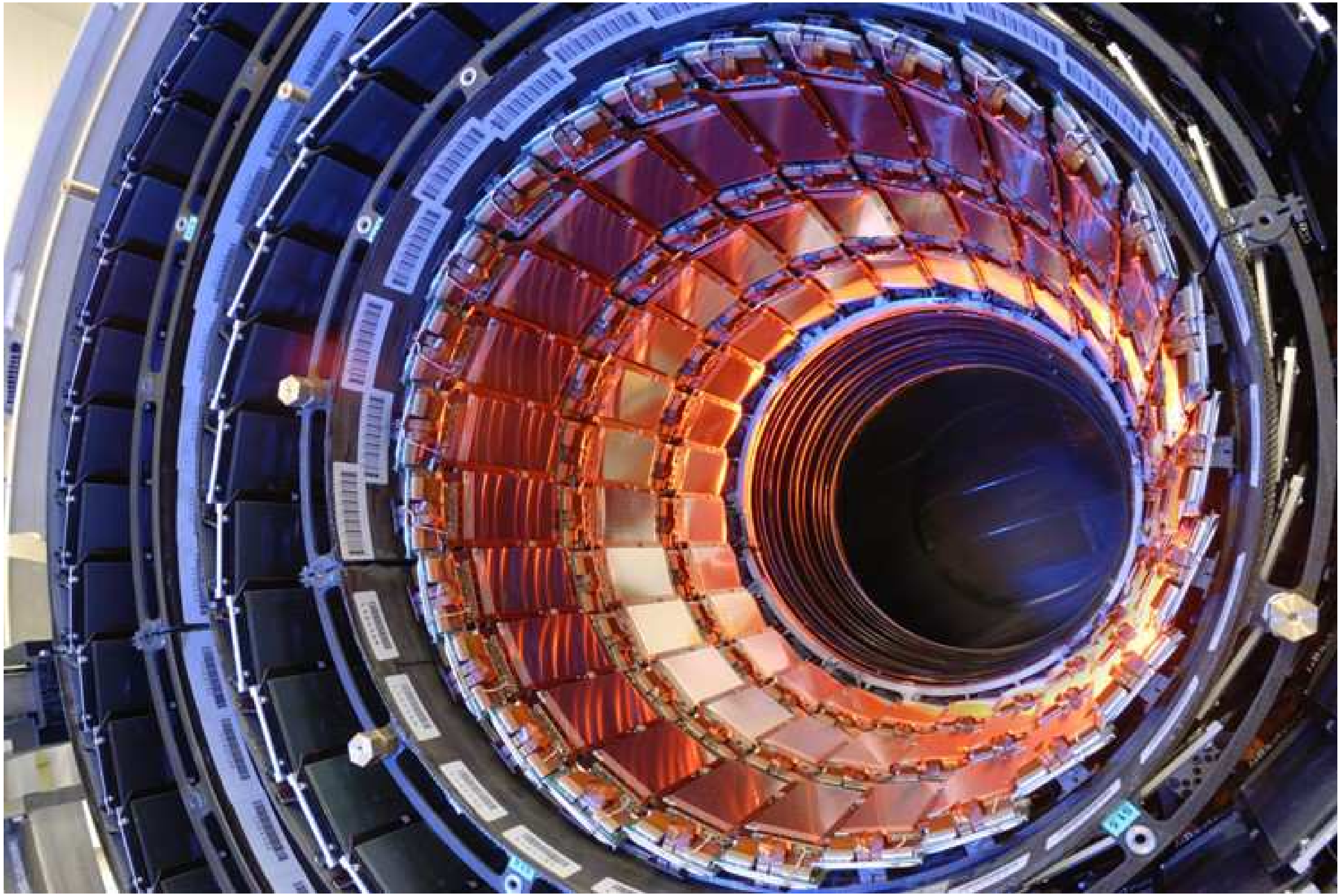
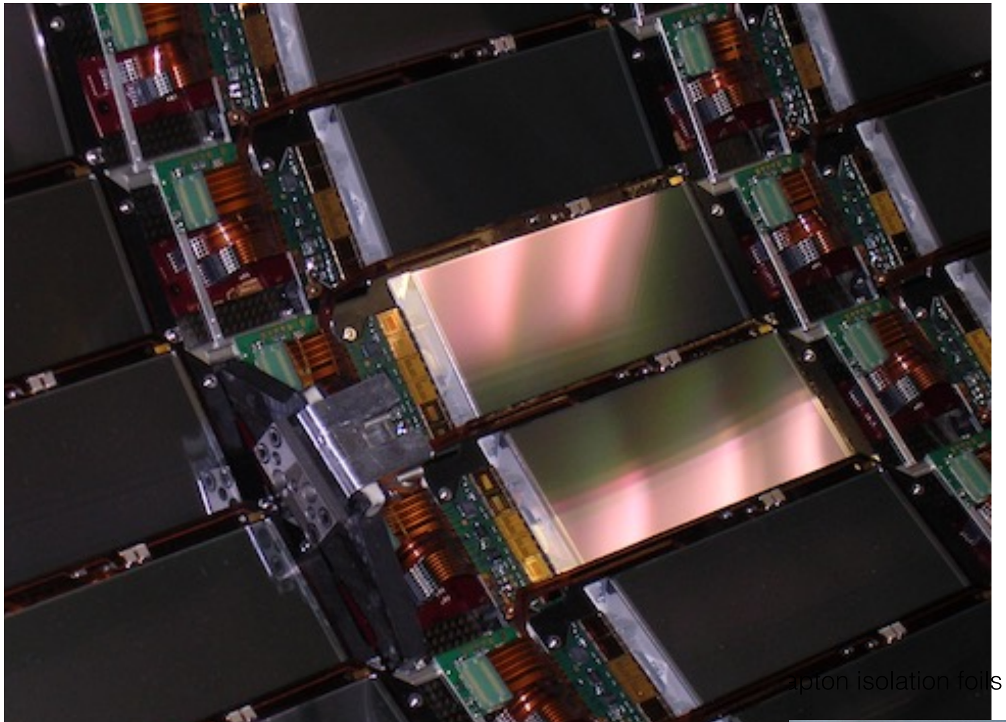
Microelectronics

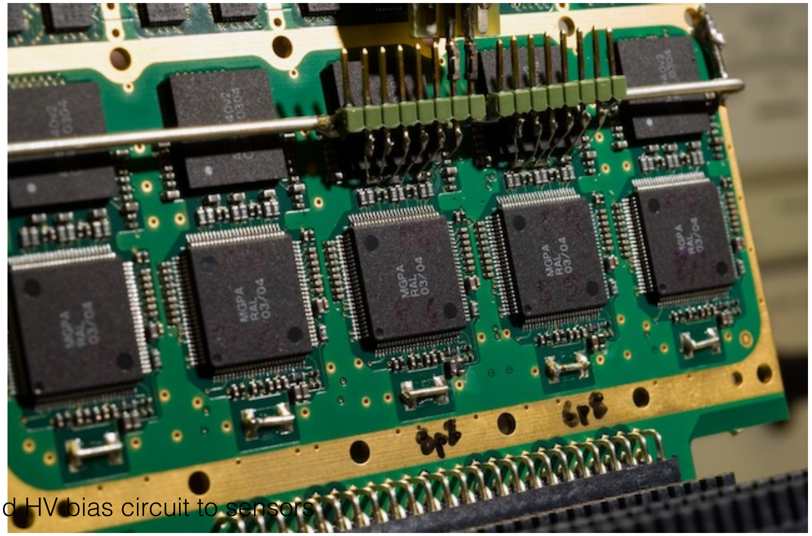
The interior of the CMS Silicon tracker during assembly in CERN



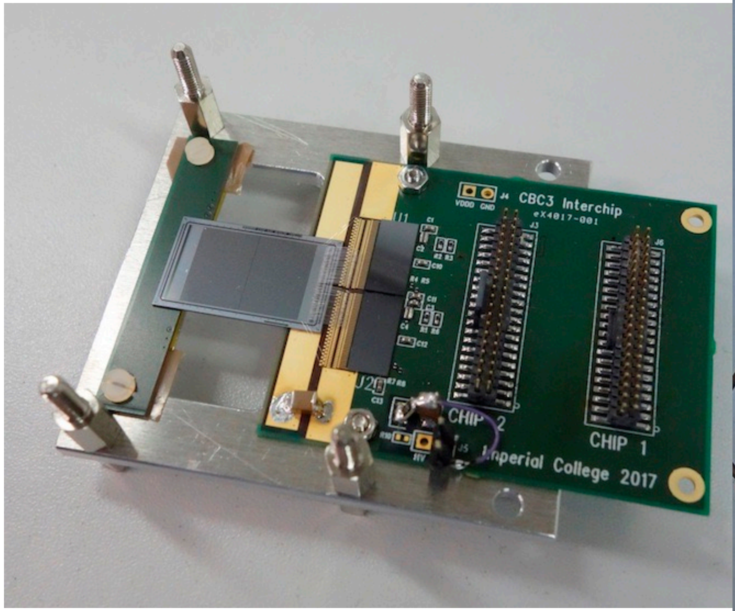
Geoff Hall

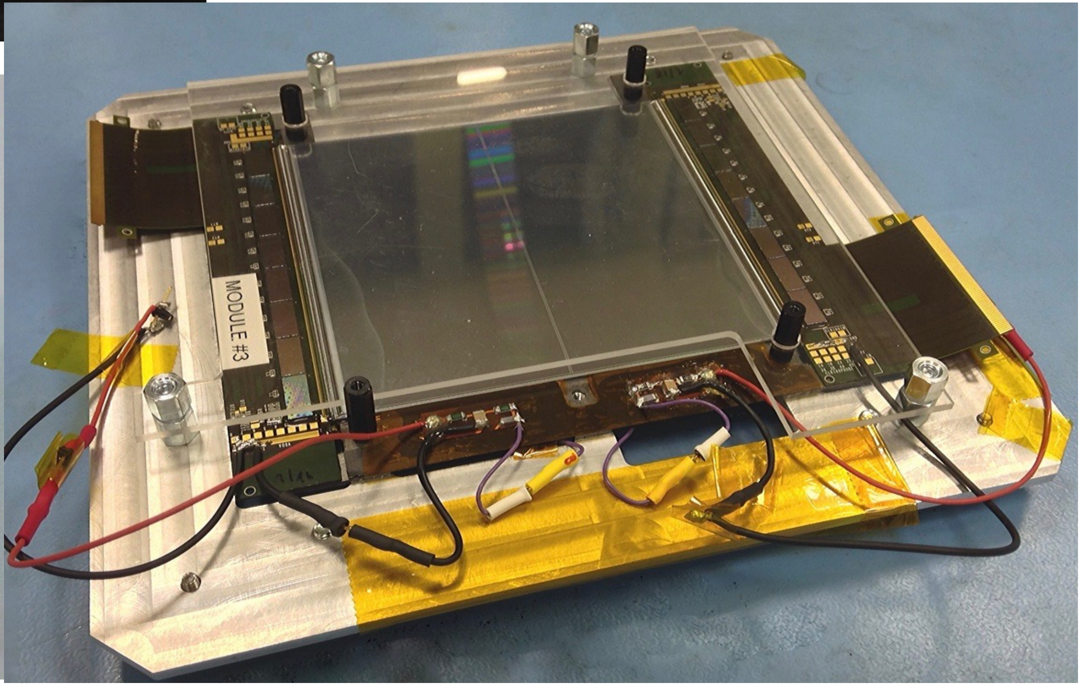
Spot the ASIC





apton isolation foils and HV bias circuit to sensors





Microelectronics

- A brief introduction to three subjects

- Noise in front-end electronics
  - Now well established, and you may not need to know the details
  - But at least you should know why and how it arises

- How microelectronic circuits (and silicon sensors) are made
  - Try to give some insight into factors that affect this (expensive) technology

- A short summary of how radiation affects integrated circuit electronics
  - highly relevant to LHC
  - but also some future projects, such as muon colliders

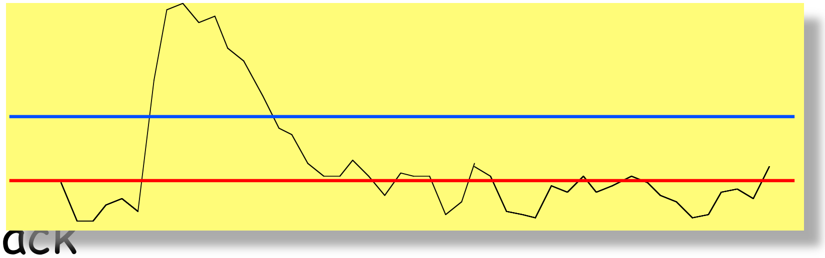
- Some additional backup slides in case further details are of interest

Noise

- What is NOISE? *A definition:*

  Any unwanted signal obscuring signal to be observed

  two main origins



- EXTRINSIC NOISE examples...

  pickup from external sources unwanted feedback

  RF interference from system or elsewhere, power supply fluctuations

  ground currents

  small voltage differences => currents can couple into system

  may be hard to distinguish from genuine signals *but* AVOIDABLE

  Assembly & connections, especially to ground, are important

- INTRINSIC NOISE

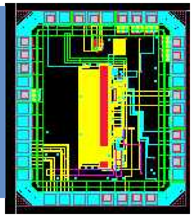
  Fundamental property of detector or amplifying electronics

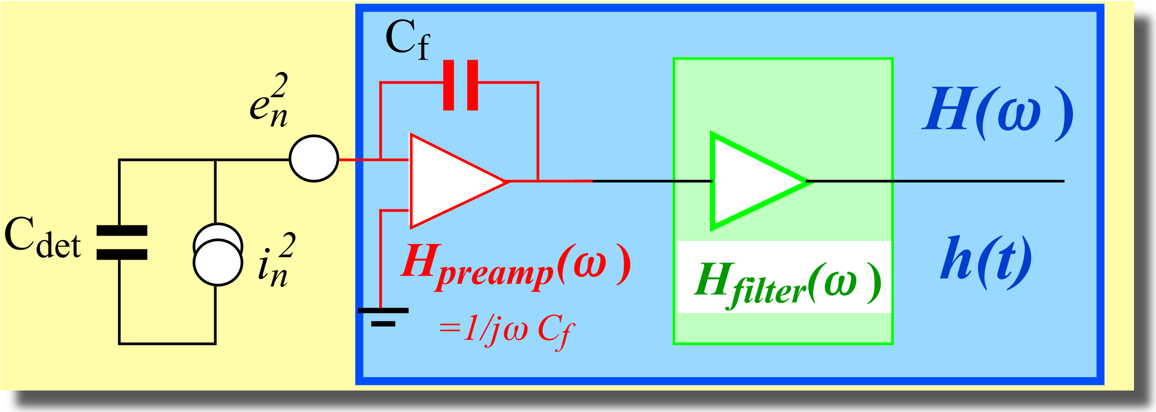
  Can't be eliminated but can be MINIMISED

Noise sources

- Thermal noise
  - Quantum-statistical phenomenon; carriers in constant thermal motion
    - macroscopic fluctuations in electrical state of system
  - Typically associated with input transistor or resistive components
- Shot noise
  - Random fluctuations in DC current flow
  - Typically associated with sensor
- *1/f* noise
  - commonly associated with interface states in MOS electronics
  - Luckily, less important for high speed electronics

Noise in amplifier systems





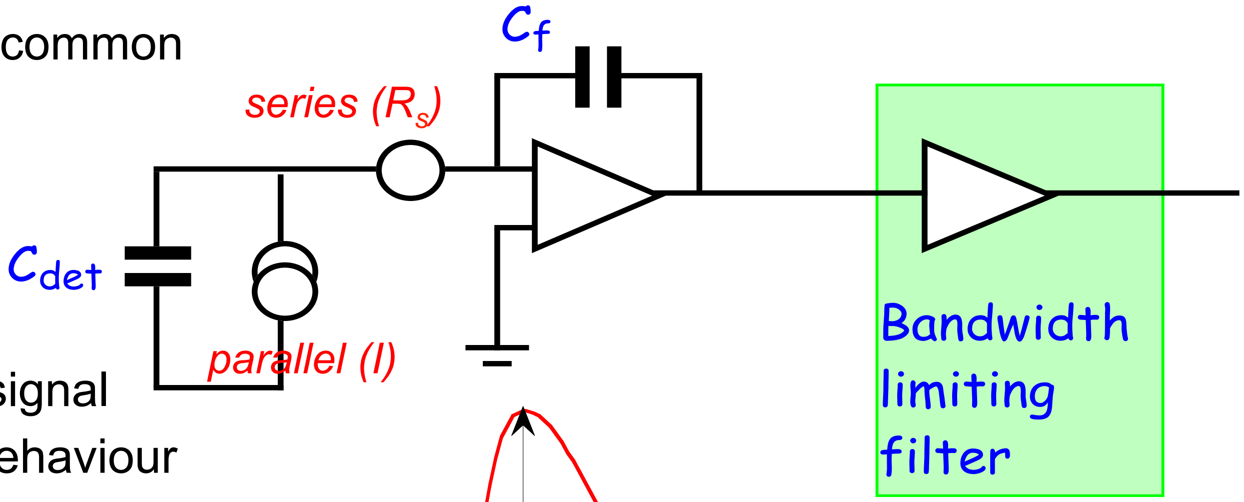
- VFE systems comprise
  - preamplifier - with noise sources
  - shaping amplifier or other filter

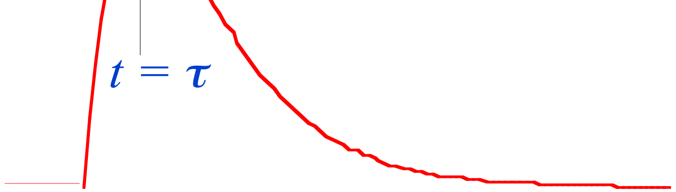
- Preamplifier usually designed with noise as an important consideration
  - preamplifier pulse shape is long duration with short, sharp peak
  - so modify it with shaper to
    - optimise signal to noise
    - generate a more practical pulse shape, avoiding pile-up
  - the first (pre-) amplifier is the most important part of the system for noise

- The system noise can be calculated once sources are understood
  - relies on Campbell's theorem and summation over bandwidth

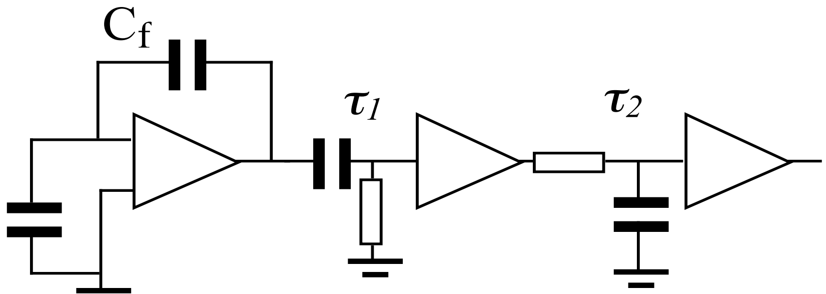
Signal processing

- If noise sources are defined, their impact can be calculated
  - **pulse shaping** is most common





  - **sampling** an amplifier signal can produce equivalent behaviour



  - Useful point of comparison: CR-RC filter

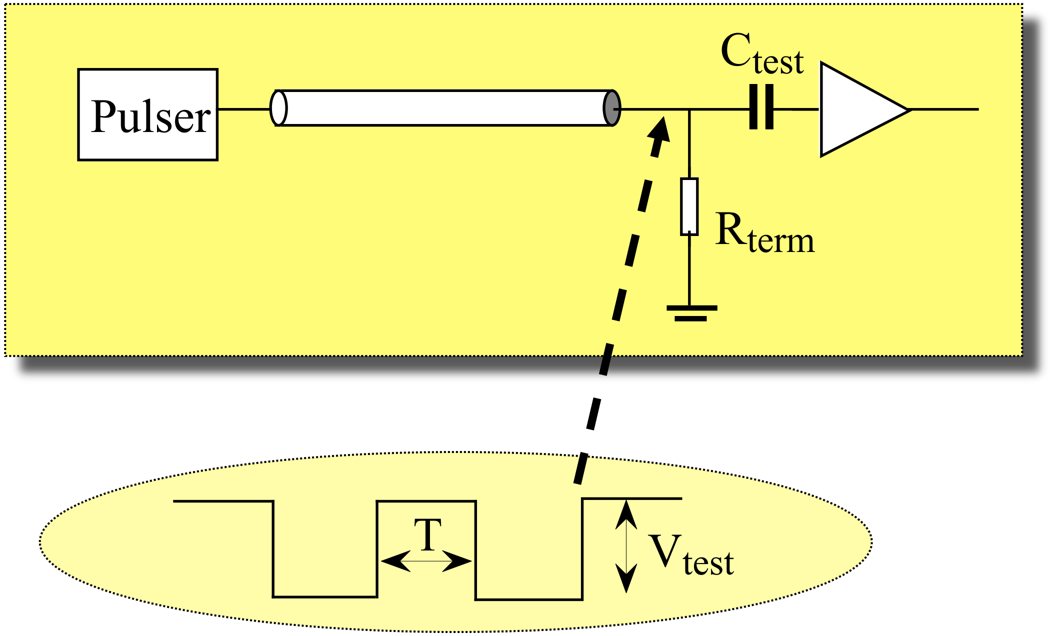
numerical result for many cases

$$ENC^2 = \frac{e^2}{8}\left(\frac{4kTR_sC_{tot}^2}{\tau} + 2eI\tau\right)$$

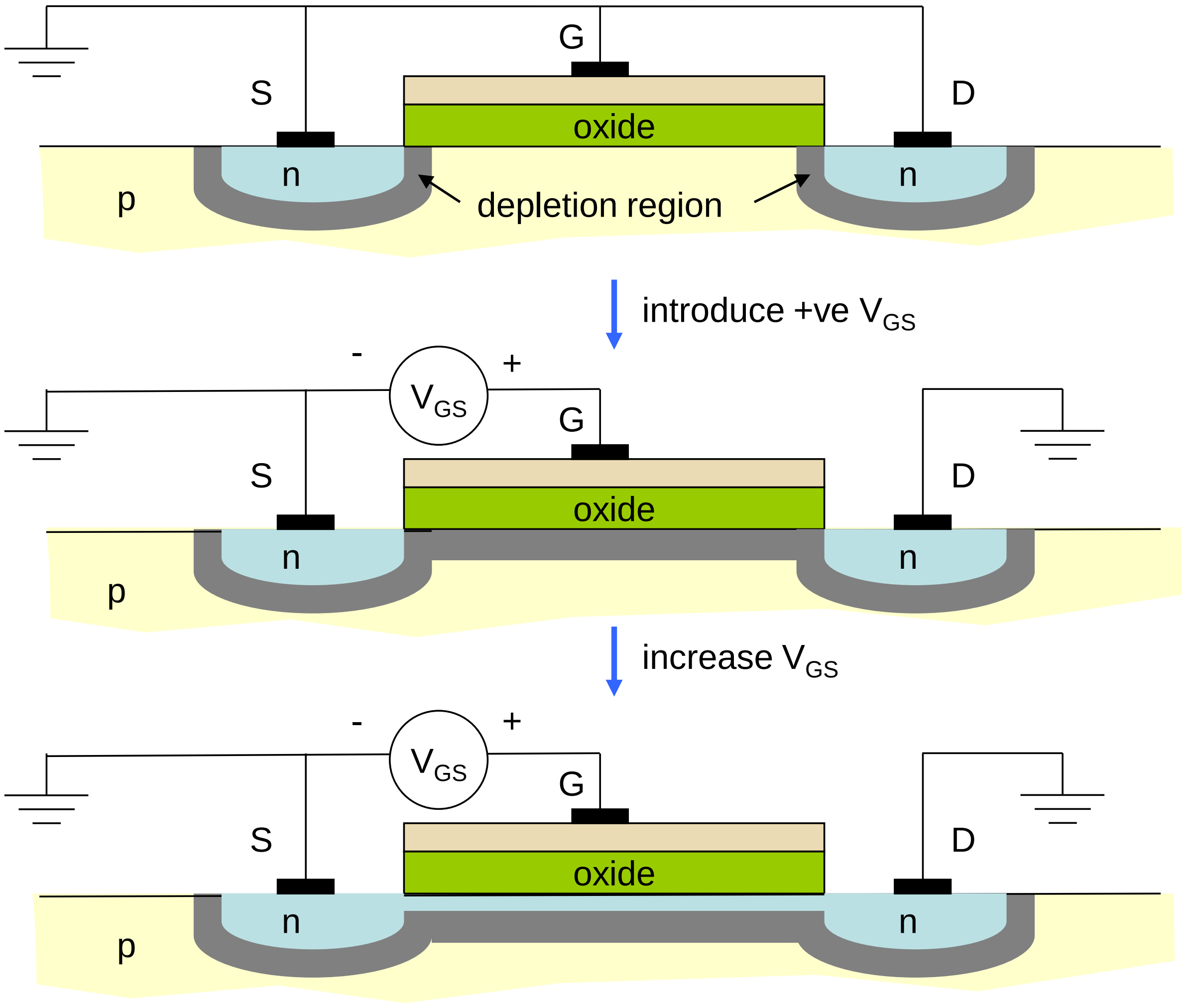
Equivalent Noise Charge

- Systems need to be calibrated:
- ENC is the signal magnitude which produces an output amplitude equal to the r.m.s. noise
  - *ideally measure in some absolute units - e, coul, keV(Si),… rather than ADC channels*
- to calibrate
  - inject charge and look at result
    - eg x-ray signal of known size
    - or electronic test pulse
      - *preferably in-situ*
  - measure V_{out} for known Q_{in}

$$Q_{test} = C_{test}V_{test} = Ne$$



MOSFETs



channel just forms at $V_{GS} = V_T$ = threshold voltage

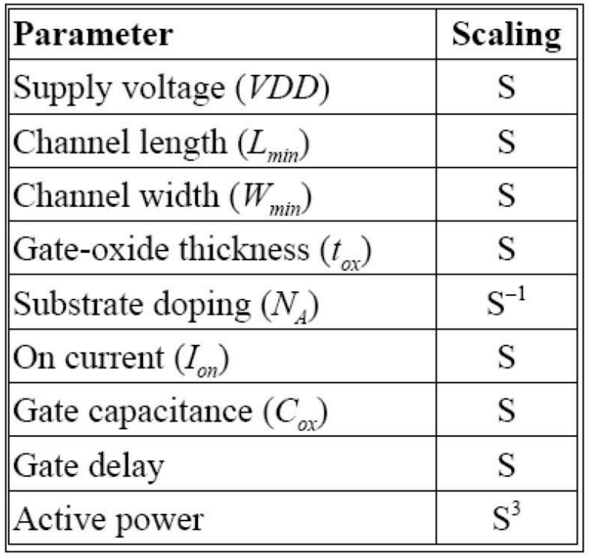
Bias gate to control current under oxide

Why is CMOS so important?

Only consumes power when switching

Simple scaling of functions with size

Table 6.3 CMOS scaling relationships.

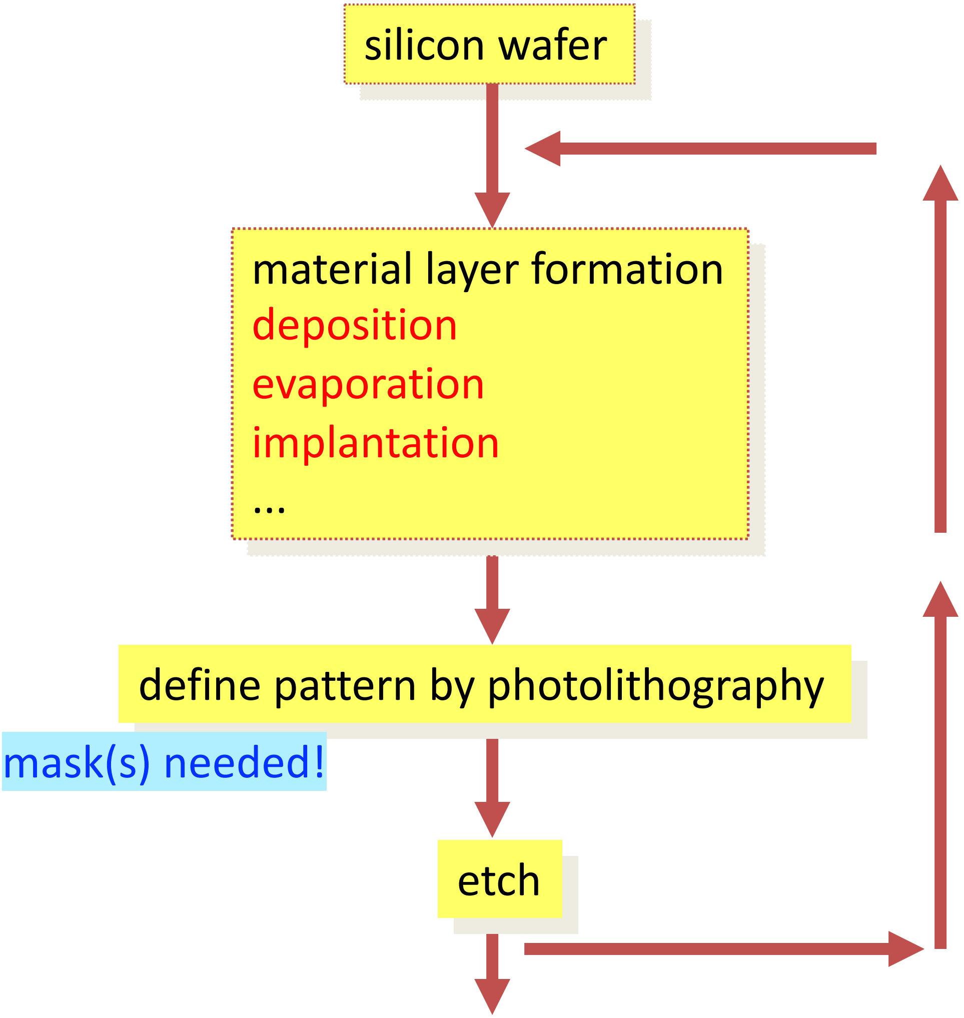


Parameter	Scaling
Supply voltage (*VDD*)	S
Channel length (L_{min})	S
Channel width (W_{min})	S
Gate-oxide thickness (t_{ox})	S
Substrate doping (N_A)	S^{-1}
On current (I_{on})	S
Gate capacitance (C_{ox})	S
Gate delay	S
Active power	S^3

Manufacture

- Repeat basic step many times
  - Select from:

- Wafer preparation
- Oxidation
- Lithography
- Etching
- Diffusion
- Ion implantation
- Metallisation
- Deposition
- Thermal treatment
- …



silicon wafer

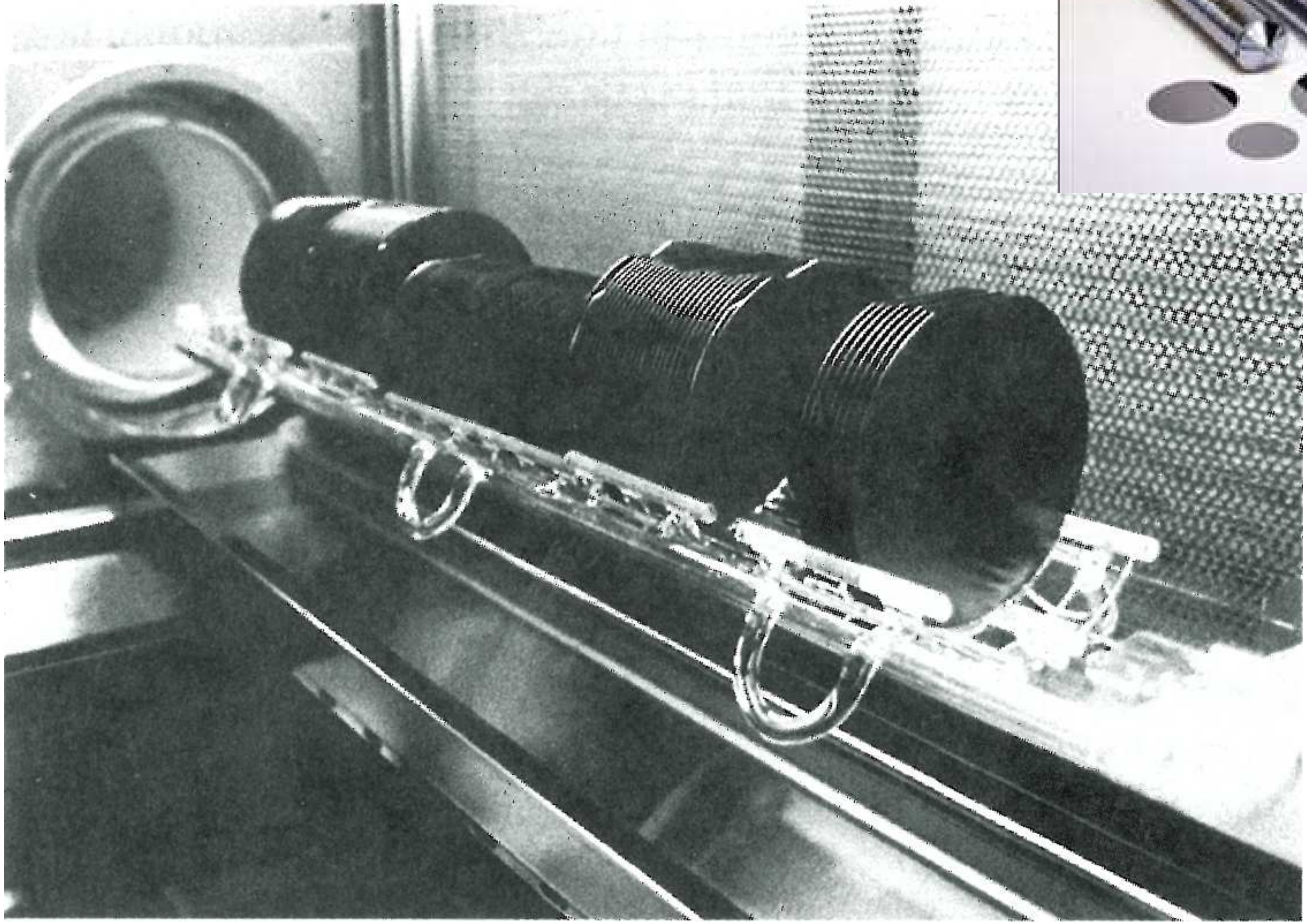
material layer formation
deposition
evaporation
implantation
…

define pattern by photolithography

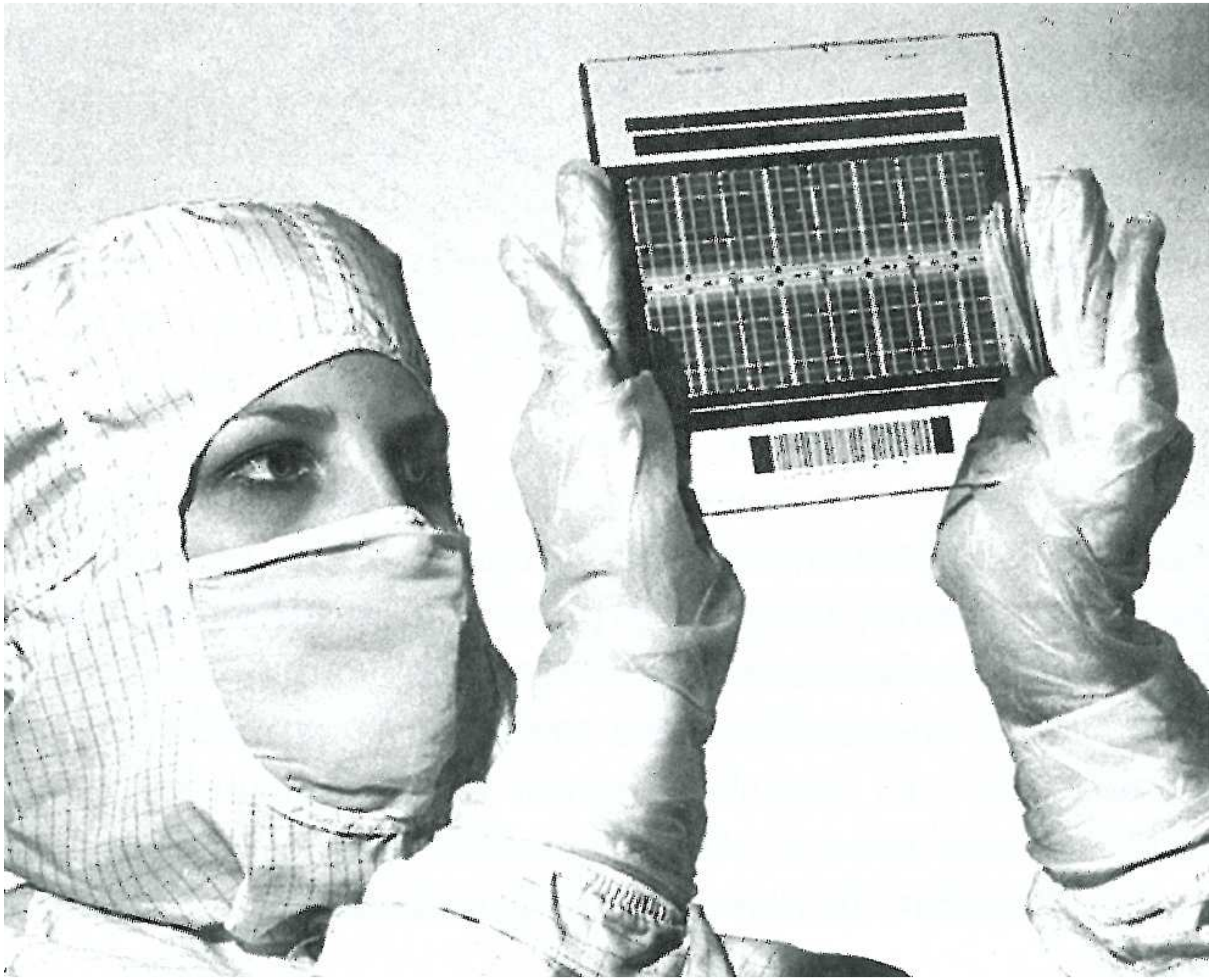
mask(s) needed!

etch

Ingots and wafers



Masks



Thermal oxidation

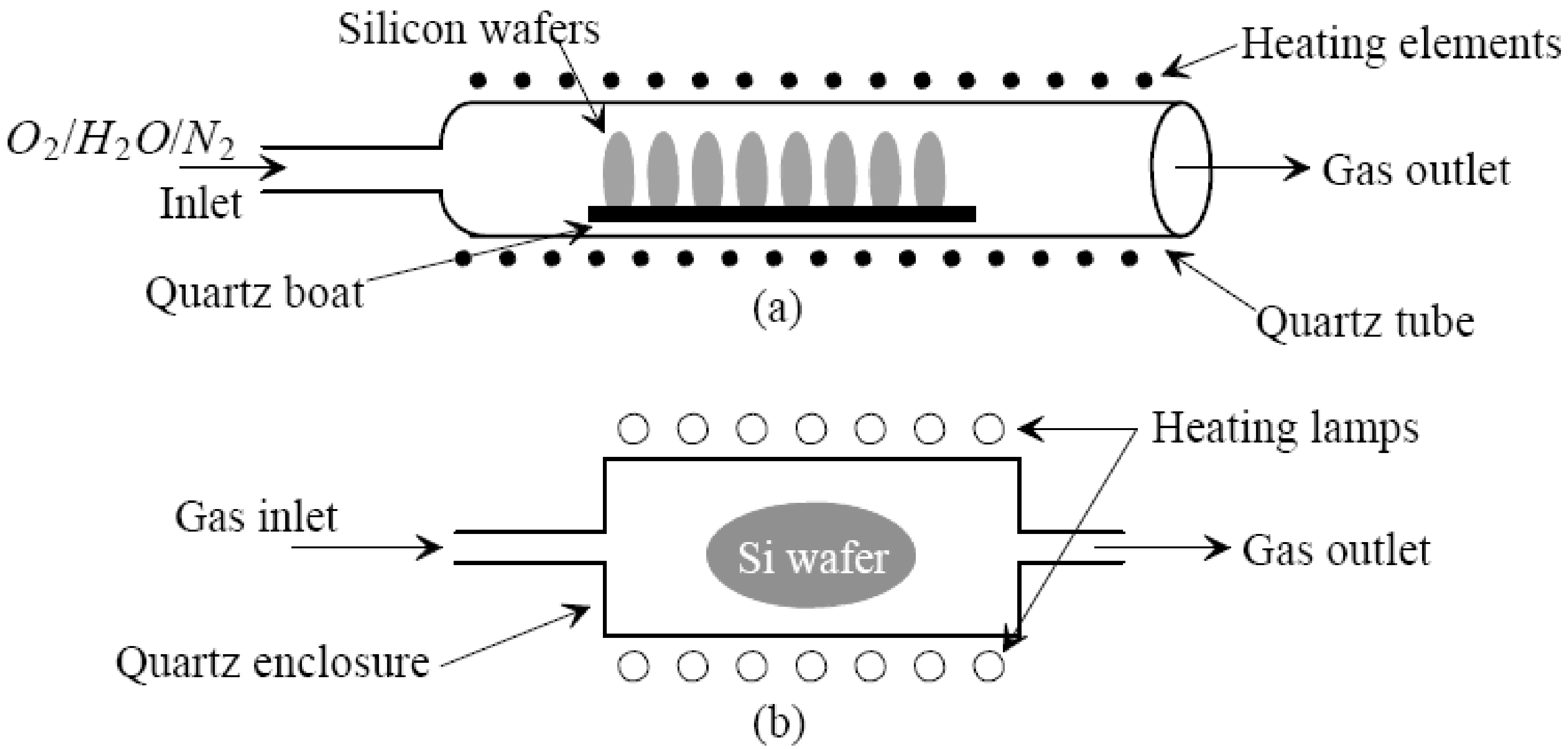


Figure 7.4 (a) Simplified representation of an oxidation tube furnace and (b) simplified diagram for rapid thermal processing.

Pattern wafers using lithography

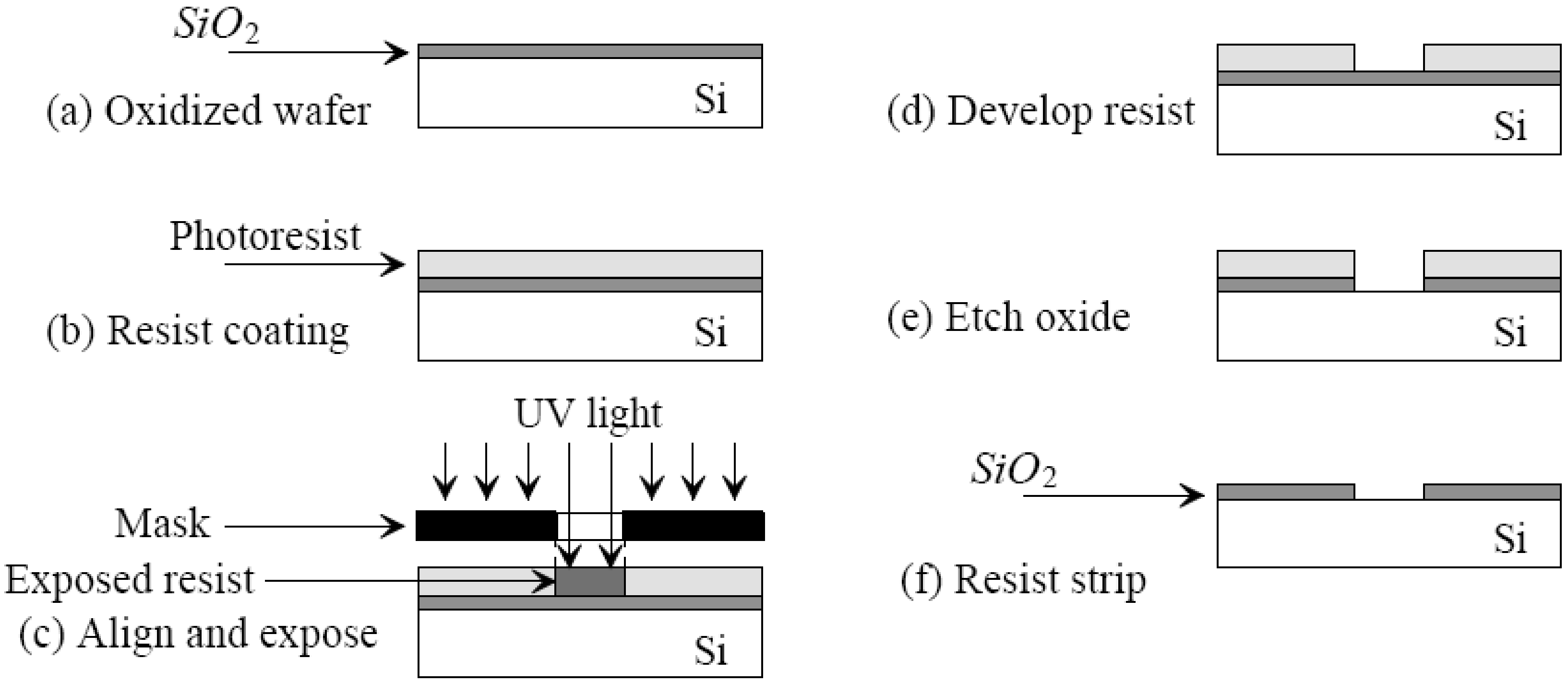
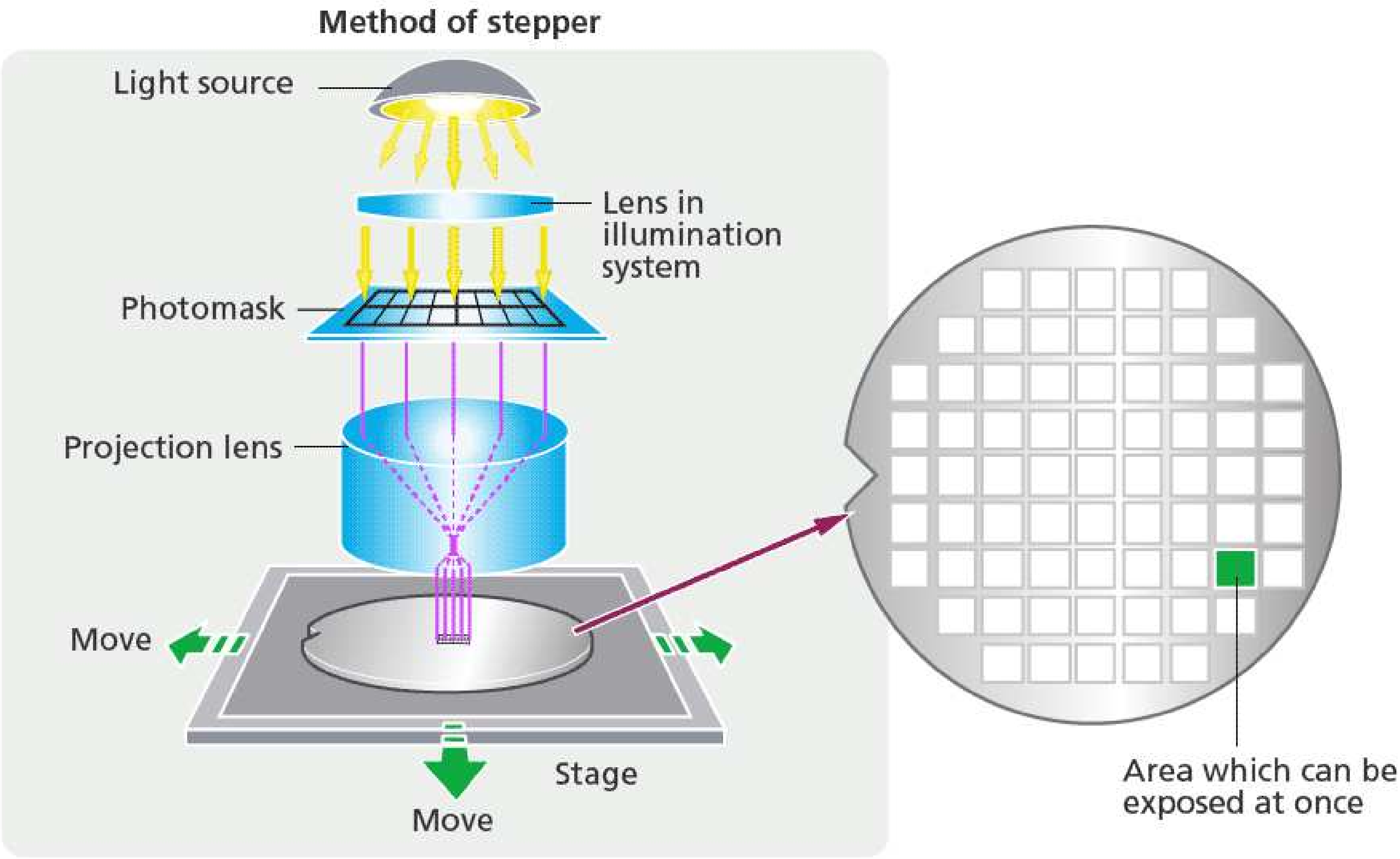


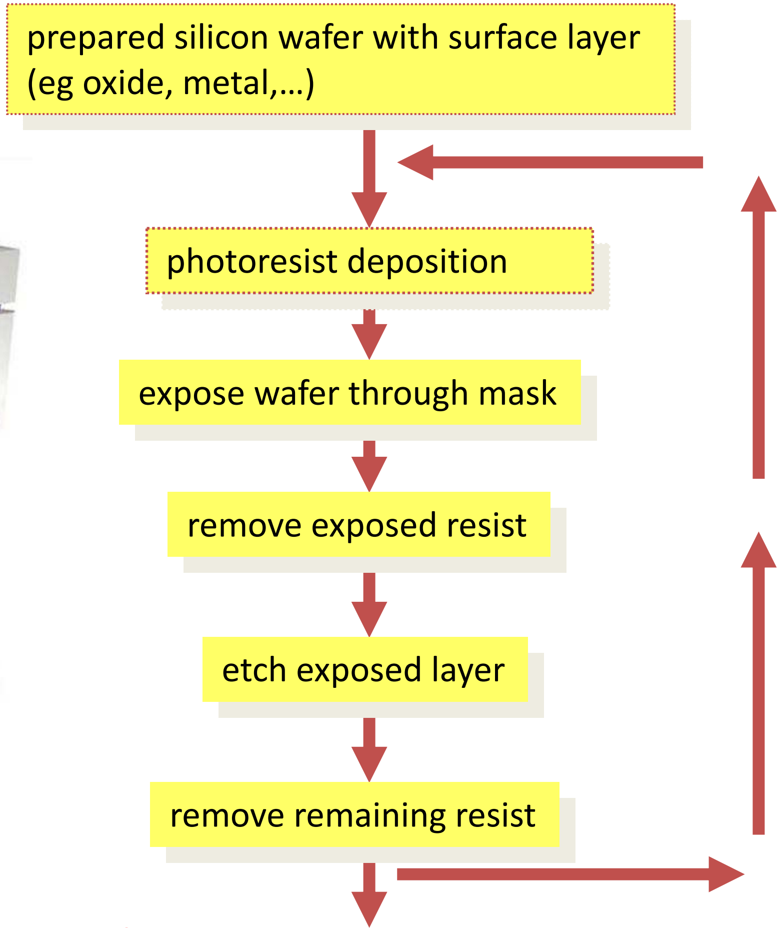
Figure 7.8 Simplified representation of the primary steps required for the implementation of photolighography and pattern transfer.

Photolithograpy



Lithography in the fab

- One of the most crucial steps:
  - nm features require ultra-short wavelengths, and high precision handling



prepared silicon wafer with surface layer (eg oxide, metal,…)

photoresist deposition

expose wafer through mask

remove exposed resist

etch exposed layer

remove remaining resist

Avoid people & wafer handling in super-clean environment using super-expensive, highly optimised equipment

Evaporation deposition

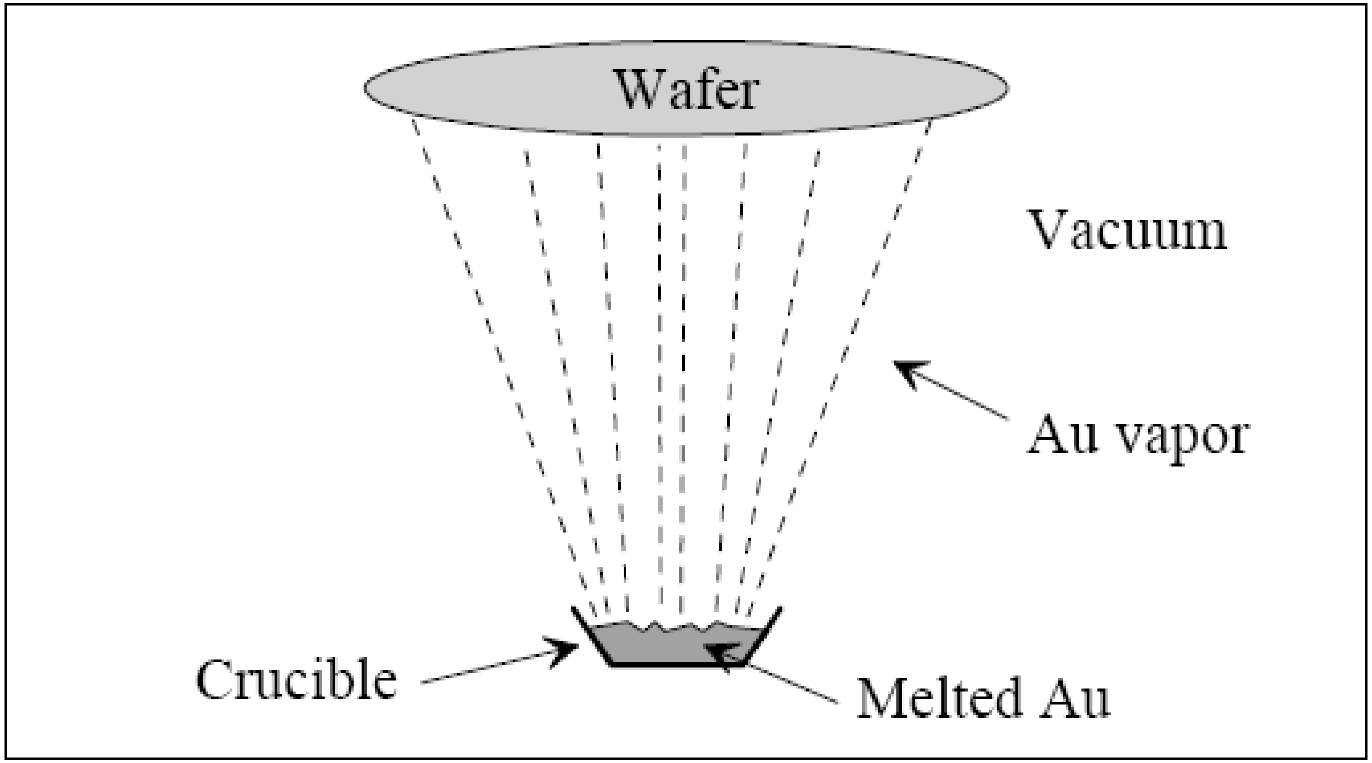
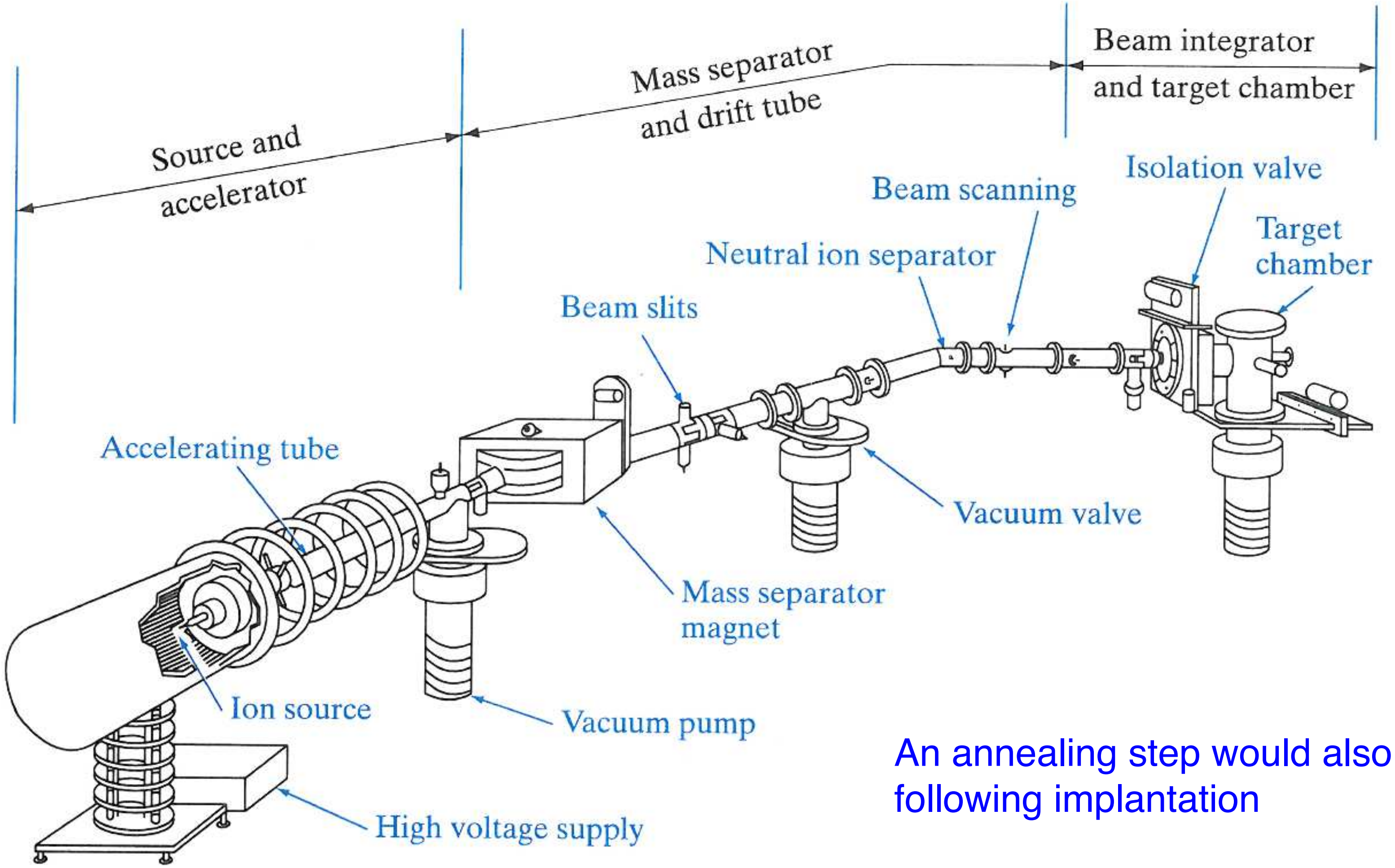


Figure 7.21 Simplified diagram of an evaporation deposition process.

Many different metals are used in ICs, although gold is often avoided in sensors at least.

Ion implantation



An annealing step would also be used following implantation

Diffusion of dopants

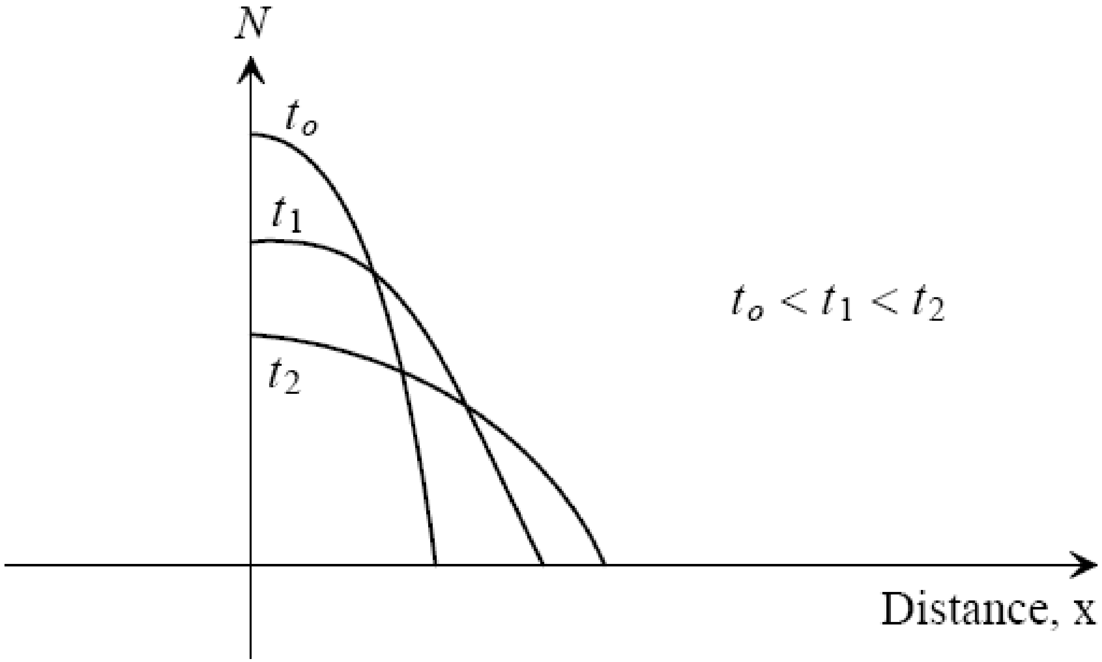


Figure 7.7 Idealized limited-source diffusion profile showing the effects of drive-in time on the profile. Notice that the peak concentration occurs at the surface of the substrate ($x = 0$) and that the area under the curves is constant.

Annealing is important to restore the crystalline structure and activate the dopants as well as define the dopant profile

Integrated circuit cross-section

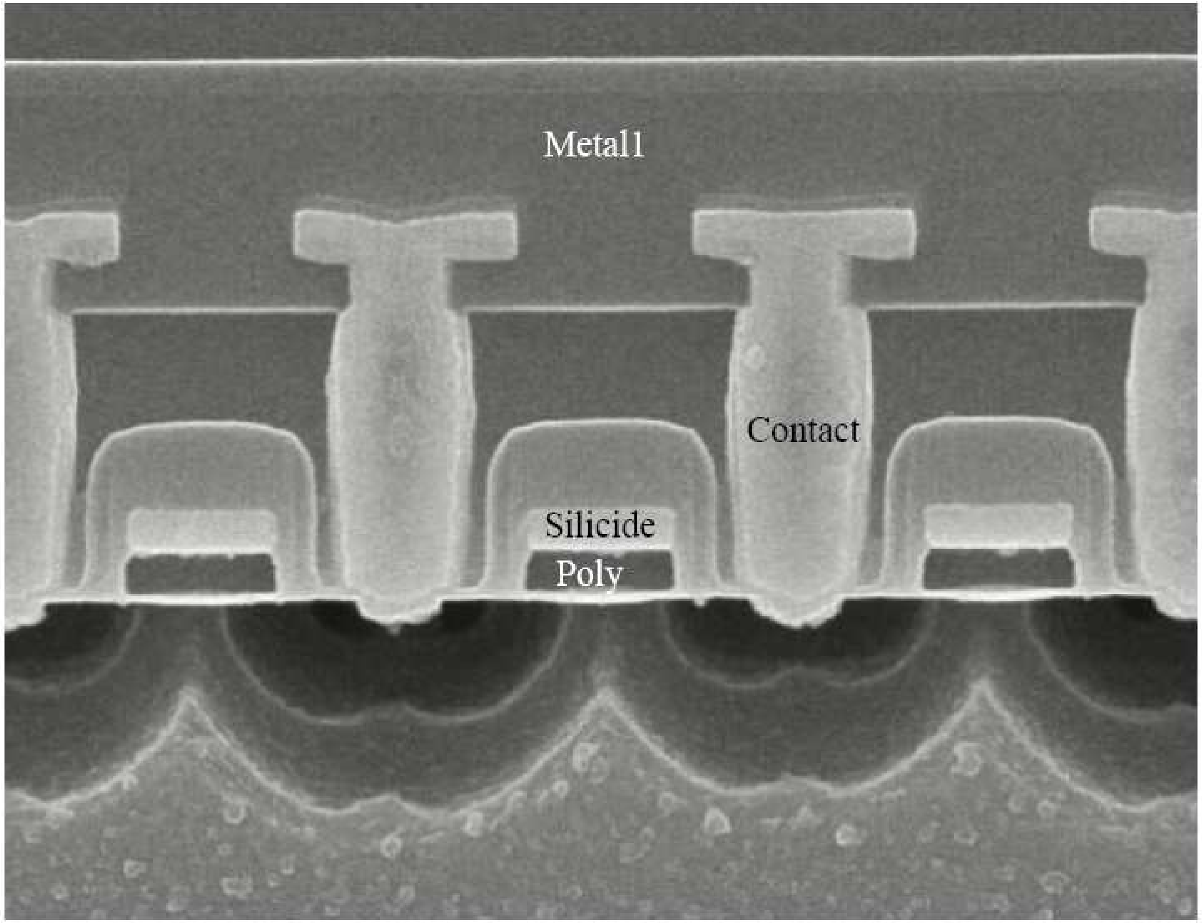
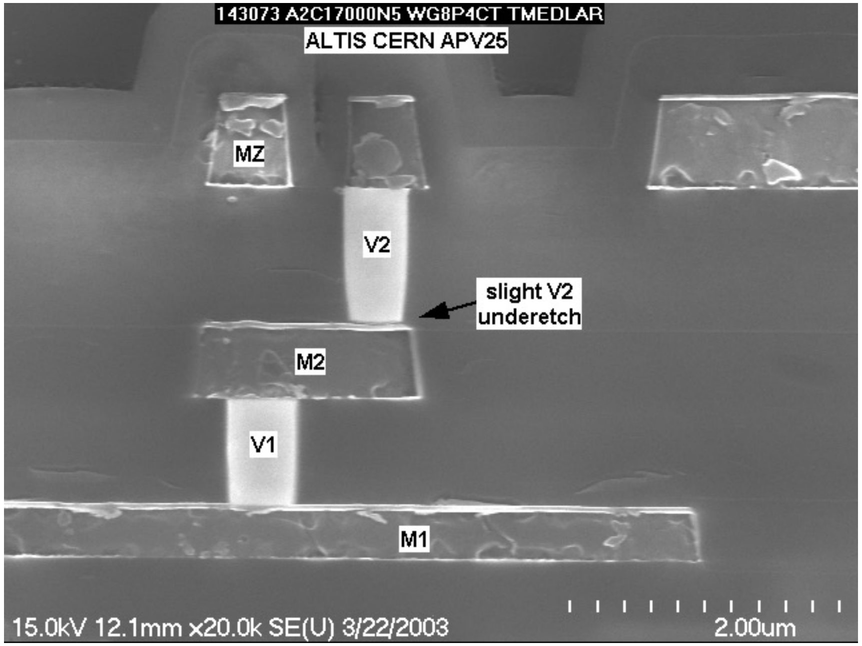
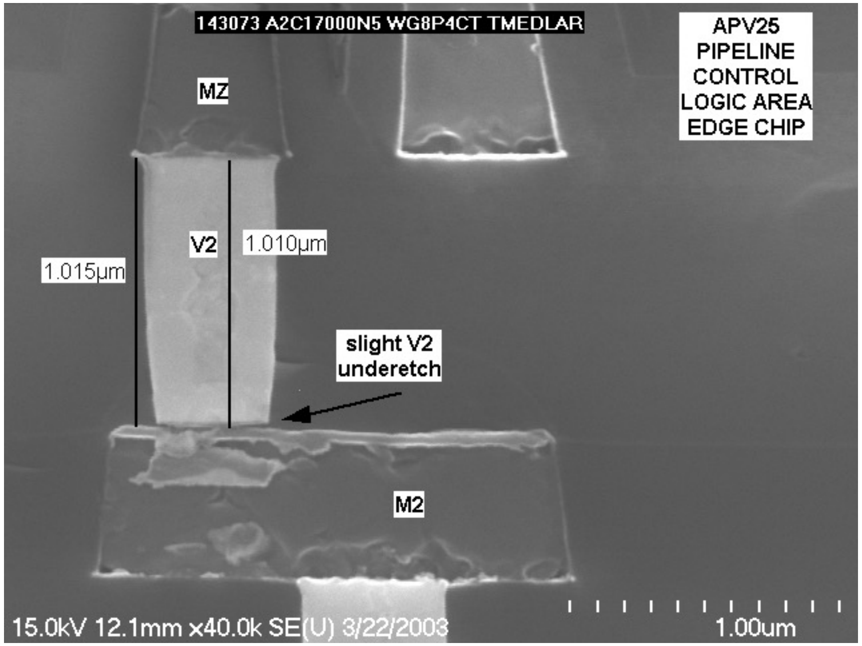
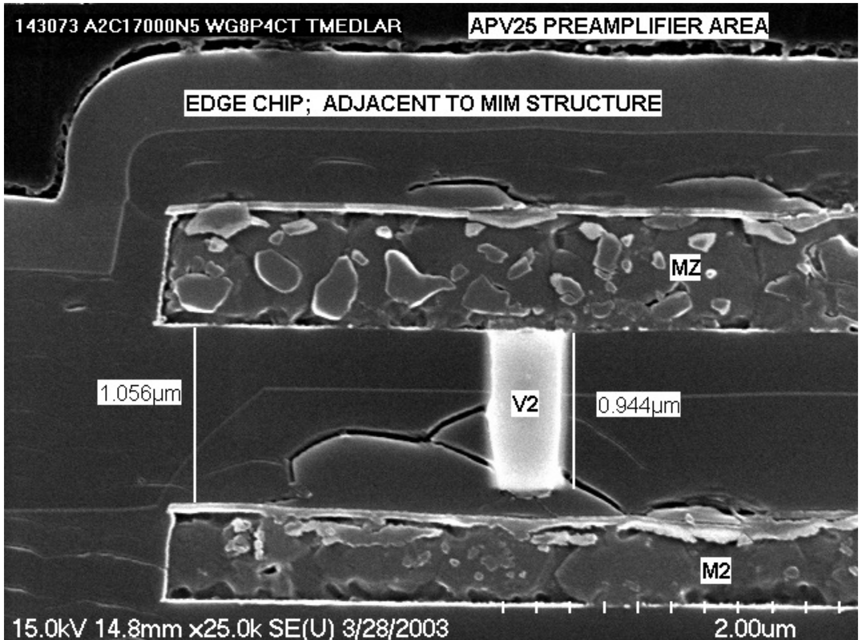


Figure 5.22 SEM image of the cross-section of three MOSFETs.

APV25 sections

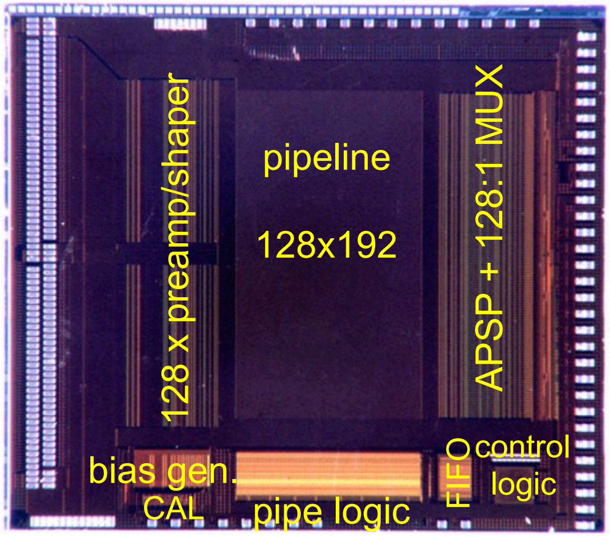






CMS Tracker ASIC evolution

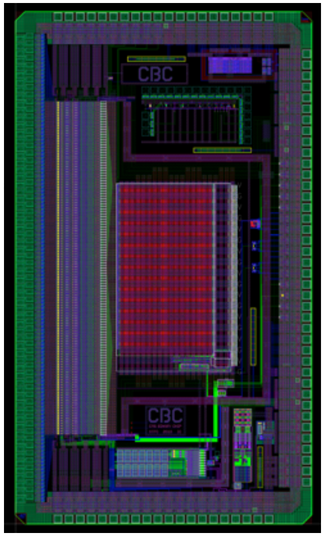
- 1999: APV25 0.25µm
  - 7 mm x 8mm (128 chan)



programmable settings (now standard)
analogue data
~4 µs latency
wire-bondable
pulse-shaping choice

2011: CBC 0.13µm

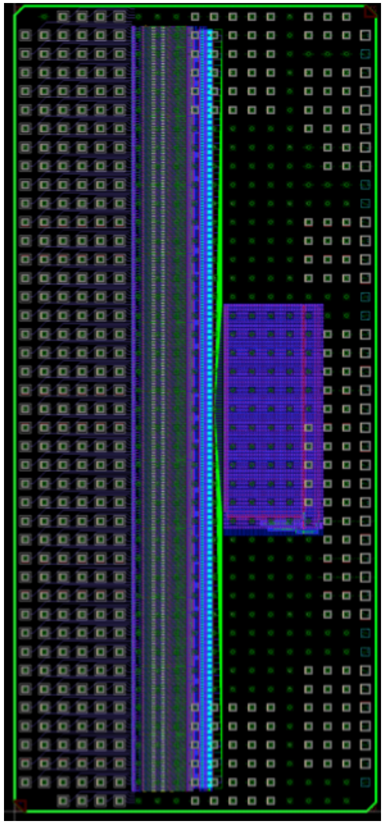
7mm x 4mm (128 chan)



binary data,
6.4 µs latency
wire-bondable

2013: CBC2 0.13µm

11mm x 5mm (254 chan)

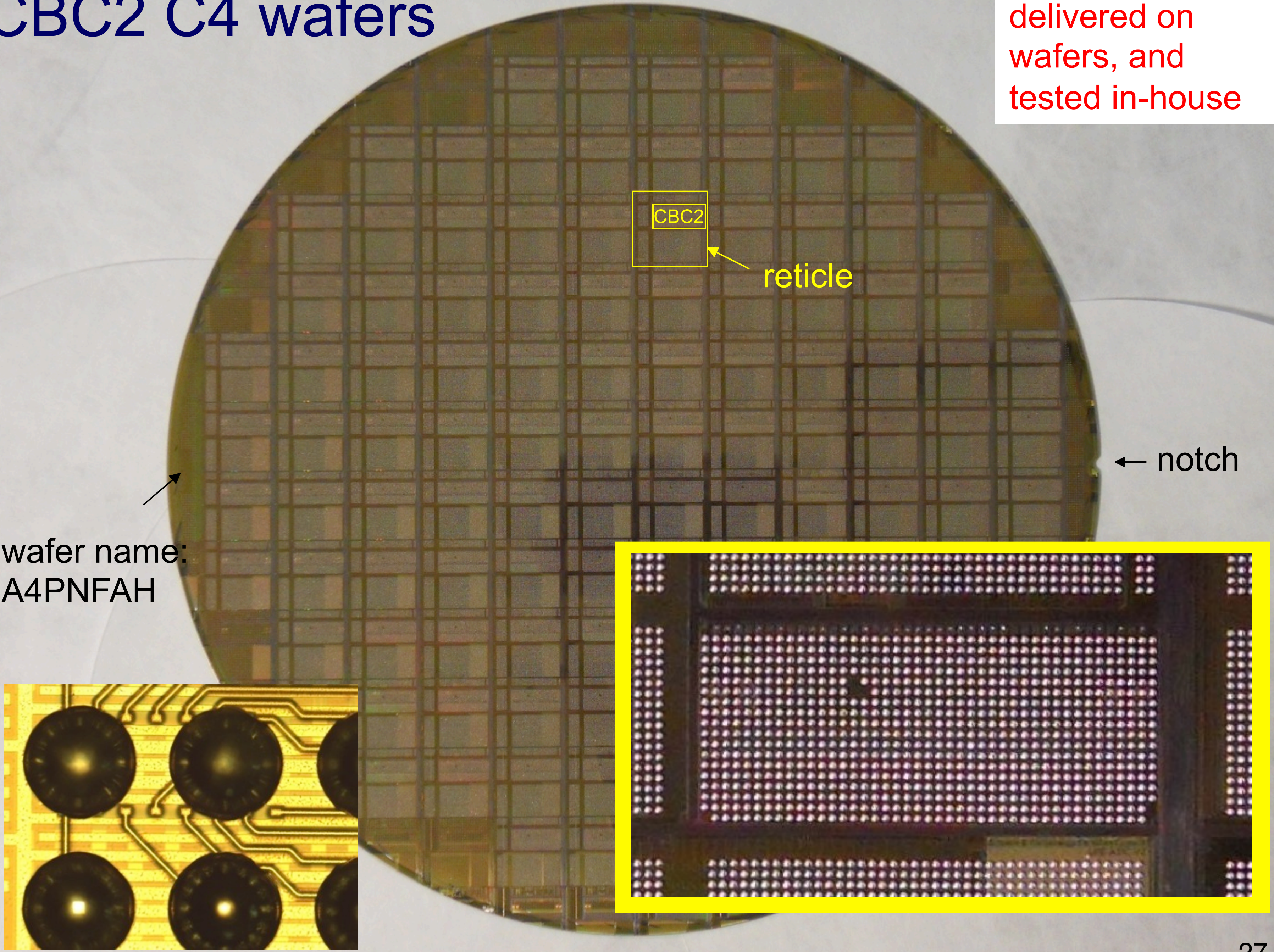


bump-bondable,
cluster & correlation logic

Final version of CBC is CBC3.1 now complete & tested

CBC2 C4 wafers

delivered on wafers, and tested in-house

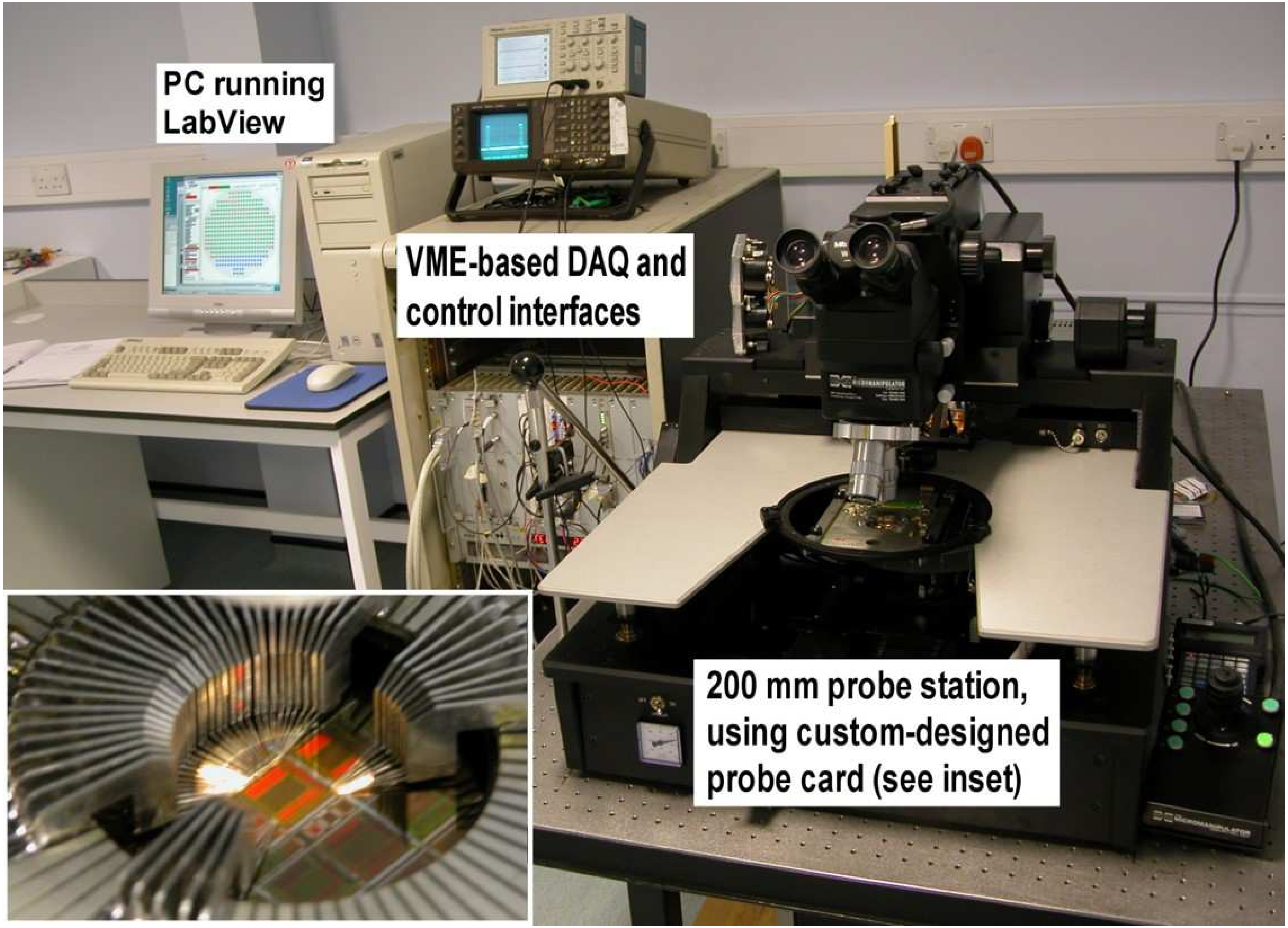


reticle

← notch

wafer name: A4PNFAH

Wafer probing

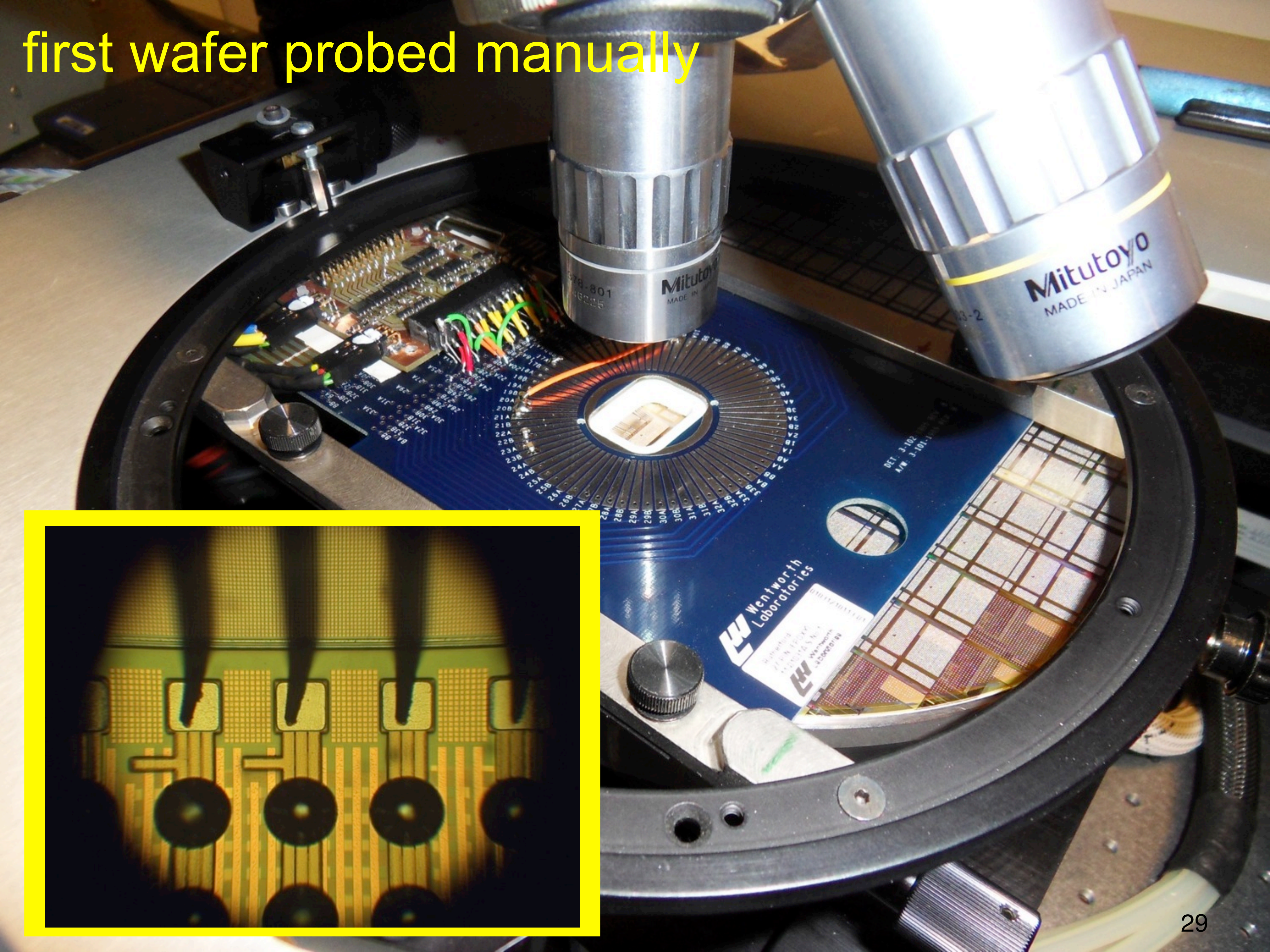


PC running LabView

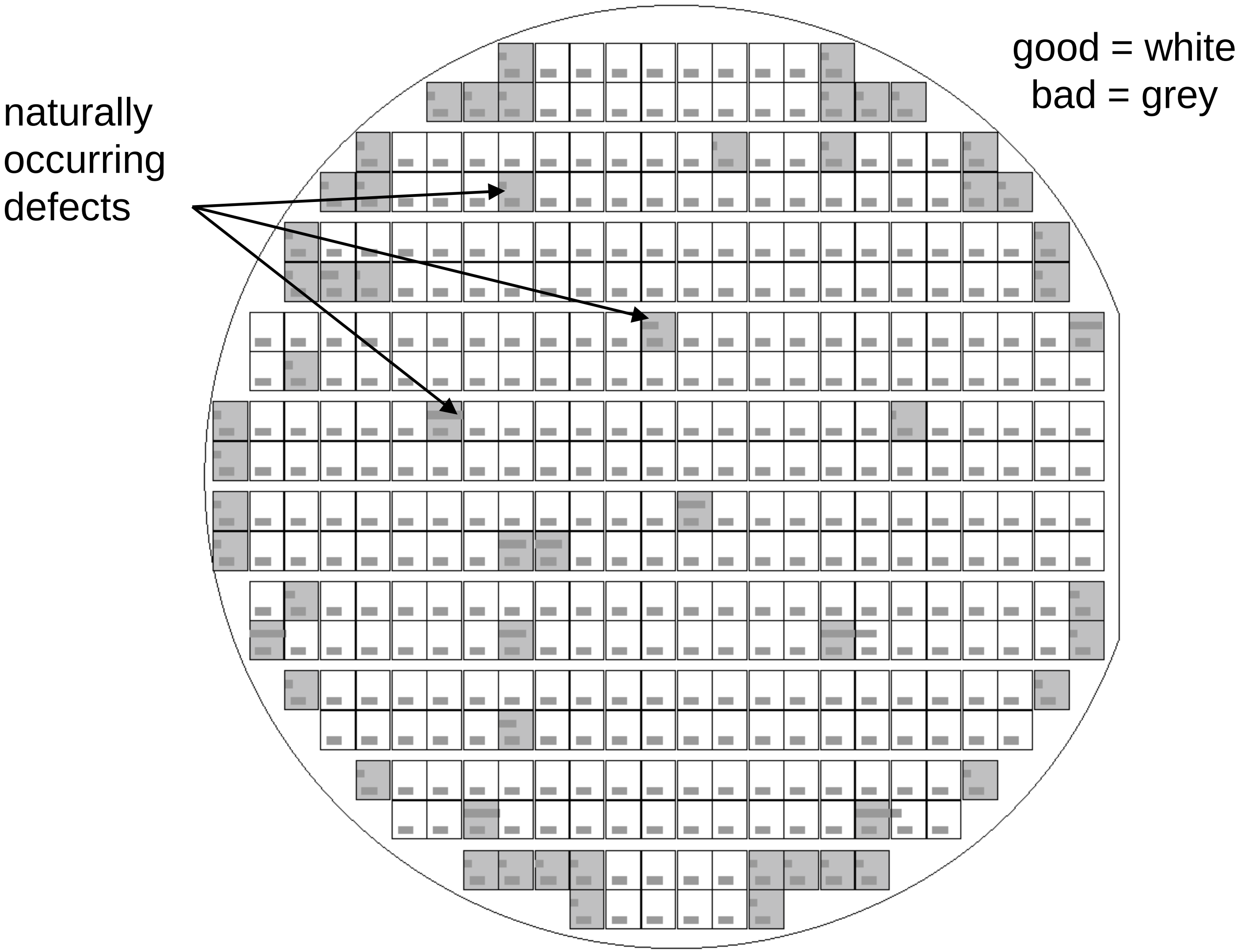
VME-based DAQ and control interfaces

200 mm probe station, using custom-designed probe card (see inset)

first wafer probed manually

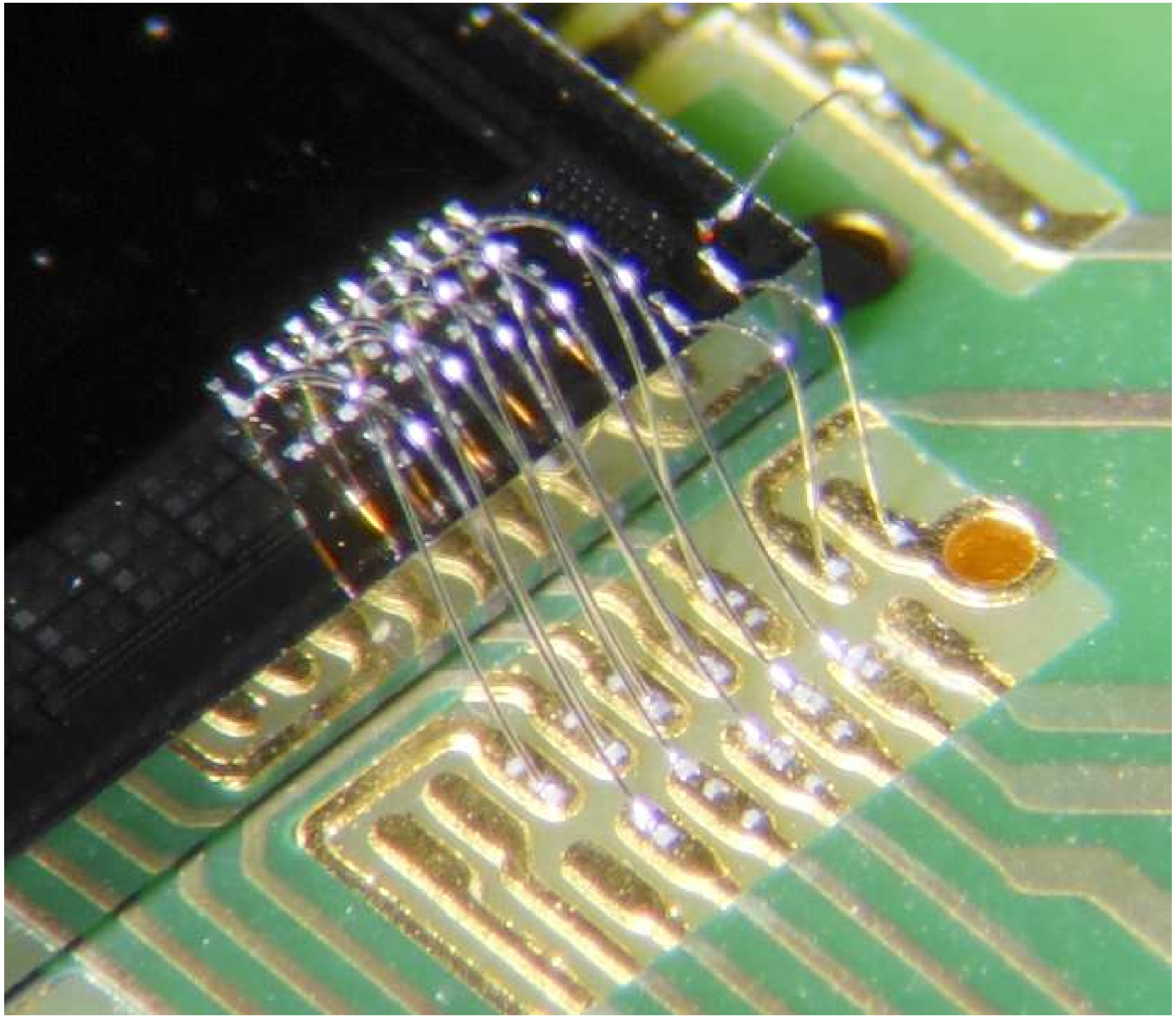


Defects

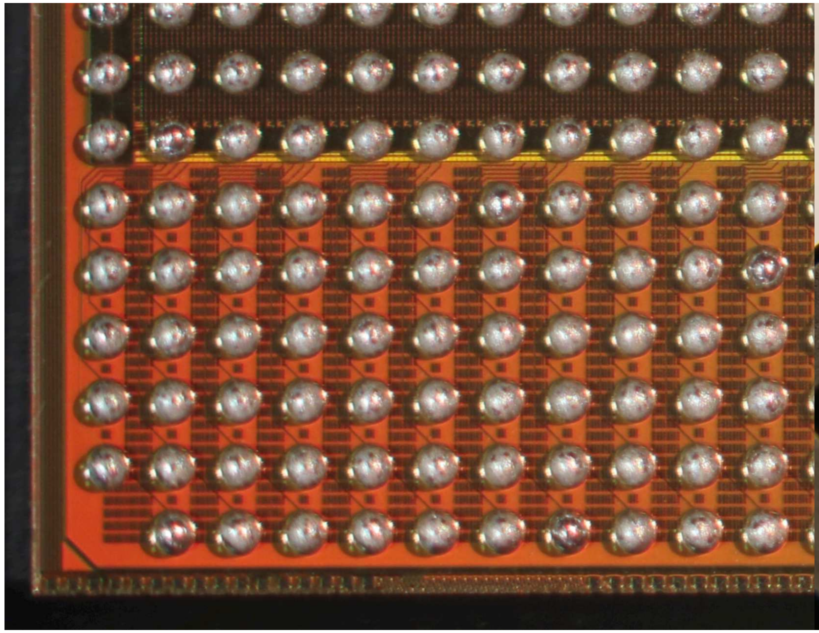


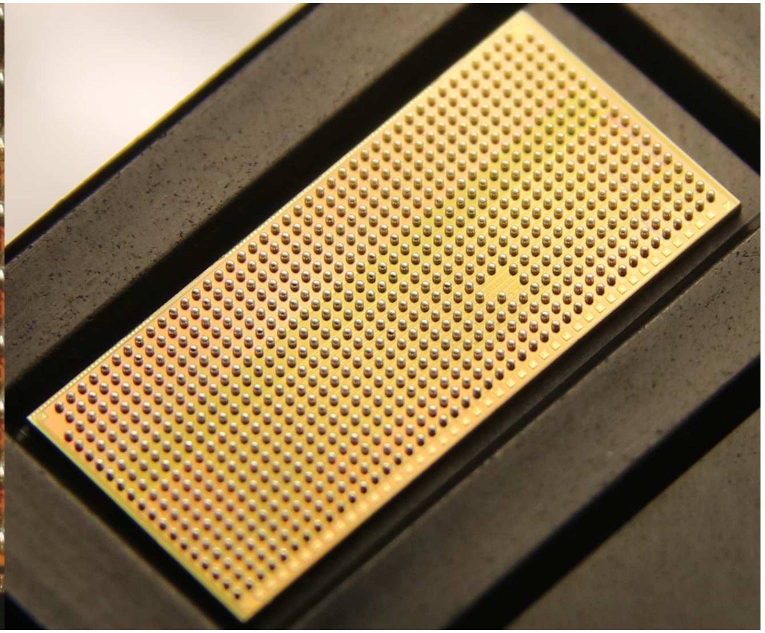
Chips can fail for several reasons. Natural process variations in parameters are expected and are taken into account in the design.

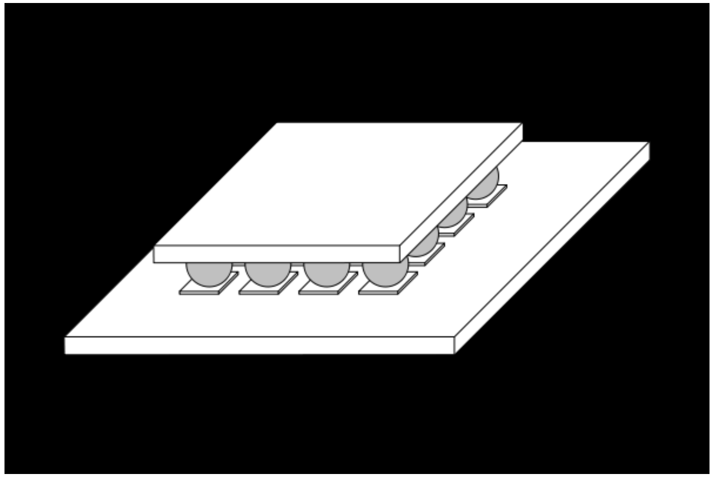
Wire bonding



Bump bonding







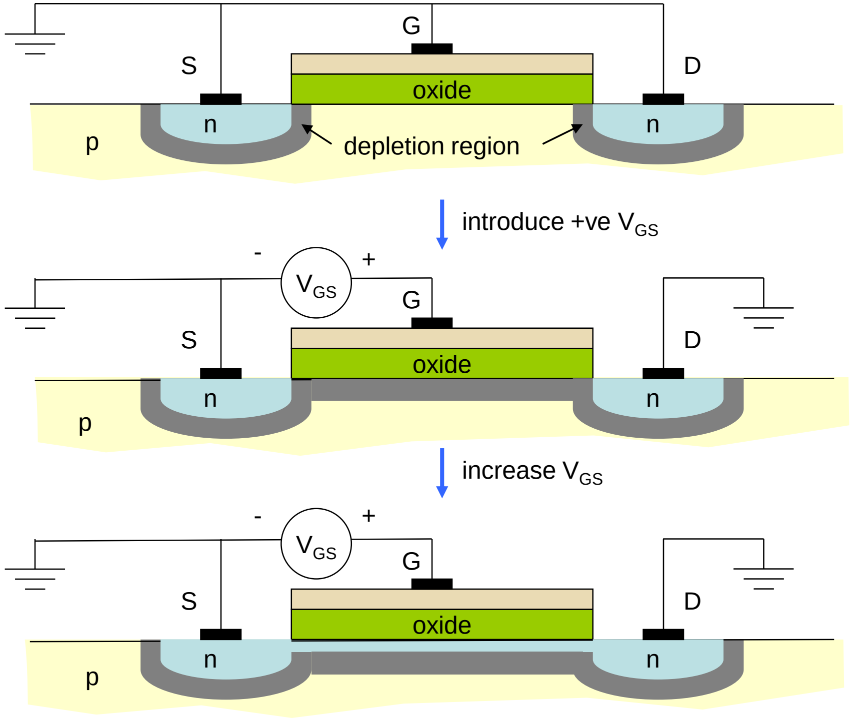
Radiation effects on IC electronics

- **CMOS circuits**
  - mostly sensitive to surface states at oxide-silicon interface
  - charge build-up, some fixed and some less permanent
  - changes conditions under gate, so alters transistor behaviour

- Other transient effects
  - Single Event Upset – charge in a small volume changes a binary state
    - typically generated by knock-on ion, which can deposit very large charge
  - Latch-up – charge generates parasitic circuit connection
    - can be destructive – but generally avoided by manufacturing process

- **Silicon sensors**
  - atomic displacement is the most important effect
  - leads to increased leakage current (noise, power) and changes in effective dopant concentration

MOSFETs and ionizing radiation

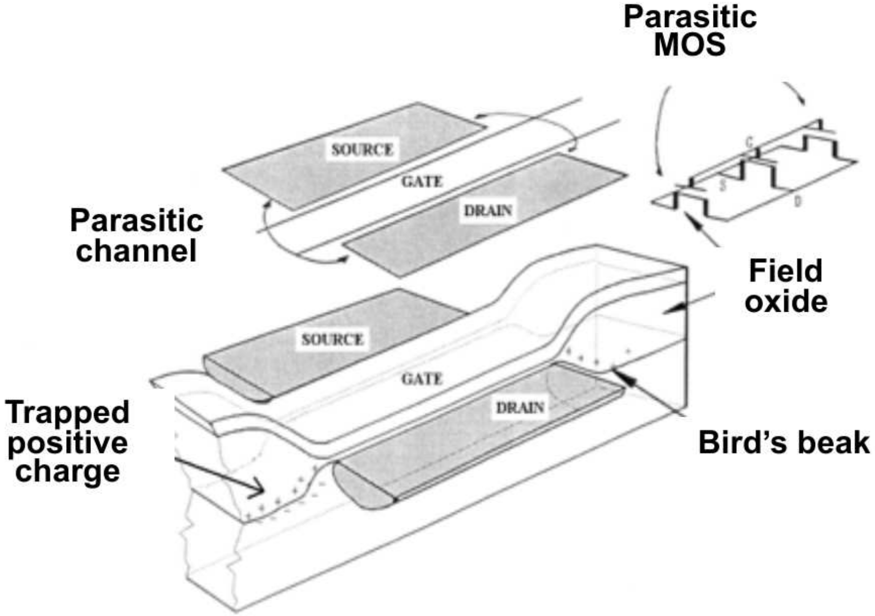


channel just forms at $V_{GS} = V_T$ = threshold voltage

Trapped charge in the gate oxide:

- makes N-MOS transistors fast but increases leakage
- makes P-MOS transistors slow but reduces leakages

Trapped charge next to the transistor



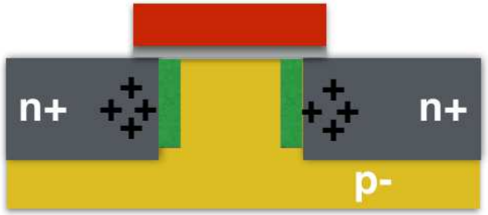
Parasitic MOS

Parasitic channel

Field oxide

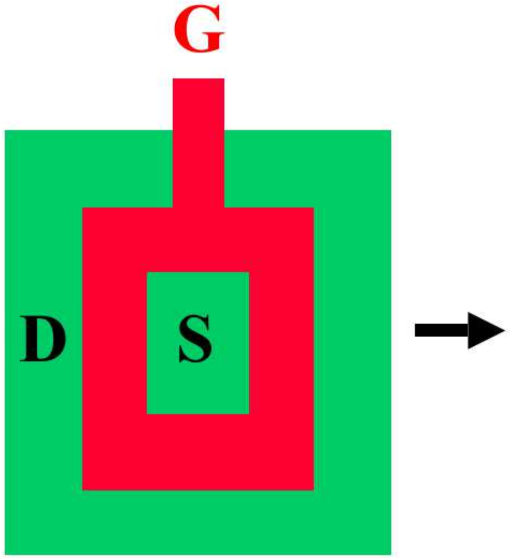
Trapped positive charge

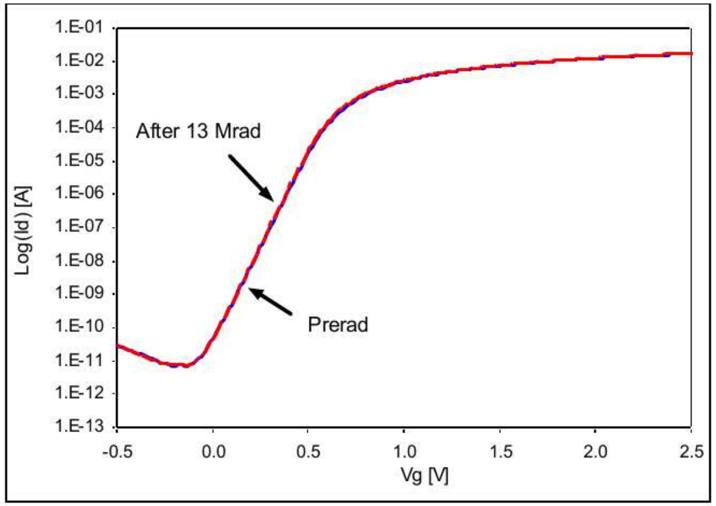
Bird’s beak



Solution: Enclosed layout transistors

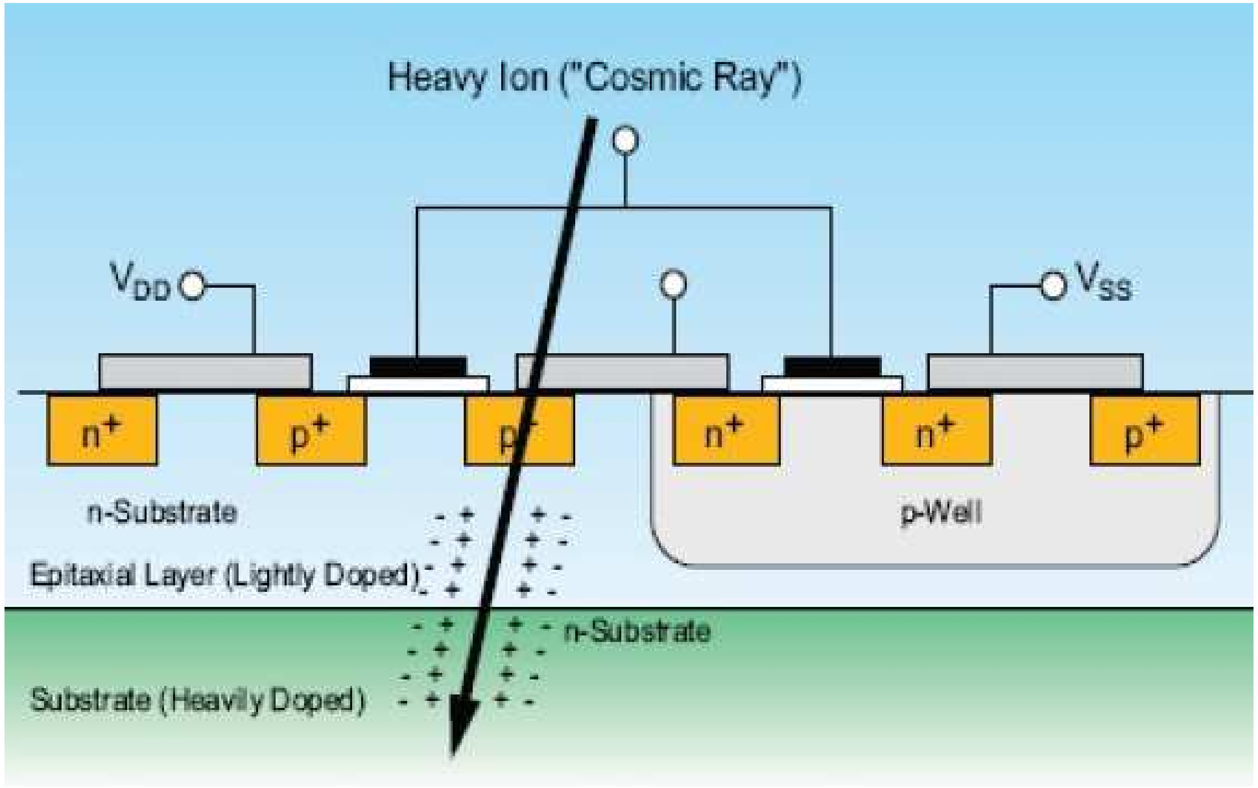
Enclosed layout transistors





Enclosing the active gate area prevents unwanted leakage current paths between source and drain. In this region the thicker oxide, which is also not so precisely controlled, is subject to more charge accumulation.

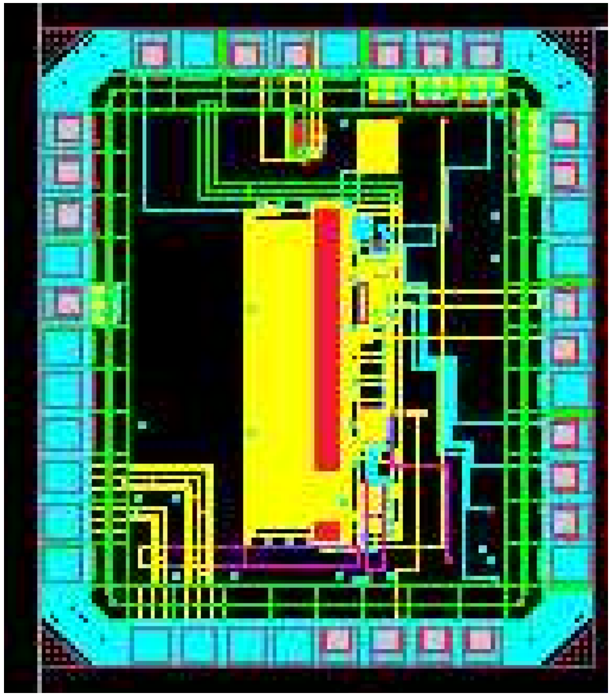
Single-event upsets



Solution: Redundant circuits and/or periodic reconfiguration

Other conditions are possible, such as latchup, ...

Some backup reference material



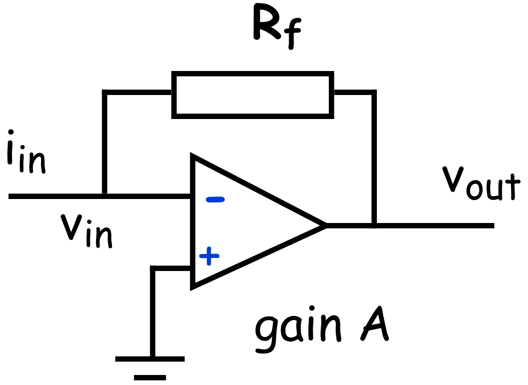
Preamplifier types

- Current sensitive - common for photodiode signals

  $v_{out} \approx -i_{in}R_f$

- signals follow input current, ie fast response

  but not lowest noise



- Charge sensitive amplifier

  Ideally, simple integrator with C_f

  but need means to discharge capacitor

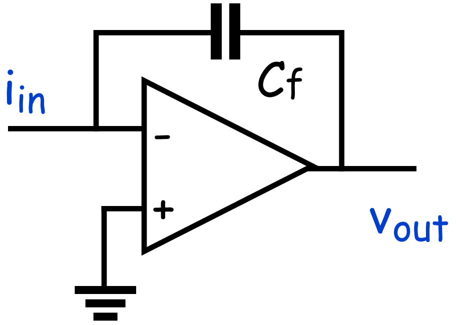
  - large R_f

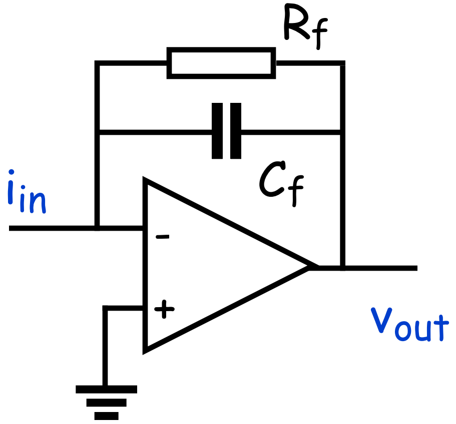
- Simple integrator

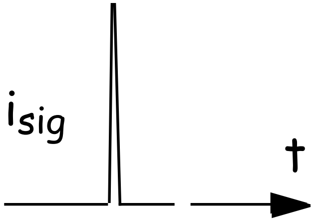
  $v_{out} \approx -Q/C_f$

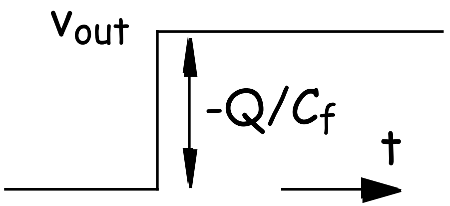
- with feedback resistor R_f

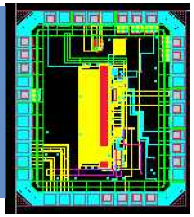
  $v_{out}(t) \approx -(Q/C_f)\exp(-t/\tau) \qquad \tau = R_f C_f$







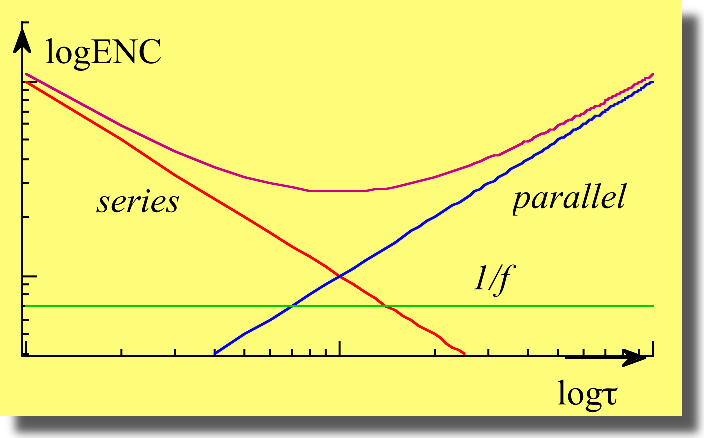




Noise calculations

- Summary of principles
  - integrate signal spectrum over bandwidth
  - integrate noise in quadrature over bandwidth
  - computation can be done in time or frequency domain

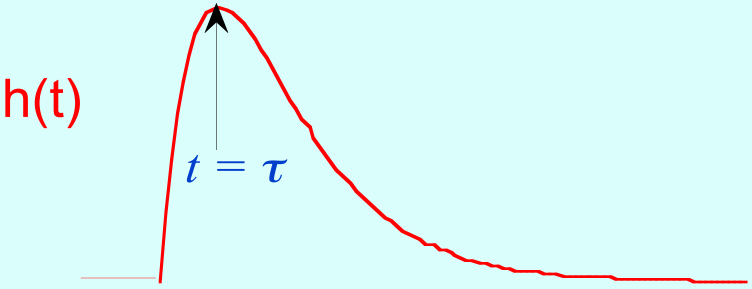
    but simplifications are often possible



- System noise can be computed with knowledge of impulse response and noise sources
  - $\sigma^2 \sim e_n^2 C^2 \int [h'(t)]^2\, dt + i_n^2 \int [h(t)]^2\, dt$
  - provided noise sources e_n & i_n are white
  - *properly normalise to signal of unit amplitude*

Impulse response =

output of system following fast δ-like input signal



Campbell's theorem

Omit

- Most amplifying systems designed to be linear

  $S(t) = S_1(t) + S_2(t) + S_3(t) + \dots$

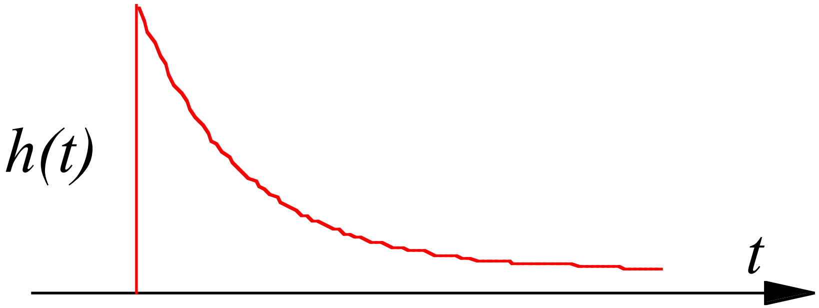
- Impulse response

  $h(t)$ = response to δ

- Transfer function

  $H(\omega) = v_{out}(\omega)/v_{in}(\omega) = \int_{-\infty}^{\infty} h(t).e^{-j\omega t}\,dt$

  ie impulse response $h(t)$ and transfer function $H(\omega)$ are Fourier pair



- In a linear system, if random impulses occur at rate n

average response $\langle v \rangle = n \int_{-\infty}^{t_{obs}} h(t)dt$

variance $\sigma^2 = n \int_{-\infty}^{t_{obs}} [h^2(t)]dt$

i.e. sum all pulses preceding time, t_{obs}, of observation

so $\sigma^2 = n \int_{-\infty}^{\infty} h^2(t)\,dt = n \int_{-\infty}^{\infty} |H(\omega)|^2\,df$

"Rules" of low noise amplifier systems

- Combine uncorrelated noise sources in quadrature

  $e^2_{tot} = e_1^2 + e_2^2 + e_3^2 + \ldots + i_n^2 R^2 + \ldots$

  follows from Campbell's theorem

  consider as combinations of gaussian distributions

- First stage of amplifier dominates

  noise originates at input

  input transistor is most important - defines noise in most cases

- Noise is independent of amplifier gain or input impedance

  so noise can be referred to input

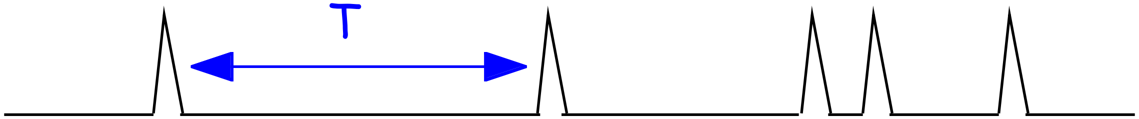
- In real systems both are approximations - but normally good ones

  so often sufficient to focus on input device

Shot noise

- **Poisson fluctuations of charge carrier number**

  eg arrival of charges at electrode in system - induce charges on electrode



quantised in amplitude and time

- **Examples**

  electrons/holes crossing potential barrier in diode or transistor

  electron flow in vacuum tube

$< i_n^2 > = 2qI.\Delta f$ WHITE (NB notation $e = q$)

I = DC current

gaussian distribution of fluctuations in i

Thermal noise

- Einstein (1906) , Johnson, Nyquist (1928)

  Mean voltage $\langle v \rangle = 0$

  Variance $\langle v^2 \rangle = 4kT.R.\Delta f$ Δf = observing bandwidth

  gaussian distribution of fluctuations in v

  $\sigma(v) = \sqrt{\langle v^2 \rangle} = 1.3\ 10^{-10}\,(R.\Delta f)^{1/2}$ volts at 300K

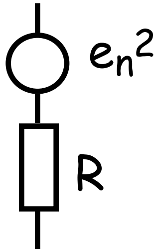
  e.g. $R = 1M\Omega$ $\Delta f = 1Hz$ $\sigma(v) = 0.13\mu V$

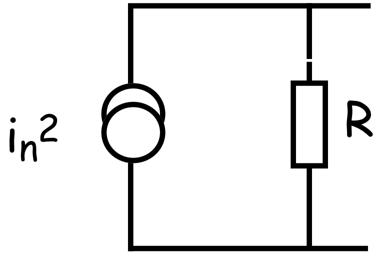
  Noise power = $4kT.\Delta f$

  independent of R & q independent of f - WHITE

- Circuit representations

  Noise generator + noiseless resistance R





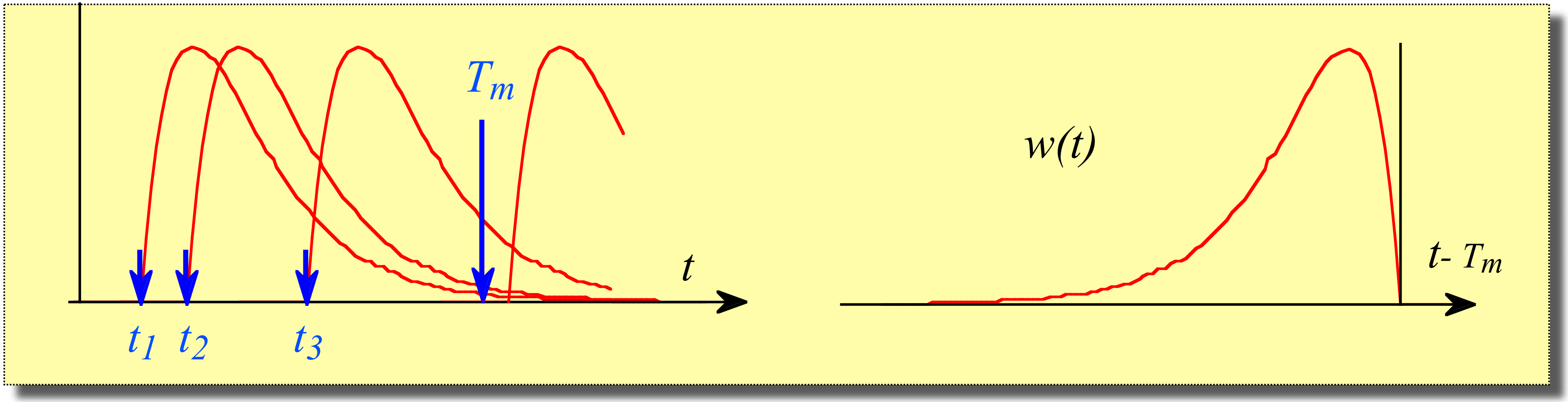
- Spectral densities

  mean square noise voltage or current per unit frequency interval

  $w_V(f) = 4kTR$ (voltage) $w_I(f) = 4kT/R$ (current)

Weighting function

- How to calculate noise of time variant systems?
  - What output is produced at T_m by impulse at time t?
  - consider all t - defines weighting function



- Time invariant filter *w(t)* is mirror image of *h(t)*

- Noise calculation

$$ENC^2 = e_n^2 C^2 \int [w'(t)]^2 dt + i_n^2 \int [w(t)]^2 dt$$

Geoff Hall

Some numerical values

- An approximate numerical value

$$ENC^2[e^2] \approx \left(\frac{24^2 R_s[k\Omega] C_{tot}^2[pF]}{\tau[\mu s]} + 100^2 I\tau[\mu s] \right)$$

- using CR-RC filter, ignoring 1/f noise

ie

I = 1nA $\tau = 1\mu s$ $ENC_p \approx 100e$

$R_s = 10\Omega$ C = 10pF $\tau = 1\mu s$ $ENC_s \approx 24e$