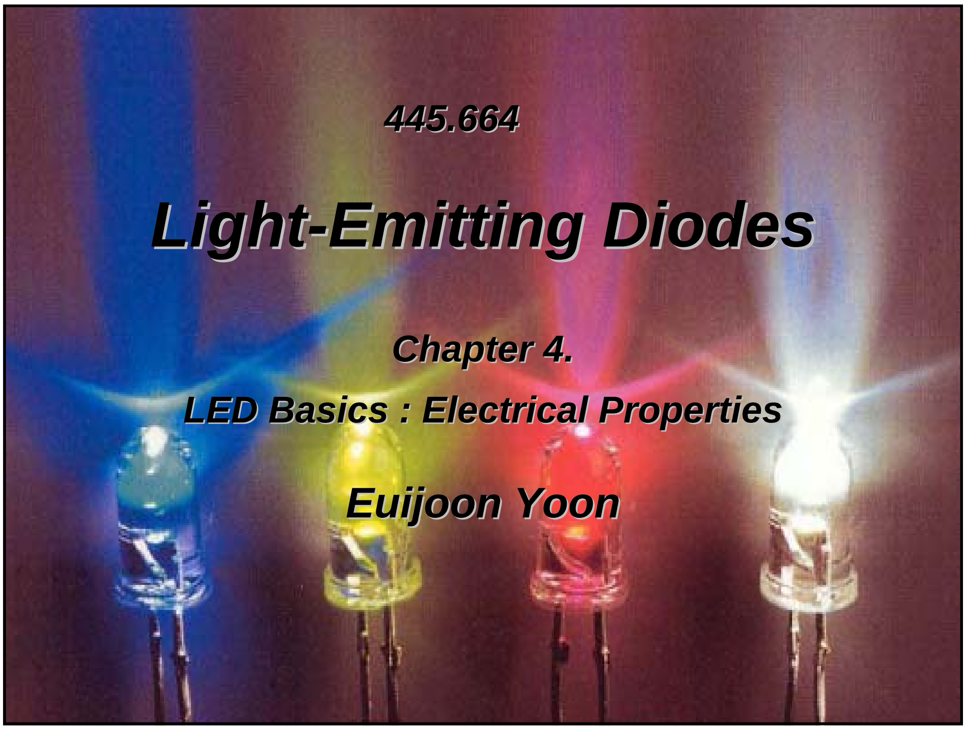

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Light-Emitting Diodes

Chapter 4.

LED Basics : Electrical Properties

Euijoon Yoon

p-n junction band diagram

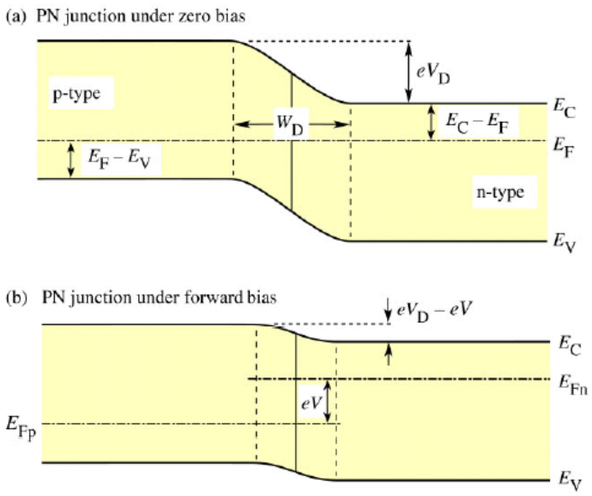


Fig. 4.1. P-N junction under (a) zero bias and (b) forward bias. Under forward bias conditions minority carriers diffuse into the neutral regions where they recombine.

Schockley Equation

- V_D (diffusion voltage) $$V_D = \frac{kT}{e} \ln \frac{N_A N_D}{n_i^2}$$

N_A, N_D : acceptor and donor concentration
n_i : intrinsic carrier concentration

The diffusion voltage represents the barrier that free carriers must overcome in order to reach the neutral region of opposite conductivity type.

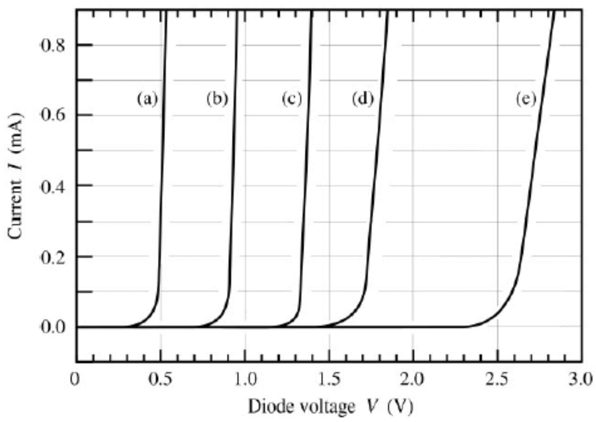
- **Schockley equation (the I-V characteristic of a p-n junction)**

$$I = eA\left(\sqrt{\frac{D_p}{\tau_p}} N_A + \sqrt{\frac{D_n}{\tau_n}} N_D\right)\{e^{e(V - V_D)/kT} - 1\}$$

$D_{n,p}$: electron and hole diffusion constants
$\tau_{n,p}$: electron and hole minority carrier lifetimes
A : cross-sectional area, V : diode bias voltage

- ***Threshold voltage (V_{th})***
-the voltage at which the current strongly increase
- $V_{th} \sim V_D$

Diode current-voltage characteristics



$T = 300$ K
(a) Ge $E_g \simeq 0.7$ eV
(b) Si $E_g \approx 1.1$ eV
(c) GaAs $E_g \approx 1.4$ eV
(d) GaAsP $E_g \simeq 2.0$ eV
(e) GaInN $E_g \approx 2.9$ eV

Fig. 4.2. Room temperature current - voltage characteristics of p-n junctions made of different semiconductors.

- **Forward voltage is approximately equal to E_g/e.**

Diode forward voltage

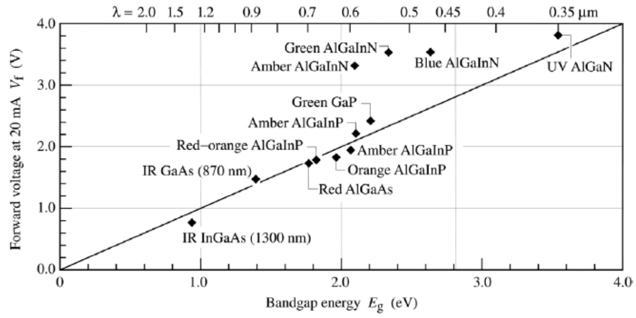


Fig. 4.3. Typical diode forward voltage versus bandgap energy for LEDs made from different materials (after Krames *et al.*, 2000; updated with UV LED data of Emerson *et al.*, 2002).

- **Most semiconductor LEDs follow the solid line, except for LEDs based on III-V nitrides.**

1. Large bandgap discontinuities -> additional voltage drop
2. Poor contact technology in the nitrides
3. Low p-type conductivity in bulk GaN
4. Parastic voltage drop in the n-type buffer layer

Deviations from the ideal I-V characteristic

- $I = I_s e^{eV/(n_{ideal} kT)}$
- $I - \frac{(V - IR_s)}{R_p} = I_s e^{e(V - IR_s)/(n_{ideal} kT)}$

n_{ideal} : ideality factor

R_s : parasitic series resistance

R_p : parasitic parallel resistance

Non-ideal I-V characteristics

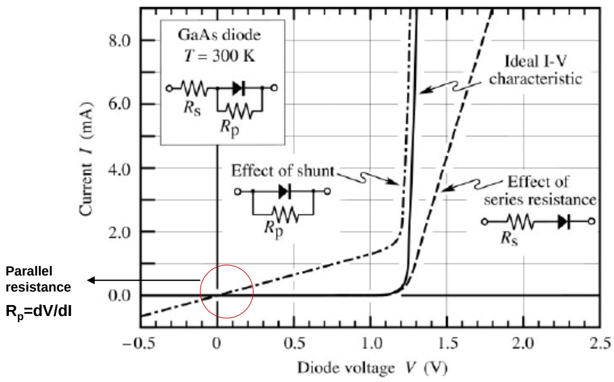


Fig. 4.4. Effect of series resistance and parallel resistance (shunt) on the I-V characteristic of a p-n-junction diode.

- **Problems area of diodes can be identified from I-V characteristic.**
  - **A series resistance can be caused by contact resistance or by the resistance of the neutral region.**
  - **A parallel resistance can be caused by any channel that bypasses the p-n junction. The bypass can be caused by damaged regions of the p-n junction or by surface imperfections.**

Methods to determine series resistance

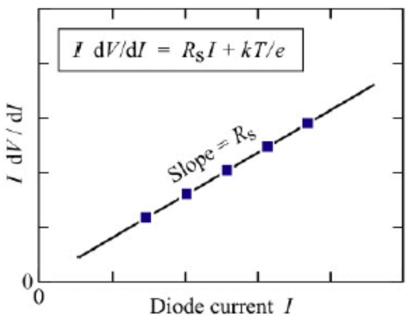


Fig. 4.5. Method for evaluating the diode series resistance. The equation shown as an inset is valid for forward bias ($V >> kT / e$)

- **Method shown above suitable for series resistance measurement.**
- **At high currents, diode I-V becomes linear due to dominance of series resistance. Diode series resistance can be extracted in linear regime.**

Carrier distribution in p-n homo- and heterojunctions

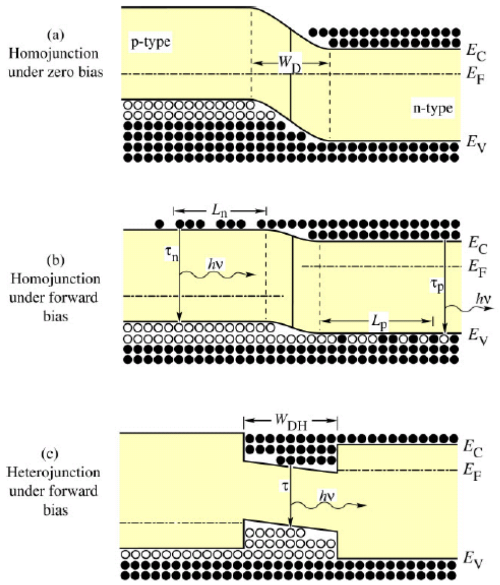


Fig. 4.6. P-N homojunction under (a) zero and (b) forward bias. P-N heterojunction (c) under forward bias. In homojunctions, carriers diffuse, on average, over the diffusion lengths L_n and L_p before recombining. In heterojunctions, carriers are confined by the heterojunction barriers.

Double heterostructure (DH)

- **Einstein relation**
  - **$D_n = kT\mu_n / e$**
  - **$D_p = kT\mu_p / e$**
- **Diffusion length (L)**
  - **$L_n = (D_n\tau_n)^{1/2}$**
  - **$L_p = (D_p\tau_p)^{1/2}$**

- **In typical semiconductors, the diffusion length is of the order of a several micrometers.**
  ex) in p-type GaAs, $L_n = (220\ cm^2/s \times 10^{-8}\ s)^{1/2} = 15\mu m$

- **Minority carriers are distributed over quite a large distance. The *large recombination region in homojunctions* is not beneficial for efficient recombination.**

- **Introduction of double heterostructure (DH) makes it possible to confine the carriers in active region. The thickness of the region in which carriers recombine *is given by the thickness of the active region rather than the diffusion length.***

The effect of heterojunctions on device resistance

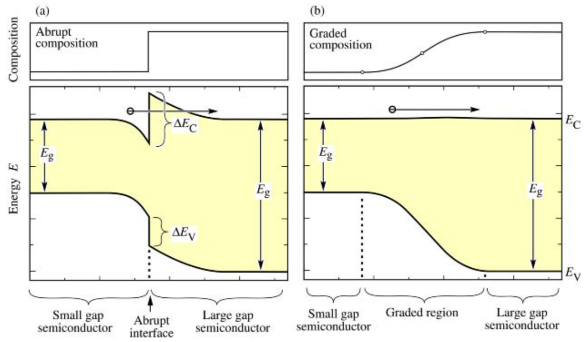


Fig. 4.7. Band diagram of (a) an abrupt n-type–n-type heterojunction and (b) a graded heterojunction of two semiconductors with different bandgap energy. The abrupt junction is more resistive than the graded junction due to the electron barrier forming at the abrupt junctions.

• **One of the problem introduced by heterostructures is *the resistance caused by the heterointerface* and it can have a strong deleterious effect on device performance, especially in high-power devices.**

• **The resistance introduced by abrupt heterostructures can be completely eliminated by *parabolic grading*.**

Grading of heterostructures

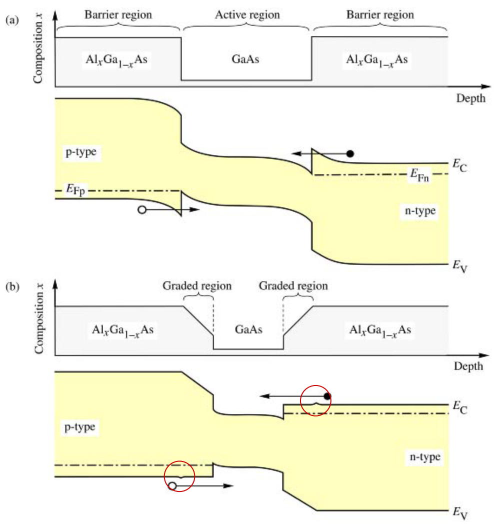


Fig. 4.8. Band diagram of (a) an abrupt double heterostructure and (b) a graded double heterostructure. The barrier-well interface of the abrupt junction is more resistive than the graded junction due to barriers forming at the interfaces.

$$\phi = \frac{eN_D}{2\varepsilon} x^2$$

• **In order to compensate for the parabolic shape of the depletion potential, the composition of the semiconductor *is varied parabolically as well*, so that an *overall flat potential* results.**

• **If the potential created in the depletion region is equal to $\Delta E_g/e$, then electrons will no longer transfer to the small-bandgap material. The thickness of the depletion region is,,,**

$$W_D = \sqrt{\frac{2\varepsilon \Delta E_C}{e^2 N_D}}$$

• **The "spikes" are a result of the linear grading assumed, and would not result for parabolic grading.**

Carrier loss in double heterostructures

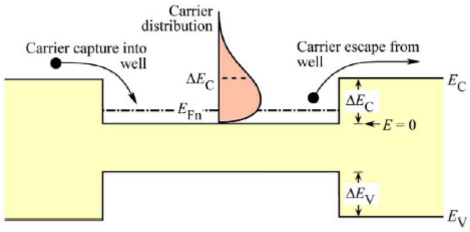


Fig. 4.9. Carrier capture and escape in a double heterostructure. Also shown is the carrier distribution in the active layer.

- **The concentration of electrons with energy higher than the barrier**

$$n_B = \int_{E_B}^{\infty} \rho_{DOS} f_{FD}(E)dE \longrightarrow n_B = N_C e^{(E_{Fn}-E_B)/kT}$$

(Fermi-Dirac distribution) **(Boltzmann distribution)**

- **The diffusion current density of electrons leaking over the barrier**

$$J_n\big|_{x=0} = -eD_n \frac{dn_B(x)}{dx}\bigg|_{x=0} = -eD_n \frac{n_B(0)}{L_n}$$

$$n_B(x) = n_B(0)e^{-x/L_n} = N_C e^{-(E_B-E_{Fn})/kT} e^{-x/L_n}$$

Carrier overflow in double heterostructures

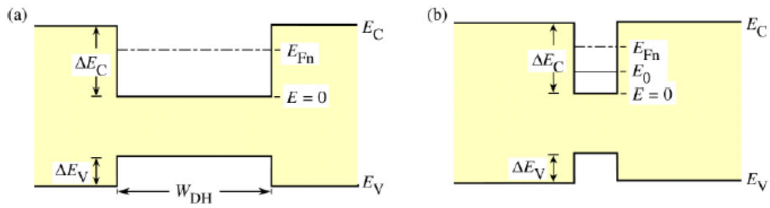


Fig. 4.10. Fermi level (E_{Fn}) and subband level (E_0) in (a) double hetero-structure and (b) a quantum well structure.

- **The current density at which the active region overflows,,,**

$$J_{overflow} = \left(\frac{4N_C}{3\sqrt{\pi}}\right)^2 \left(\frac{\Delta E_C}{kT}\right)^3 eBW_{DH}$$ **(for DH structure LED)**

$$J_{overflow} = \left[\frac{m^*}{\pi(h/2\pi)^2}(\Delta E_C - E_o)\right]^2 \frac{eB}{W_{QW}}$$ **(for QW structure LED)**

Carrier overflow - For DH structure LED

• The rate equation of carrier supply to (by injection) and removal from the active region (by recombination) is given by

$$\frac{dn}{dt} = \frac{J}{eW_{DH}} - Bnp$$ (B: the bimolecular recombination coefficient)

• For high injection densities: *n=p*
• *Under steady-state conditions (dn/dt=0),* ➔ $n = \sqrt{\frac{J}{eBW_{DH}}}$

• In the high-density approximation, the Fermi level is given by

$$\frac{E_F - E_C}{kT} = \left(\frac{3\sqrt{\pi}}{4}\frac{n}{N_C}\right)^{2/3}$$ (Nc: effective density of states)

• At high injection levels, the Fermi energy rises and will eventually reach the top of the barrier. At that point, $E_F - E_C = \Delta E_C$. Using this value, the current density at which the active region overflows is given by

$$J_{overflow} = \left(\frac{4N_C}{3\sqrt{\pi}}\right)^2 \left(\frac{\Delta E_C}{kT}\right)^3 eBW_{DH}$$

Carrier overflow - For QW structure LED

• For QW structures, we must employ the 2D density of states, rather than the 3D density of states. The Fermi level in a QW with one quantized state with energy E_0 is given by

$$\frac{E_F - E_0}{kT} = \ln\left[\exp\left(\frac{n^{2D}}{N_c^{2D}}\right) - 1\right]$$ (n^{2D} : the 2D carrier density per cm^2, N_c^{2D} : the effective 2D density of states)

• Nc^{2D} is given by

$$N_C^{2D} = \frac{m^*}{\pi(h/2\pi)^2}kT$$

• The high-degeneracy approximation (at high carrier densities) is employed and one obtains

$$E_F - E_0 = \frac{\pi(h/2\pi)^2}{m^*}n^{2D}$$

Carrier overflow - For QW structure LED

• The rate equation for the QW of carrier supply to (by injection) and removal from the active region (by recombination) is given by

$$\frac{dn^{2D}}{dt} = \frac{J}{e} - B^{2D} n^{2D} p^{2D}$$

($B^{2D} \approx B/W_{QW}$: the bimolecular recombination coefficient for a 2D structure)

• For high injection densities: $n^{2D}=p^{2D}$
• *Under steady-state conditions ($dn^{2D}/dt=0$),* ➜ $n^{2D} = \sqrt{\frac{J}{eB^{2D}}} = \sqrt{\frac{JW_{QW}}{eB}}$

• At high injection levels, the Fermi energy will reach the top of the barrier. At that point, $E_F - E_0 = \Delta E_C - E_0$. Using this value, the current density at which the active region overflows is given by

$$J_{overflow} = \left[\frac{m^*}{\pi(h/2\pi)^2}(\Delta E_C - E_o)\right]^2 \frac{eB}{W_{QW}}$$

Saturation of output power due to leakage

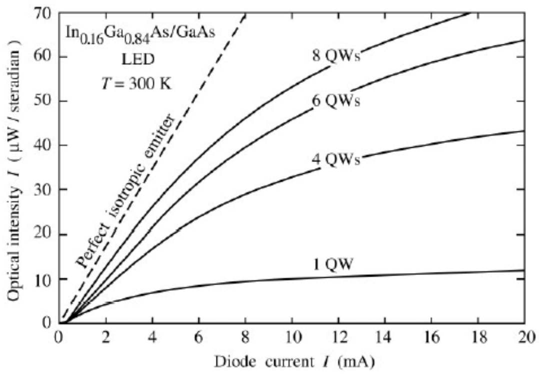


Fig. 4.11. Optical intensity emitted by $In_{0.16}Ga_{0.84}As$ / GaAs LEDs with active regions consisting of 1, 4, 6, and 8 quantum wells and theoretical intensity of a perfect isotropic emitter (dashed line) (after Hunt *et al.*, 1992).

• In order to avoid the carrier overflow, high current LEDs must employ *thick* DH active regions, or *many* QWs of multiple QW (MQW) active regions, or a large injection (contact) area.

Electron blocking layers

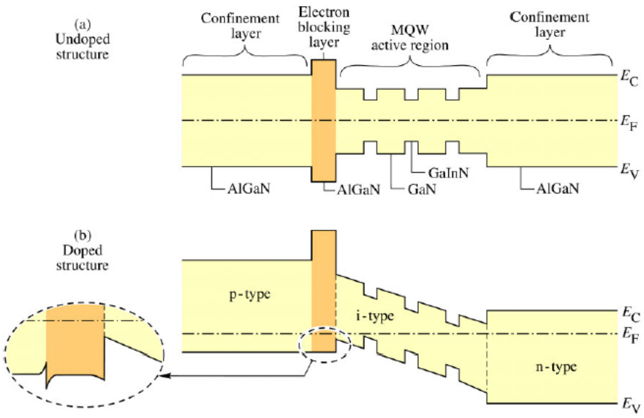


Fig. 4.12. Illustration of an AlGaN current blocking layer in an AlGaN / GaN / GaInN multi-quantum well (MQW) LED structure. (a) Band diagram without doping. (b) Band diagram with doping. The Al content in the electron blocking layer is higher than in the p-type confinement layer.

- **The barrier in the valence band is screened by free carriers so that there is *no barrier* to the flow of *holes* in the p-type confinement layer.**

Diode forward voltage

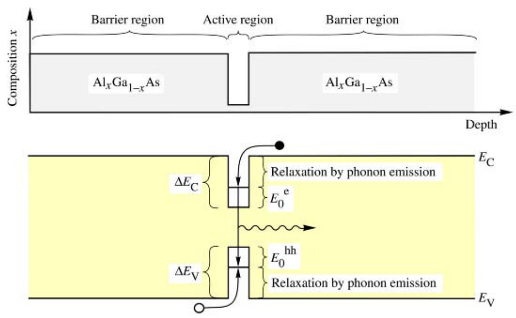


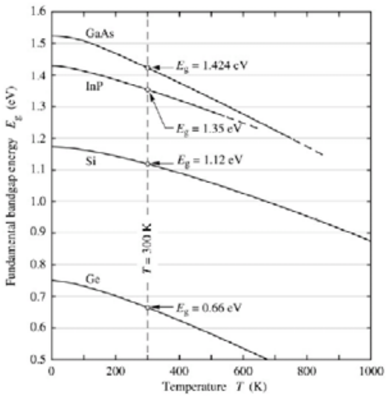
Fig. 4.13. (a) Chemical composition and (b) band diagram of a quantum well structure illustrating the energy loss of carriers as they are captured into the quantum well.

- **The total voltage drop across a forward-biased LED is given by**

$$V = \frac{E_g}{e} + IR_S + \frac{\Delta E_C - E_o}{e} + \frac{\Delta E_V - E_o}{e}$$

- **One finds experimentally that the diode voltage can be *slightly lower than the minimum value* predicted by above Eq'n, i.e. ~ E_g/e**

Temperature dependence of diode voltage



$$E_g = E_g(0K) - \frac{\alpha T^2}{T+\beta}$$

	E_g(0K)	α (10^{-4} $\frac{eV}{K}$)	β (K)
GaAs	1.519	5.41	204
InP	1.425	4.50	327
Si	1.170	4.73	636
Ge	0.744	4.77	235

Fig. 4.14. Fundamental bandgap energy of GaAs, InP, Si, and Ge as a function of temperature. The bandgap energy is approximated by a parabolic equation with the fitting parameters α and β.

- **The temperature dependence of the diode voltage**

$$V(T) = \frac{kT}{e} \ln \frac{I}{Is^*} + \frac{Eg(T)}{e}$$

- **first term : due to the changes of the Fermi level with temperature**
- **The contribution of the first term is generally smaller than the contribution of the second term.**

- **Diode voltage decreases with increasing temperature due to decrease in energy gap and increase in saturation current density.**

Temperature dependence of diode voltage

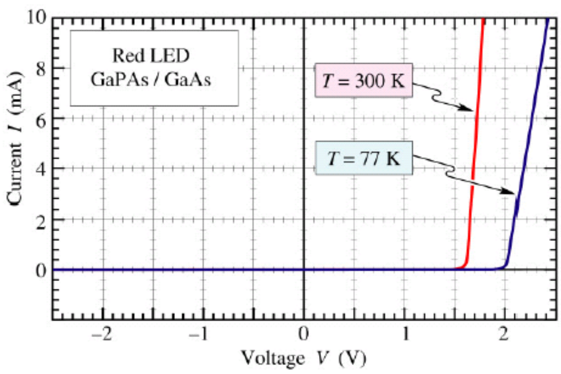


Fig. 4.15. Current-voltage characteristic of a GaAsP / GaAs LED emitting in the red part of the visible spectrum, measured at 77 K and 300 K. The threshold voltages are 2.0 V and 1.6 V, at 77 K and 300 K respectively.

- **Diode forward voltage can be used to assess junction temperature with high accuracy.**

Drive circuits

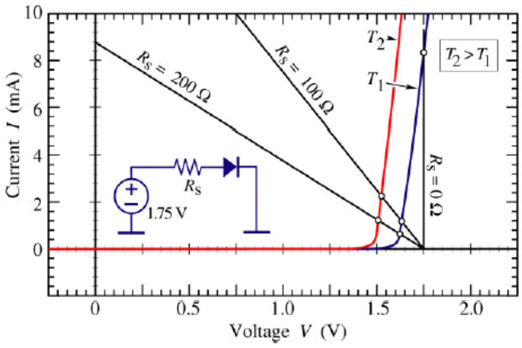


Fig. 4.16. LED drive circuit with series resistance R_S. The intersection between the diode I-Vs and the load lines are the points of operation. Small series resistances result in an increased diode current at high temperatures, thus allowing for compensation of a lower LED radiative efficiency.

- **Constant current-drive circuit**
- **Constant voltage-drive circuit**
- **What are the advantages and disadvantages?**