Queen Mary
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Science and Engineering

Radiation Detectors (SPA 6309)

Lecture 6

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What is this lecture about?

- The principles of detection of ionising radiation
  - Interaction of charged and neutral particles with matter
  - Gaseous sensors
  - Semiconductor sensors
  - Scintillators
- Sensor systems used in particle and nuclear physics
  - Calorimeters
  - Tracking detectors
  - Neutrino detectors

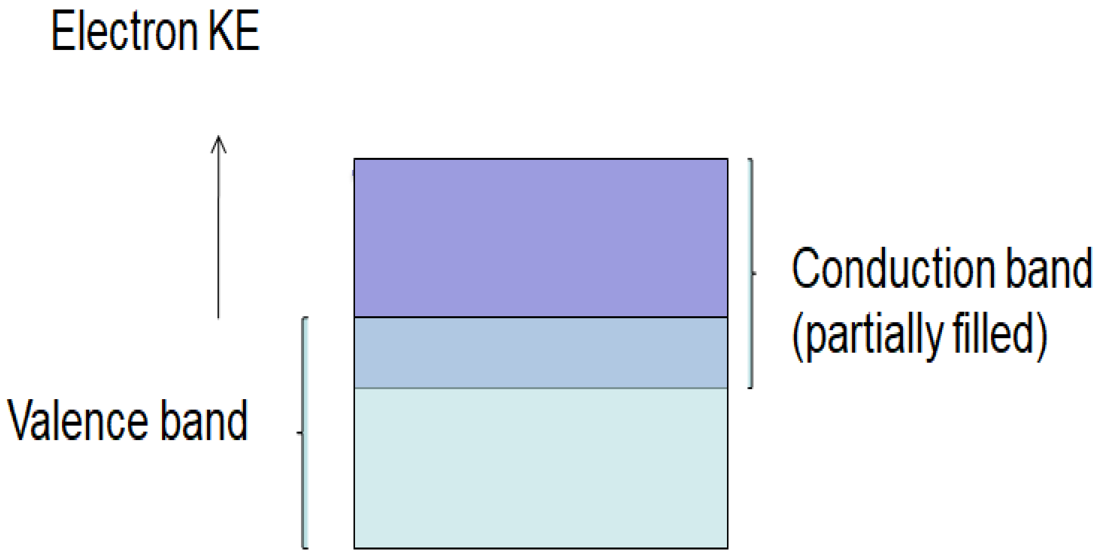
Key points from previous lecture

- Multi-wire proportional counter (MWPC)
- Drift chamber
  - Traditional (with wires like a MWPC)
  - Microstrip gas chamber
- Resistive Plate Chamber
  - Used where very large areas, good time resolution and moderate spatial resolution is needed, e.g. muon chambers in CMS at the LHC.
- Time Projection Chamber (TPC)
  - Uses very long drift distances in ultra pure gas (or noble liquid) to provide the third spatial coordinate.
  - ~ zero material within the volume (bremsstrahlung, pair production minimised)
  - Important **current technology** for huge neutrino detectors (e.g. DUNE)

Silicon Sensors – basic semiconductor physics

n, p	Total electron/hole carrier concentrations
n_i, p_i	Intrinsic electron/hole carrier concentrations
n_0, p_0	Thermal equilibrium electron/hole carrier concentrations
$\hat{n}, \hat{p}$	Excess carrier concentration (e.g. due to majority carrier injection)
τ_e, τ_h	electron/hole minority carrier lifetime
m^*	"Effective" mass (of electron or hole)
μ_e, μ_h	electron/hole mobility; units $[L]^2[V.T]^{-1}$
σ, ρ	conductivity, resistivity (e.g. of a Si-wafer) and $\rho = \frac{1}{\sigma}$
G, R	Generation, Recombination rates (e-h pairs per unit volume per second)
D_e, D_h	Diffusivity of electrons/holes; units $[L]^2[T]^{-1}$

Conductors vs Insulators

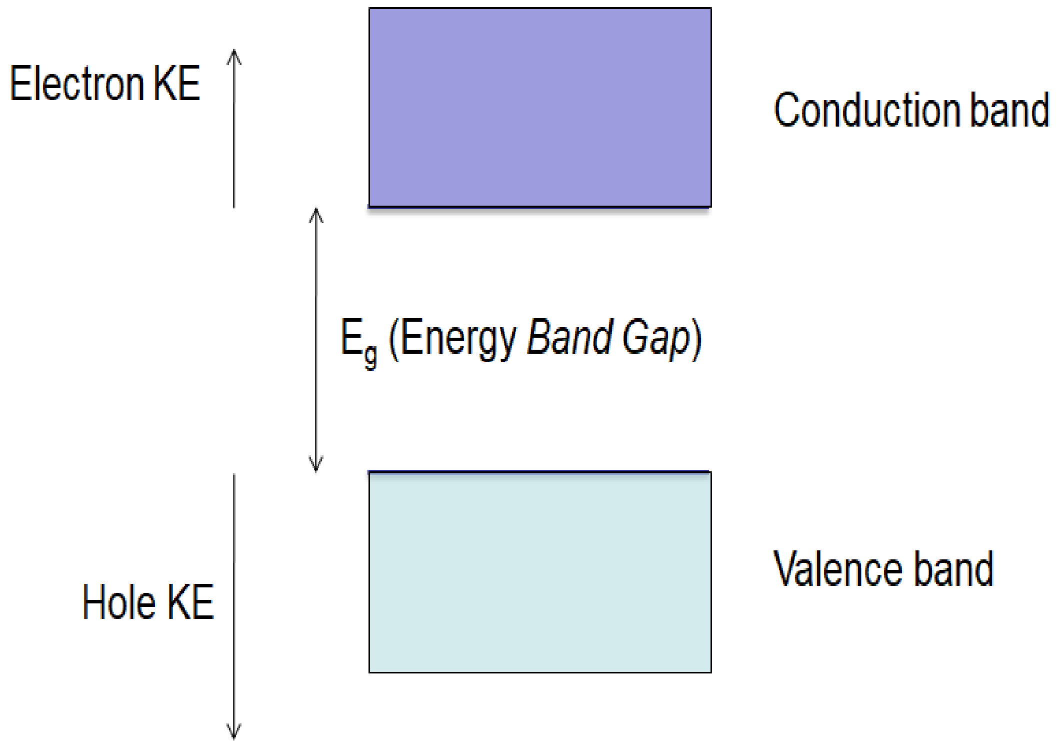


Electron KE

Conduction band
(partially filled)

Valence band

Conductors (essentially “free” electrons)



Electron KE

Conduction band

E_g (Energy *Band Gap*)

Valence band

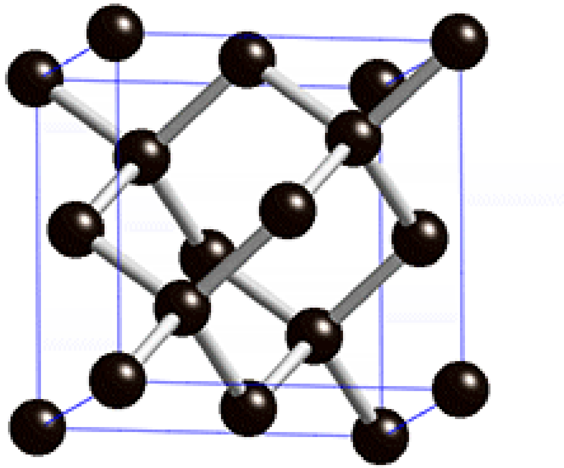
Hole KE

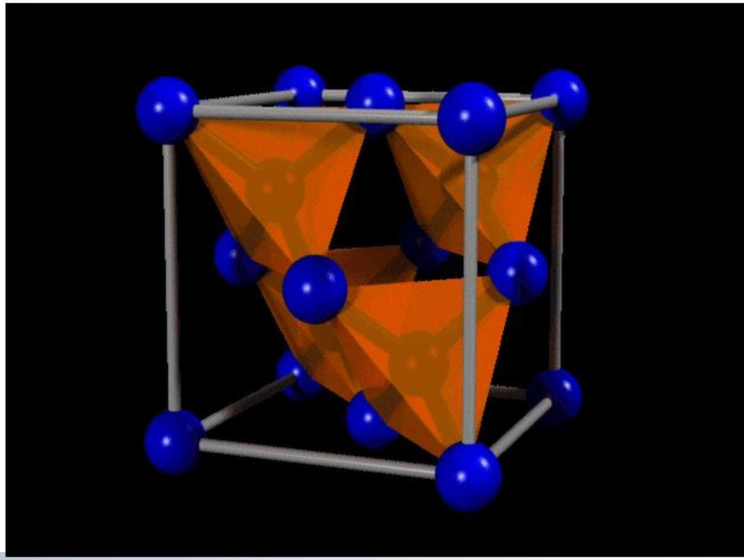
insulators, semiconductors

What we call a semiconductor is an insulator whose electrical properties can be easily modified by adding impurities (e.g. n or p-type silicon).

Band gaps

- Typically quoted in eV (“electron volts)
- 1 eV = 1.602×10^{-19} J
- Some important semiconductor band gaps (in eV):
  - Ge: 0.7 (indirect)
  - **Si: 1.1 (indirect)**
  - GaAs: 1.4 (direct)
  - GaP: 2.3 (direct)
  - 4H-SiC: 3.3 (indirect) Note: the “H” here indicates a particular structure.
  - GaN: 3.4 (direct)
  - C (diamond): 5.5 (indirect)
- A useful database of relevant material properties
  - http://www.ioffe.ru/SVA/NSM/Semicond/index.html



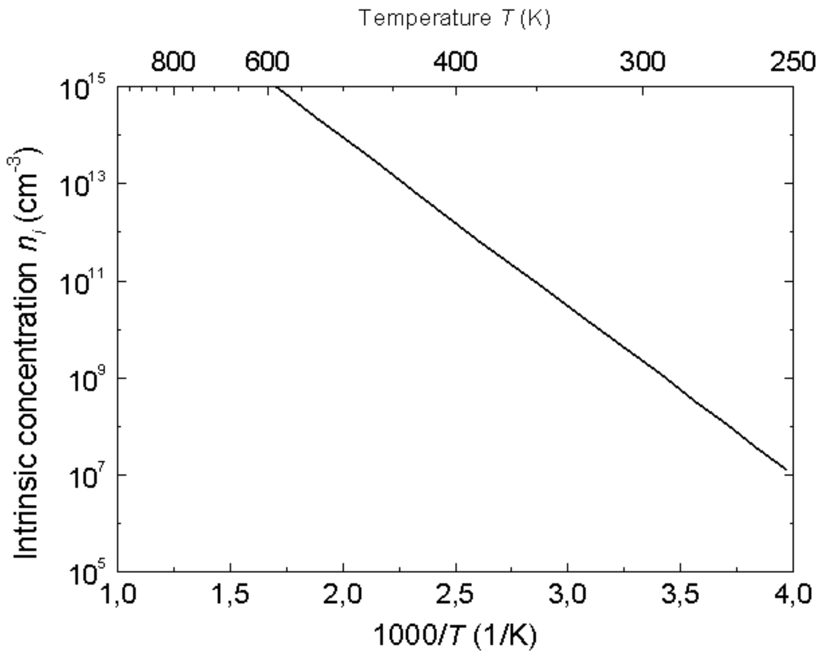


Thermal equilibrium

- DEFINITION: Intrinsic semiconductor: $n_i = p_i$

$$n_i = B(T)\exp\left(\frac{-E_g}{2kT}\right)$$

- k is Boltzmann's constant* and $B(T)$ depends on the material and temperature.
- At 300K, $n_i = 1.3\times10^{10}$ cm^{-3} for Si and $n_i = 2\times10^{6}$ cm^{-3} for GaAs



*(1.38×10^{-23} JK^{-1}) but in more useful units, $k = 8.62\times10^{-5}$ eV.K^{-1}

Dynamic process

- Continual *generation* and *recombination* of electrons and holes.
- For band-band direct generation only the temperature is relevant.
- For recombination the carrier density is relevant

$$\boxed{\begin{aligned} n_o p_o &= n_i p_i \\ n_o p_o &= n_i^2 \end{aligned}}$$

← Mass Action Law

- If an external source of carriers is available (optical/electrical/ionising radiation) then e/h concentrations can be raised above their thermal equilibrium value.

$$n = n_o + \hat{n}$$

$$p = p_o + \hat{p} = p_o + \hat{n}$$

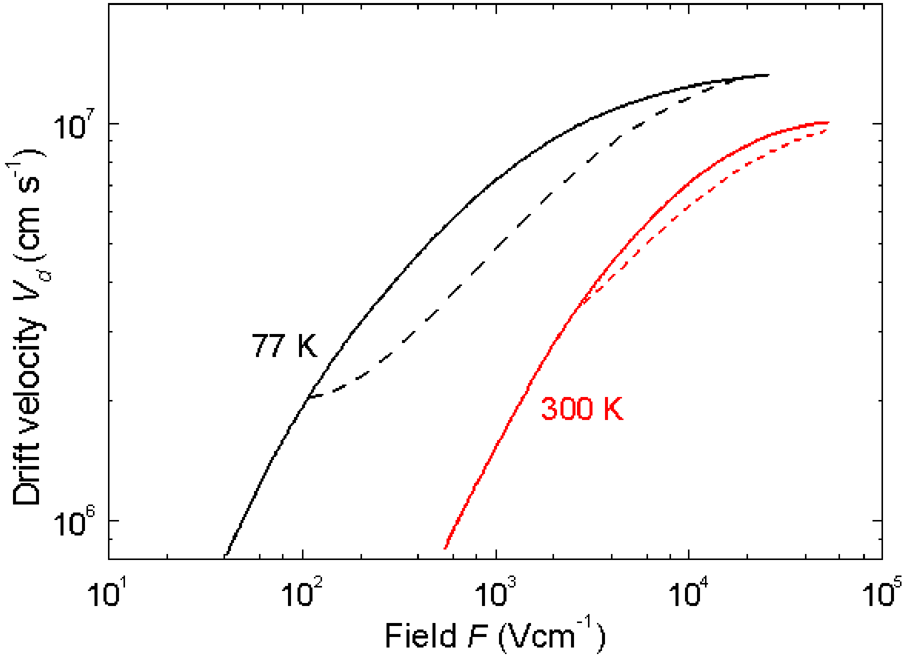
$$np \neq n_i^2 \quad \text{out of equilibrium}$$

Drift current

- Thermal KE: $\frac{1}{2}m^*v_{th}^2 = \frac{3}{2}kT \quad k \text{ is Boltzmann's constant}$
  - Drift velocity due to an applied electric field *E*

    $$v_d\mathbf{x} = \mu_e E\mathbf{x} \quad \text{where } \mu_e \text{ is electron mobility}$$

  - Note linear dependence on *E*. This holds up to quite high fields (~3 kV/cm for n-type Si) after which the velocity saturates at its scatter-limited value.



$$J\mathbf{x} = q(n\mu_e + p\mu_h)E\mathbf{x}$$

$$J\mathbf{x} = \sigma E\mathbf{x} \quad \text{Ohm's Law}$$

$$\text{thus} \quad \sigma = q(n\mu_e + p\mu_h)$$

J is current density, *A* is cross-sectional area, *JA* is the drift current, σ is conductivity.

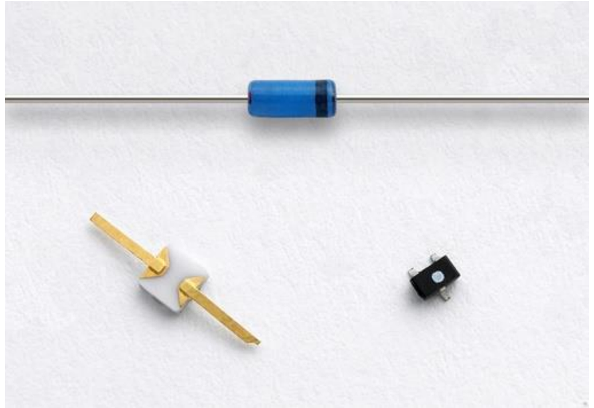
Diffusion Current

- Often in real devices one has both diffusion and drift simultaneously. Assume a pn junction plus an external applied electric field.
- Minority carrier holes are injected from p to n (diffusing away from p region) and then drift due to applied field.

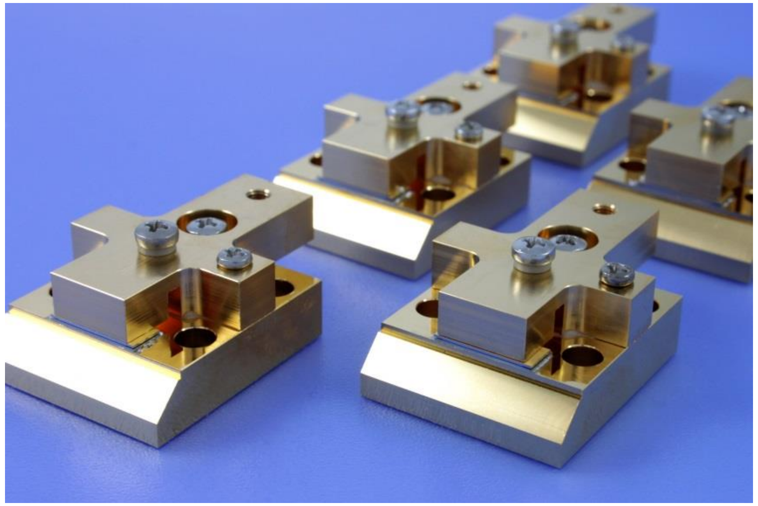
$$J_h\mathbf{x} = \left(q\mu_h pE - qD_h \frac{dp}{dx} \right)\mathbf{x} \quad \text{Total hole current in x - direction}$$

Diodes

Dynex high power rectifier diode

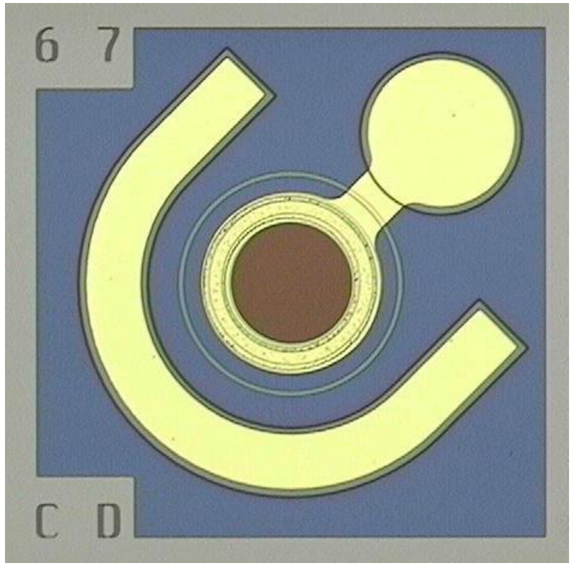


Noisecom noise diodes



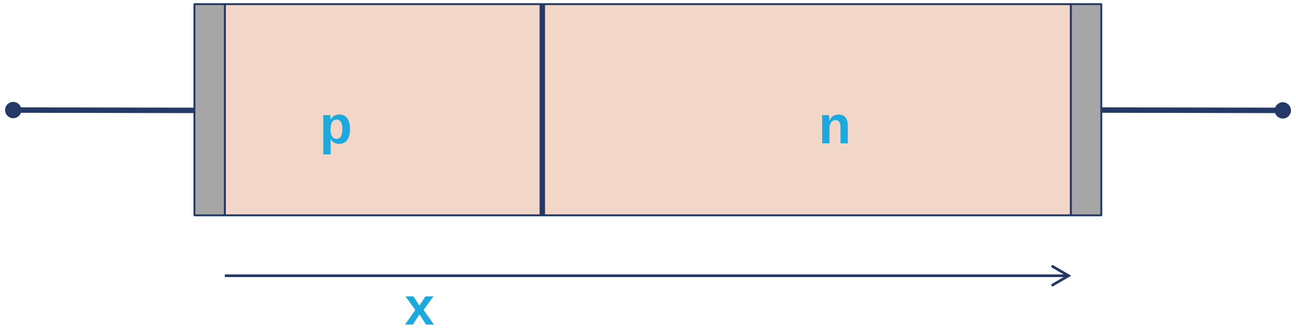
High power (2 kW) infrared laser bars

(Credit: FBH/P. Immerz)



High speed avalanche pin photodiode

1-D model



p-type region

- >Concentration of holes ≫ holes in the n-type region
- >This concentration gradient drives a *diffusion* current of holes to the *right*.
- >Thermal equilibrium ⇒ zero net hole current thus there *must* be a flow of holes to the *left* which **exactly cancels** the flow to the *right.*
- >This **cannot** be a *diffusion* current; it is in fact a *drift* current.

Transport equations

$$J_h\mathbf{x} = \left(q\mu_h pE - qD_h \frac{dp}{dx} \right)\mathbf{x} \quad \text{Total hole current in x - direction}$$

$$J_e\mathbf{x} = \left(q\mu_e nE \enclose{circle}{+} qD_e \frac{dn}{dx} \right)\mathbf{x} \quad \text{Total electron current in x - direction}$$

$$\mathbf{J}_{\mathbf{total}} = \mathbf{J}_{\mathbf{h}} + \mathbf{J}_{\mathbf{e}} \qquad \text{Total current density}$$

NOTE: change of sign!

Often in devices, e.g. bipolar, electron & hole currents vary with distance. Total current can be evaluated *at any plane*.

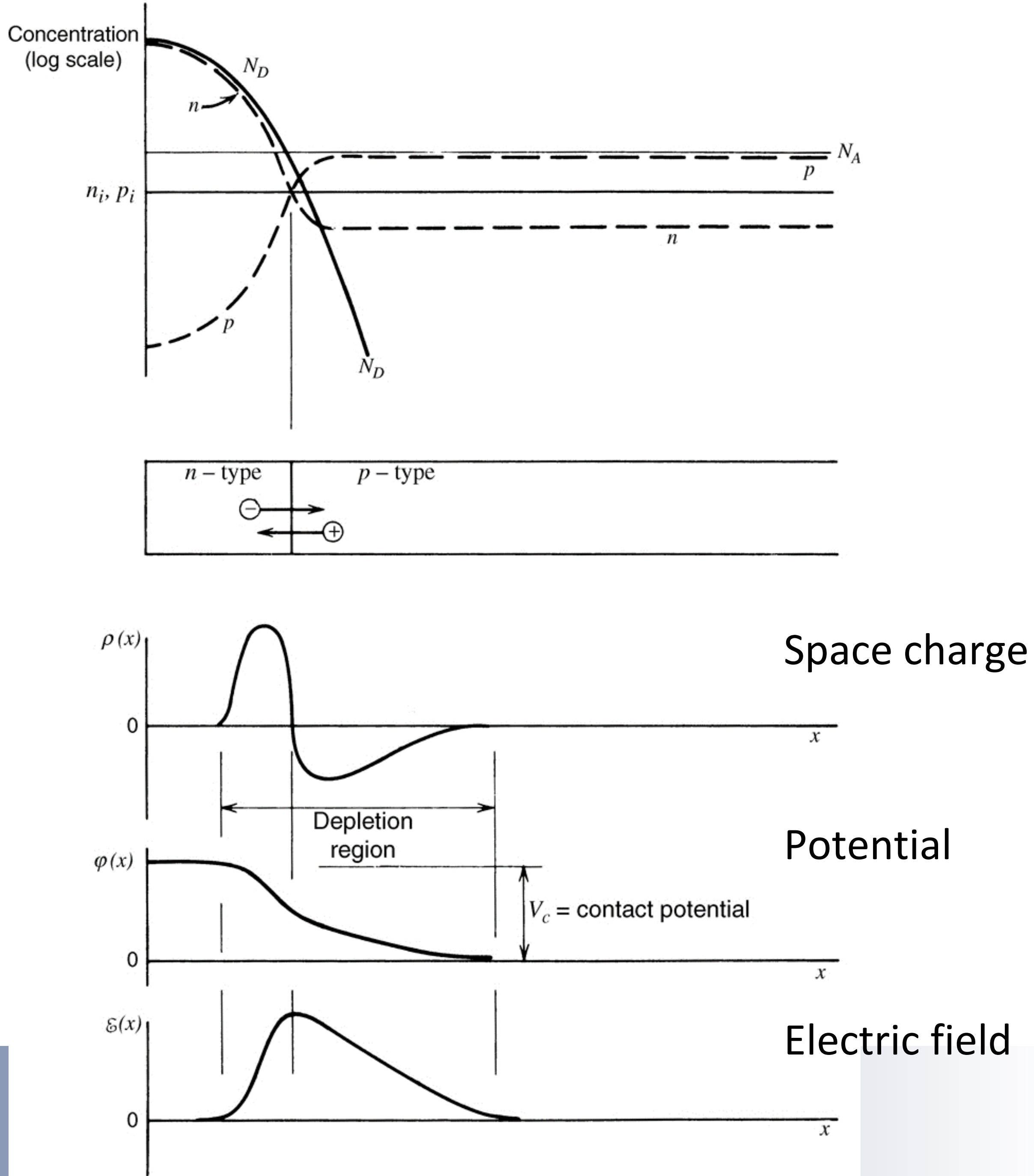
pn junction

Depletion Region:

A buffer zone where, in thermal equilibrium, there is no *net* flow of electrons *or* holes.

Using Einstein relationship the electric field is:

$$\mathrm{E} = \frac{kT}{qp}\frac{dp}{dx} = -\frac{kT}{qn}\frac{dn}{dx}$$



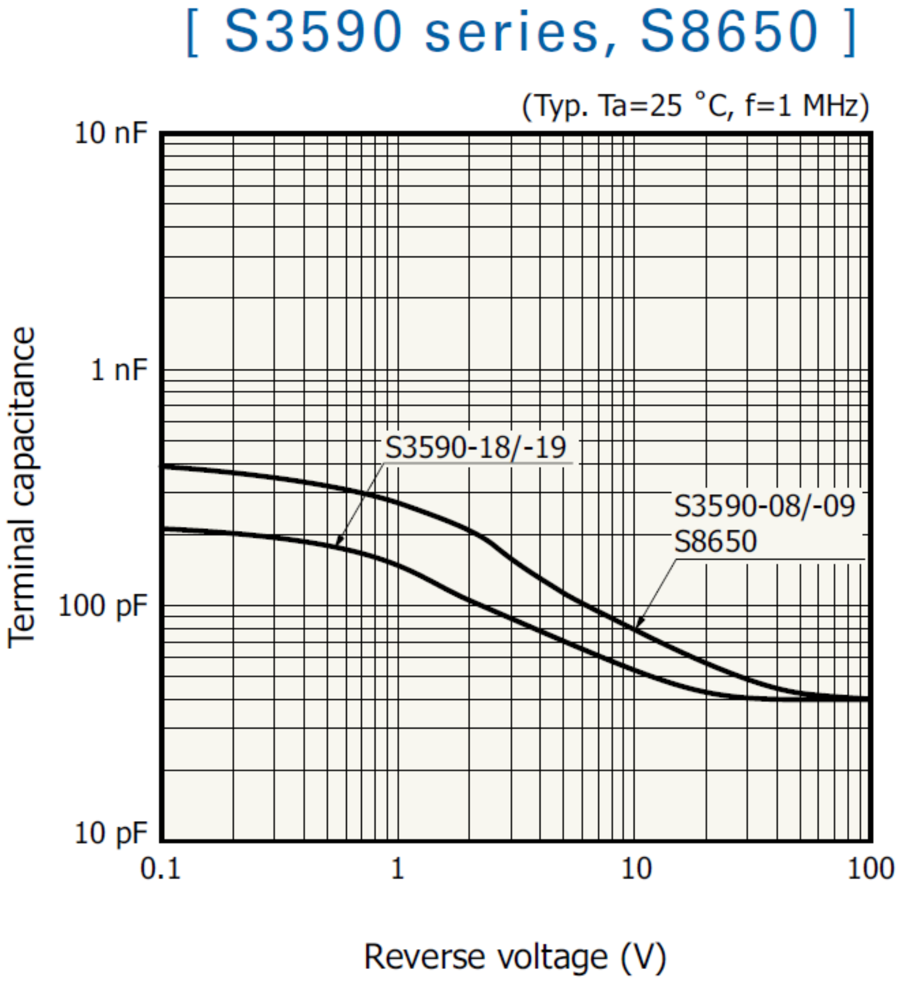
Ideal Diode Equation (neglects carrier generation in the depletion region!)

$$J = J_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

where J_0 is the saturation current density

A reverse biased diode (the type we are interested in) has capacitance due to the space charge, it varies with bias voltage V_R:

$$\frac{1}{C^2} = \frac{2(V_C + V_R)}{q\varepsilon_r\varepsilon_0 N_D}$$



A 100 mm^2 PIN diode (Hamamatsu Photonics KK, Japan)

Take away: key points

1. Semiconductors work with two types of charge carriers (electrons and holes).
2. The drift in electric fields with mobilities which depend on the semiconductor, the type of carrier and the temperature.
3. A pn junction diode has in built potential (from space charge) which separates any e/h pairs created in the depletion region.
4. Note some similarities with the principles of gas detectors from (Lectures 4 and 5) – pn junction devices are solid-state ionization chambers in some sense.