date: 2023-10-26

Diodes

Why

Diodes are a magical [1] semiconductor device that conduct current in one direction. It's one of the fundamental electronics components, and it's a good idea to understand how they work.

[1] It doesn't stop being magic just because you know how it works. Terry Pratchett, The Wee Free Men

Intrinsic carrier concentration

The intrinsic carrier concentration of silicon, or how many free electrons and holes at a given temperature, is given by

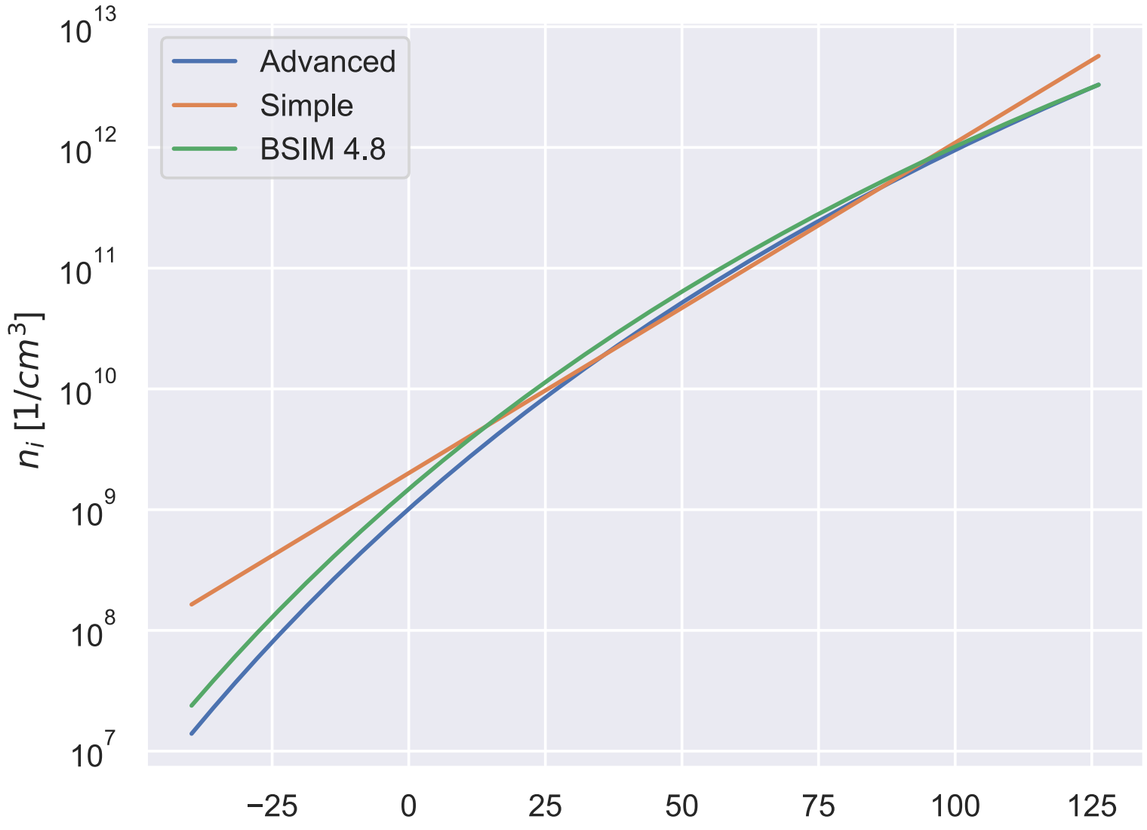
$$n_i = \sqrt{N_c N_v} e^{-\frac{E_g}{2kT}}$$

The density of states are

$$N_c = 2\left[\frac{2\pi kTm_n^*}{h^2}\right]^{3/2} \quad N_v = 2\left[\frac{2\pi kTm_p^*}{h^2}\right]^{3/2}$$

In BSIM 4.8 [@bsim] the intrinsic carrier concentration is

$$n_i = 1.45e10 \frac{TNOM}{300.15} \sqrt{\frac{T}{300.15} \exp^{21.5565981 - \frac{E_g}{2kT}}}$$



Density of states

$$-\frac{\hbar^2}{2m}\nabla^2\psi = E\psi$$

$$m^* = \frac{\hbar^2}{\frac{d^2E}{dk^2}}$$

$$N(dk) = \frac{2}{(2\pi)^p}dk$$

$$N(E)dE = \frac{2}{\pi^2}\frac{m^*}{\hbar^2}^{3/2}E^{1/2}dE$$

$$E(k) = \frac{\hbar^2 k^2}{2m^*}$$

$$f(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$

$$N_e dE = N(E) f(E) dE$$

$$n_e = 2\left(\frac{2\pi m^* kT}{h^2}\right)^{3/2} e^{(E_F - E_C)/kT}$$

For intrinsic silicon at thermal equlibrium, we could write

$$n_0 = 2\left(\frac{2\pi m^* kT}{h^2}\right)^{3/2} e^{-E_g/(2kT)}$$

Doping

The number of electrons and holes in a n-type material is

$$n_n = N_D \ , p_n = \frac{n_i^2}{N_D}$$

and in a p-type material

$$p_p = N_A \ , n_p = \frac{n_i^2}{N_A}$$

PN junctions

Built-in voltage

$$n = \int_{E_C}^{\infty} N(E) f(E) dE$$

$$n_n = e^{E_{F_n}/kT} \int_{E_C}^{\infty} N_n(E) e^{-E/kT} dE$$

$$n_p = e^{E_{F_p}/kT} \int_{E_C}^{\infty} N_p(E) e^{-E/kT} dE$$

$$\frac{n_n}{n_p} = \frac{e^{E_{F_n}/kT}}{e^{E_{F_p}/kT}} = e^{(E_{F_n} - E_{F_p})/kT}$$

$$E_{F_n} - E_{F_p} = q\Phi$$

$$\frac{N_A N_D}{n_i^2} = e^{q\Phi_0/kT}$$

or rearranged to

$$\Phi_0 = \frac{kT}{q} ln \left(\frac{N_A N_D}{n_i^2} \right)$$

Current

$$\frac{p_p}{p_n} = e^{-q\Phi_0/kT}$$

$$\frac{p(-x_{p0})}{p(x_{n0})} = e^{q(V-\Phi_0)/kT}$$

$$\frac{p(x_{n0})}{p_n} = e^{qV/kT}$$

$$\Delta p_n = p(x_{n0}) - p_n = p_n\left(e^{qV/kT} - 1\right)$$

$$J(x_n) = -qD_p\frac{\partial\rho}{\partial x}$$

$$\partial\rho(x_n) = \Delta p_n e^{-x_n/L_p}$$

$$J(0) = q\frac{D_p}{L_p}p_n\left(e^{qV/kT} - 1\right)$$

$$I = qAn_i^2 \left(\frac{1}{N_A} \frac{D_n}{L_n} + \frac{1}{N_D} \frac{D_p}{L_p} \right) \left[e^{qV/kT} - 1 \right]$$

Forward voltage temperature dependence

$$V_D = V_T \ln\left(\frac{I_D}{I_S}\right)$$

$$V_D = V_T \ln I_D - V_T \ln I_S$$

$$\ln I_S = 2 \ln n_i + \ln Aq \left(\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D} \right)$$

$$n_i = \sqrt{B_c B_v} T^{3/2} e^{\frac{-E_g}{2kT}}$$

$$B_c = 2 \left[\frac{2\pi k m_n^*}{h^2} \right]^{3/2} \quad B_v = 2 \left[\frac{2\pi k m_p^*}{h^2} \right]^{3/2}$$

$$2 \ln n_i = 2 \ln \sqrt{B_c B_v} + 3 \ln T - \frac{V_G}{V_T}$$

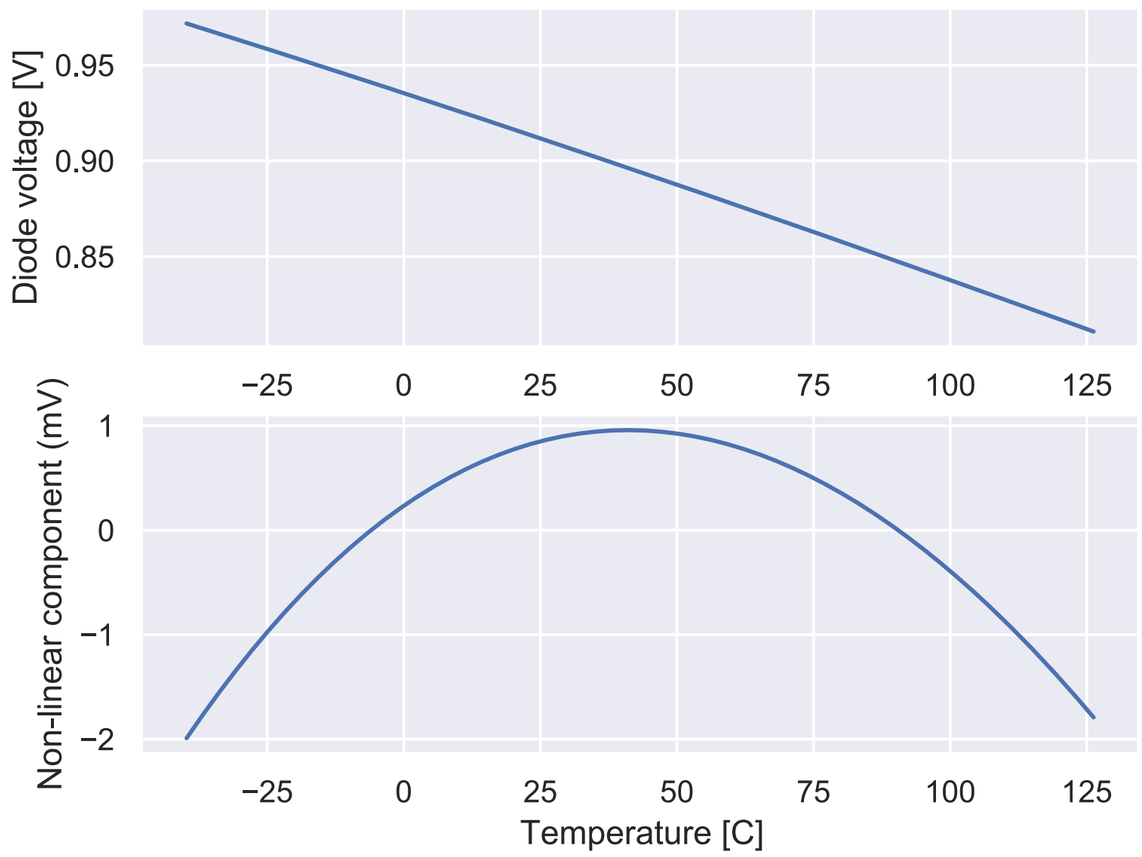
$$V_D = \frac{kT}{q} (\ell - 3 \ln T) + V_G$$

$$\ell = \ln I_D - \ln \left(Aq \frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D} \right) - 2 \ln \sqrt{B_c B_v}$$

From equations above we can see that at 0 K, we expect the diode voltage to be equal to the bandgap of silicon. Diodes don't work at 0 K though.

Although it's not trivial to see that the diode voltage has a negative temperature coefficient, if you do compute it as in vd.py, then you'll see it decreases.

The slope of the diode voltage can be seen to depend on the area, the current, doping, diffusion constant, diffusion length and the effective masses.

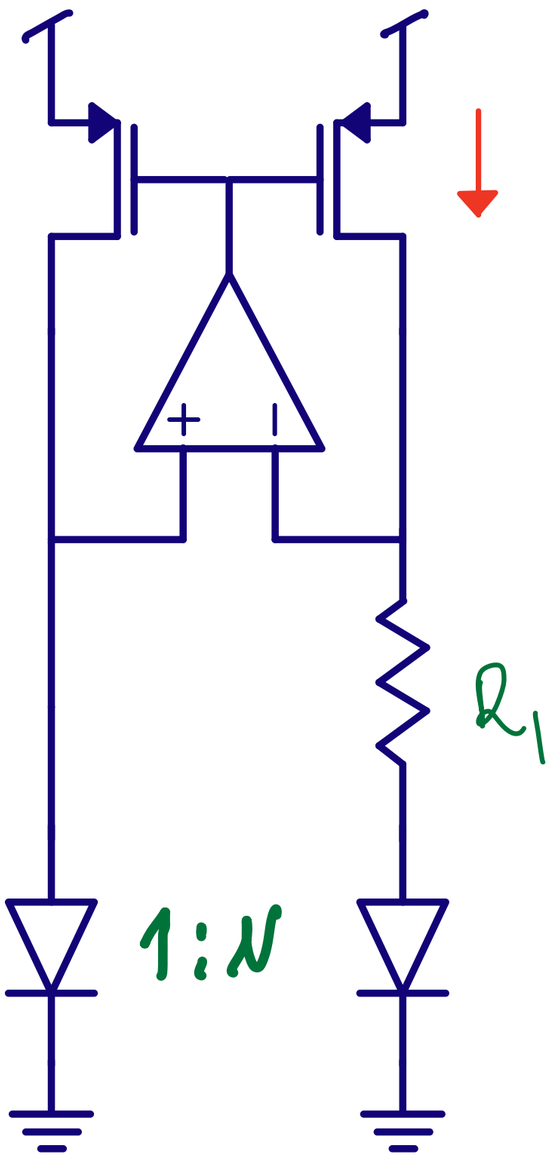


Current proportional to temperature

$$I_S e^{\frac{qV_{D1}}{kT}} = N I_S e^{\frac{qV_{D2}}{kT}}$$

Taking logarithm of both sides, and rearranging, we see that

$$V_{D1} - V_{D2} = \frac{kT}{q} \ln N$$



Thanks!

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