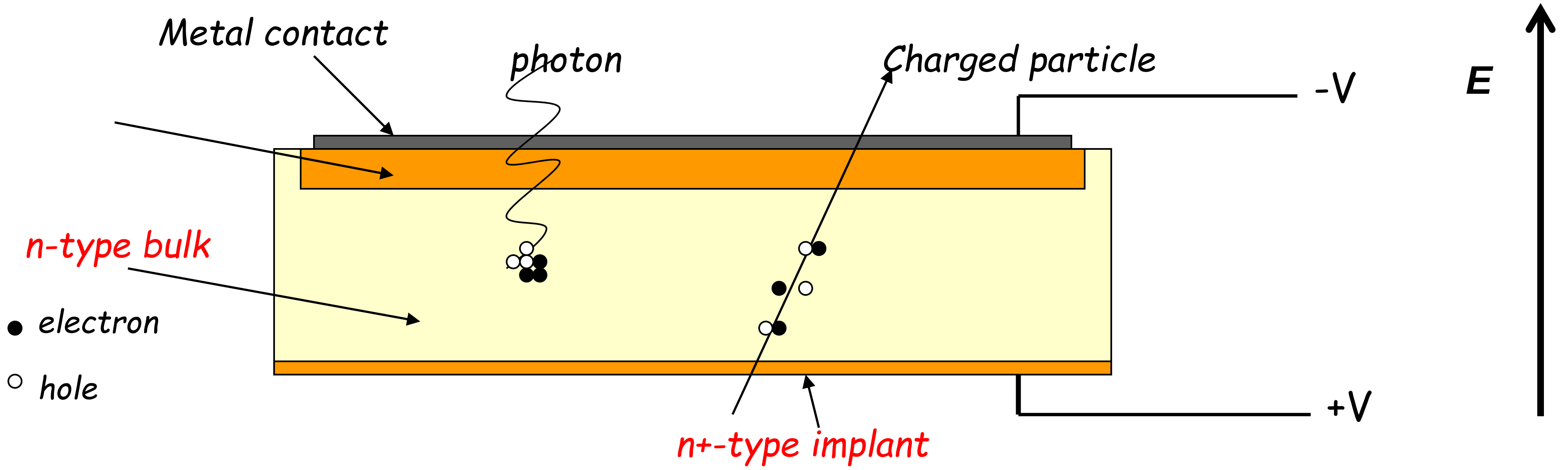
Mechanism of radiation detection

Ionizing radiation (photons or charged particles) creates free electron/hole pairs in the bulk, by releasing energy allowing the electrons in the valence band to hop into the conduction band, leaving a hole behind.
Electrons and holes drift in opposite directions, following the electric field lines. While this drift occurs, current pulses are generated at the electrodes.



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The Ramo theorem

Proceedings of the IRE, September 1939, page 584.

Currents Induced by Electron Motion*

SIMON RAMO†, ASSOCIATE MEMBER, I.R.E.

Summary—*A method is given for computing the instantaneous current induced in neighboring conductors by a given specified motion of electrons. The method is based on the repeated use of a simple equation giving the current due to a single electron's movement and is believed to be simpler than methods previously described.*

Introduction

In designing vacuum tubes in which electron transit-time is relatively long, it becomes necessary to discard the low-frequency concept that the instantaneous current taken by any electrode is proportional to the number of electrons received by

Method of Computation

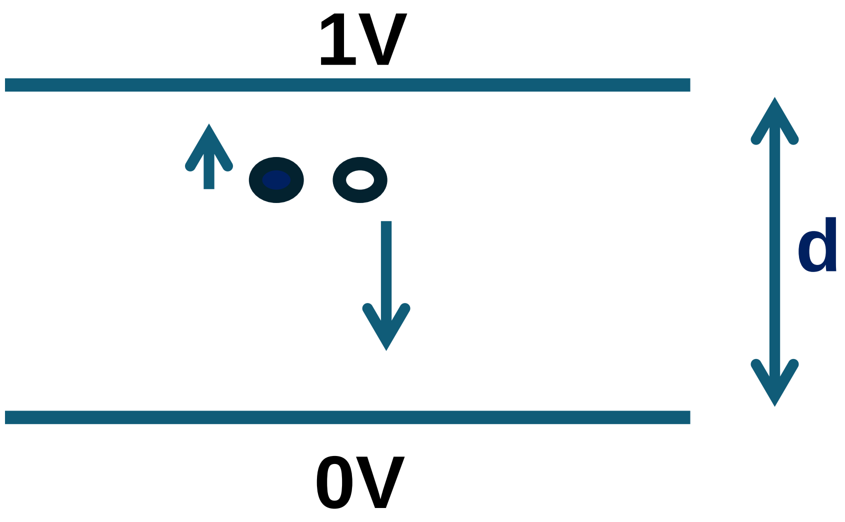
The method is based on the following equation, whose derivation is given later:

$$i = E_v e v \qquad (1)$$

where i is the instantaneous current received by the given electrode due to a single electron's motion, e is the charge on the electron, v is its instantaneous velocity, and E_v is the component in the direction v of that electric field which would exist at the electron's instantaneous position under the following circumstances: electron removed, given electrode raised to unit potential, all other conductors grounded. The equation involves the usual assump-

- Currents induced at the electrodes when charges are moving (no charge movement → no current)
- Concept of "weighting field", units of an electric field but **it is not the electric field**!!!!!

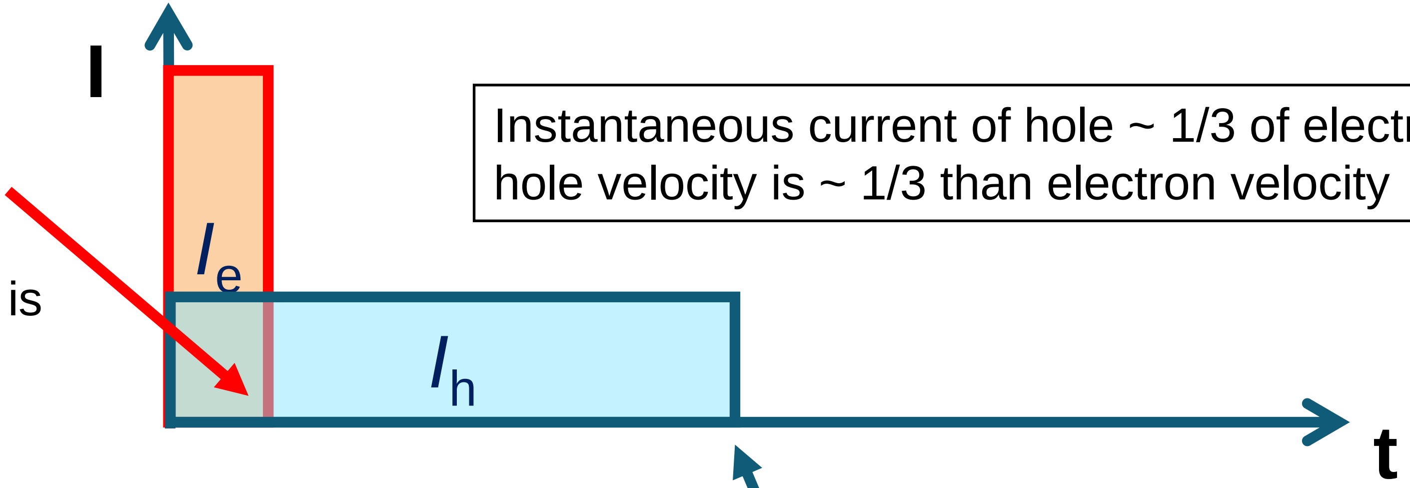
Example: 1D diode



- Weighting field, **W** = 1/d (V/cm)
- Electric field, **E**~ V/d (V/cm) (defines $\mathbf{v}_e$, $\mathbf{v}_h$)

- If the electron drifts up with velocity v_e
  - $I_e = - q\, v_e\, W$

- If the hole drifts down with velocity v_h
  - $I_h = - q\, v_h\, W$



Instantaneous current of hole ~ 1/3 of electrons as hole velocity is ~ 1/3 than electron velocity

Collection time of electron. Pair is produced close to n-terminal, so signal of electron is smaller

Collection time of hole

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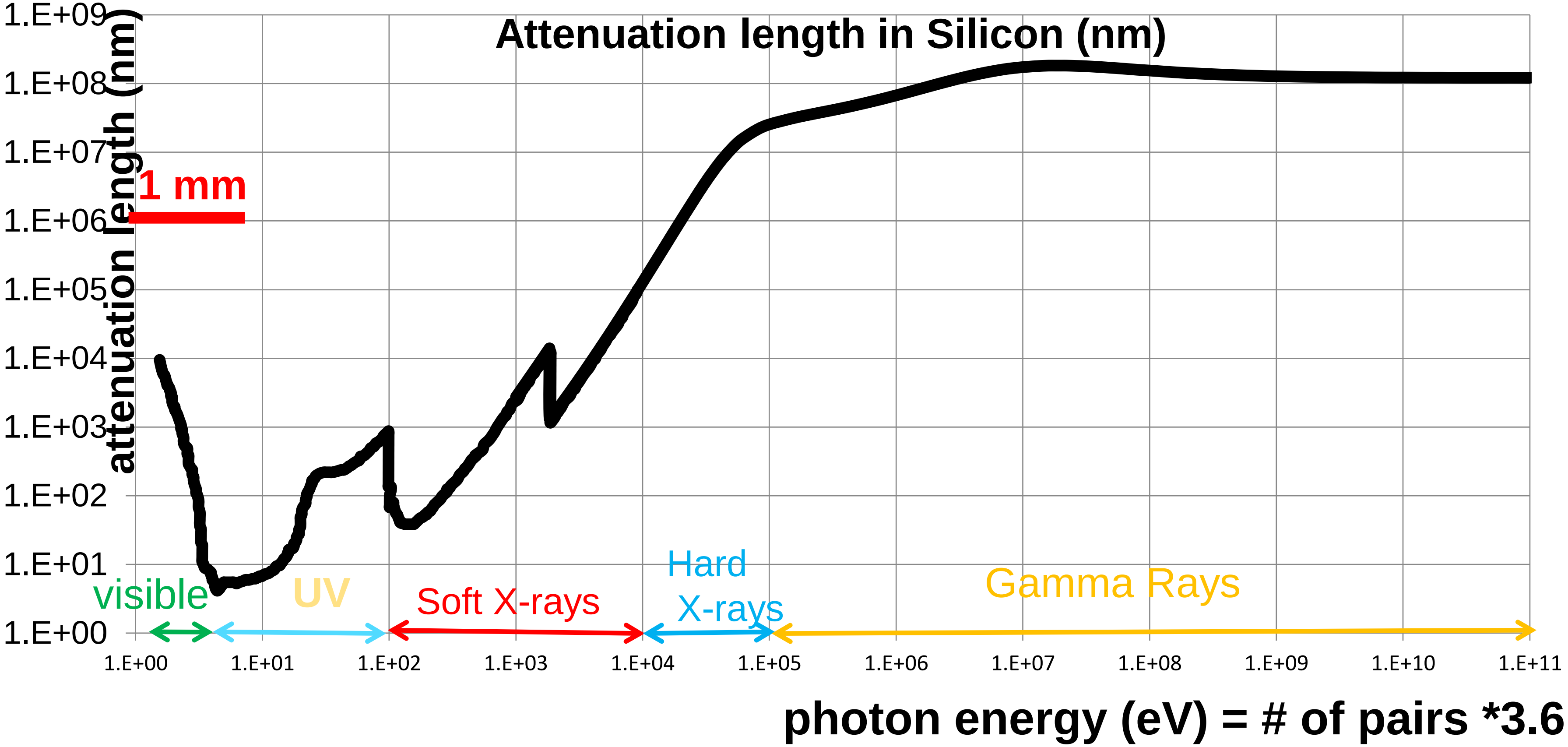
Absorption of photons in Silicon

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^+

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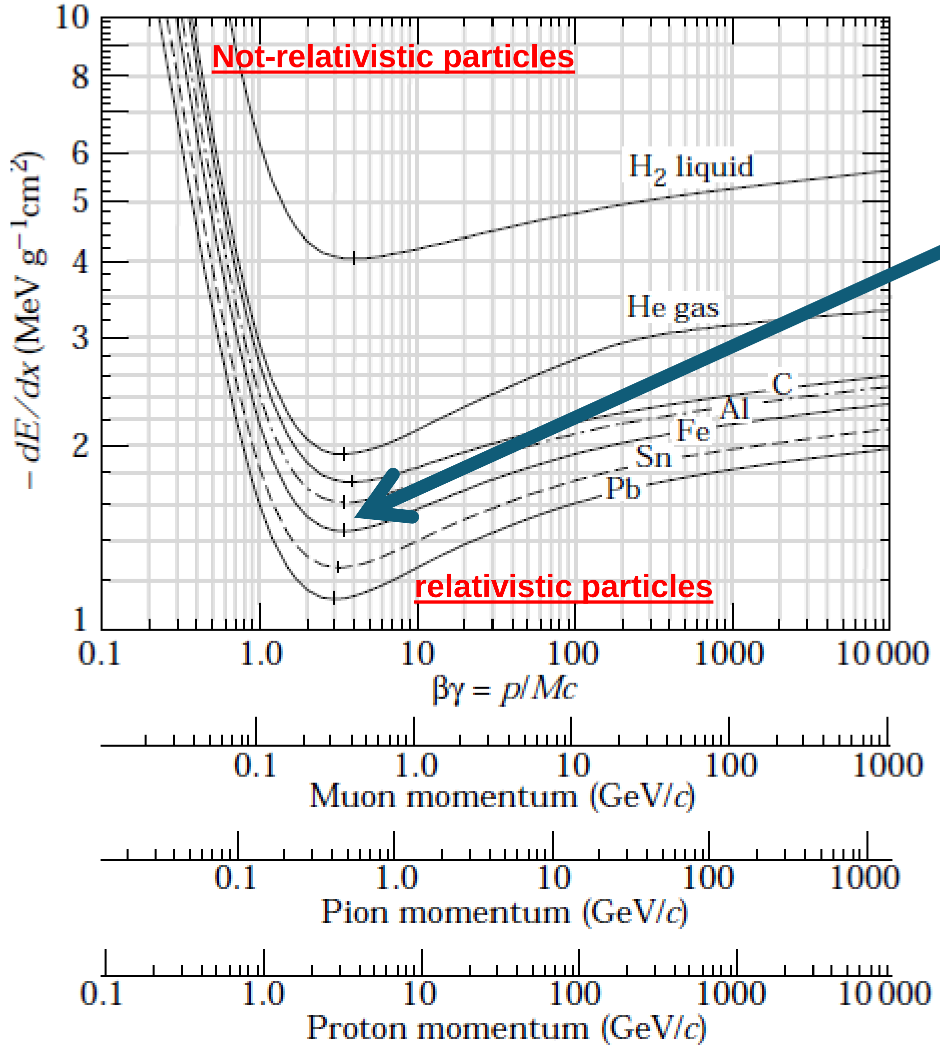
Interaction of charged particles with silicon: the Bethe Block formula

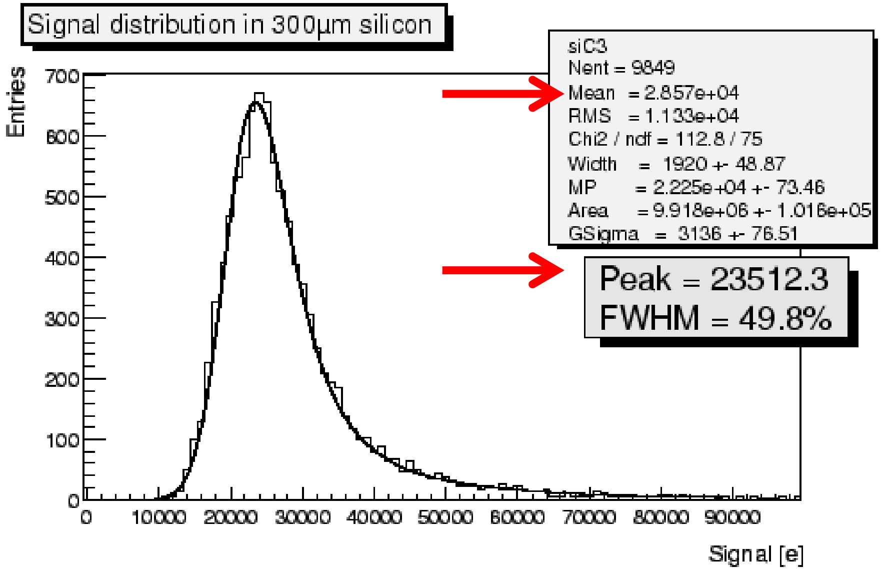


In most practical cases,

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



End of Part 1

Questions?

BACK UP

Fabrication:

let’s make a diode

Before starting: dress up properly!!!

Hood (hair net underneath)

googles

Face mask

coverall

gloves

Boots (shoe covers underneath)

Control of dust particles in the **clean – room** prevents defects in the process

For example:
Class-100 Clean room means less than 100 particles/cubic foot

Oxidation

Chemical reaction …

Growth of pure high-quality silicon oxide films ranging in thickness from 100 angstroms to 1 micron.

Temperature from 200C to 1100C.

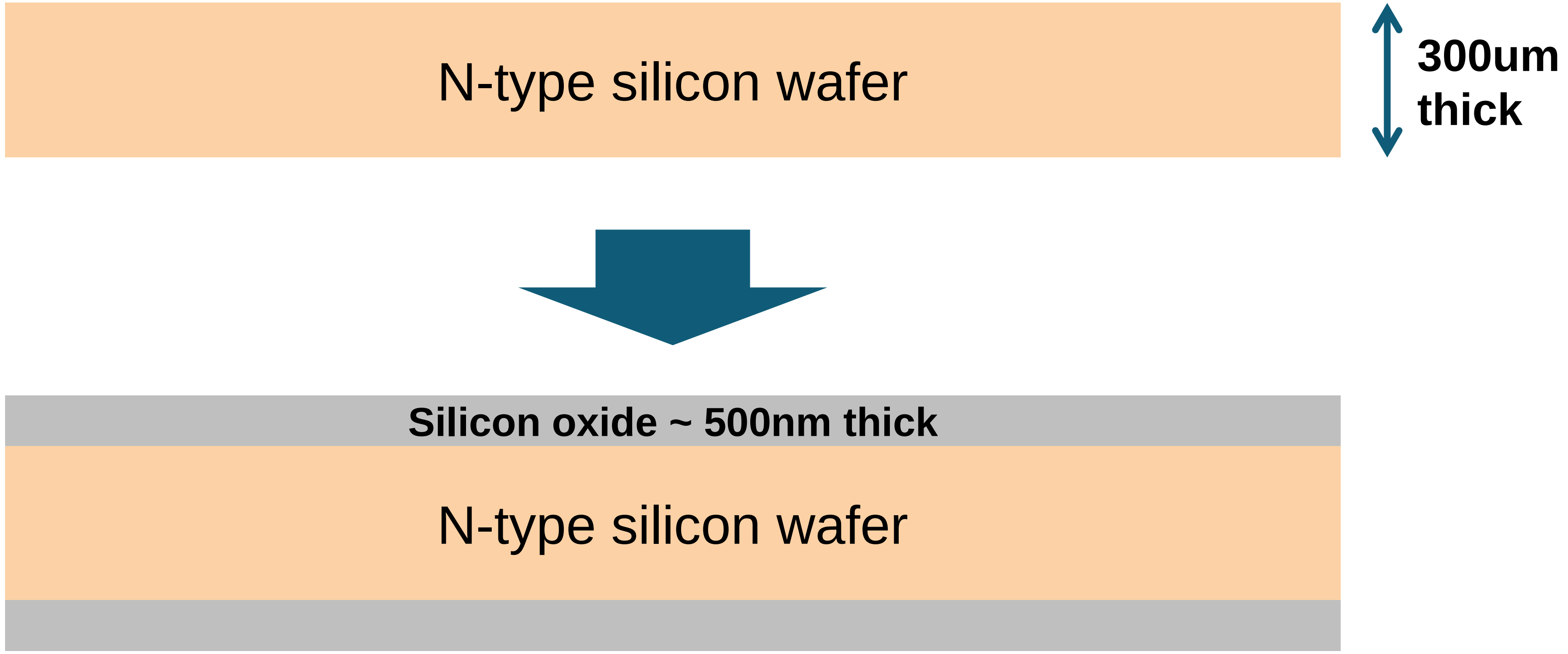
Nitrogen annealings also.

Quartz boats on cantilever arm host the wafers.

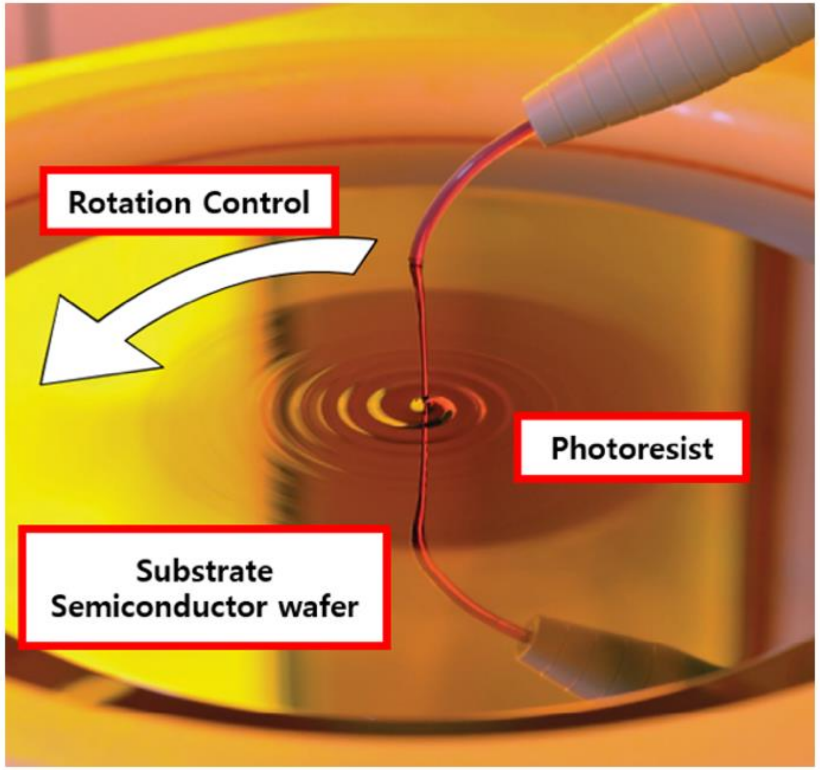
Oxidation

Initial wafer

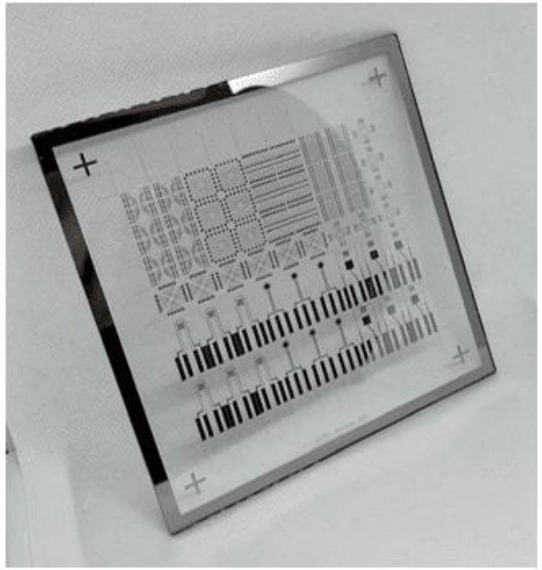
oxidation

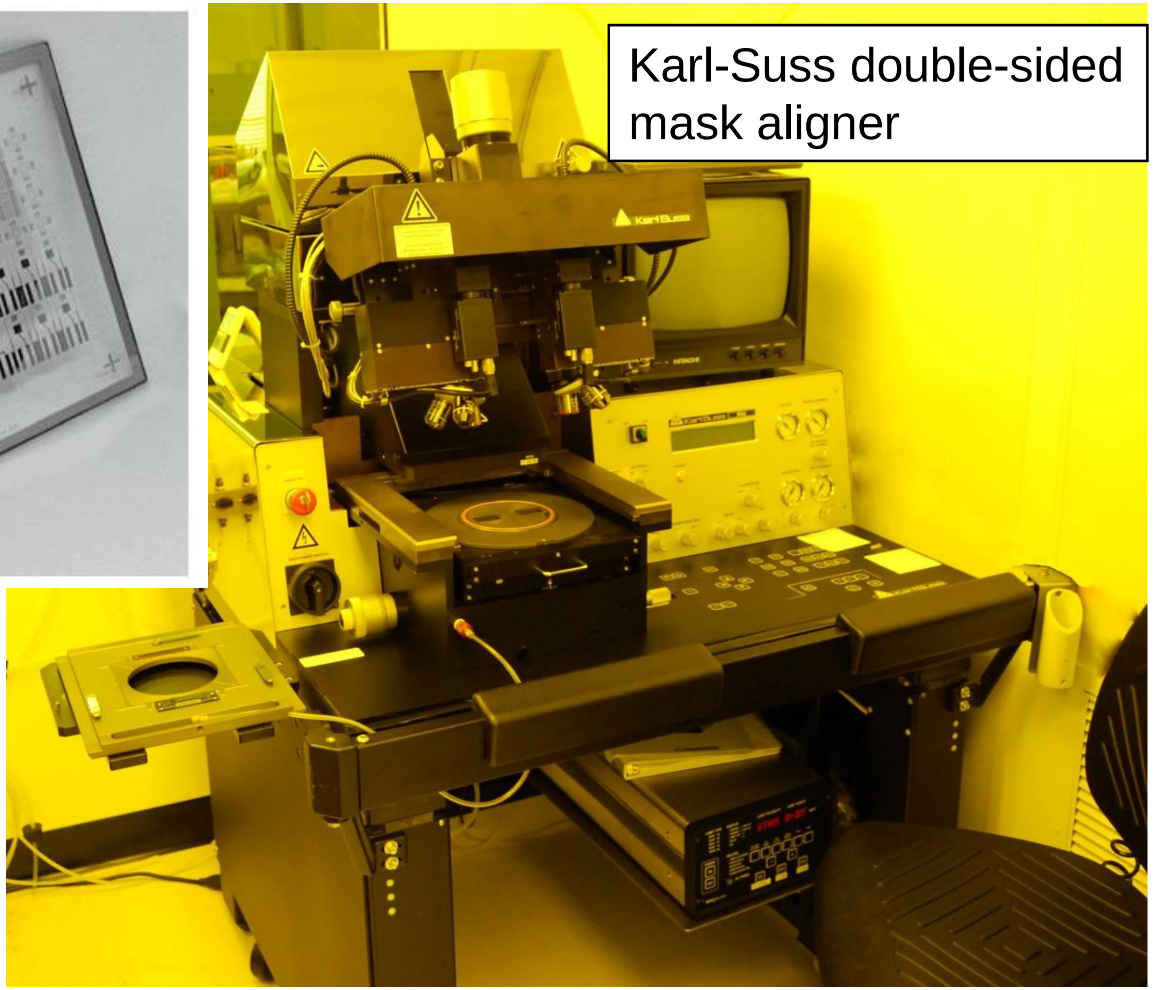


Lithography



Photoresist is spun on the wafer

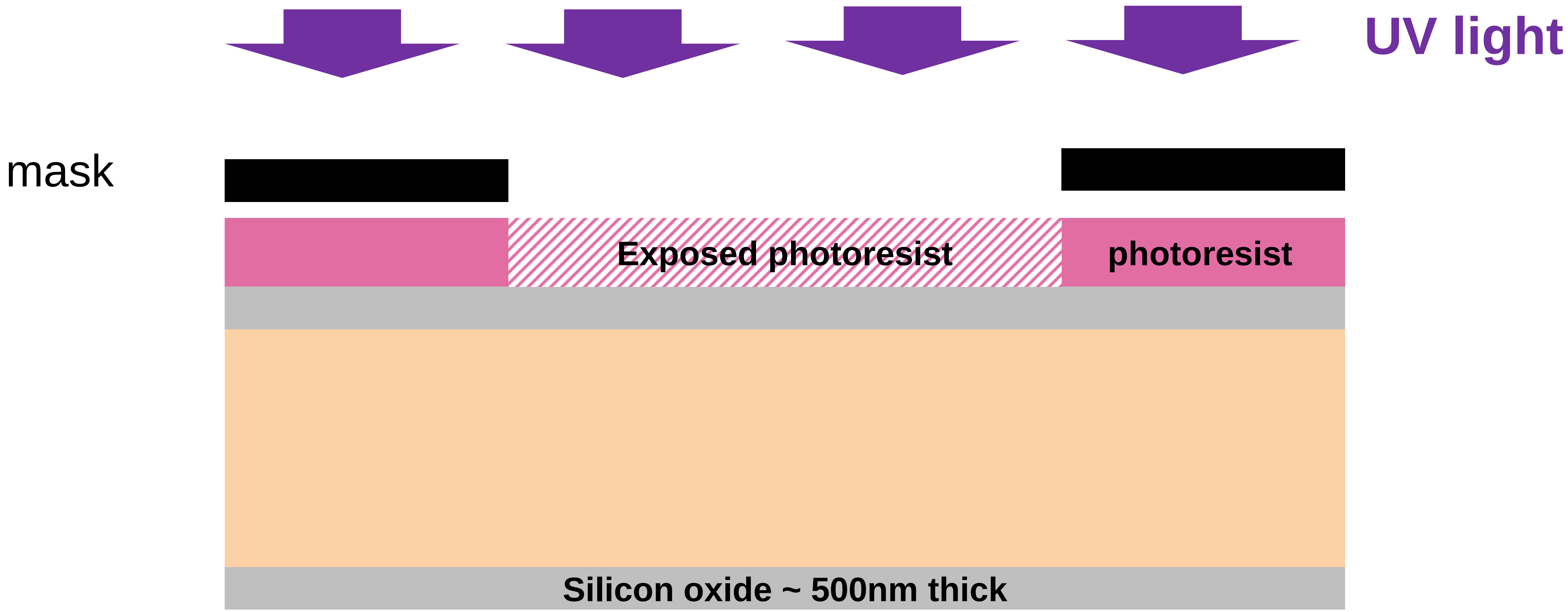




Karl-Suss double-sided mask aligner

Image (layer) is on a photomask (glass with pattern in chrome), which is placed on the wafer and a UV light shines through the glass, exposing the photoresist.

lithography

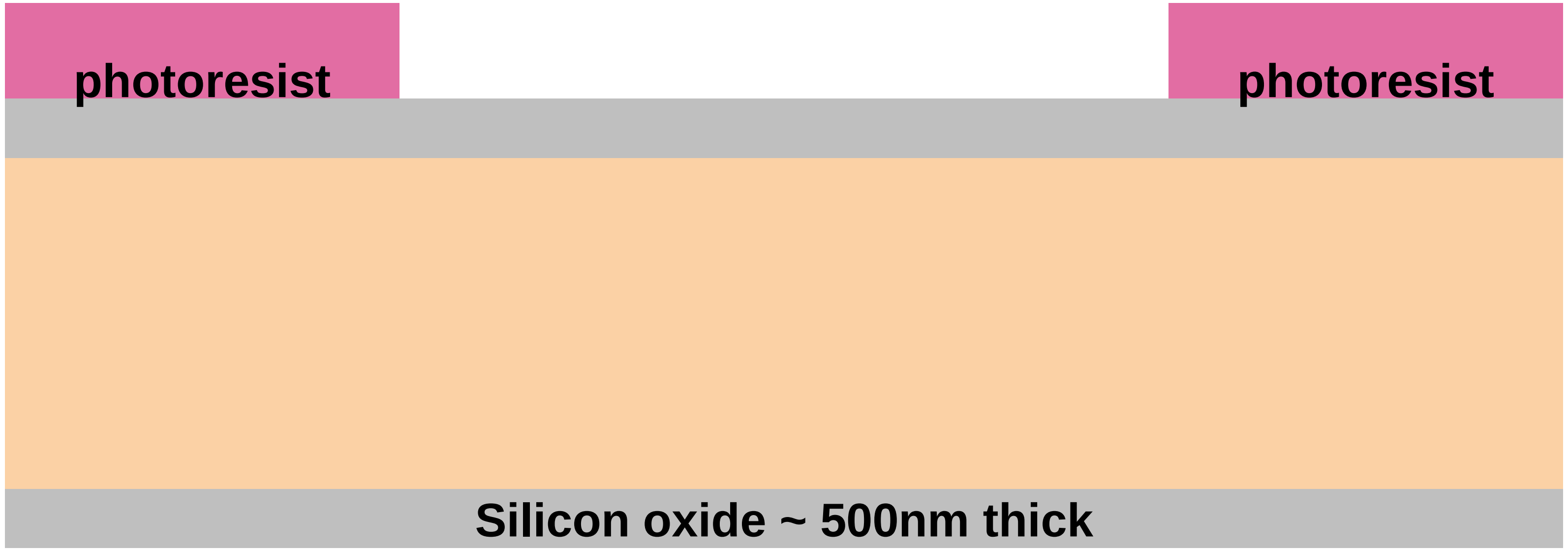


Resist Development

Developing solution is sprayed on the wafers, to get rid of the exposed photoresist.
Wafer is then rinsed in DI and dried.

Resist Development

Image is transferred from photolitographic mask to the resist covering the wafer.



Etching

Wet etch

- Very selective
  - HF for silicon oxide
  - HNO for polysilicon
  - Alu etch for aluminum
  - …
- Unexpensive
- Unbreakable
- Very clean

Dry etch

Wafers exposed to a gas in an RF field

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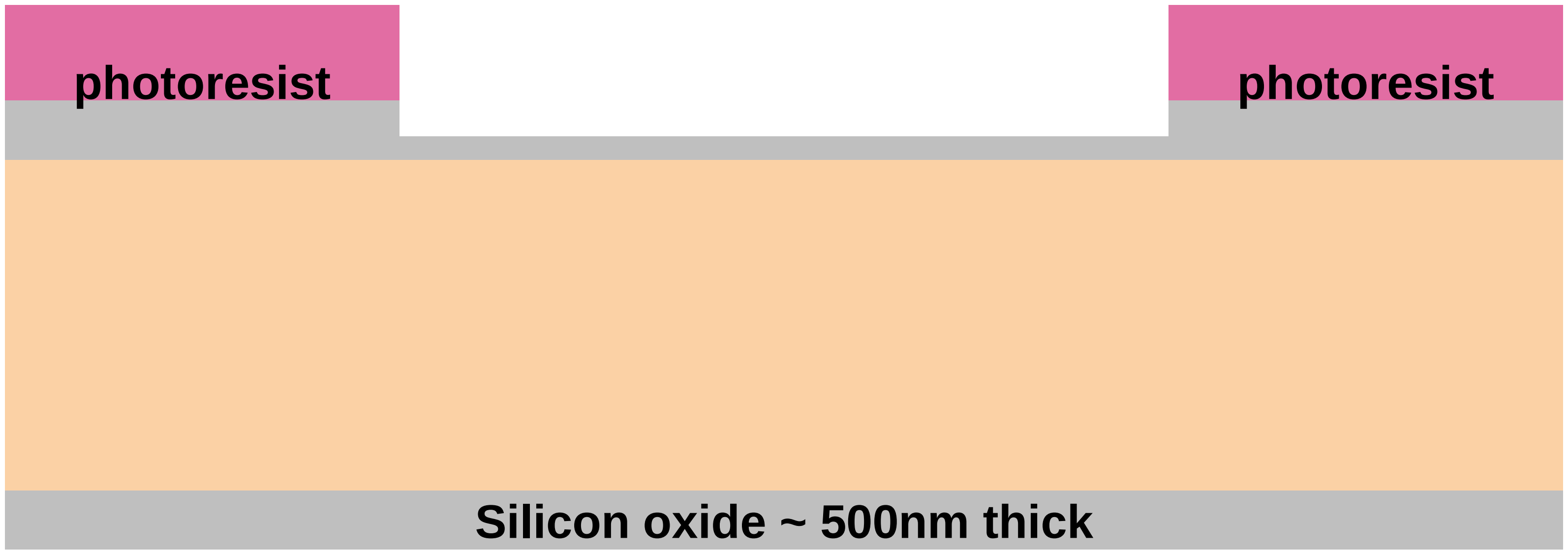
Etching

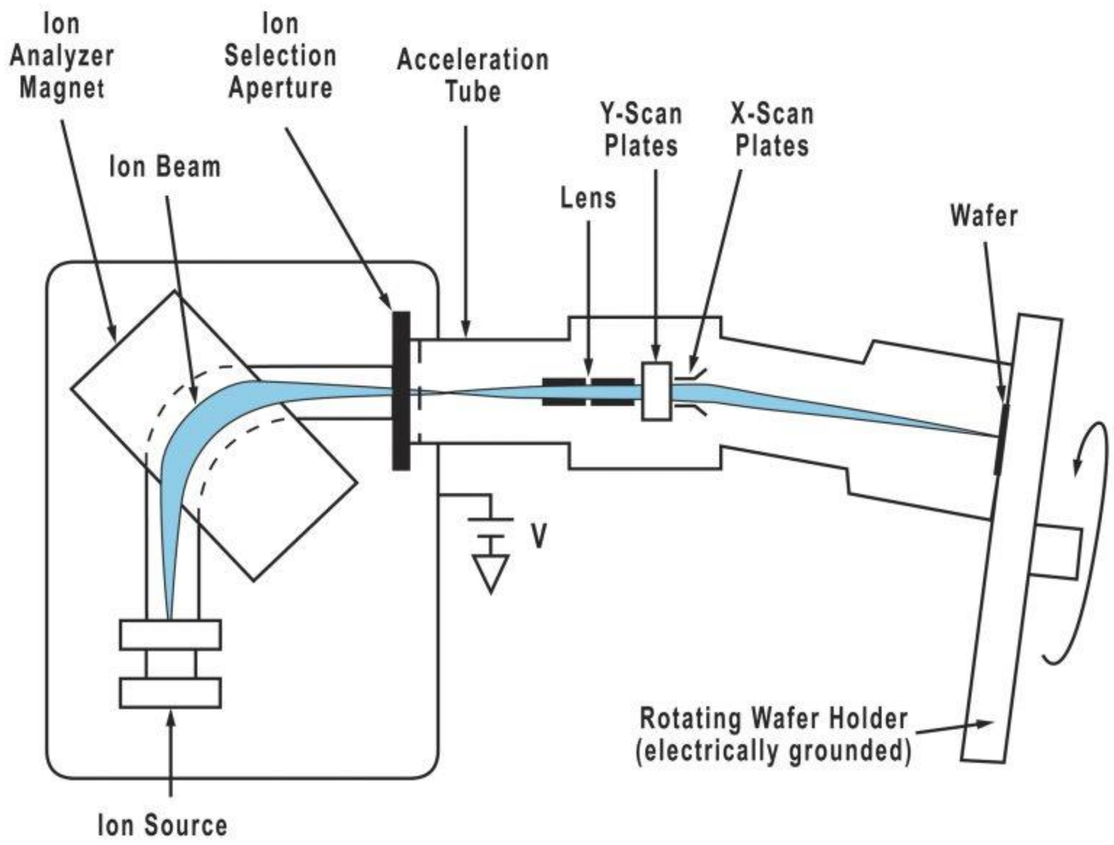
Photoresist “resists” acid attacks and RIE attacks (for some time).

In this example, oxide is thinned down.



Ion Implantation

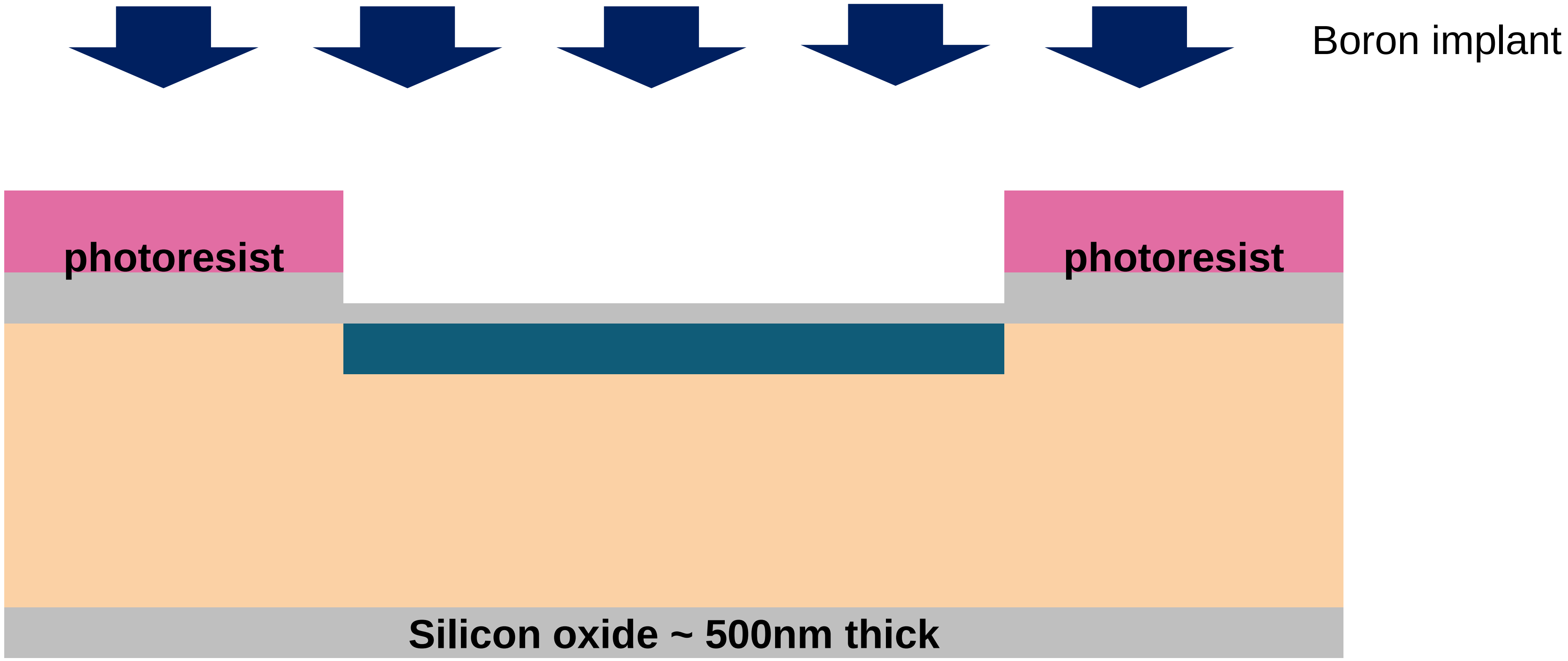
Insertion of doping in silicon



An Ion implanter is an accelerator, it requires a medium facility and fabrication volume to justify the cost. Often outsourced.

Tandem van Der Graaff @ BNL can be used as a (high energy) ion implanter as well!

Ion Implantation



Resist stops the implant (also oxide does, so energy must be calibrated)

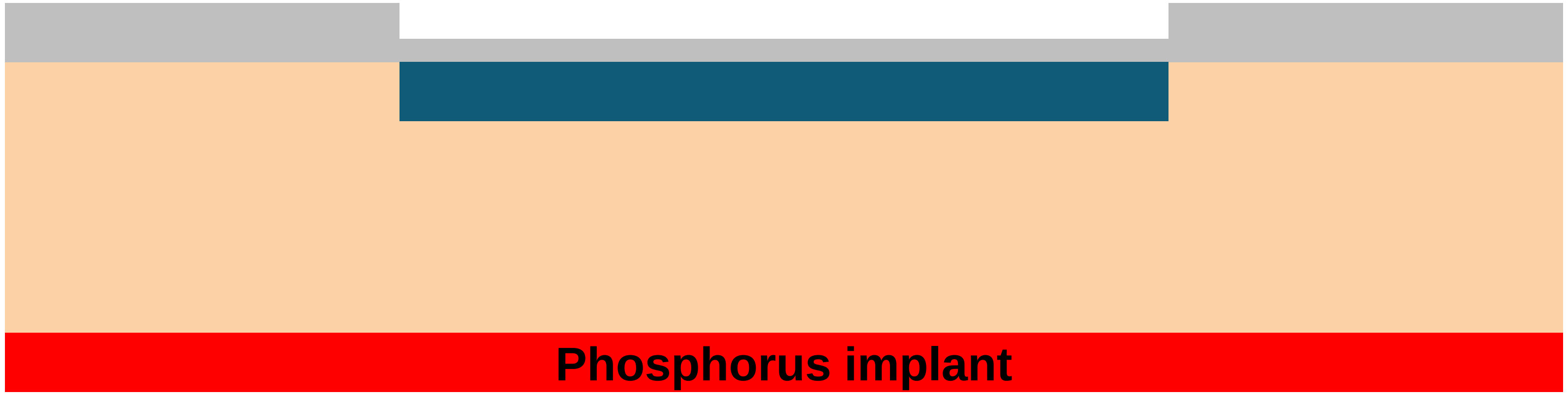
Resist strip

Wet method:
 - stripper
- Piranha etch (Caro etch): sulfuric acid and hydrogen peroxide at > 100C

Dry method:
ashing in oxygen plasma

Resist stripping

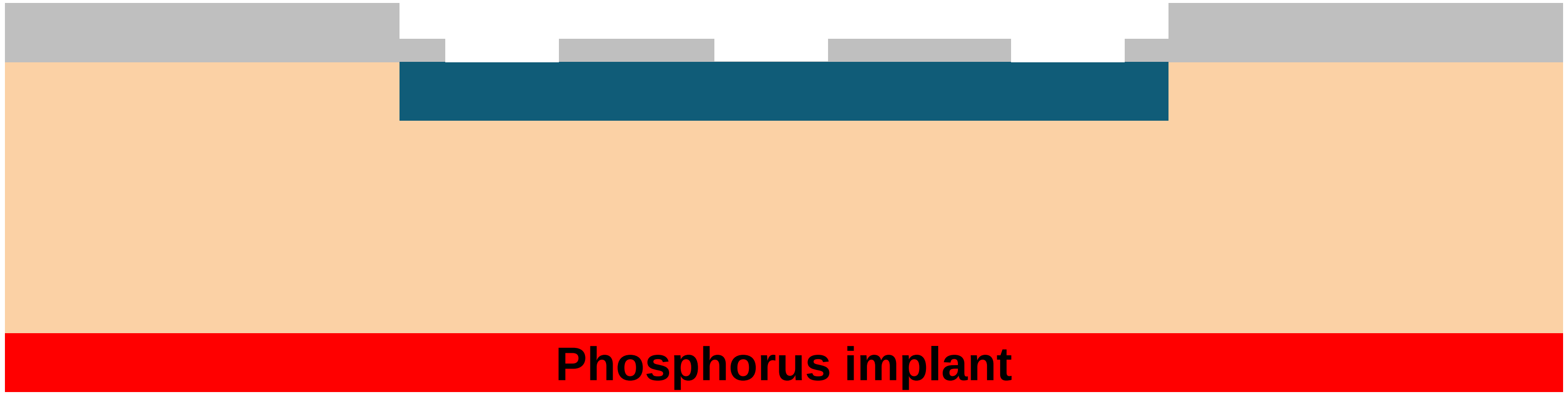
Ion implantation on the back of the wafer as well, same type as the substrate for a good ohmic contact



Contact opening

Another lithographic step is required:

1. resist spinning,
2. photolithographic mask exposure,
3. etching to expose the silicon
4. resist stripping



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Metal sputtering

- RF Sputtering System for high purity Aluminum/Titanium Metallization

- Ion Gun for removal of native oxide in Double metal applications

Lesker sputtering system

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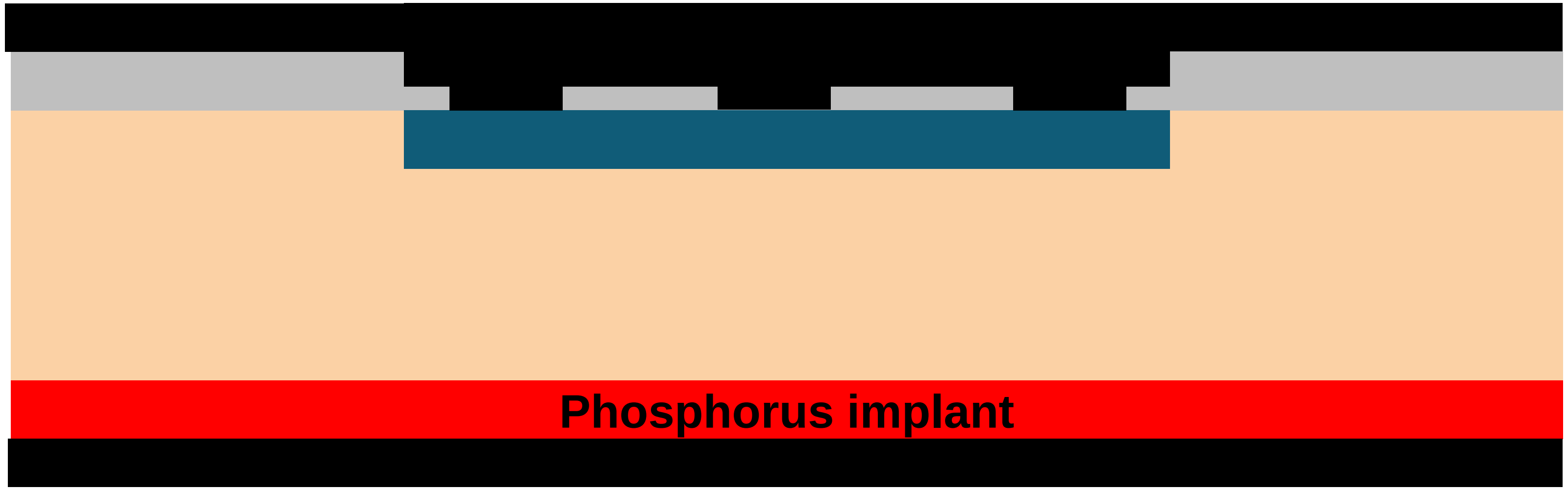
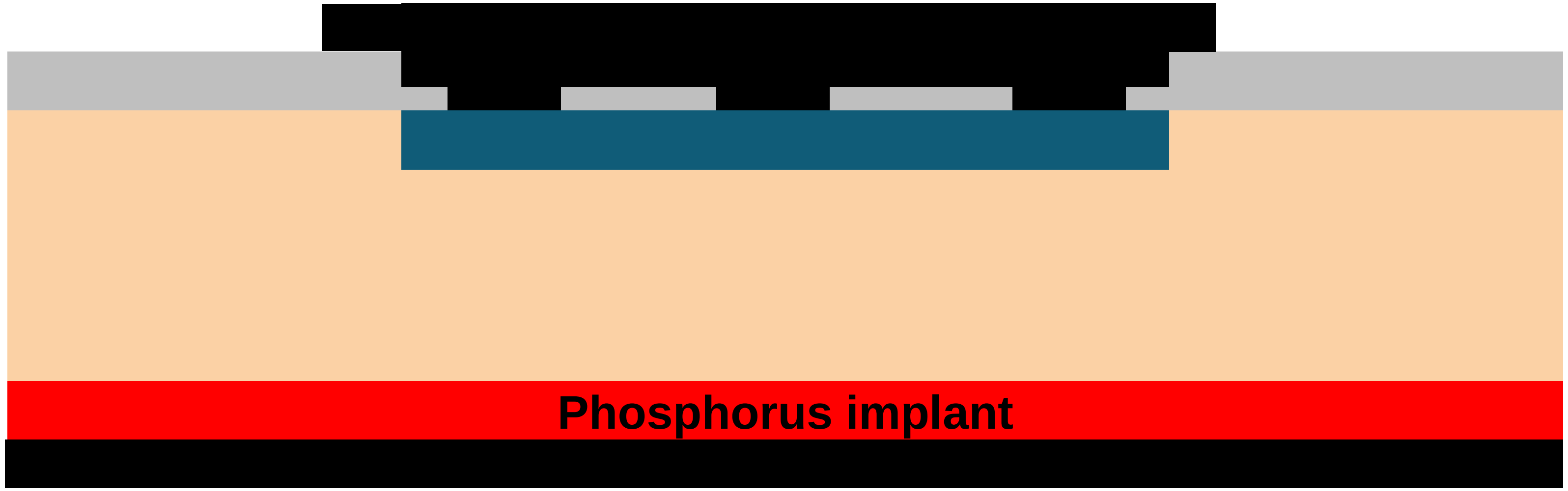
Metal sputtering (both sides)



Metal definition (lithography) – wet or dry



Thin-Film deposition

Aluminum melts at 400C, so no more furnaces after its deposition.
We may want to add some thin film as anti-scratch layer (passivation).
This can be done my PECVD deposition (plasma chamber) or LPCVD (low-temperature furnace).
Nitrides and oxides are usually deposited.

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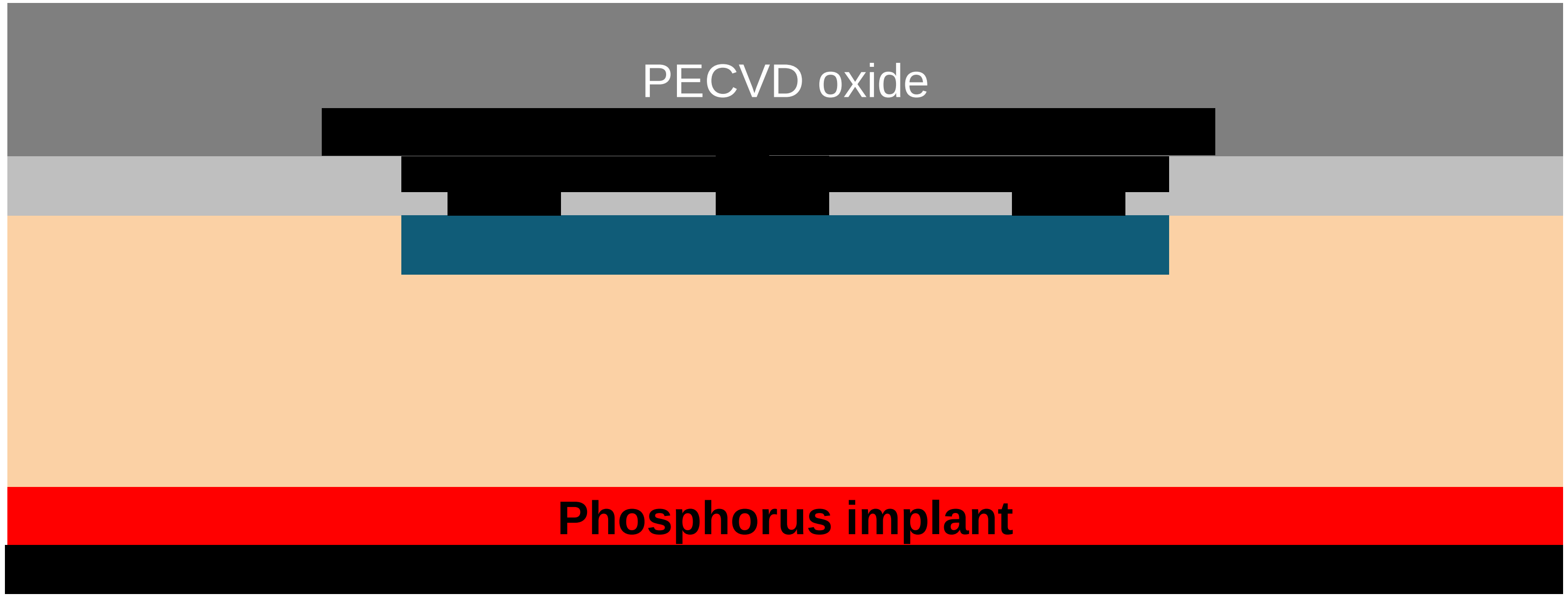
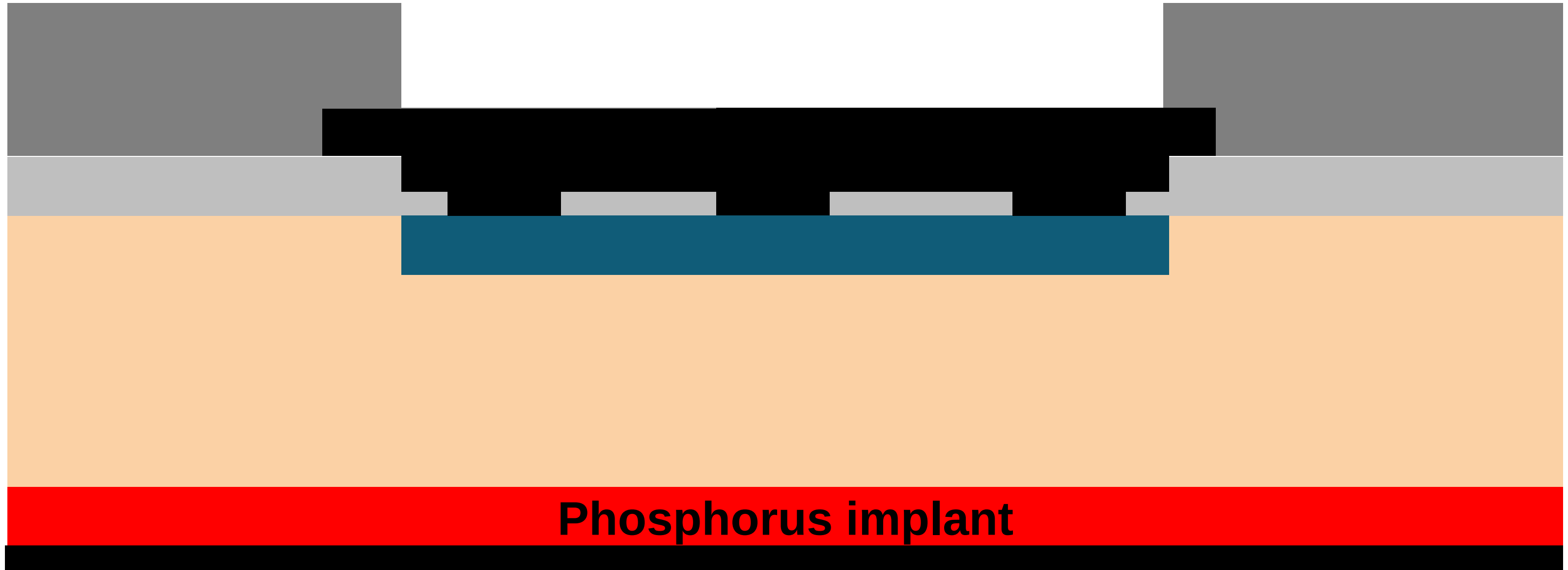
Passivation deposition and opening



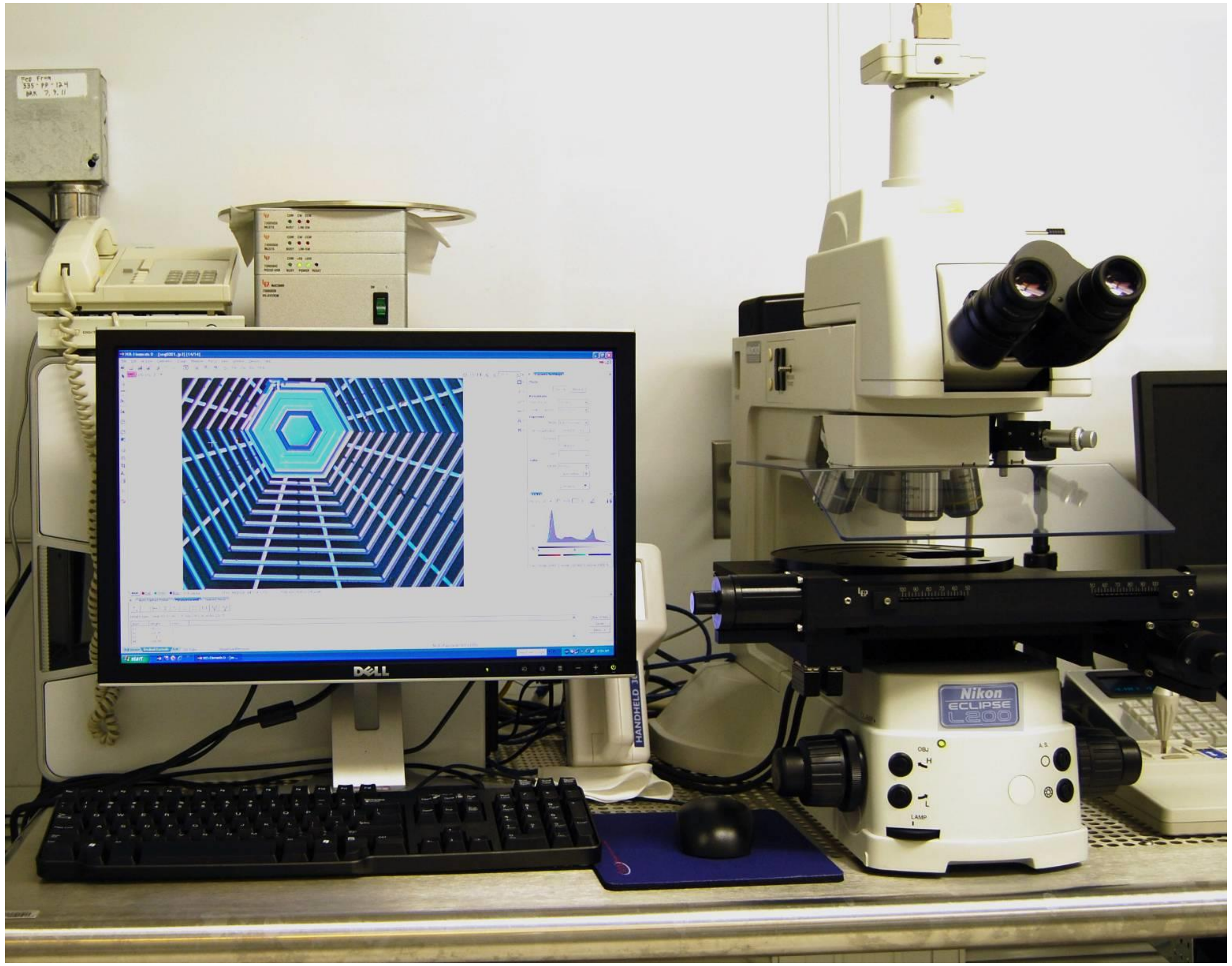


Wafer Inspection

- Following every process step, each wafer needs to be methodically inspected for potential defects

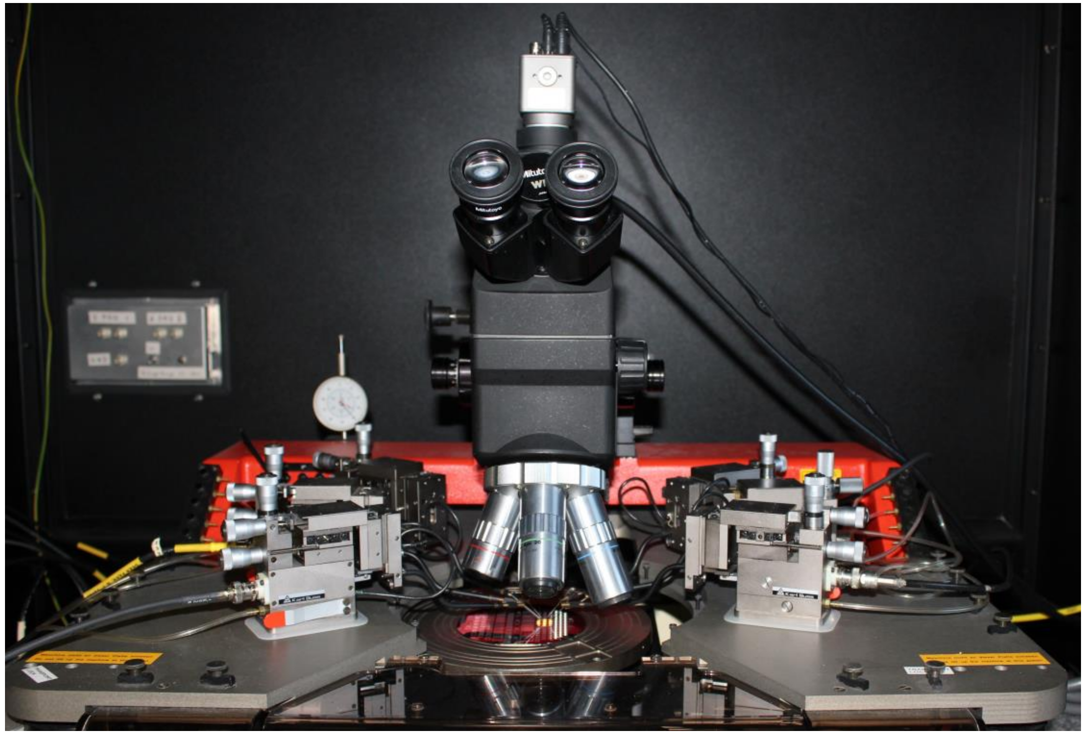
- FILMETRICS© for thin-film thickness measurement

- Ellipsometer for *n* and thickness



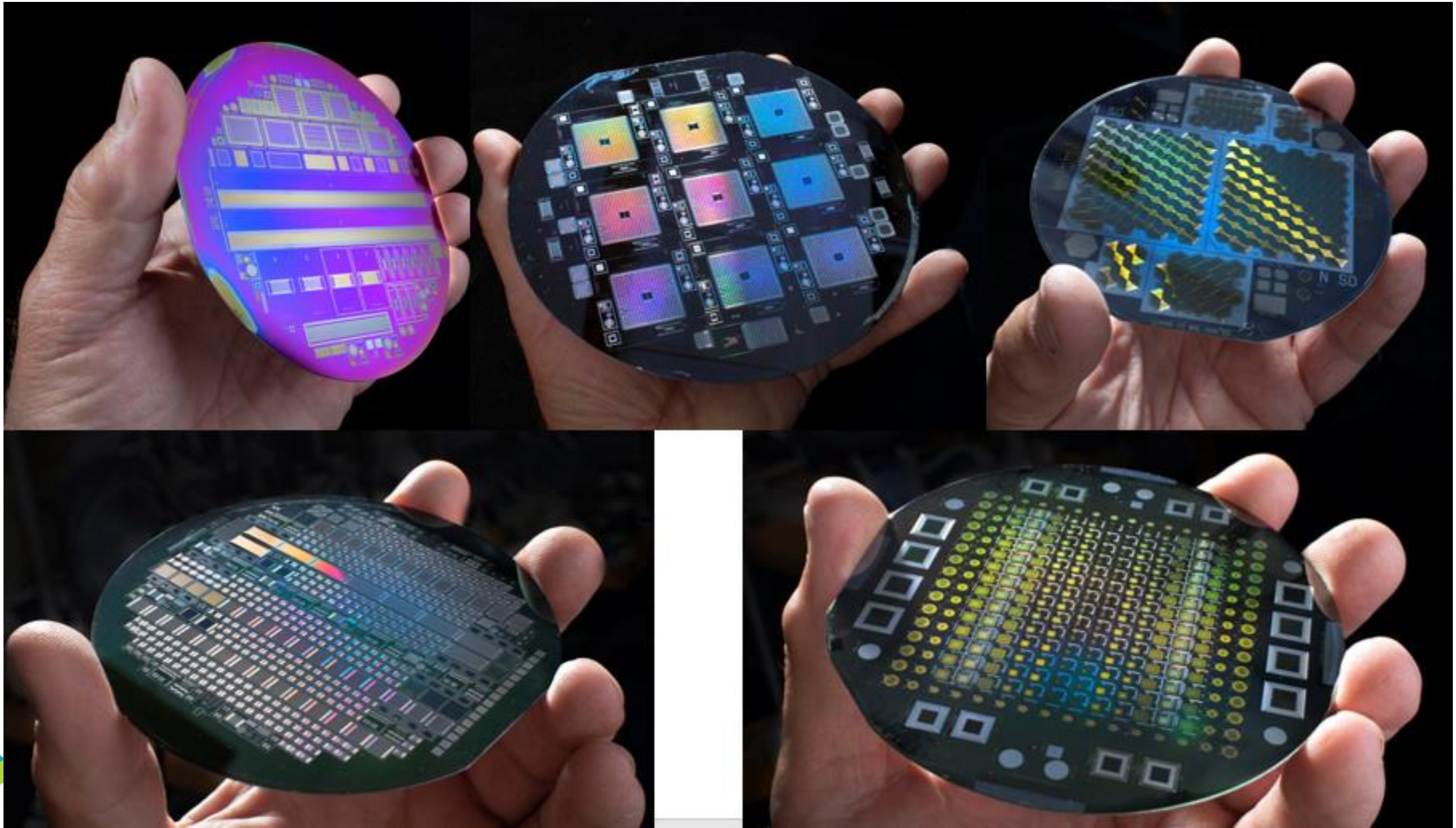
Testing

BNL manual probe station



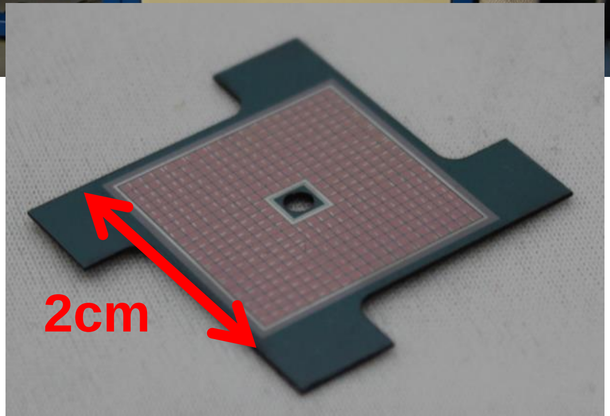
Automatic probe station for volume productions

The final wafer



Dicing Systems

BNL laser dicing
(allows arbitrary shapes, not only straight cuts)



Disco © saw dicing

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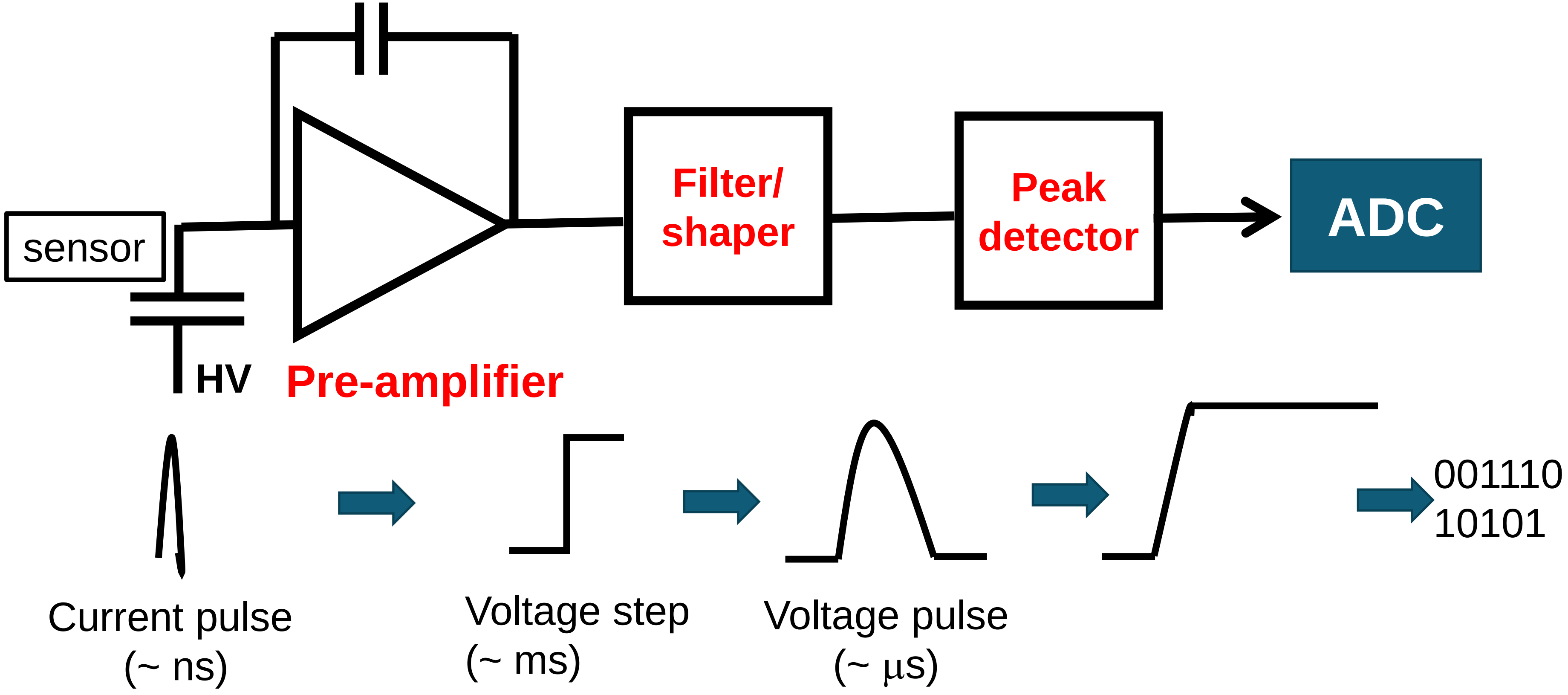
More manual dicing systems

(very basic) Read-out chain



- Can be made by separate blocks
- Modern trend: integrate everything in an IC (especially if # of channels is high)
  ASIC: Application Specific Integrated Circuit, designed in house but fabricated in TSMC, IBM, AMS, ST, …

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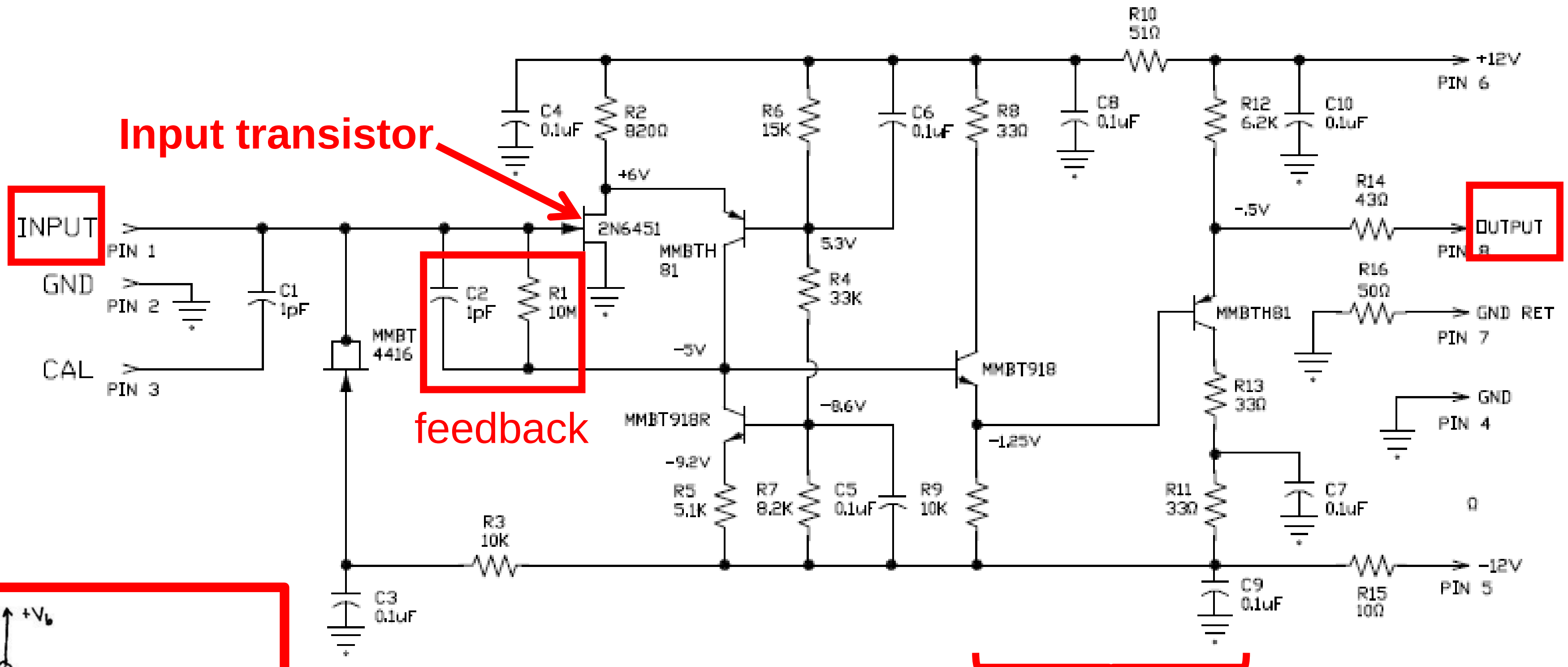
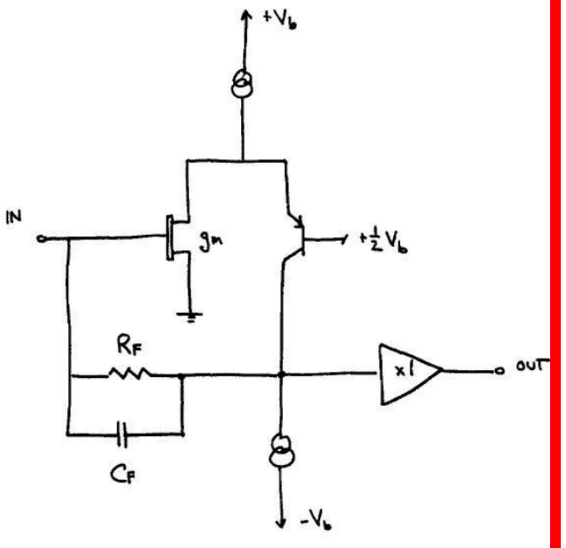
Charge Sensitive Pre-Amplifier



Double source-follower stage



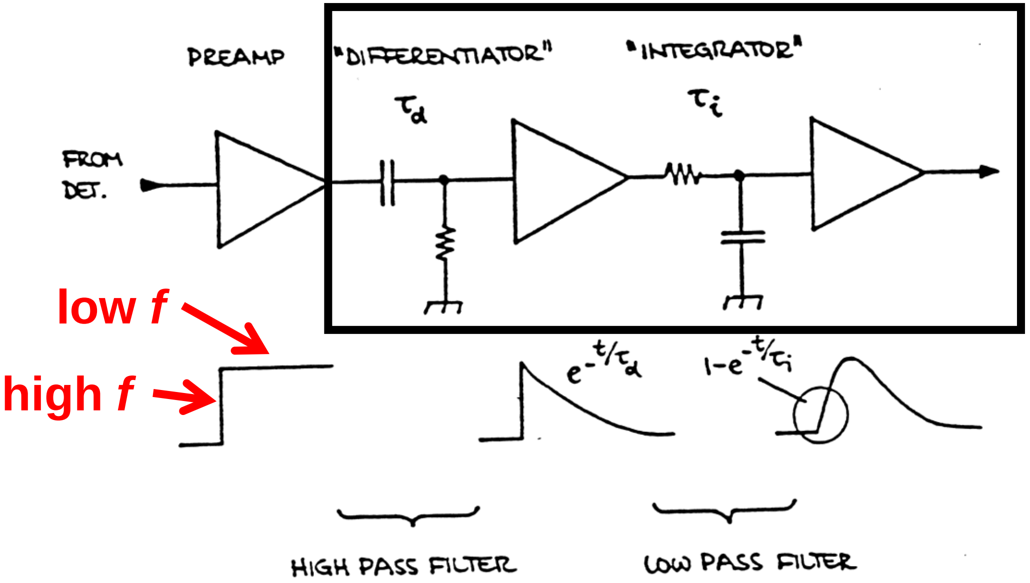
Charge preamp ©Radeka 68

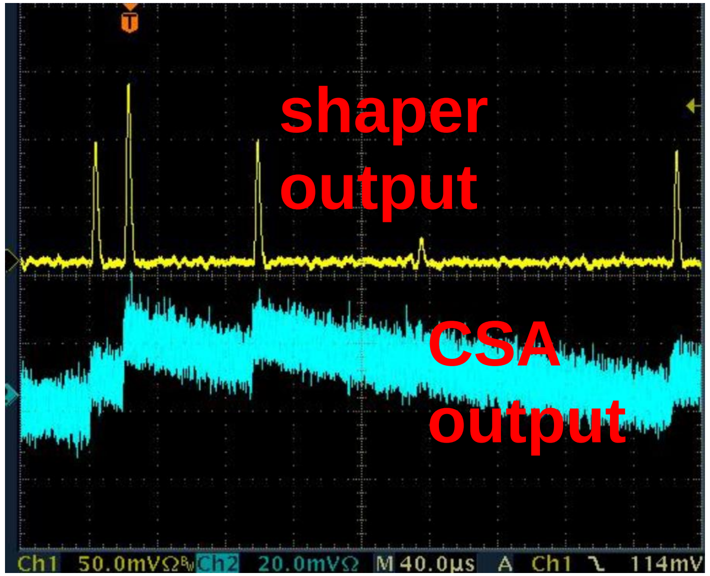
The common trend is to fabricate the CSA in CMOS technology:

- smaller, good electrical properties, cheap.

For example, state-of-the-art is CUBE (Politecnico Milano) ~1x1x1 mm^3

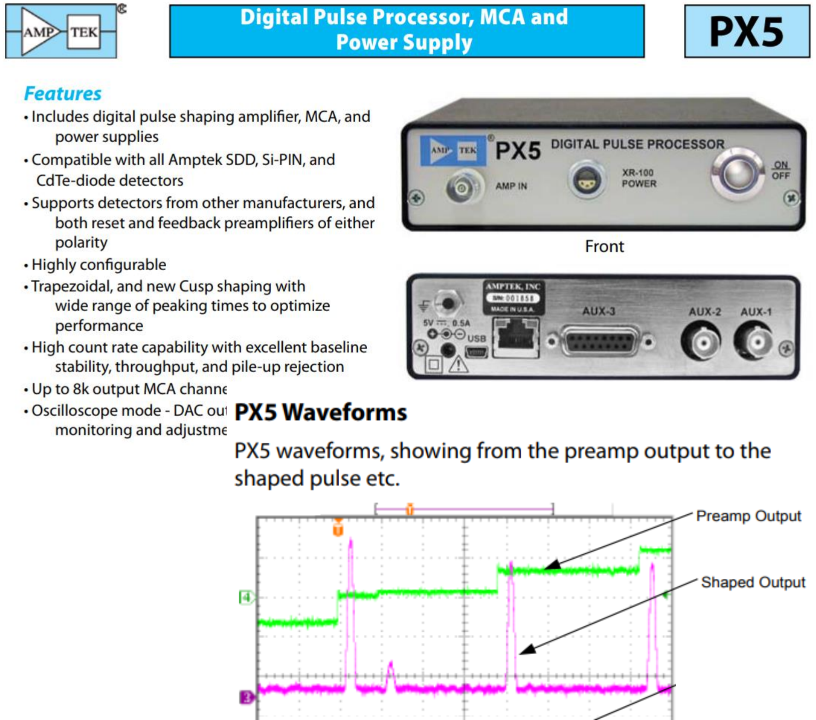
Filter/shaper





- 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

NIM analog shaper


AMPTEK | Digital Pulse Processor, MCA and Power Supply | PX5

Features
- Includes digital pulse shaping amplifier, MCA, and power supplies
- Compatible with all Amptek SDD, Si-PIN, and CdTe-diode detectors
- Supports detectors from other manufacturers, and both reset and feedback preamplifiers of either polarity
- Highly configurable
- Trapezoidal, and new Cusp shaping with wide range of peaking times to optimize performance
- High count rate capability with excellent baseline stability, throughput, and pile-up rejection
- Up to 8k output MCA channe
- Oscilloscope mode - DAC ou monitoring and adjustme

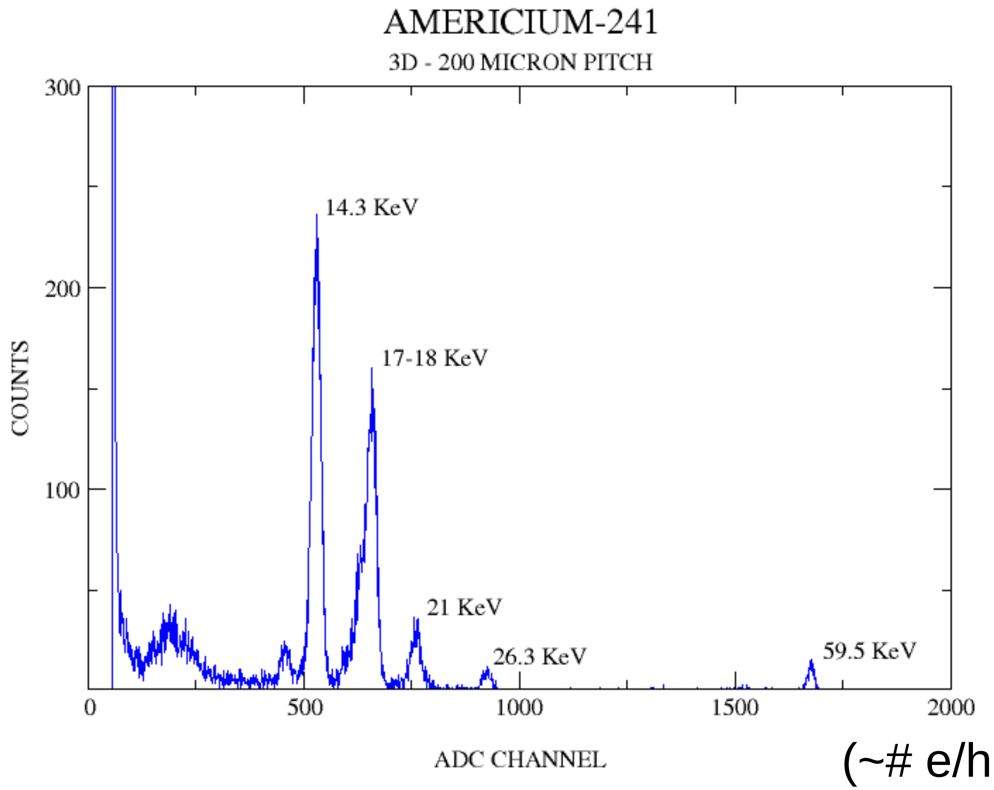
PX5 Waveforms

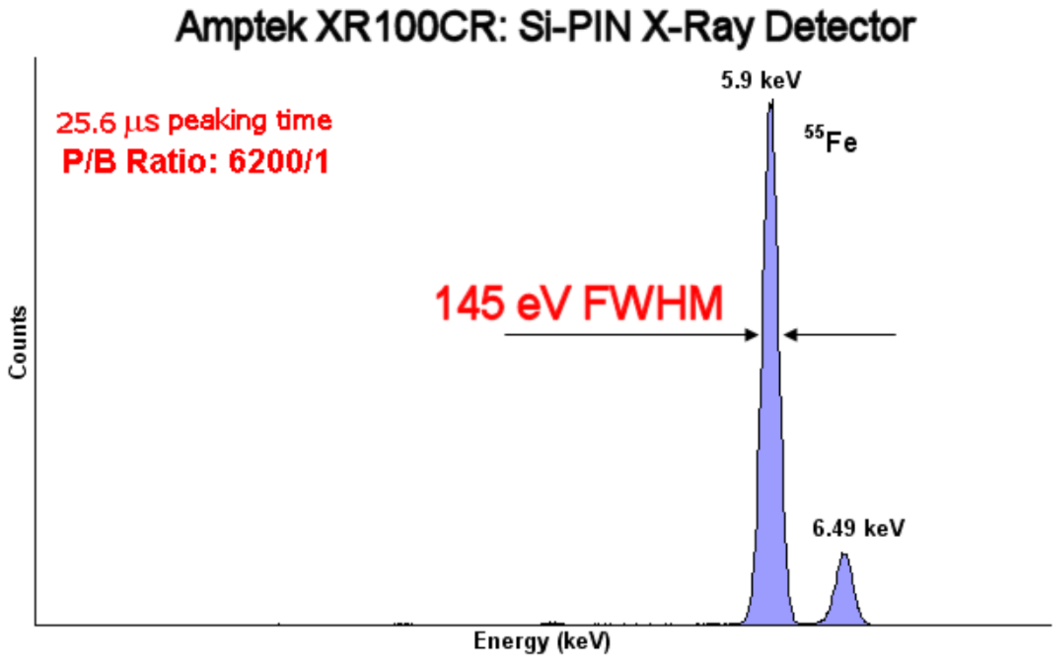
PX5 waveforms, showing from the preamp output to the shaped pulse etc.

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





(~# e/h pairs, ~ energy)

Low-activity X-ray-emitting radioactive materials are used as calibration sources

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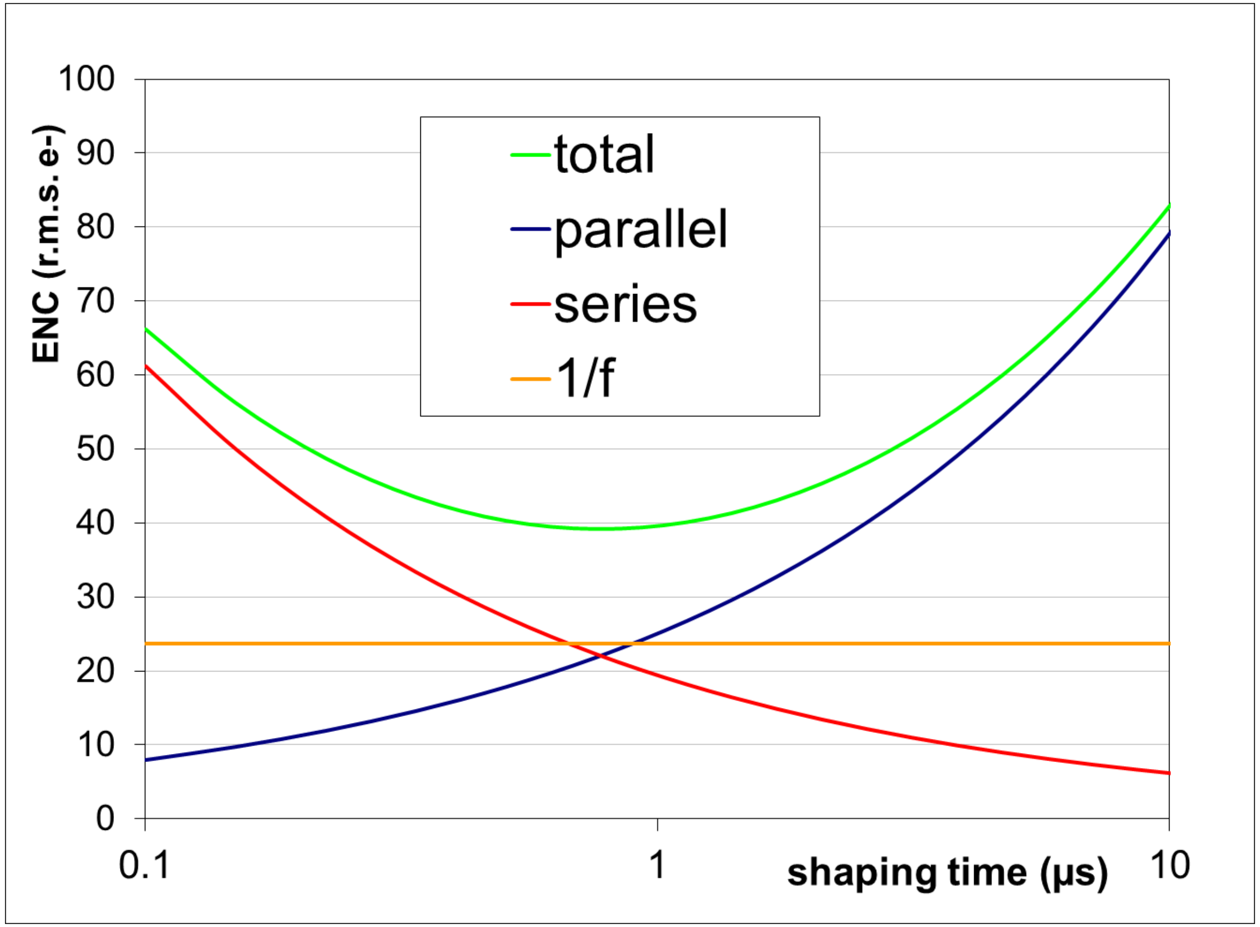
Noise in a detection system

Intrinsic (physical) properties of sensor/detection system introduce noise in the read-out.
Equivalent Noise Charge (ENC) is the charge for which Signal-to-Noise ratio is 1.
Can be optimized, never eliminated, by wisely minimizing Capacitance (C) and sensor leakage current (as much as possible), designing good read-out (peaking time τ), etc.



$ENC^2_{parallel} \sim I_{leakage}\, \tau$

$ENC^2_{series} \sim C^2/\tau$

$ENC^2_{flicker} \sim C^2$

$ENC^2_{total} = ENC^2_{parallel} + ENC^2_{series} + ENC^2_{flicker}$