**MIS capacitor**

- Elementary device
  - Oxide well matched to silicon
  - Transparent to wide range
  - Excellent insulator
  - Nitride frequently used in addition
  - Larger ε

<table>
<thead>
<tr>
<th></th>
<th>SiO₂</th>
<th>Si₃N₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>g.cm⁻³</td>
<td>2.2</td>
</tr>
<tr>
<td>Refractive index</td>
<td></td>
<td>1.46</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>V/cm</td>
<td>3.9</td>
</tr>
<tr>
<td>Dielectric strength</td>
<td>V/cm</td>
<td>10⁷</td>
</tr>
<tr>
<td>Energy gap</td>
<td>eV</td>
<td>9</td>
</tr>
<tr>
<td>DC resistivity at 25°C</td>
<td>Ω.cm</td>
<td>10¹⁴⁻¹⁰¹⁶</td>
</tr>
</tbody>
</table>
MOS capacitor characteristics

• Apply bias voltage to influence charge under oxide
  - depletion - potential well which can store charge
  - inversion - thin sheet of charge with high density
    allows conduction in transistor
    very close to Si-SiO₂ interface

Basis of MOS transistor operation

*images of MOS transistor operation under different conditions*

- V < -V_t
- V
- +V

n-type semiconductor

depletion

accumulation layer

inversion layer
**CCD - Charge Coupled Device**

- 2-d array of MOS capacitors
  - electrode structures isolate pixels
  - allow to transfer charge
  - thin sensitive region
  - signals depend on application
  - low noise, especially if cooled
- Video requirements different to scientific imaging
  - persistent image
  - smaller area & pixels
  - Readout time long \( \text{ms-s} \)
  - all pixels clocked to readout node
- Applications
  - astronomy, particle physics, x-ray detection, digital radiography,...
**CCD charge transfer**

- Change voltages on pixels in regular way ("clock")
  3 gates per pixel
  3 phases per cycle
  depletion depth in adjacent regions changes
  E field transfers charge to next pixel
  - finally to output register
Silicon detector radiation damage

- As with all sensors, prolonged exposure to radiation creates some permanent damage
  - two main effects

  **Surface damage**  Extra positive charge collects in oxide
  all ionising particles generate such damage
  MOS devices - eg CCDs - are particularly prone to such damage
  Microstrips - signal sharing & increased interstrip capacitance - noise

  **Bulk damage** atomic displacement damages lattice and creates traps in band-gap
  only heavy particles (p, n, π, …) cause significant damage
  increased leakage currents - increased noise
  changes in substrate doping
Signals

• Signal
  generalised name for input into instrument system

• Might seem logical to consider signals before sensors but can now see
  wide range of signal types are possible
  depend on sensor
  depend on any further transformation - eg light to electrical

• Most common types of signal
  short, random pulses, usually current, amplitude carries information
    typical of radiation sensors
  trains of pulses, often current, usually binary
    typical of communication systems
  continuous, usually slowly varying, quantity - eg. current or voltage
    slow - typical of monitoring instruments
    fast - eg cable TV, radio

• terms like “slow”, “fast” are very relative!
### Typical signals

- **Some examples**

<table>
<thead>
<tr>
<th>Signal source</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inorganic scintillator</td>
<td>$e^{-t/\tau}$ $\tau \sim \text{few $\mu$s}$</td>
</tr>
<tr>
<td>Organic scintillator</td>
<td>$e^{-t/\tau}$ $\tau \sim \text{few ns}$</td>
</tr>
<tr>
<td>Cerenkov</td>
<td>$\sim\text{ns}$</td>
</tr>
<tr>
<td>Gaseous</td>
<td>few ns - $\mu$s</td>
</tr>
<tr>
<td>Semiconductor</td>
<td>$\sim\text{10ns}$</td>
</tr>
<tr>
<td>Thermistors</td>
<td>continuous</td>
</tr>
<tr>
<td>Thermocouple</td>
<td>continuous</td>
</tr>
<tr>
<td>Laser</td>
<td>pulse train $\sim\text{ps rise time}$ or short pulses $\sim\text{fs}$</td>
</tr>
</tbody>
</table>

- However, we will find later that speed of signal is not always sufficient to build fast responding systems.
Signal formation

• Issues in practical applications
  
  duration
  radiation: depends on transit time through sensor and details of charge induction process in external circuit
  
  linearity
  most radiation sensors characterised, or chosen for linearity
  for commercial components can expect non-linearity, offset and possible saturation
  
  reproducibility
  eg. many signals are temperature dependent in magnitude - mobility of charges
  other effects easily possible
  
  ageing
  sensor signals can change with time for many reasons
  natural degradation of sensor, variation in operating conditions, radiation damage,...

• all these effects mean one should always be checking or calibrating measurements intended for accuracy as best one can
Optical transmitters

- Semiconductor lasers most widely used
  - Now dominate telecomms industry
    - >> Gb/s operation

- Principle
  - Forward biased p-n diode
    - => population inversion
  - direct band gap material
    - GaAs ~850nm
    - GaAlAs ~600-900nm
    - In, Ga, As, P ~0.55-4µm
  - + polished optical facets
    - => Fabry-Perot cavity
    - optical oscillator
    - lase at $I > I_{\text{threshold}}$
    - photon losses from cavity or absorption
      - often very linear
Modern semiconductor lasers

• Quantum well structures
  confine charge carriers to active layer
  refractive index difference
  $\Rightarrow$ waveguide confines light
  minimise lateral dimensions for efficiency
  & low $I_{\text{threshold}}$
  $\Rightarrow$ low power (~mW), miniature devices
  well matched for optical fibre transmission

• VCSELs  Vertical Cavity Surface Emitting Laser
  emit orthogonal to surface
  ultra-low power
  cheap to make (test on wafer)
  can be made in arrays
  non-linear L-I characteristic
  but very suitable for digital applications
Passage of radiation through matter

• Need to know a few elementary aspects of signal formation whether interested in light or other radiation
  How far does radiation penetrate?
  How much of incident energy is absorbed?

• Signal current - duration and magnitude
  consequence of charge carriers generated
  electrons + holes (semiconductor) or ions (gases, liquids)
  current duration depends on
    distance over which charge deposited
      rapid absorption or thin sensor give fast signals
    electric field
      only charges in motion generate currents
  current in external circuit is **induced**
Light

\[ I \sim I_0 \exp\left(-\frac{L}{L_{\text{abs}}}\right) \]

\[ \frac{1}{L_{\text{abs}}} = N_{\text{atom}} \sigma \quad N_{\text{atom}} = \rho N_{\text{Avogadro}} / A = \text{no. atoms per unit volume} \]

**Photoabsorption**

\[ E \sim \text{eV} - 100\text{keV} \quad \text{atom ionised in single process, all photon energy transferred} \]

at low energies depends on atomic properties of material

at higher energies \[ \sigma_{pa} \sim Z^{4-5}/E_{\gamma}^3 \] above K-shell edge

**Compton scattering**

\[ \sim \text{MeV} \quad \text{quantum collision of photon with charged particle, usually e}^- \]

transfer of part of photon energy, often small

**Pair production**

\[ \gg \text{MeV} \]

all energy transferred to e+e- pair

to conserve momentum and energy, needs recoil

must take place in field of nucleus or electron
Light absorption:

- **Low energies**
  - see consequence of atomic behaviour
  - eg silicon bandgap
  - NB strong dependence on wavelength in near-visible regions

- **High energies**
  - atomic shell structure visible
  - then electrons appear as quasi-free
  - Compton scattering starts to dominate at ~60keV - not shown

![Graph showing absorption length vs photon energy for silicon](image)
Light absorption

- Far UV to x-ray energies
  - atomic shell structure
  - photo-absorption

  coherent = Rayleigh scattering
  atom neither ionised nor nor excited

  incoherent = Compton
  \[ \sigma = Z f(E_\gamma) \]

  pair production \( E_\gamma > 2m_e \)
  contributions from nucleus (~\( Z^2 \))
  and atomic electrons (~\( Z \))

  small contribution from nuclear interactions
Charged particles

• Ionisation dominates  Units: $x = \text{density} \times \text{thickness} = [g.cm^{-2}]$

  Stopping power = $dE/dx$  scales in similar way for all particles with $p/m = \beta\gamma$

  dominated by interactions with atomic electrons

• low energies

  slow particles lose energy rapidly

  $dE/dx$ increases with $\beta$ to maximum

  Bragg peak

• relativistic energies

  decline $\sim 1/\beta^2$

  to minimum value

  further slow rise $\sim \log(p/m)$

• most cosmic rays and high energy particles approximately MIPs
dE/dx

- Measured energy loss can provide another way of identifying particles
  - gas detectors with multiple samples of $\Delta E$ from same particle
  - momentum measurement is needed - from bending in B field
  - accompanied by good calibration of $p$ and $dE/dx$
Electrons

• are special because of their low mass
  classically accelerated charge radiates
• brehmstrahlung radiation in matter
  acceleration in nuclear field
• synchrotron radiation in accelerators
  generates beams of low energy x-rays
  typical E ~ 1-10keV
  widely used for studying atomic properties, eg protein crystallography
Other neutral particles

• neutrons
do not generate ionisation directly so hard to measure

• at low energies
mostly elastic collisions with atoms in material
simple kinematics determines energy transfer

\[ \Delta T_{\text{max}} = \frac{4AT_{\text{inc}}}{(1+A)^2} \]

low Z materials favoured to absorb neutron energy
C, D\(_2\)O moderators in nuclear reactors
hydrogenous or boron compounds used as detectors
Sensor equivalent circuits

• Many of the sensors considered so far can be modelled as current source + associated capacitance
  typical values ~ few pF
  but can range from
  ~100fF semiconductor pixel
  ~10-20pF gas or Si microstrip, PM anode
  ~100pF large area diode
  ~μF wire chamber
  usually there is some resistance associated with the sensor, eg leads or metallisation but this has little effect on signal formation or amplification

• Notable exception: microstrips - gas or silicon
  the capacitance is distributed, along with the strip resistance
  forms a dissipative transmission line