NE 205: Semiconductor Devices and IC Technology

Homework 2

Name : Gaurav Somani

SR No. : 16082

1)

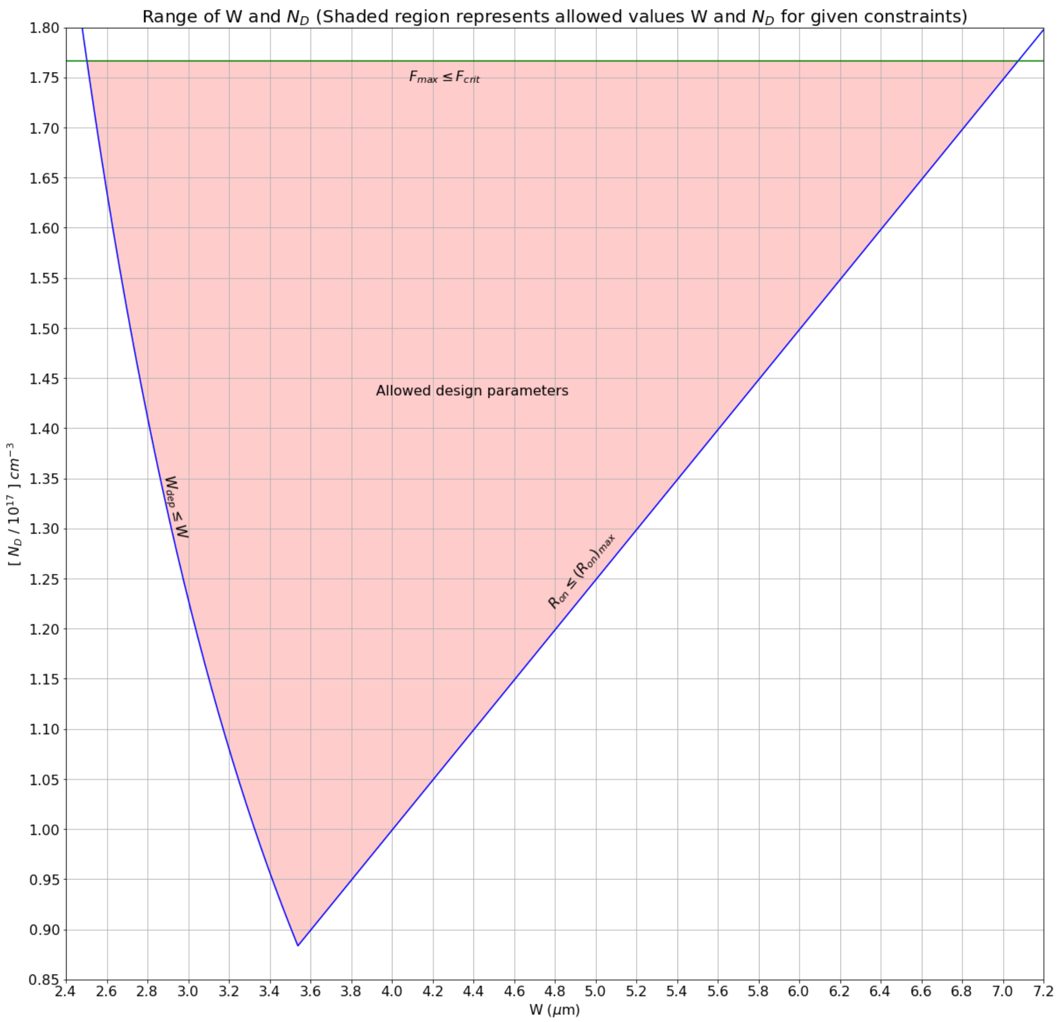
$$R_{on} = \frac{W}{q\mu N_D}$$

$$W_{dep} \approx \sqrt{\frac{2\epsilon_0\epsilon_r(\phi_B + V_R)}{qN_D}}$$

$$F_{max} \approx \sqrt{\frac{2qN_D(\phi_B + V_R)}{\epsilon_0\epsilon_r}}$$

$$\boxed{\begin{aligned} &(R_{on})_{max} = 0.1m\Omega - cm^2 \\ &F_{crit} = 8MV/cm \\ &(V_R)_{max} = 1000V \\ &\mu = 250\, cm^2/Vs \\ &\epsilon_r = 10 \\ &\phi_B = 1\, V \\ &R_{on} \leq (R_{on})_{max} \\ &F_{max} \leq F_{crit} \;\; at \;\; V_R = (V_R)_{max} \\ &W_{dep} \leq W \;\; at \;\; V_R = (V_R)_{max} \end{aligned}} \tag{1}$$

$$\implies \boxed{\frac{\epsilon_0\epsilon_r(F_{crit})^2}{2q(\phi_B + (V_R)_{max})} \geq N_D \geq max(\frac{2\epsilon_0\epsilon_r(\phi_B + (V_R)_{max})}{qW^2}, \frac{W}{q\mu(R_{on})_{max}})} \tag{1.1}$$



From above plot, designed parameters are bounded by the rectangle defined by these parameters.

$$0.88 \times 10^{17} cm^{-3} \leq N_d \leq 1.77 \times 10^{17} cm^{-3}$$

$$2.5\ \mu m \leq W \leq 7.1\ \mu m$$

2)

$$\boxed{\begin{aligned}&N_D = 10^{17} cm^{-3}\\&N_A = 2\times 10^{17} cm^{-3}\\&D_n = 40\, cm^2/s\\&D_p = 10\, cm^2/s\\&\tau_n = \tau_p = 10^{-7} s\\&\tau_{dep} = 10^{-8} s\\&A = 10^{-4} cm^2\\&F_{breakdown} = 300\, kV/cm\\&\epsilon_r = 11.7\\&T = 300K\end{aligned}} \tag{2}$$

$$I_o = qAn_i^2\left(\sqrt{\frac{D_p}{\tau_p}}\frac{1}{N_D} + \sqrt{\frac{D_n}{\tau_n}}\frac{1}{N_A}\right)$$

$$I_{ideal} = I_o(e^{\frac{qV}{k_BT}} - 1)$$

$$W_{dep} = \sqrt{\frac{2\epsilon_0\epsilon_r(V_{bi}-V)}{q}\left(\frac{1}{N_D} + \frac{1}{N_A}\right)}$$

$$|I_{gen}| \approx \frac{qAn_iW_{dep}}{2\tau_{dep}}$$

$$I_{rec} \approx \frac{qAn_iW_{dep}}{2\tau_{dep}}e^{\frac{qV}{k_BT}} \approx |I_{gen}|\, e^{\frac{qV}{k_BT}}$$

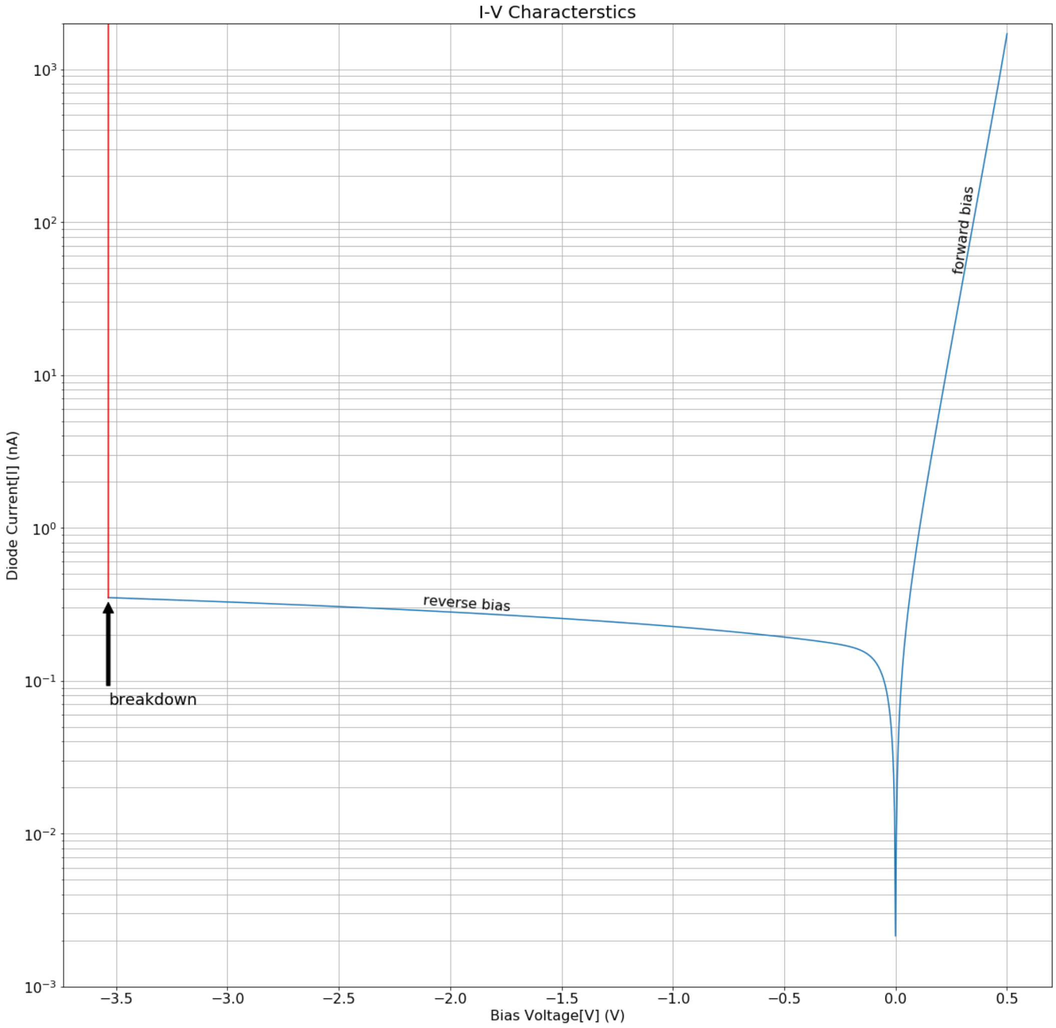
$$I = I_{ideal} + I_{rec} - |I_{gen}|$$

$$\implies \boxed{I \approx I_o(e^{\frac{qV}{k_BT}} - 1) + I_{gen}(e^{\frac{qV}{2k_BT}} - 1)} \tag{2.1}$$

$$\boxed{F_{max} = \sqrt{\frac{2q(V_{bi}+V_R)}{\epsilon_0\epsilon_r}\frac{N_AN_D}{N_A+N_D}}} \tag{2.2}$$

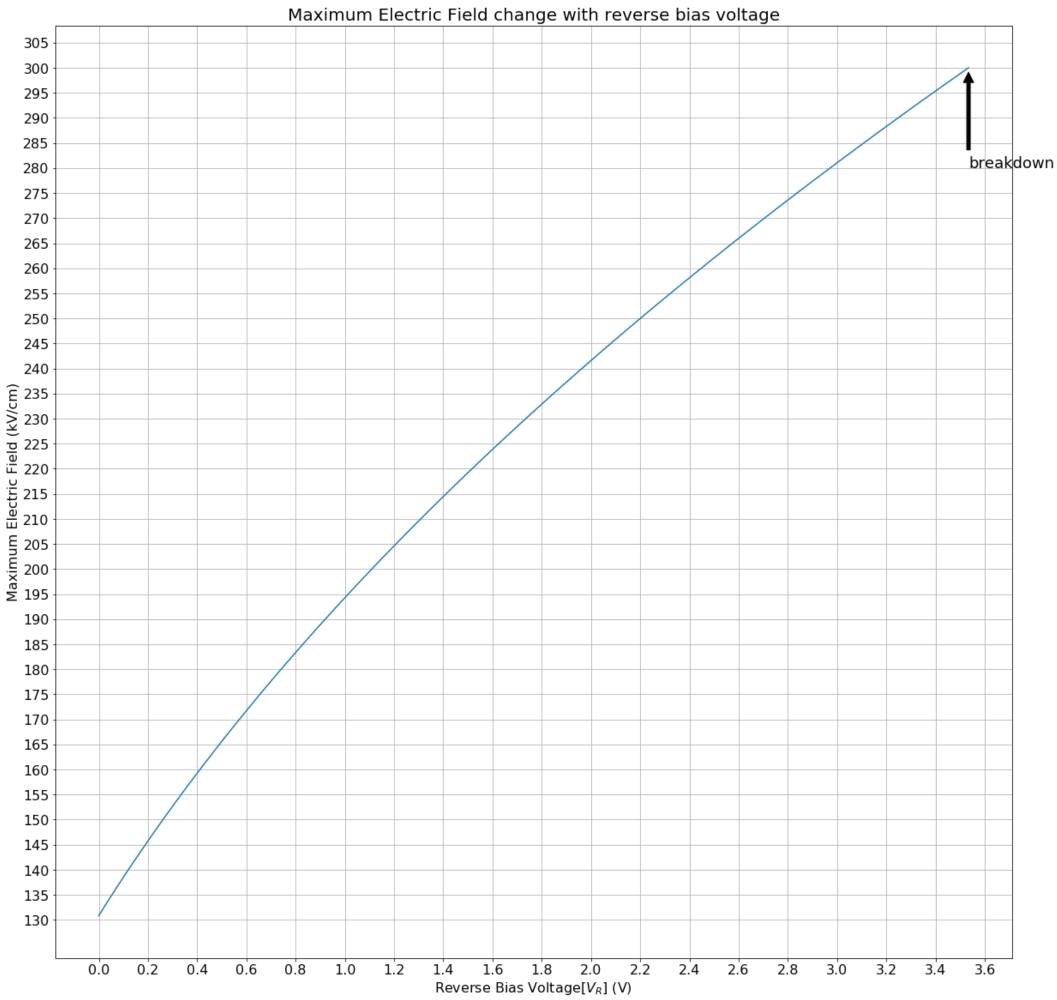
$$\implies \boxed{(V_R)_{breakdown} = \frac{F_{breakdown}^2\epsilon_0\epsilon_r}{2q}\left(\frac{1}{N_D} + \frac{1}{N_A}\right) - V_{bi}} \tag{2.3}$$

2(a)



I-V Characterstics
Diode Current[I] (nA)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
0.5
Bias Voltage[V] (V)
forward bias
reverse bias
breakdown

2(b)



Breakdown Voltage ≈ 3.5 V

3)

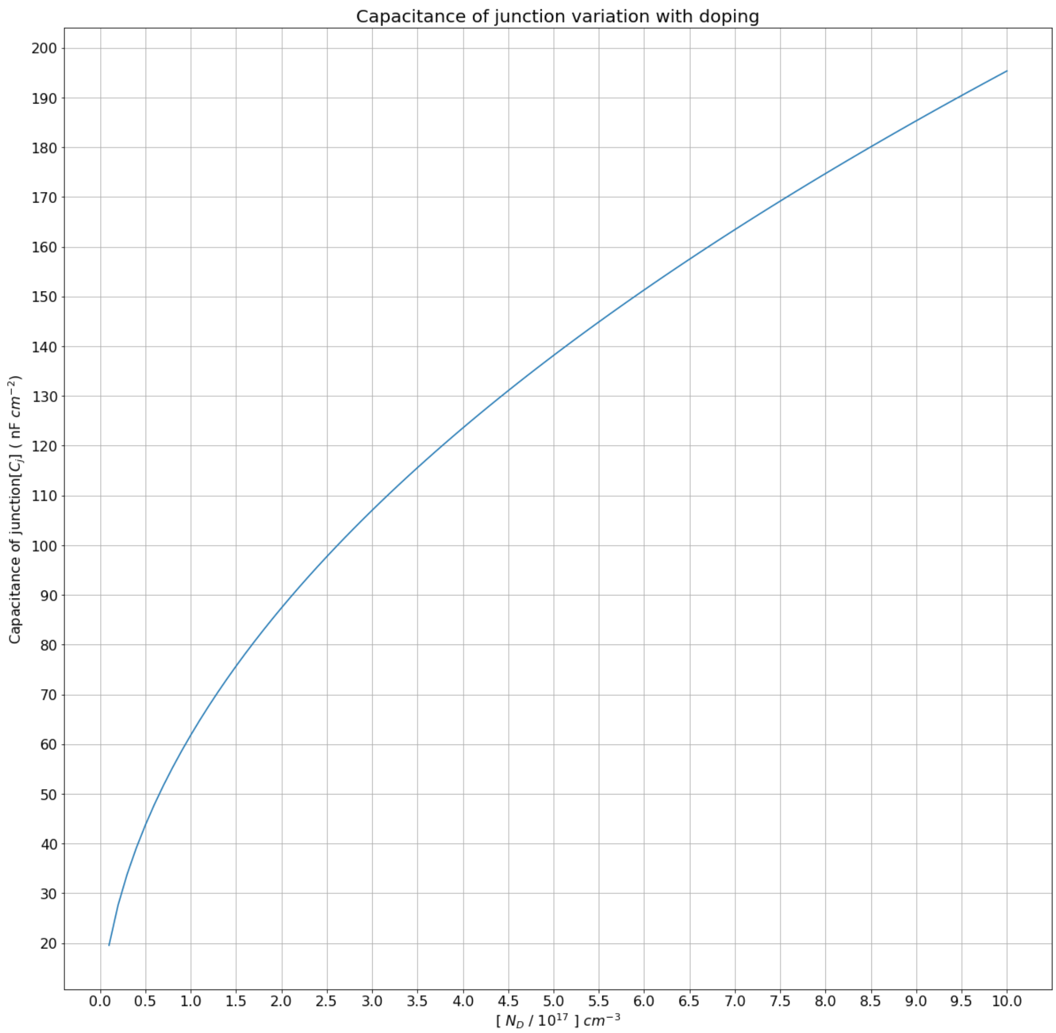
$$\boxed{\begin{aligned}&\phi_B = 0.35\,V\\ &N_C = 3.2\times10^{19}cm^{-3}\\ &V_R = 2\,V\\ &\epsilon_r = 11.7\\ &T = 300K\end{aligned}} \tag{3}$$

$$\boxed{V_{bi} = \phi_B + \frac{k_BT}{q}\;ln\frac{N_D}{N_C} - \frac{k_BT}{q} \qquad (-\frac{k_BT}{q}\;accounting\;for\;Gummel\;correction)} \tag{3.1}$$

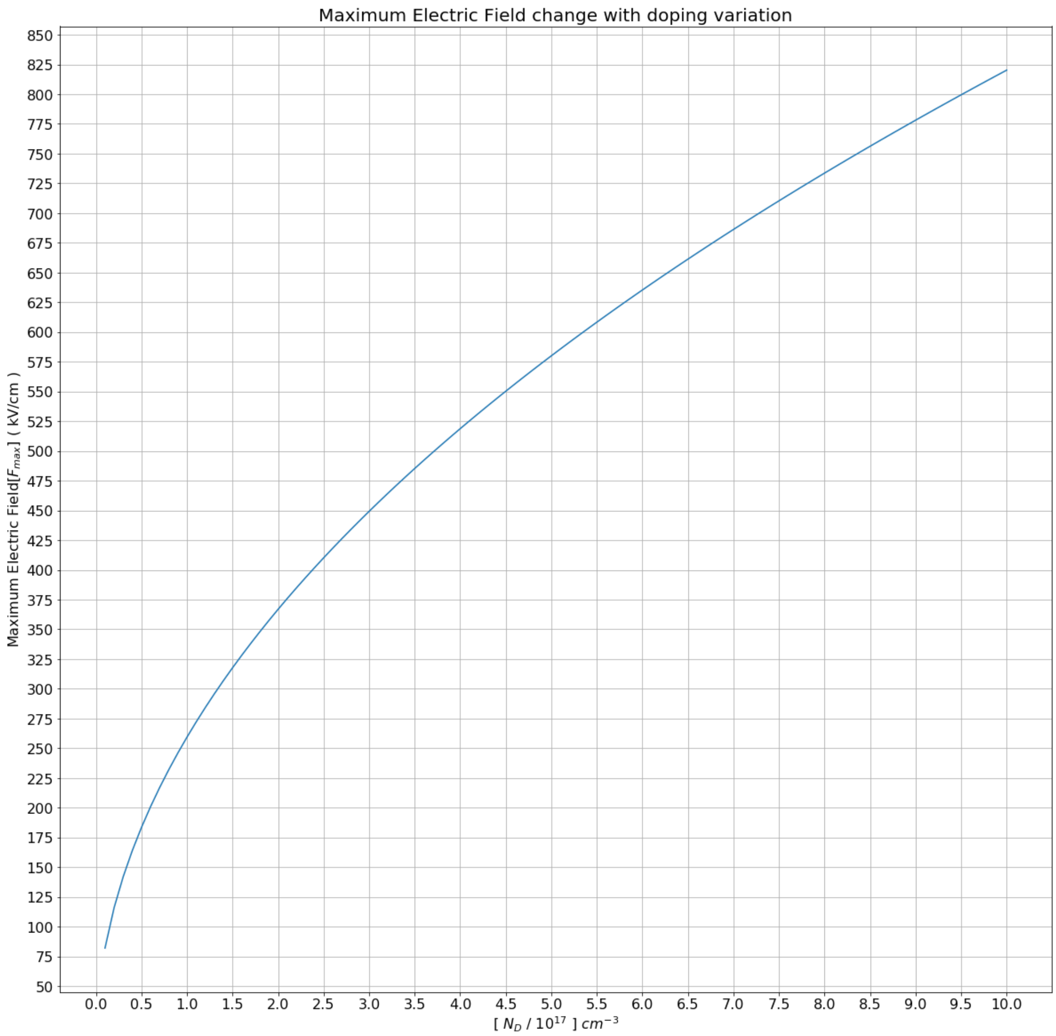
$$\boxed{F_{max} = \sqrt{\frac{2qN_D(V_{bi}+V_R)}{\epsilon_0\epsilon_r}}} \tag{3.2}$$

$$W_{dep} = \sqrt{\frac{2\epsilon_0\epsilon_r(V_{bi}+V_R)}{qN_D}}$$

$$\implies \boxed{C_j = \frac{\epsilon_0\epsilon_r}{W_{dep}} = \sqrt{\frac{q\epsilon_0\epsilon_r N_D}{2(V_{bi}+V_R)}}} \tag{3.3}$$



Capacitance of junction variation with doping
Capacitance of junction[C_j] (nF cm^{-2})
[N_D / 10^{17}] cm^{-3}


Maximum Electric Field change with doping variation
Maximum Electric Field[F_{max}] (kV/cm)
[N_D / 10^{17}] cm^{-3}
850
825
800
775
750
725
700
675
650
625
600
575
550
525
500
475
450
425
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0

4)

$$\boxed{\begin{array}{l} N_D = 10^{17} cm^{-3} \\ N_C = 5 \times 10^{17} cm^{-3} \\ E_C - E_A = 0.3\, eV \\ E_C - E_D = 0.5\, eV \\ \epsilon_r = 12.9 \\ \sigma_A = \sigma_D = \sigma \;\; (Surface\;\; density\;\; of\;\; each\;\; state) \end{array}} \tag{4}$$

$$\sigma_{A^-} = \frac{\sigma_A}{1 + 4\, e^{\frac{(E_A - E_F)_{surface}}{k_B T}}}$$

$$\sigma_{D^+} = \frac{\sigma_D}{1 + 2\, e^{\frac{(E_F - E_D)_{surface}}{k_B T}}}$$

$$q(\sigma_{A^-} - \sigma_{D^+}) = q N_D W_{dep} \;\; (Charge\;\; balance\;\; assuming\;\; complete\;\; depletion$$

$$\implies q\left(\frac{\sigma}{1 + 4\, e^{\frac{(E_A - E_F)_{surface}}{k_B T}}} - \frac{\sigma}{1 + 2\, e^{\frac{(E_F - E_D)_{surface}}{k_B T}}}\right) = \sqrt{2 N_D \epsilon_0 \epsilon_r ((E_F - E_C)_{bulk} - (E_F - E_C)_{surface}}$$

$$\boxed{(E_C - E_F)_{bulk} = -k_B T\left(\; ln\left(\frac{N_D}{N_C}\right) + \frac{1}{\sqrt{8}} \frac{N_D}{N_C}\right) \qquad (Joyce - Dixon\;\; Approximation)} \tag{4.$$

$$\boxed{L_D = \frac{1}{q} \sqrt{\frac{\epsilon_0 \epsilon_r k_B T}{N_D}}} \tag{4.2}$$

$$\boxed{W_{dep} = \frac{1}{q} \sqrt{\frac{2 \epsilon_0 \epsilon_r ((E_C - E_F)_{surface} - (E_C - E_F)_{bulk})}{N_D}}} \tag{4.3}$$

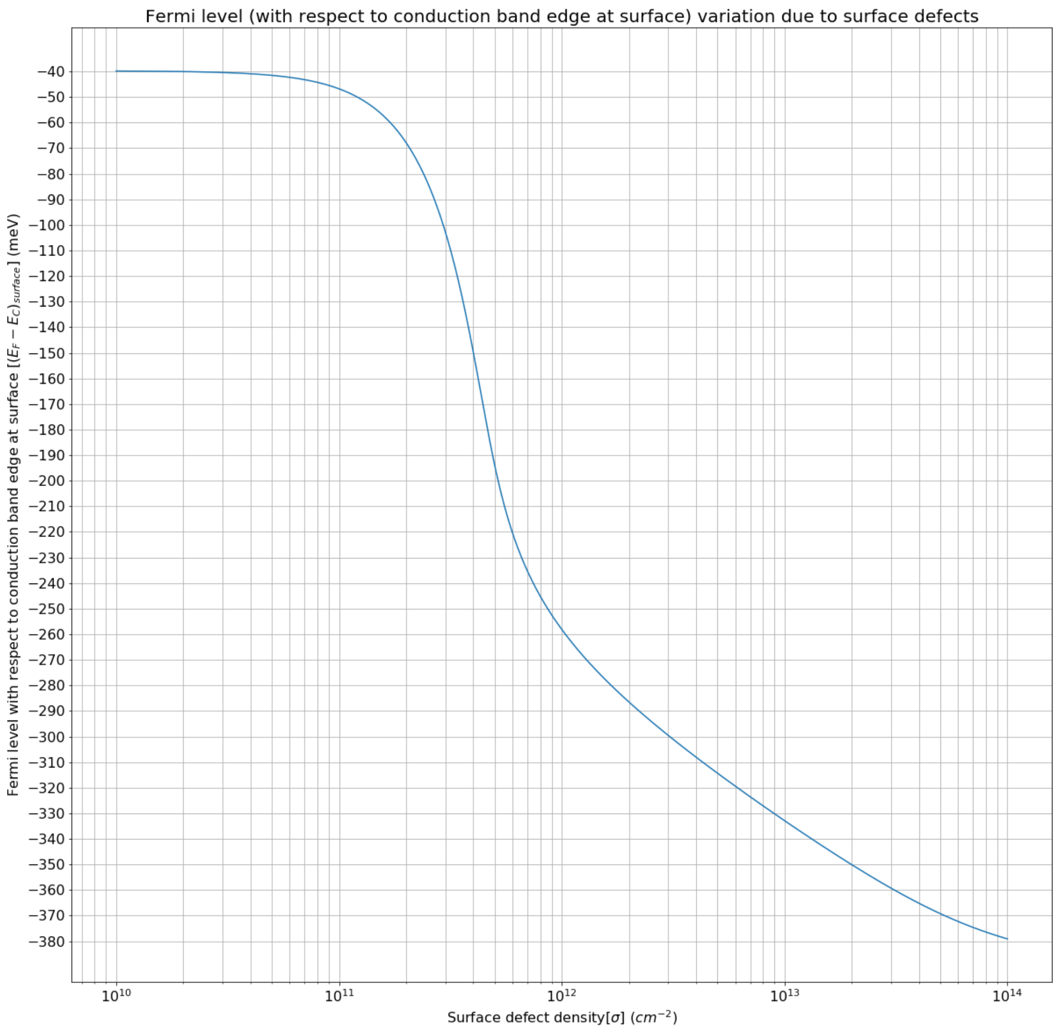
$$\implies q\left(\frac{\sigma}{1 + 4\, e^{\frac{(E_A - E_F)_{surface}}{k_B T}}} - \frac{\sigma}{1 + 2\, e^{\frac{(E_F - E_D)_{surface}}{k_B T}}}\right) = \sqrt{2 N_D \epsilon_0 \epsilon_r ((E_C - E_F)_{surface} - (E_C - E_F)_{bulk}}$$

$$\implies \boxed{\begin{array}{l} q\sigma\left(\dfrac{1}{1 + 4e^{\frac{-(E_C - E_A)_{surface} + (E_C - E_F)_{surface}}{k_B T}}} - \dfrac{1}{1 + 2e^{\frac{(E_C - E_D)_{surface} - (E_C - E_F)_{surface}}{k_B T}}}\right) \\ \qquad = \sqrt{2 N_D \epsilon_0 \epsilon_r ((E_C - E_F)_{surface} - (E_C - E_F)_{bulk})} \end{array}} \tag{4.4}$$

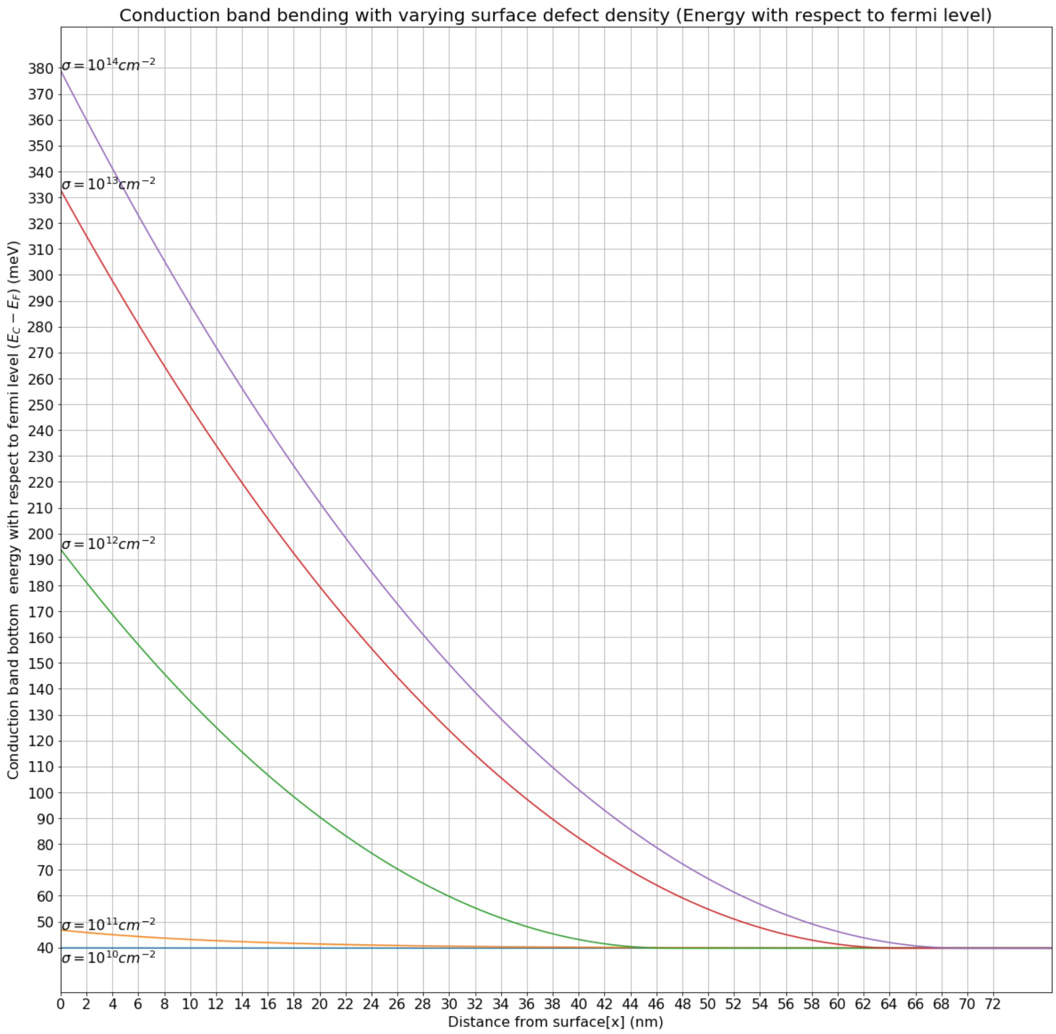
Using (4.1) and (4.4), $(E_C - E_F)_{surface}$ can be calculated by bisection method for a paticular σ.

Band bending (conduction band edge) in depletion region can be approximated as

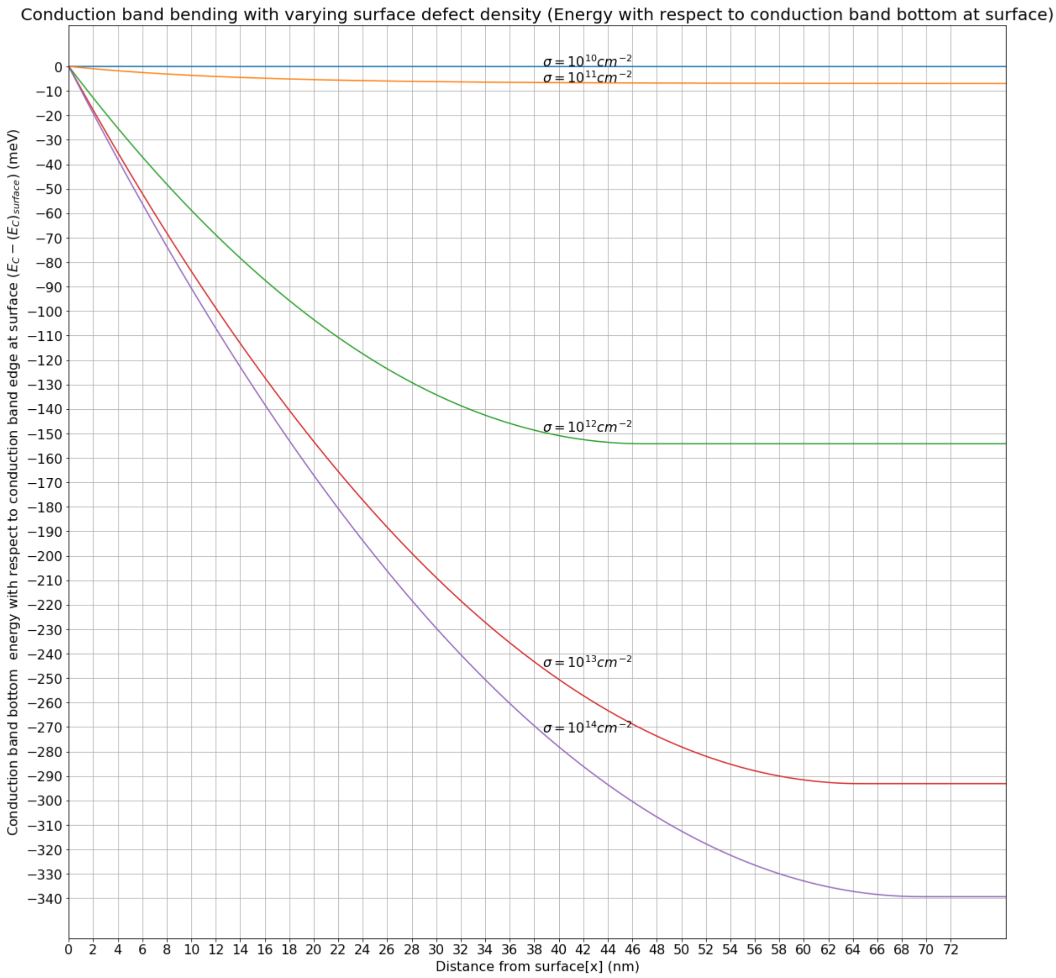
$$\boxed{\begin{array}{l} E_C - E_F = (E_C - E_F)_{bulk} + \dfrac{q^2 (x - W_{dep})^2 N_D}{2 \epsilon_0 \epsilon_r} \\ \qquad\qquad where\;\; 0 \leq x \leq W_{dep} \\ when\; (E_C - E_F) \;\; ... \;\; - (E_C - E_F);\; ... > 3k_B T \end{array}} \tag{4.5a}$$



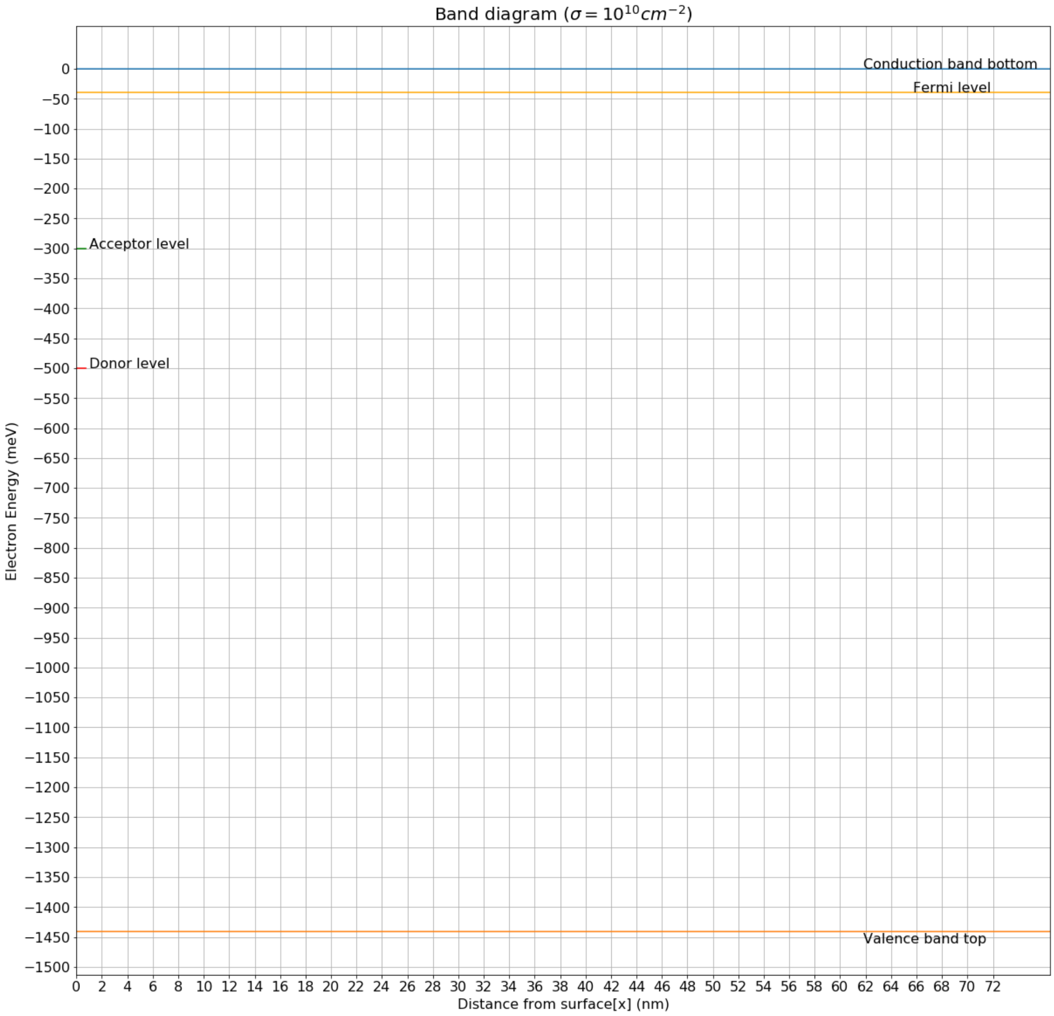
Fermi level (with respect to conduction band edge at surface) variation due to surface defects
Fermi level with respect to conduction band edge at surface [$(E_F - E_C)_{surface}$] (meV)
Surface defect density[σ] (cm^{-2})
−40
−50
−60
−70
−80
−90
−100
−110
−120
−130
−140
−150
−160
−170
−180
−190
−200
−210
−220
−230
−240
−250
−260
−270
−280
−290
−300
−310
−320
−330
−340
−350
−360
−370
−380
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}



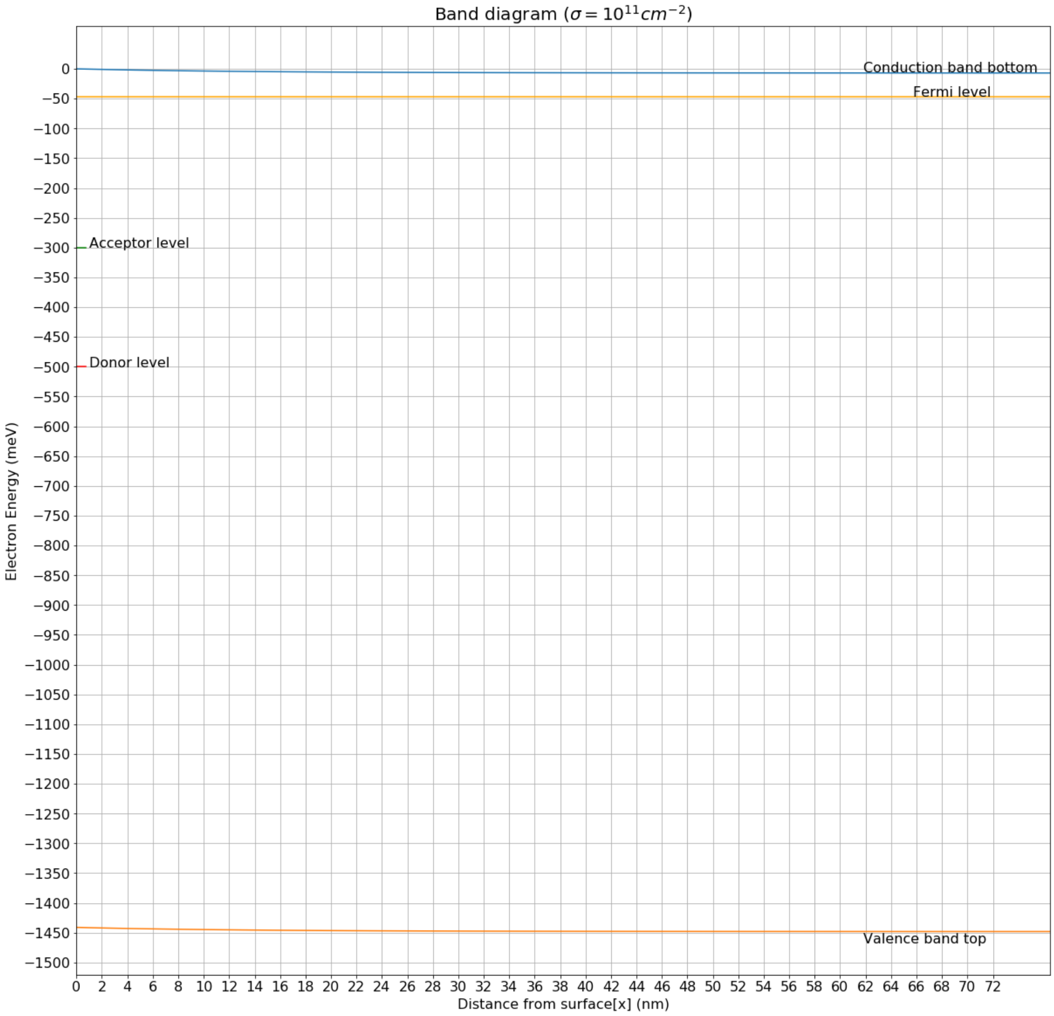
Conduction band bending with varying surface defect density (Energy with respect to fermi level)
$\sigma = 10^{14} cm^{-2}$
$\sigma = 10^{13} cm^{-2}$
$\sigma = 10^{12} cm^{-2}$
$\sigma = 10^{11} cm^{-2}$
$\sigma = 10^{10} cm^{-2}$
Conduction band bottom energy with respect to fermi level ($E_C - E_F$) (meV)
Distance from surface[x] (nm)



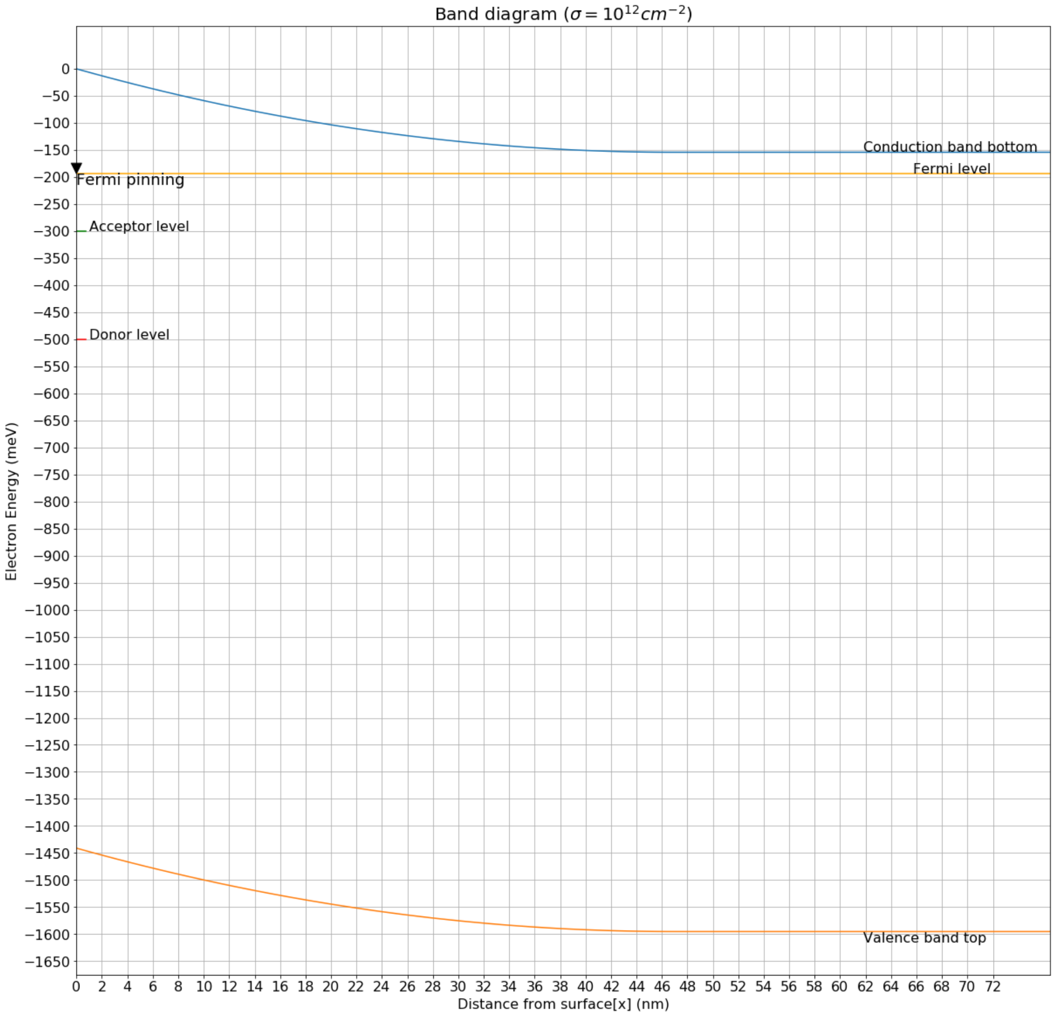
Conduction band bending with varying surface defect density (Energy with respect to conduction band bottom at surface)
$\sigma = 10^{10} cm^{-2}$
$\sigma = 10^{11} cm^{-2}$
$\sigma = 10^{12} cm^{-2}$
$\sigma = 10^{13} cm^{-2}$
$\sigma = 10^{14} cm^{-2}$
Conduction band bottom energy with respect to conduction band edge at surface $(E_C - (E_C)_{surface})$ (meV)
Distance from surface[x] (nm)

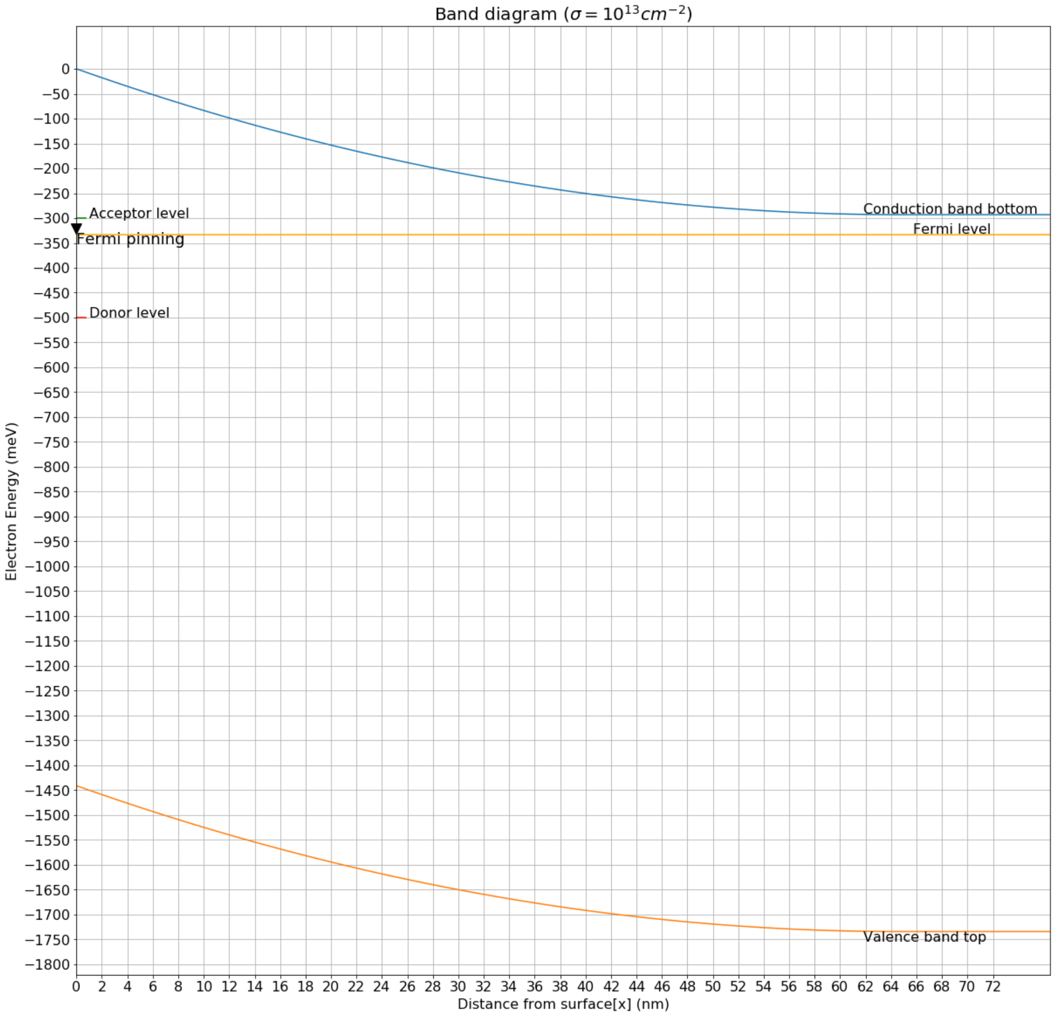


Band diagram ($\sigma = 10^{10} cm^{-2}$)
Conduction band bottom
Fermi level
Acceptor level
Donor level
Valence band top
Electron Energy (meV)
Distance from surface[x] (nm)

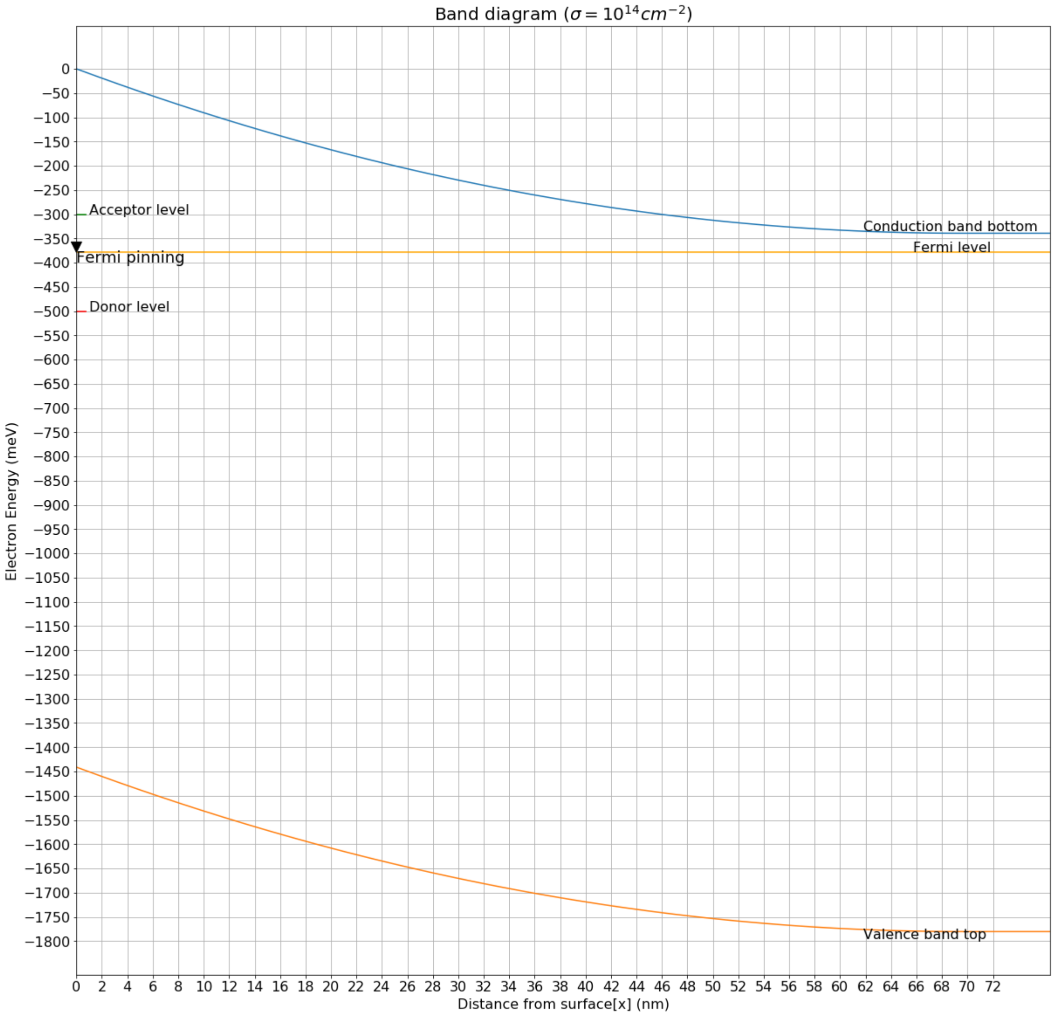


Band diagram ($\sigma = 10^{11} cm^{-2}$)
Conduction band bottom
Fermi level
Acceptor level
Donor level
Valence band top
Electron Energy (meV)
Distance from surface[x] (nm)
0
−50
−100
−150
−200
−250
−300
−350
−400
−450
−500
−550
−600
−650
−700
−750
−800
−850
−900
−950
−1000
−1050
−1100
−1150
−1200
−1250
−1300
−1350
−1400
−1450
−1500
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72


Band diagram ($\sigma = 10^{12} cm^{-2}$)
Electron Energy (meV)
Distance from surface[x] (nm)
Conduction band bottom
Fermi level
Fermi pinning
Acceptor level
Donor level
Valence band top



Band diagram ($\sigma = 10^{13} cm^{-2}$)
Acceptor level
Fermi pinning
Donor level
Conduction band bottom
Fermi level
Valence band top
Electron Energy (meV)
Distance from surface[x] (nm)



Significant fermi pinning is observed when σ**(surface defect density)** $\geq 10^{12} cm^{-2}$. It becomes increasingly effective as **(surface defect density)**σ increases from $10^{12} cm^{-2}$ to $10^{14} cm^{-2}$.

5)

For **p+/n junction** in a long diode,

$$I(t) = \frac{d}{dt}Q_p(t) + \frac{Q_p(t)}{\tau_p}$$

Multiplying both sides by $e^{\frac{t}{\tau_p}}$,

$$I(t)e^{\frac{t}{\tau_p}} = e^{\frac{t}{\tau_p}}\frac{d}{dt}Q_p(t) + \frac{e^{\frac{t}{\tau_p}}}{\tau_p}Q_p(t)$$

$$\implies I(t)e^{\frac{t}{\tau_p}} = \frac{d}{dt}(e^{\frac{t}{\tau_p}}Q_p(t))$$

$$\implies \int_0^t I(t')e^{\frac{t'}{\tau_p}}dt' = \int_0^t d(e^{\frac{t'}{\tau_p}}Q_p(t'))$$

$$\implies \int_0^t I(t')e^{\frac{t'}{\tau_p}}dt' = e^{\frac{t}{\tau_p}}Q_p(t) - Q_p(0)$$

$$\implies \boxed{Q_p(t) = \left(\ Q_p(0) + \int_0^t I(t')e^{\frac{t'}{\tau_p}}dt'\ \right)\ e^{\frac{-t}{\tau_p}}} \tag{5.1}$$

$$I_{steady} = \frac{Q_p}{\tau_p}\quad since\quad \frac{d}{dt}Q_p(t) = 0$$

$$\implies I(0) = \frac{Q_p(0)}{\tau_p}$$

$$\implies \boxed{Q_p(0) = I(0^-)\tau_p} \tag{5.2}$$

Using (5.1) and (5.2),

$$\boxed{Q_p(t) = \left(\ I(0^-)\tau_p + \int_0^t I(t')e^{\frac{t'}{\tau_p}}dt'\ \right)\ e^{\frac{-t}{\tau_p}}} \tag{5.3}$$

Stored charge $Q_p(t)$ can be calclated as total charge of excess holes in n-region of diode. Here, x=0 represents the end of depletion adjacent to n-region of diode and x > 0 in n-region of diode.

$$Q_p(t) = \int_0^\infty qA\Delta p_n(x,t)\ dx$$

$$\implies Q_p(t) = \int_0^\infty qA\Delta p_n(0,t)\ e^{\frac{-x}{L_p}}\ dx \quad since \quad \Delta p_n(x,t) = \Delta p_n(0,t)\ e^{\frac{-x}{L_p}}$$

$$\implies Q_p(t) = qAL_p\Delta p_n(0,t)\int_0^\infty \frac{1}{L_p}\ e^{\frac{-x}{L_p}}\ dx$$

$$\implies Q_p(t) = qAL_p\Delta p_n(0,t)\int_0^\infty\ d(-e^{\frac{-x}{L_p}})$$

$$\implies \boxed{Q_p(t) = qAL_p\Delta p_n(0,t)} \tag{5.4}$$

Voltage across diode $V(t)$ can be given by minority carrier concentration profile (holes in n-region) assuming quasi-fermi level of holes completely dropping across n-region near depletion region.

$$V(t) = \frac{k_B T}{q} \; ln(\frac{p_n(0,t)}{p_{n_0}})$$
$$\implies V(t) = \frac{k_B T}{q} \; ln\;(\;1 + \frac{\Delta p_n(0,t)}{p_{n_0}}\;)$$

Using (5.4),

$$\implies \boxed{V(t) = \frac{k_B T}{q} \; ln\;(\;1 + \frac{Q_p(t)}{qAL_p p_{n_0}}\;)} \tag{5.5}$$

Let I_0 be reverse saturation current of the diode. Then, for **p+/n junction**,

$$I_0 = qA\frac{L_p}{\tau_p}p_{n_0}$$
$$\implies I_0\tau_p = qAL_p p_{n_0}$$

Putting this in (5.5),

$$\boxed{V(t) = \frac{k_B T}{q} \; ln\;(\;1 + \frac{Q_p(t)}{I_0\tau_p}\;)} \tag{5.6}$$

Using (5.3), $Q_p(t)$ can be calculated and putting $Q_p(t)$ in (5.6), $V(t)$ can be calculated.

a)

$$\boxed{\begin{array}{l} I(t) = I_F \;\; when \;\; t < 0 \\ I(t) = I_F e^{\frac{-t}{\tau_p}} \;\; when \;\; t \geq 0 \end{array}} \tag{5.a}$$

Putting (5.a) in (5.3),

$$Q_p(t) = (\; I_F\,\tau_p + \int_0^t I_F \;dt'\;)\; e^{\frac{-t}{\tau_p}} \qquad since \quad I(0^-) = I_F$$
$$\implies Q_p(t) = (\; I_F\,\tau_p + I_F\,t\;)\; e^{\frac{-t}{\tau_p}}$$
$$\implies \boxed{Q_p(t) = \;\; I_F\,(\tau_p + t)\; e^{\frac{-t}{\tau_p}}} \tag{5.a1}$$

Putting (5.a1) in (5.6),

$$V(t) = \frac{k_B T}{q} \; ln\;(\;1 + \frac{I_F\,(\tau_p + t)\; e^{\frac{-t}{\tau_p}}}{I_0\tau_p}\;)$$
$$\implies \boxed{V(t) = \frac{k_B T}{q} \; ln\;(\;1 + \frac{I_F}{I_0}(1 + \frac{t}{\tau_p})e^{\frac{-t}{\tau_p}}\;)} \tag{5.a2}$$

b)

$$\boxed{\begin{array}{l} I_0 = 0.2\mu A \\ I_F = 5mA \\ t = 10\mu s \\ \dfrac{V(t)}{V(0)} = \dfrac{2}{3} \end{array}} \tag{p.5b}$$

$$\boxed{\begin{array}{l} I(t) = I_F \;\; when \;\; t < 0 \\ I(t) = 0 \;\; when \;\; t \geq 0 \end{array}} \tag{5.b}$$

Putting (5.b) in (5.3),

$$Q_p(t) = (\; I_F\, \tau_p + \int_0^t 0 \; dt' \;)\; e^{\frac{-t}{\tau_p}} \qquad since \quad I(0^-) = I_F$$

$$\implies \boxed{Q_p(t) = \;\; I_F\, \tau_p \;\, e^{\frac{-t}{\tau_p}}} \tag{5.b1}$$

Putting (5.b1) in (5.6),

$$V(t) = \frac{k_B T}{q}\; ln\,(\,1 + \frac{I_F \tau_p\, e^{\frac{-t}{\tau_p}}}{I_0 \tau_p}\;)$$

$$\implies \boxed{V(t) = \frac{k_B T}{q}\; ln\,(\,1 + \frac{I_F}{I_0} e^{\frac{-t}{\tau_p}}\;)} \tag{5.b2}$$

$$\implies \boxed{V(0) = \frac{k_B T}{q}\; ln\,(\,1 + \frac{I_F}{I_0}\;)} \tag{5.b3}$$

Dividing (5.b2) by (5.b3),

$$\implies \frac{V(t)}{V(0)} = \frac{ln\,(\,1 + \frac{I_F}{I_0} e^{\frac{-t}{\tau_p}}\,)}{ln(1 + \frac{I_F}{I_0})}$$

$$\implies \frac{V(t)}{V(0)}\; ln(1 + \frac{I_F}{I_0}) = ln\,(\,1 + \frac{I_F}{I_0} e^{\frac{-t}{\tau_p}}\,)$$

$$\implies exp(\,\frac{V(t)}{V(0)}\; ln(1 + \frac{I_F}{I_0})\,) = 1 + \frac{I_F}{I_0} e^{\frac{-t}{\tau_p}}$$

$$\implies (1 + \frac{I_F}{I_0})^{\frac{V(t)}{V(0)}} = 1 + \frac{I_F}{I_0} e^{\frac{-t}{\tau_p}}$$

$$\implies \frac{I_0}{I_F}\;(\,(1 + \frac{I_F}{I_0})^{\frac{V(t)}{V(0)}} - 1\,) = e^{\frac{-t}{\tau_p}}$$

$$\implies ln\,(\,\frac{I_0}{I_F}\;(\,(1 + \frac{I_F}{I_0})^{\frac{V(t)}{V(0)}} - 1\,)\,) = \frac{-t}{\tau_p}$$

$$\implies \boxed{\tau_p = \frac{-t}{ln\,(\,\frac{I_0}{I_F}\;(\,(1 + \frac{I_F}{I_0})^{\frac{V(t)}{V(0)}} - 1\,)\,)}} \tag{5.b4}$$

Putting (p.5b) in (5.b4), τ_p (hole lifetime in n-region of the diode) can be calculated.

```
Hole lifetime in the neutral n-region of the diode ≈ 3 μs
```