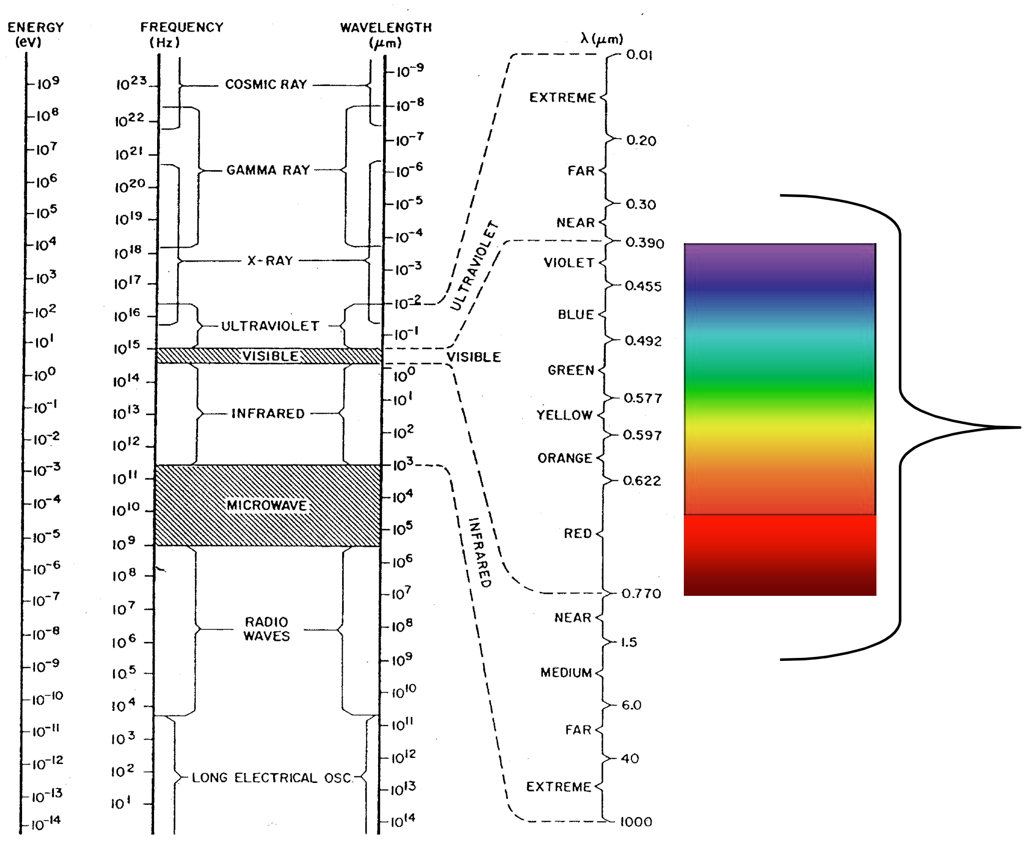
# SENSORS and TRANSDUCERS

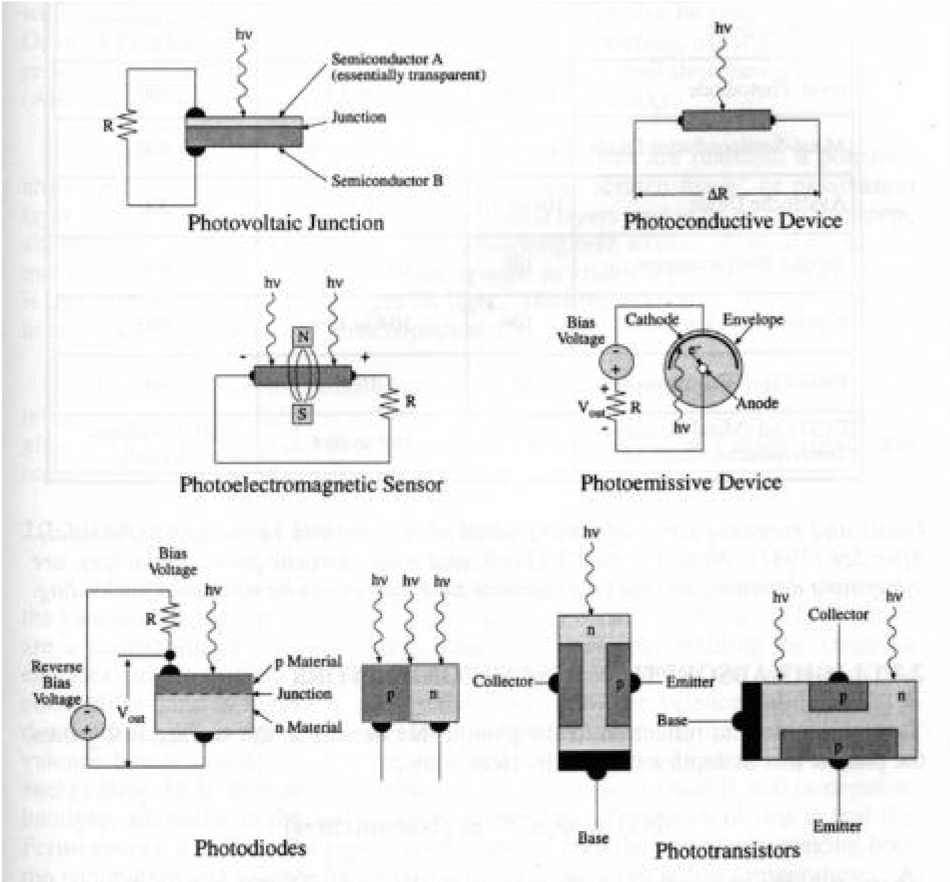
Klas Hjort, Materialvetenskap

- Microsensors in The Optical Energy Domain
  - Examples of microsensors in the optical energy domain
  - Semiconductor physics
  - Photodiodes
  - Phototransistors
  - Charge-coupled image sensors (CCDs)

# Optical Energy Domain - Spectrum



# Optical Energy Domain - Sensor Types



# Optical Energy Domain - Definitions

Responsivity:

$$R_I = \frac{\text{output current}}{\text{optical input power}} = \frac{I_p}{P_{opt}} = \frac{\eta\, q}{h\,\nu} = \frac{\eta\,\lambda(\mu m)}{1.2398}$$

where η is the quantum efficieny:

$$\eta = \frac{\left(\frac{I_p}{q}\right)}{\left(\frac{P_{opt}}{h\nu}\right)}$$

Detectivity:

$$D^* \equiv \frac{\sqrt{A}}{NEP} \quad \text{in} \quad \frac{cm\sqrt{Hz}}{W}$$

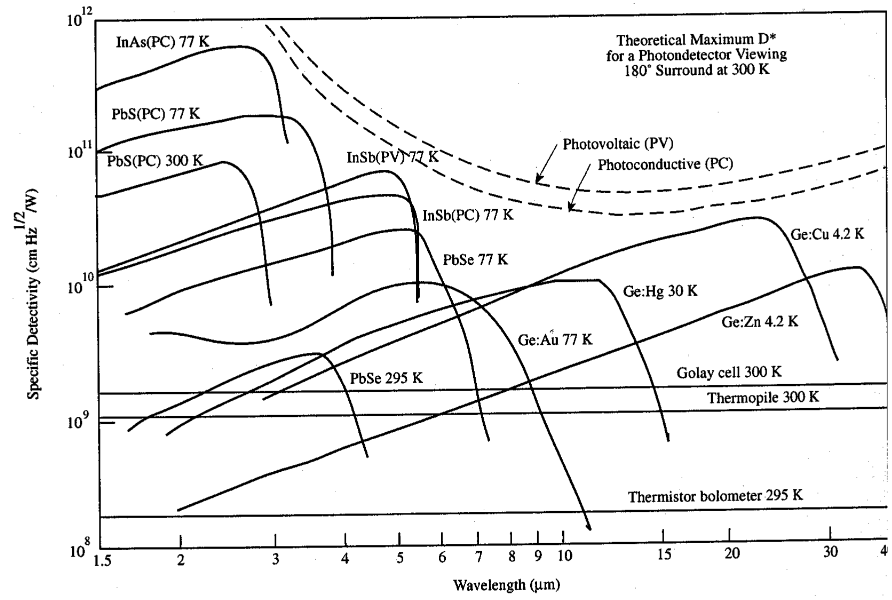
where the NEP is the noise equivalent power:

$$NEP \equiv \frac{\text{RMS noise current}\left(\frac{A}{\sqrt{Hz}}\right)}{R_I\left(\frac{A}{W}\right)} \quad \text{in} \left(\frac{W}{\sqrt{Hz}}\right)$$

or, for a voltage-output device as,

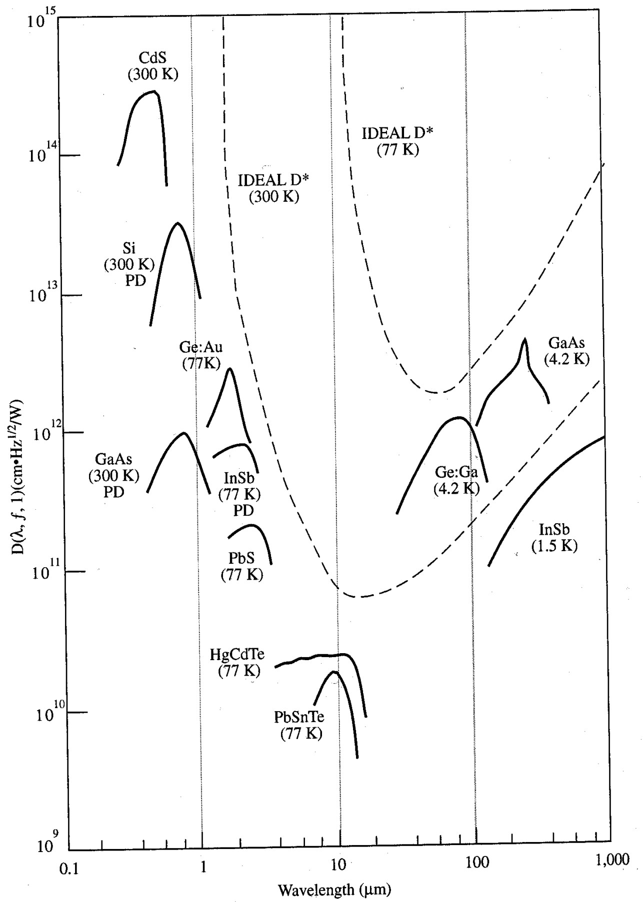
$$NEP \equiv \frac{\text{RMS noise voltage}\left(\frac{V}{\sqrt{Hz}}\right)}{R_V\left(\frac{V}{W}\right)} \quad \text{in} \left(\frac{W}{\sqrt{Hz}}\right)$$

# Optical Energy Domain - Physics




*Plots of detectivities of various detectors, including Golay cells, thermopiles, and bolometers for comparison. After Cobbold (1974). Photovoltaic and photoconductive devices are identified as "PC" and "PV," respectively.*

# Optical Energy Domain - Physics



# Optical Energy Domain - Physics

- Interaction of electromagnetic radiation with semiconductors
  - When a photon with energy $E_{ph} > h\nu = E_g$ coincides with a semiconductor an electron-hole pair is generated
  - The absorption is a function of temperature that can be described with

$$\Phi(x) = \eta \cdot \Phi_0 \cdot \exp(-\alpha \cdot x)$$

where: $\eta$ - fraction of photons that coincide at the surface

$\alpha$ - absorption coefficient

  - Bandgap distance
    - » Si - 1.15 eV
    - » GaAs - 1.43 eV

# Optical Energy Domain - Physics

- Influence of tmperature and radiation on conductivity

In a *p*-*n* junction the number of electron-hole pairs per unit volume determines the conductivity $\sigma$

The influence of temperature can be expressed in general as

$$\sigma_T = q\left[n(T)\mu_n(T) + p(T)\mu_p(T)\right] \quad where \quad \sigma_T(\Omega^{-1}m^{-1})$$

where: *n, p* - density of charge carriers

$\mu$- mobility of the charge carriers

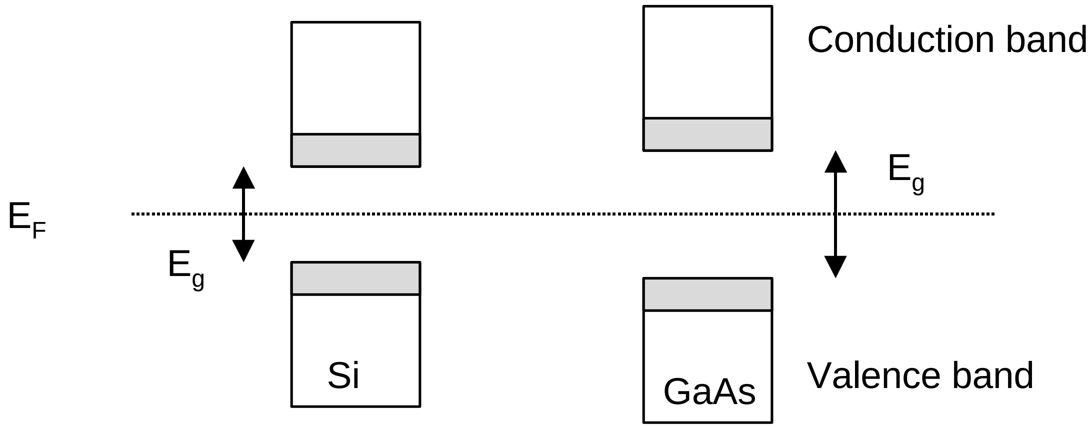
The increase of conductivity due to the radiation can be expressed in general as

$$\sigma_I = q\left[n(I)\mu_n + p(I)\mu_p\right]$$

$$\sigma = \sigma_T + \sigma_I$$

# Optical Energy Domain - Physics

- Interaction of electromagnetic radiation with semiconductors



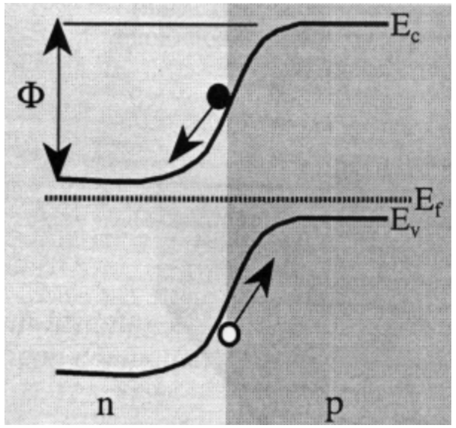

$E_F$ - Fermi level

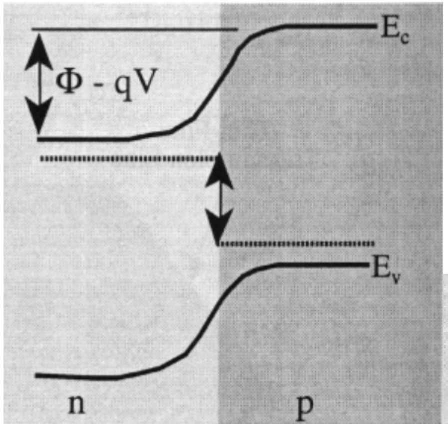
$E_g$ - bandgap distance (Si - 1.15 eV, GaAs - 1.43 eV)

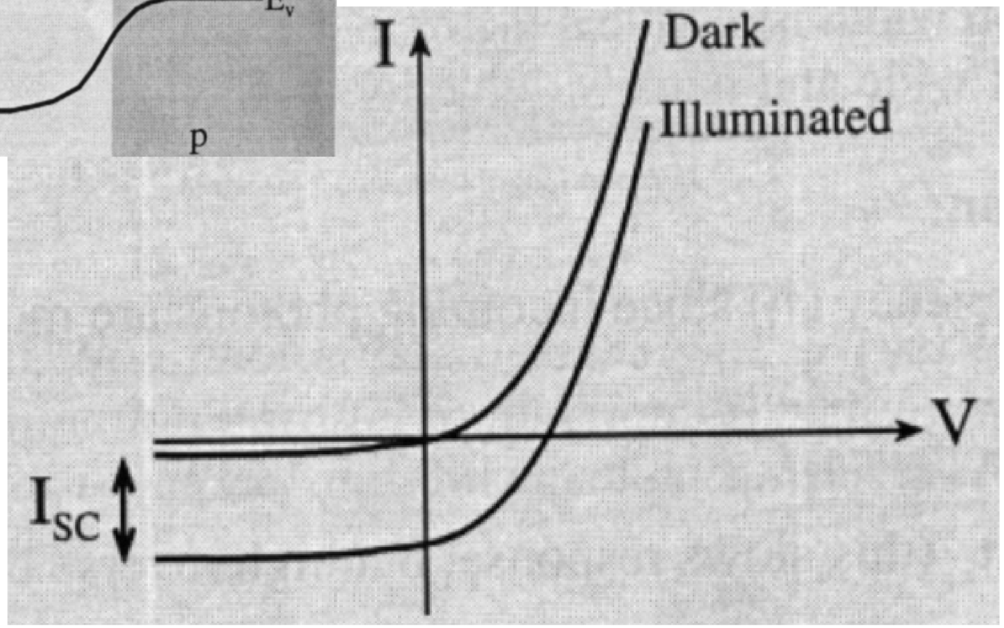
# Optical Energy Domain - Physics

| Semiconductor | Bandgap (eV) 300 K | Bandgap (eV) 0 K | $\lambda_{max}$ ($\mu$m) 300 K |
|---|---|---|---|
| BN | 7.500 | - | 0.165 |
| C | 5.470 | 5.480 | 0.227 |
| ZnS | 3.680 | 3.840 | 0.337 |
| GaN | 3.360 | 3.500 | 0.369 |
| ZnO | 3.350 | 3.420 | 0.370 |
| Alpha-SiC | 2.996 | 3.030 | 0.414 |
| CdS | 2.420 | 2.560 | 0.512 |
| GaP | 2.260 | 2.340 | 0.549 |
| BP | 2.000 | - | 0.620 |
| CdSe | 1.700 | 1.850 | 0.729 |
| AlSb | 1.580 | 1.680 | 0.785 |
| CdTe | 1.560 | - | 0.795 |
| GaAs | 1.420 | 1.520 | 0.873 |
| InP | 1.350 | 1.420 | 0.919 |
| Si | 1.120 | 1.170 | 1.107 |
| GaSb | 0.720 | 0.810 | 1.722 |
| Ge | 0.660 | 0.740 | 1.879 |
| PbS | 0.410 | 0.286 | 3.024 |
| InAs | 0.360 | 0.420 | 3.444 |
| PbTe | 0.310 | 0.190 | 4.000 |
| InSb | 0.170 | 0.230 | 7.294 |
| Sn | - | 0.082 | 15.122 @ 0 K |

# Optical Energy Domain - Physics



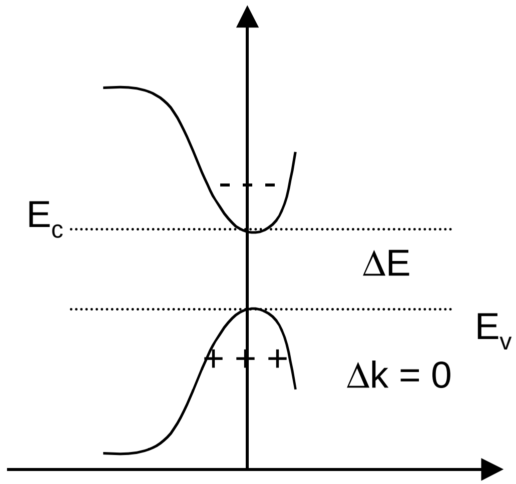




Generation of a voltage at a pn-junction by creating an electron-hole pair

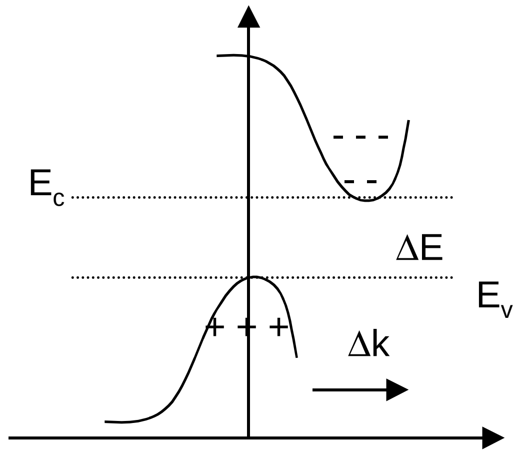
# Optical Energy Domain - Physics

- Direct- and indirect- bandgap materials




GaAs

Transition requires
change in energy only




Si

Transition requires
change in energy and wave number

# Optical Energy Domain - Physics

- Direct- and indirect- bandgap materials

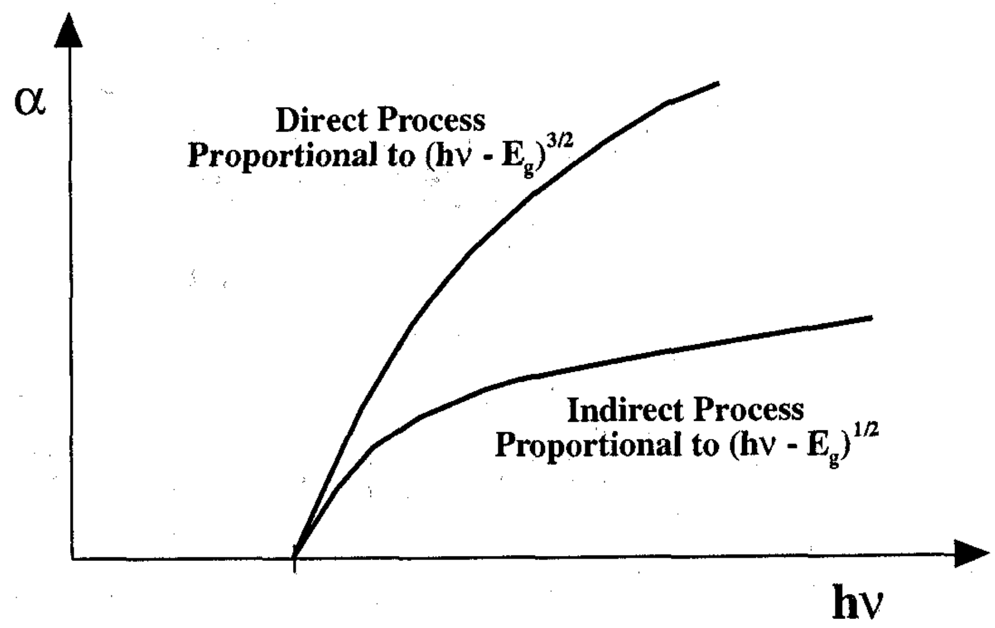
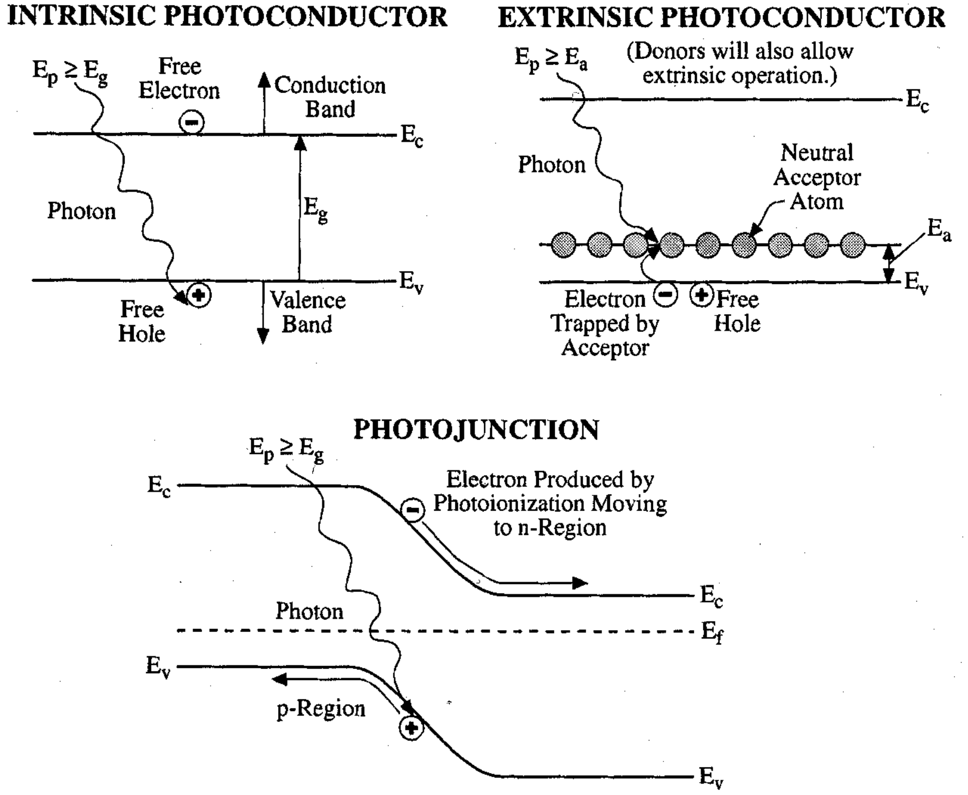



*Illustration of the absorption spectra of direct and indirect processes.*

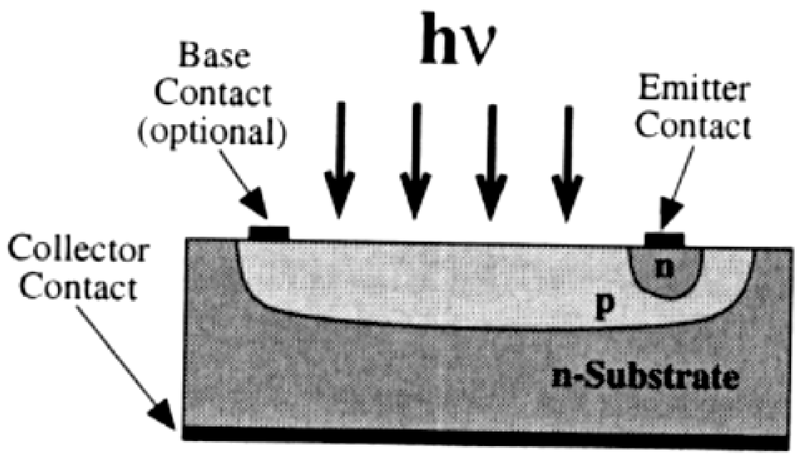
# Optical Energy Domain - Physics

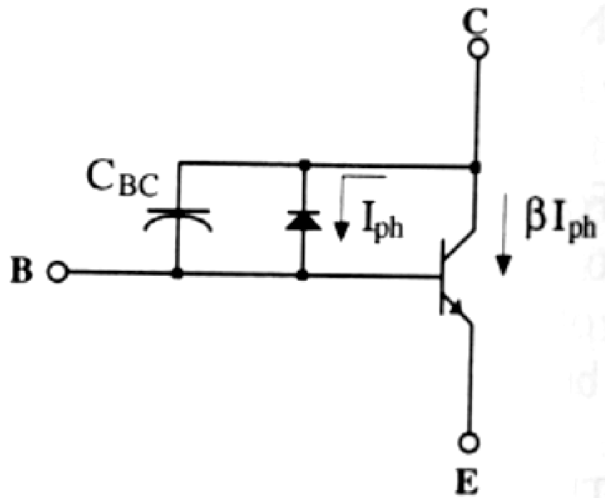



*Comparative band diagrams for intrinsic-, extrinsic- and photojunction-type optical sensors. After Cobbold (1974).*

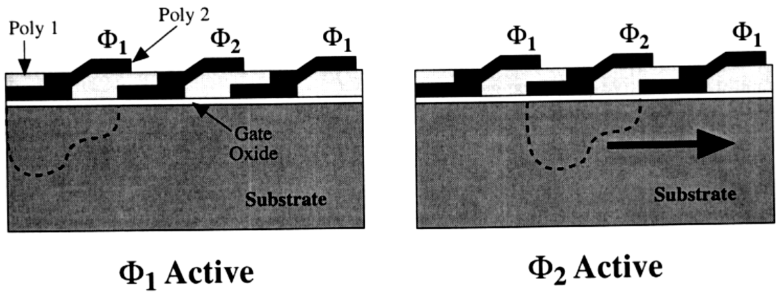
# Optical Energy Domain - Physics

## Phototransistors - bipolar



# Charge-coupled image sensors (CCD)



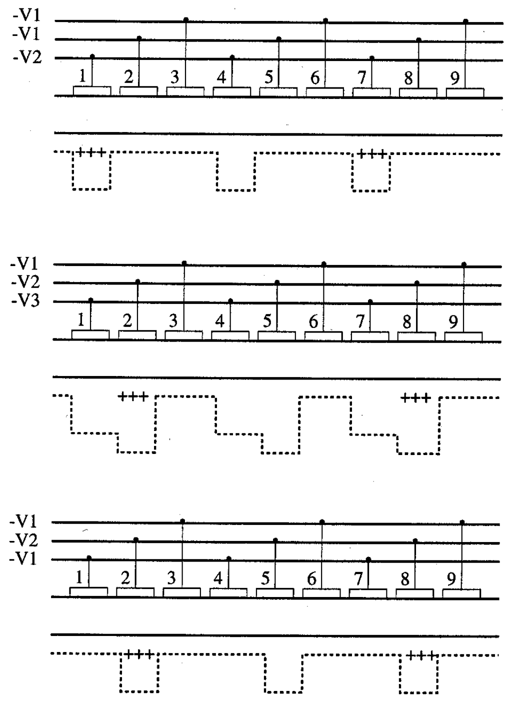




*Illustration of operating mode of (older style) a three-phase CCD array showing the mechanism of the charge transfer between depleted MOS capacitors. Adapted from Millman (1979).*