TFE4152 - Lecture 3

PN Junctions

Source

Goal for today

- Refresh what you should aready know about PN
- Carrier concentrations
- Built in voltage
- Reverse bias
- Forward bias
- Small signal models

Want to go deeper

Feynman lectures on physics

MIT 8.04 Quantum Mechanics I

MIT 8.05 Quantum Mechanics II

ieeexplore.ieee.org

Introduction to ieeexplore

$$q = 1.6 \times 10^{-19}\,[C]$$
$$k = 1.38 \times 10^{-23}\,[J/K]$$

$$\mu_0 = \frac{2\alpha}{q^2}\frac{h}{c} = 1.26 \times 10^{-6}\,[H/m]$$

$$\epsilon_0 = \frac{1}{\mu_0 c^2} = 8.854 \times 10^{-12}\,[F/m]$$

where q is unit charge, k is Boltzmann's constant, h is Plancks constant, c is speed of light and alpha is the fine structure constant

```
from scipy import constants
import numpy as np
h = constants.physical_constants["Planck constant"][0]
k = constants.Boltzmann
q = constants.physical_constants["elementary charge"][0]
c = constants.c
alpha = constants.physical_constants["fine-structure constant"][0]

mu = 2* alpha*h/(c*np.power(q,2))
print("Permiability of free space = %g" % mu)

epsilon = 1/(mu* c**2)
print("Permitivity of free space = %g" % epsilon)
```

```
wulff@lectures$  python l3_constants.py
Permiability of free space = 1.25664e-06
Permitivity of free space = 8.85419e-12
```

Computer models

http://bsim.berkeley.edu/models/bsim4/

http://bsim.berkeley.edu/BSIM4/BSIM480.zip

$n_i \approx 1 \times 10^{16} [1/m^3] = 1 \times 10^{10} [1/cm^3]$ at 300 K

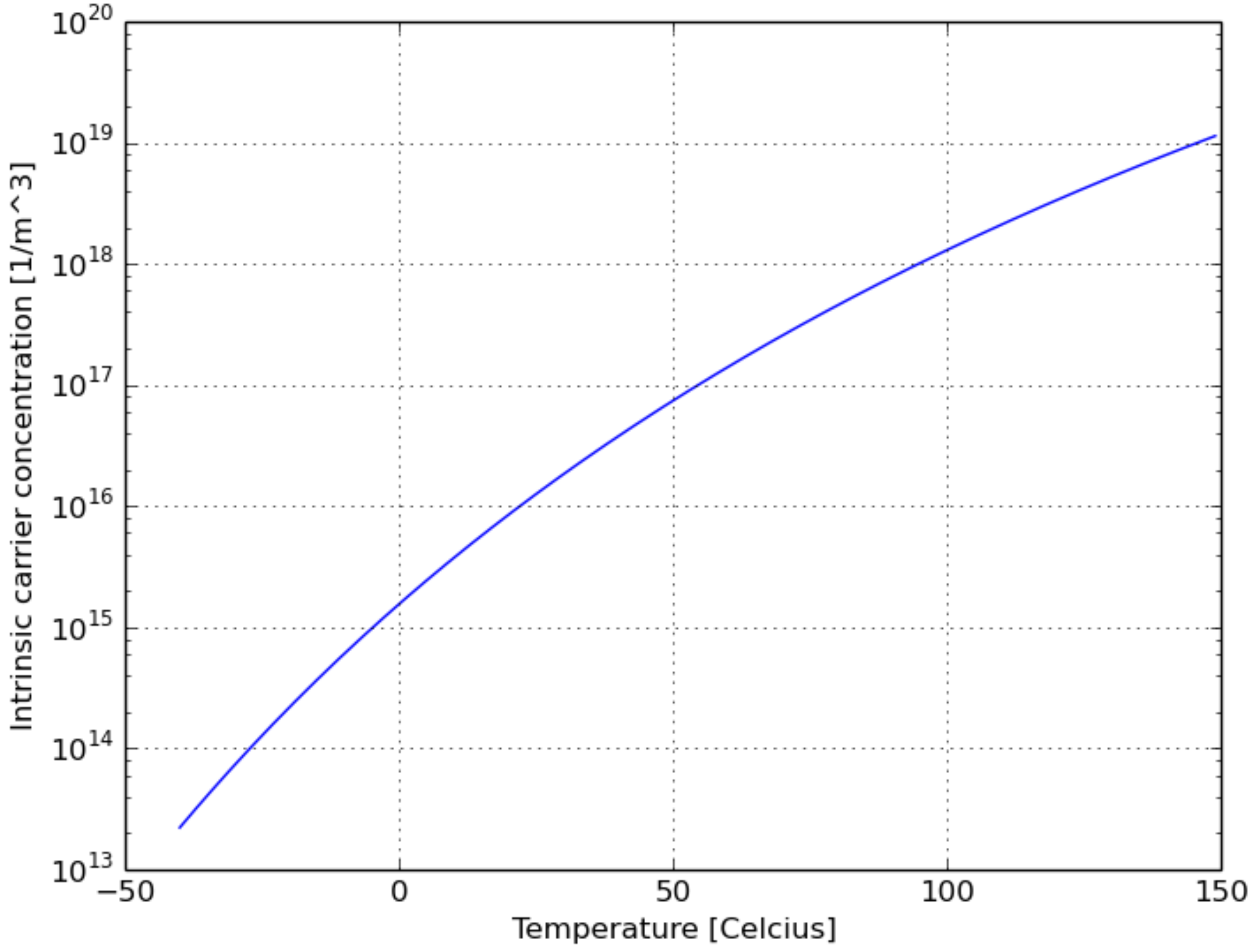
$$n_i^2 = n_0 p_0$$

$$n_i = \sqrt{N_C N_V} e^{\frac{-E_g}{2kT}}$$

$$N_C = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

$$N_V = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$$

https://github.com/wulffern/dic2021/blob/main/2021-07-08_diodes/intrinsic.py



Solid state physics:

$$n_i = \sqrt{N_C N_V} e^{\frac{-E_g}{2kT}}$$

BSIM 4.8, Intrinsic carrier concentration (page 122)

$$n_i = 1.45e10 \frac{TNOM}{300.15} \sqrt{\frac{T}{300.15}} exp \left[21.5565981 - \frac{qE_g(TNOM)}{2k_b T} \right]$$

How do charge carriers in intrinsic silicon move?

Drift and Diffusion

Group → / Period ↓	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

n-type

$$n_n \approx N_D$$

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

p-type

$$p_p \approx N_A$$

$$p_n = \frac{n_i^2}{N_A}$$

PN junctions

Symbol

How carriers move

Carrier distribution

Depletion zone

Current characteristics

Avalanche

Built in voltage

$$\frac{n_n}{n_p} = e^{\frac{q\Phi_0}{kT}}$$

where $q\Phi_0$ is the energy required to climb the potential barrier, kT is the thermal energy, and n_n and n_p are the electron concentrations in the n-type and p-type.

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

$$V_T = \frac{kT}{q}$$

Depletion widths

$$x_n = \left(\frac{2K_s\epsilon_0\Phi_0}{q}\left[1 + \frac{V_R}{\Phi_0}\right]\frac{N_A}{N_D(N_A+N_D)}\right)^{l_1}$$

where, $K_s = 11.8$ is the relative perimittivity of silicon, and $l_1 \approx 0.5$ to almost unity, depending on the doping profile

For x_p replace $N_A = N_D, N_D = N_A$

Junction capacitance of reversed bias junctions

CJM, single sided diode:

$$C_j = C_{j0}\left[1 + \frac{V_R}{\Phi_0}\right]^{-1/2}$$

BSIM 4.8:

$$C_{jbs} = CJS(T)\left(1 - \frac{V_{BS}}{PBS(T)}\right)^{-MJS}$$

$$CJS(T) = CJS(TNOM) + TCJ(T - TNOM)$$

$$PBS(T) = PBS(TNOM) - TPB(T - TNOM)$$

Small-Signal model under forward bias

Large signal current $I_D = I_s(e^{V_D/V_T} - 1)$

Small signal conductance $g_d = \frac{dI_D}{dV_D} = \frac{I_D}{V_T} = \frac{1}{r_d}$

Capacitance of forward bias

C_j is similar (but not same) as reverse bias (page 106 in BSIM 4.8)

Additional term due to the increased minority carrier on the "other side"

$$C_d = \tau_T \frac{I_D}{V_T} = \frac{\tau_T}{r_d}$$

$$C_T = C_j + C_d$$

where τ_T is the transit time of the diode

Thanks!