Cheat Sheet - EE130

q = 1.6*10^{-19} C   e$_0$ = 8.85*10^{-14} F/cm

K_S = 11.8, K_O = 3.9   Eg (Si) = 1.12 eV

Boltzman k = 8.62*10^{-5} eV/K

Planck h = 4.14*10^{-15} eV*s

Free e Mass, m$_0$ = 9.1*10^{-31} kg

Effective density of states Nc = 3.22*10^19 cm-3

dEg = 3.5*10^(-8) * N^(1/3) eV

Basic Semiconductors Fundamentals

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

Charge Neutrality: $p-n+N_D-N_A=0$

$n_i=\sqrt{N_C N_V e^{\frac{-E_G}{2kT}}}$ $g_c(E)=\frac{m_n\sqrt{2m_n(E-E_C)}}{pi^2 h^3}$

$n=\frac{N_D-N_A}{2}+[(\frac{N_D-N_A}{2})^2+n_i^2]^{\frac{1}{2}}$ Mn > Mp in Si

$p=n_i e^{\frac{E_i-E_F}{kT}}$ $E_i=\frac{E_c+E_v}{2}+\frac{3}{4}kTln(\frac{m_p}{m_n})$

$n=n_i e^{\frac{E_F-E_i}{kT}}$ $E_F-E_i=kTln(\frac{n}{n_i})=-kTln(\frac{p}{n_i})$

Low T = freeze out; high t = intrinsic; else extrinsic

$J_P=J_{drift}+J_{diff}=q\mu_p pE-qD_P\frac{dp}{dx}$

$J_N=J_{drift}+J_{diff}=q\mu_n nE+qD_N\frac{dn}{dx}$

mobility units cm^2/(s*V), diffusion = cm^2/s

Diff len.: $L_N=\sqrt{D_N\tau_n}$ $v_{th}=\sqrt{\frac{3kT}{m_{eff}}}$ $v=\mu E$

$\frac{D}{\mu}=\frac{kT}{q}$ $\mu_p=\frac{q\tau_{mp}}{m_p}, units: \frac{q\tau_{mp}}{m_p}$ $F=\frac{-qE}{m_p}$

hi T = phonon scattering, low T = ion scattering

$\rho=\frac{1}{q(\mu_n n+\mu_p p)}$ $\sigma=q(\mu_n n+\mu_p p)\Omega^{-1}cm^{-1}$

Generation: band2band, R-G center, impact ion

Recomb: direct, R-G, Auger (2 collide, excite 1)

$rate\ of\ recombination=\frac{dn}{dt}=\frac{\Delta n}{\tau}=\frac{\Delta p}{\tau}$

Semiconductor Fabrication:

*oxidation = deposition of SiO2 layer

dry = thin, slow, precise, wet = thick, fast, imprecise

*lithography/etching = remove SiO2 with photoresist

*Dry/wet etch; dry=precise, wet = easy, cut sides

Antenna effect, charges left after etching, tunnel

*Ion Implantation = dopant atoms introduce into Si

low T vs diff. Dominant process now.

*Annealing/Diffusion = clean and spread

*Thin Film Deposition, spray metal, > clean sputter

*CVD – deposit ions/nitrides, etc.

Advanced lithography – EUV photo, ebeam, dip-pen

Positive = light, softens, negative = light hardens

Antenna effect – e- flow tunnel beneath oxide

Dop gasphase,solid source,in situ (deposit on surface)

PN Junctions

Forward Bias = Current flows P->N

Dep approx: assume carrier inside dep. region = 0

charge density out dep reg = 0 and q(Nd-Na) inside

$\frac{d^2V}{dx^2}=\frac{-dE}{dx}=\frac{-\rho}{\epsilon_s}$ n: $V(x)=V_{bi}-\frac{qN_D}{2\epsilon_s}(x_n-x)^2$

$W=\sqrt{\frac{2\epsilon_s(V_{bi}-V_A)}{q}(\frac{1}{N_A}+\frac{1}{N_D})}$

$v_{bi}=\frac{kT}{q}\ln(\frac{N_aN_d}{n_i^2})$ p: $V(x)=\frac{qN_A}{2\epsilon_s}(x+x_p)^2$

n-side: $V(x)=V_{bi}-\frac{qN_D}{2\epsilon_s}(x_n-x)^2$

$N_Ax_p=N_Dx_n$ common field in depletion region

one that reaches first is first to depleted

Dep reg. Widens under reverse bias

E-field: $E(x)=\frac{-qN_A}{\epsilon_s}(x_p+x)$

Peak E-field: $E(0)=\frac{2qN}{\epsilon_s}(V_{bi}+|V_r|)^{1/2}$

Brkd Voltage: $V_{BR}=\frac{\epsilon_s E_{crit}^2}{2qN}-V_{bi}$

Cap diagram slope = $2/qN\epsilon_s A^2$

cap/volt characteristics: $\frac{1}{C_{dep}^2}=\frac{W_{dep}^2}{A^2\epsilon_s^2}=\frac{2(V_{bi}-V_A)}{qN\epsilon_sA^2}$

Vbr decreases with increasing N or decreasing Eg

$p_{p0}(-x_p)=N_A$ $n_{n0}(-x_n)=N_D$ majority

$n_{p0}(-x_p)=\frac{n_i^2}{N_A}$ $p_{n0}(-x_n)=\frac{n_i^2}{N_D}$ minority

$pn=n_i^2e^{qV_A/kT}$ @ edge of dep region; maj/min

$n_p=n_{p0}+\Delta n_p(x)$ $p_n=p_{n0}+\Delta p_n(x)$

Drift doesn't change with V b/c low numbers

Forward bias = more minority @ dep edge

Reverse bias = black hole @ dep edge

$\frac{\partial\Delta n_p}{\partial t}=D_N\frac{\partial^2\Delta n_p}{\partial x^2}-\frac{\Delta n_p}{\tau_n}+G_L$ assume E = 0

$\frac{\partial\Delta p_n}{\partial t}=D_P\frac{\partial^2\Delta p_n}{\partial x^2}-\frac{\Delta p_n}{\tau_p}+G_L$ $L_p=\sqrt{D_p\tau_p}$

Steady State: $\frac{\partial\Delta p_n}{\partial t}\to 0$

No gradient/diff current: $D_P\frac{\partial^2\Delta p_n}{\partial x^2}\to 0$

No thermal R-G: $\frac{\Delta p_n}{\tau_p}\to 0$ No light: $G_L\to 0$

Diode Saturation Currents:

$I_0=Aqn_i^2(\frac{D_p}{L_pN_d}+\frac{D_n}{L_nN_a})$ $I=I_0(e^{qV/kT}-1)$

IV curve shifts left @ high T b/c more diffusion

Charge storage: $I=Q/\tau_s$ charge/carrier lifetime

Capacitance: $C=\tau_sG$ Conductance: $G=\frac{I_{DC}q}{kT}$

PIN Junctions

Only e/h generated in dep reg contribute to current

Only light absorbed in dep reg is useful. Avalanches.

MS Junctions

lightly doped rectifying, heavily doped ohmic

Ideal assumptions: intimate contact, no oxide/charge

Not ideal: interface pinned Ef 0.4-0.9 eV below Ec

$\Phi_{BN}=\Phi_M-X$ Barrier height; work(metal) – EA

$\Phi_{BN}=qV_{bi}+[\frac{1}{2}E_G-(E_{FS}-E_i)_{FB}]$ barrier height

$\Phi_{BP}=X+E_G-\Phi_M$ holes' barrier

$V_{bi}=\Phi_M-\Phi_S=\Phi_B-(E_C-E_F)$ built-in potential

$W=\sqrt{\frac{2\epsilon_s(V_{bi}-V_A)}{qN_D}}=\sqrt{\frac{2\epsilon_s(V_{bi}+V_A)}{qN_A}}$

PN higher V for same I. MS more reverse current.
MS = Ideal for rectifying high I, low V. I0 > PN's
Contact both directions, dope heavily to tunnel
Actual, MS is rectifying. Ohmic needs high N(thin)

$P=e^{-H(\Phi_B-V_A)/\sqrt{N_D}}$ Ohmic when small barrier

Reduce height/reduce width. 2nd works. 1st too rare

Carrier injection @ contact: 3 modes (parameter)

thermionic emission (work fcn, T, Forward bias),
tunneling (high doping)
thermally activated tunneling (high T, high doping)

MOSC

Ideal assumption: no charge in oxide, same Work Fcn

$$\Phi_M=E_0-E_{FM} \qquad \Phi(x)=\frac{1}{q}[E_{i(bulk)}-E_{i(x)}]$$

$$\Phi_S=\frac{1}{q}[E_{i(bulk)}-E_{i(surface)}] \qquad \Phi_F=\frac{1}{q}[E_{i(bulk)}-E_F]$$

$$W=\sqrt{\frac{2\epsilon_{si}|(\Phi_s)|}{qN}} \qquad E_{ox}=(\epsilon_{si}/\epsilon_{ox})E_{si} \qquad \phi_s=2\phi_f$$

$$E_{max}=-\sqrt{\frac{2qN_D}{2\epsilon_{si}}}|(\Phi_s)|=\sqrt{\frac{2qN_A}{2\epsilon_{si}}}|(\Phi_s)| \quad \text{n/p type}$$

$$V_G=\phi_S+x_{ox}\frac{K_{si}}{K_{ox}}\sqrt{(\frac{2qN}{K_{si}\epsilon 0}\phi_s)} \quad \text{neg for N silicon}$$

Decrease t_ox decreases V_T and C_min

$$C_G=\frac{C_{ox}}{1+\frac{\epsilon_{ox}W}{\epsilon_{si}x_{ox}}} \quad \text{Poly gate:} \quad C=\frac{\epsilon_{ox}}{T_{ox}+W_{dpoly}/3}$$

$$C_{ox}=\epsilon_{ox}A/t_{ox} \qquad C_{si}=\epsilon_{si}A/W \quad \text{Hi N = little effect}$$

Nonideal: nonmetal gate, charge traps, FB voltage
Threshold voltage: larger doping requires small t_ox.
Nonmetal gate is problematic; small oxide is good, but hard to get smaller. Want high dope in body.

Poly gate: $W_{dpoly}=\epsilon_{ox}V_{ox}/T_{ox}qN_{poly}$

$$W_{dpoly}=\sqrt{\frac{2\epsilon_s V_{poly}}{qN_{poly}}} \qquad V_{fb}=\frac{E_g}{q}-\frac{kT}{q}\ln(\frac{N_{gate}}{N_{body}})$$

$$V_{th}=V_{fb}+\phi_s+t_{ox}\frac{\epsilon_{si}}{\epsilon_{ox}}\sqrt{\frac{2qN_A\phi_s}{\epsilon_{si}}}$$

Effective tox increase: $\frac{\epsilon_{ox}}{T_{ox}+W_{dpoly}/3}$

Fixed charge $\Delta V_T=\frac{-1}{\epsilon_{ox}}\int_0^{t_{ox}} x\rho_{ox}(x)dx$ alter mobilit

$$V_{FB}=\phi_{MS}-\frac{t_{ox}}{\epsilon_{SiO2}}Q_F \qquad \Delta V_{G(¿)}=\frac{-Q_F}{C_{ox}}$$

Fixed charge due to ionized silicon not oxidized.
Mobile ions shift CV curves. Positive shifts left
Interface traps smooth out curve; degrade mobility
More surface scattering with lower t_ox
Lower t_ox shifts CV curve down, lowers V_t

MOSFET

$$V_G=2\phi_F+x_{ox}\frac{\epsilon_{si}}{\epsilon_{ox}}\sqrt{(\frac{2qN}{\epsilon si}\phi_s)} \quad \text{n chan (p-si)}$$

$$V_G=2\phi_F-x_{ox}\frac{\epsilon_{si}}{\epsilon_{ox}}\sqrt{(\frac{2qN}{\epsilon si}\phi_s)} \quad \text{p chan (n-si)}$$

$$I_D=\frac{W\mu_n}{L}C_{ox}(V_G-V_TV_{DS}-\frac{V_{DS}^2}{2});0<V_{DS}<V_{DSsat}$$

$$I_D=\frac{W\mu_n}{2L}C_{ox}(V_G-V_T)^2;V_{DS}>V_{DSsat};V_G>V_T$$

For above, C_ox = e_ox/t_ox, or cap per unit area
Only apply to diffusive devices, today quasi-ballistic
* Square law also ignores bulk charge effect, assumes gate charge balanced by inversion charge, not dep
* Also ignores changes in dep width

Threshold and Subthreshold

Mobility degrades at high V_GS, minority carriers flow at low V_GS(subthreshold). Exponential decay. Small subthreshold swing is desirable, get sharper slope.

$$I_{ds} \quad e^{qV_{gs}/\eta kT} \qquad \eta=1+\frac{C_{dep}}{C_{ox}} \qquad S=60\text{mV}(1+\frac{C_{dep}}{C_{ox}})$$

Lower swing by Increase Cox, problem – tunneling, scattering
Decrease C_dep w/ lighter doping. Kills V_t
Decrease Temp
Velocity saturates b/c of high energy collisions.

$$I_D=WQ_{inv}v_{drift} \qquad \frac{1}{V_{Dsat}}=\frac{1}{V_{GS}-V_T}+\frac{1}{\epsilon_{sat}L}$$

$$Q_{inv}=C_{ox}(V_{GS}-V_T-V_D)$$

Ballistic devices often exceed v_sat.
Series resistance shifts IdVg curve to right.
Lowers Id/Vd curve respectively. Degrades perf.
Not all Vd drops across channel; some in contacts
Vt rolloff – V_t decreases with decreasing length
I_off becomes too large if V_t becomes too small.
Consequence of reducing oxide thickness.

Reduce tox

- Larger Cox raises Ion, better e-field
- Reduce subthreshold swing
- Control Vt rolloff
- Bad – breakdown due to high field; leakage

Define EOT = E_siO2/E_gate dielectric * t_ox
Hi-k challenges: chemical reaction w/ gate
lower surface mobility, too low V_t for PMOS
Source/drain leakage in body is a problem. Drain controls this part. Reduce this w/ UTB, FINFET, SOI.

BJT

Good design: minority carriers don't recombine in B
Emitter current almost all from carriers from B
Control doping in base but balance w/ dep width

$I_E=I_B+I_C$ current flows to C in pnp, E in npn

Bias Mode	E-B Interface	C-B Interface
Saturation	Forward	Forward
Active	Forward	Reverse
Inverted	Reverse	Forward
Cutoff	Reverse	Reverse

Pnp emitter efficiency $\gamma=\frac{I_{Ep}}{I_E}=\frac{I_{Ep}}{I_{Ep}+I_{En}}$

Base transport factor $\alpha_T=\frac{I_{Cp}}{I_{Ep}}$

Common base gain $\alpha_{dc}=\gamma\alpha_T \qquad I_C=\alpha_{dc}I_E+I_{CB0}$

Common Emitter dc gain $B_{dc}=\frac{\alpha_{dc}}{1-\alpha_{dc}}=\frac{I_C}{I_B}$

$$I_C=B_{dc}I_B+I_{CE0}$$

Base width modulation / punchthrough
High CB bias causes early effect, sloped Ic vs Vec
Base gets shorter and thinner.