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EE130
MT1

- E_g for Si is 1.12eV
- Carrier Generation]
  - Semiconductors
    - elements: Si, Ge, C
    - binary: GaAs, InSb, SiC, CdSe
    - ternary: AlGaAs, InGaAs
  - Crystal Structure 5.43 Å
    - Si: unit is cubic, 4 nearest neighbors
      - wafer w/(100) plane
- dopants { - N-type donor - Group V; ex. As, P; more e^-
- P-type acceptor - Group III; ex B; more p^+
  - III-V [illegible] in dopants
  - energy bands in crystal
    - valence band - highest filled
    - conduction band - lowest empty
    - ↓ spacing → ↑ $E_g = E_c - E_v$
    - find E_g w/ light $h\nu$
    - totally filled band == no current
      - metal are half filled
    - insulator == large E_g (9eV for SiO_2)
    - E_d - donor level right below E_c
    - E_a - acceptor level right above E_v ~50meV
    - ionization energy = $E_c - E_d$ or $E_a - E_v$

$$E_{ion} = \frac{m_0 q^4}{8\varepsilon_0^2 h^2} \quad 13.6\text{eV for H}$$

- ↑T more e^- jump dopant gap
- e^- Effective mass (charge in solid)
  - $F = ma = -q\mathcal{E}$

$$e^- \; a = \frac{-q\mathcal{E}}{m_n} \qquad p^+ \; a = \frac{q\mathcal{E}}{m_p}$$

- specified as $\frac{m_n}{m_0}$ and $\frac{m_p}{m_0}$ <1?
- Density of States

$$g(E) = \frac{\#\text{ states in }\Delta E}{\Delta E\cdot\text{volume}} \quad \frac{1}{eV\,cm^3}$$

$$g_c(E) = \frac{m_n^*\sqrt{2m_n^*(E-E_c)}}{\pi^2\hbar^3}$$

$$g_v(E) = \frac{m_p^*\sqrt{2m_p^*(E_v-E)}}{\pi^2\hbar^3}$$

- Fermi Function - prob E occupied by e^-

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

E_F = Fermi level constant at equilibrium
$f(E) = \frac{1}{2}$ if $E = E_F$

- Boltzmann Approx
  - if $E - E_F > 3kT$, $f(E) \approx e^{-(E-E_F)/kT}$
  - if $E_F - E > 3kT$, $f(E) \approx 1 - e^{(E-E_F)/kT}$
  - for hole p^+, $1 - f(E)$
- Equilibrium Distribution of Carriers

$$n = \int_{E_c}^{top \to \infty} g_c(E) f(E)\, dE$$

use Boltzmann approx, ∞ for top

$$☆ \quad n = N_c e^{-(E_c-E_F)/kT}$$

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

↑ effective density of states (conduction)

$$p = \int_{bot \to -\infty}^{E_v} g_v(E)(1-f(E))\, dE$$

$$☆ \quad p = N_v e^{-(E_F-E_v)/kT}$$

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

↑ effective density of states (valence)

- Intrinsic Semiconductor
  - $n = p = n_i$ for Si, $10^{10}cm^{-3}$
  - E_F midgap
  - n-type - E_F moves up to E_c
  - p-type - E_F moves down to E_v

- Intrinsic Carrier Concentration

$$np = n_i^2$$

$$☆ \quad n_i = \sqrt{N_c N_v}\, e^{-E_g/2kT}$$

$$n_i^2 = N_c N_v e^{-E_g/kT}$$

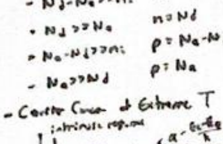
- Effects of Doping

$$☆ \quad n + N_a^- - p - N_d^+ = 0$$

↑ generally assume full ionization

- $N_d - N_a >> n_i$:	$n = N_d - N_a$
- $N_d >> N_a$	$n = N_d$
- $N_a - N_d >> n_i$:	$p = N_a - N_d$
- $N_a >> N_d$	$p = N_a$

- Carrier Conc at Extreme T



↑ E_g mostly promoted
↑ e^- stay at E_d in donor
good for IR detector

- Carrier Transport]

$$\frac{3}{2}kT = \frac{1}{2}mv^2 \quad v = \sqrt{\frac{3kT}{m^*}}$$

- drift - external E field
- diffusion - concen. diff
- recombination generation
- Drift
  - momentum $m_n^* v_d$
  - mom. gain $-q\mathcal{E}\tau_{mn}$

$$v = \frac{q\mathcal{E}\tau_{mn}}{m_n^*}$$

$$e^- \left\{ v = -\mu_n\mathcal{E} \quad \mu_n = \frac{q\tau_{mn}}{m_n} \quad \frac{cm^2}{Vs}\right.$$

$$p^+ \left\{ v = \mu_p\mathcal{E} \quad \mu_p = \frac{q\tau_{mp}}{m_p}\right.$$

μ changes w/ temp & concentration

- Carrier Scattering Mechanism
  - phonon scattering
    - ↑T → ↓μ

$$\mu \propto \tau \propto \frac{1}{\text{phonon density} \cdot \text{carrier } v_{th}} \propto \frac{1}{T\cdot T^{1/2}} \propto T^{-3/2}$$

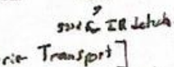
phonon density $\propto T$, carrier $v_{th} \propto T^{1/2}$

- impurity (dopant) - ion scattering (Coulombic)
  - e^- near ion dopant

$$\mu \propto \frac{v_{th}^3}{N_a + N_d} \propto \frac{T^{3/2}}{N_a+N_d}$$

- total mobility

$$\frac{1}{\tau} = \frac{1}{\tau_{phon}} + \frac{1}{\tau_{impu}}, \quad \frac{1}{\mu} = \frac{1}{\mu_{phon}} + \frac{1}{\mu_{imp}}$$



- velocity saturation - ↑KE → shed phonon
  - limits KE, capped at v_{sat}

$$☆ \quad J_{drift} = (qn\mu_n + qp\mu_p)\mathcal{E} = \sigma\mathcal{E}$$

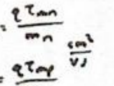
σ conductivity → $\rho = 1/\sigma$

$$R = \rho\frac{L}{A} = \rho\frac{L}{wt}$$

- Diffusion Current

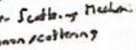
$$☆ \quad J_n = qD_n\frac{dn}{dx} \quad J_p = -qD_p\frac{dp}{dx}$$

- Band Diagram



☆ - Potential V

$$PE = -qV \rightarrow E_c - E_{ref} = -qV$$



☆ - Electric Field $\mathcal{E}$

$$\mathcal{E} = -\frac{dV}{dx} = \frac{1}{q}\frac{dE_c}{dx}$$

- Non Uniform Doped
  - equilibrium → constant E_F → J = 0
  - ↳ $J_n = qn\mu_n\mathcal{E} + qD_n\frac{dn}{dx} = 0$
- Einstein relation $\frac{dn}{dx} = -\frac{n}{kT}q\mathcal{E}$

$$☆ \quad D_n = \frac{kT}{q}\mu_n \quad D_p = \frac{kT}{q}\mu_p$$

- Generation Process
  - Band-to-band
  - R-G center
  - impact ionization } change n, p
- Recombination Process
  - direct
  - R-G center
  - Auger
- Excess Carrier & Charge Neutrality

$$n = n_0 + \Delta n \qquad \Delta n = \Delta p$$
$$p = p_0 + \Delta p$$

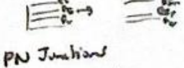
↑ otherwise drift

ex light make $\Delta n, \Delta p$ decay
↑ not equilibrium, lifetime τ
↑ low level inject
$\Delta n, \Delta p$ on dopants, equil when [illegible] it faster

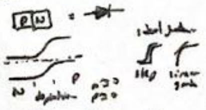
$$☆ \quad \frac{dn}{dt} = -\frac{\Delta n}{\tau} = -\frac{\Delta p}{\tau} = \frac{dp}{dt}$$

- Quasi-equilibrium, Quasi-Fermi
  - E_{Fn} and E_{Fp} - equilibrium in group

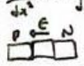
$$☆ \quad n = N_c e^{-(E_c-E_{Fn})/kT}$$
$$p = N_v e^{-(E_{Fp}-E_v)/kT}$$



- PN Junctions



$$\frac{d^2V}{dx^2} = -\frac{d\mathcal{E}}{dx} = -\frac{\rho}{\varepsilon_s}$$



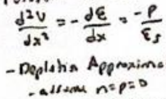
J = 0

$$☆ \quad V_{bi} = \frac{kT}{q}\ln\frac{N_dN_a}{n_i^2}$$

- Poisson's Equation

$$☆ \quad \frac{d^2V}{dx^2} = -\frac{d\mathcal{E}}{dx} = -\frac{\rho}{\varepsilon_s}$$

- Depletion Approximation
  - assume $n = p = 0$
  - assume $\rho = 0$ (charge [illegible]) and $\rho = q(N_d - N_a)$ in depletion



- P side $\rho = -qN_a$

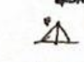
$$\mathcal{E}(x) = \frac{qN_a}{\varepsilon_s}(x_p - x)$$

- N side $n = qN_d$ ↑ equal at x=0

$$\mathcal{E}(x) = \frac{qN_d}{\varepsilon_s}(x + x_n)$$

$$☆ \quad N_a x_p = N_d x_n$$

- Depletion Potential
  - let $x = x_p$ be V = 0



- p-side

$$V(x) = \frac{qN_a}{2\varepsilon_s}(x_p - x)^2$$

↑ == at x = 0

- N-side

$$V(x) = \phi_{bi} - \frac{qN_d}{2\varepsilon_s}(x + x_n)^2$$

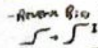
$$☆ \quad x_n = \sqrt{\frac{2\varepsilon_s\phi_{bi}}{q}\left(\frac{N_a}{N_d(N_a+N_d)}\right)}$$

$$x_p = \sqrt{\frac{2\varepsilon_s\phi_{bi}}{q}\left(\frac{N_d}{N_a(N_a+N_d)}\right)}$$

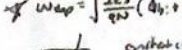
$$☆ \quad x_n + x_p = W_{dep} = \sqrt{\frac{2\varepsilon_s\phi_{bi}}{q}\left(\frac{1}{N_a}+\frac{1}{N_d}\right)}$$

- one-sided junction
  - $P^+N \rightarrow x_p = 0, \frac{1}{N_a} = 0, \frac{1}{N_d} + \frac{1}{N_a} = 1/N_d$ lightly doped
  - $N^+P \rightarrow x_n = 0, \frac{1}{N_d} = 0, \frac{1}{N_d} + \frac{1}{N_a} =$

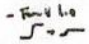
- Reverse Bias PN



$$☆ \quad W_{dep} = \sqrt{\frac{2\varepsilon_s}{qN}(\phi_{bi} + |V_a|)} \leftarrow V_{bi} + V_A$$



- Forward bias



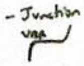
e⁻ flow

- PN Capacitance

$$☆ \quad C_{dep} = A\frac{\varepsilon_s}{W_{dep}}$$

$$\frac{1}{C_{dep}^2} = \frac{2(\phi_{bi} + V)}{qN\varepsilon_s A^2}$$

- Junction Breakdown

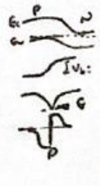


- P^+N or N^+P, $V_{BR} \propto \frac{1}{N}$
- Avalanche breakdown
  - mostly light dope
  - peak E field

impact ionization

$$\mathcal{E}_{crit} = \sqrt{\frac{2qN(V_{bi} + V_{BR})}{\varepsilon_s}}$$

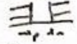
$$☆ \quad V_{BR} = \frac{\varepsilon_s\mathcal{E}_{crit}^2}{2qN} - V_{bi}$$



- Tunneling Breakdown
  - heavy dope
  - quantum tunneling
  - Zener process $J \cdot 6e^{-H/\mathcal{E}}$

$V_A >>$ forward bias
$V_A = 0$ equilibrium
$V_A < 0$ reverse bias

- Carrier Concentration
  - equilibrium



- bias?

- forward - ↓barrier
  - ↑carrier injection (diffusion)
  - ↑minority concentration

- reverse - ↑barrier
- drift little variance
- $V_a = 0$ same concentration == drift

↑ more inject in lighter dope = diffusion

- Junction Law
  - pn at edge of depletion boundary

$$☆ \quad pn = n_i^2 e^{qV_a/kT}$$

↑ when $\Delta n, \Delta p$ at boundary

- Current Densities

$$☆ \quad \frac{\partial\Delta p}{\partial t} = D_p\frac{\partial^2\Delta p}{\partial x^2} - \frac{\Delta p}{\tau_p} + G_L$$

$$\frac{\partial\Delta n}{\partial t} = D_n\frac{\partial^2\Delta n}{\partial x^2} - \frac{\Delta n}{\tau_n} + G_L$$

$\frac{\partial}{\partial t} = 0$ steady state

$$L_n = \sqrt{D_n\tau_n} \quad L_p = \sqrt{D_p\tau_p}$$

minority carrier diffusion eqn

$$\frac{\partial^2\Delta p_n}{\partial x^2} = \frac{\Delta p_n}{D_p\tau_p} = \frac{\Delta p_n}{L_p^2}$$

verify solution ↑

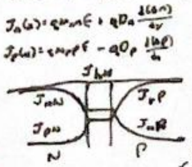
$$p(x) = A_1 e^{x/L_p} + A_2 e^{-x/L_p}$$

x'' ← 0 0 → x'
P | | N

$$\Delta p_n(x') = p_{no}(e^{qV_a/kT}-1)e^{-x'/L_p}$$

$$\Delta n_p(x'') = n_{po}(e^{qV_a/kT}-1)e^{-x''/L_p}$$

$$J_n(x) = q\mu_n n\mathcal{E} + qD_n\frac{d(\Delta n)}{dx}$$
$$J_p(x) = q\mu_p p\mathcal{E} - qD_p\frac{d(\Delta p)}{dx}$$



far away $\frac{n_i^2}{N_{A}}$

$$\text{p-side} \quad J_n = q\frac{D_n}{L_n}n_{po}(e^{qV_a/kT}-1)e^{-x''/L_n}$$

$$\text{n-side} \quad J_p = q\frac{D_p}{L_p}p_{no}(e^{qV_a/kT}-1)e^{-x'/L_p}$$

- PN current

$$☆ \quad I_0 = Aqn_i^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)$$

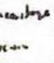
area over A

$$I = I_0(e^{qV/kT} - 1)$$

- p-i-n photodiode
  - e^-, p^+ made in depletion region
- LED & reverse band gap
- Textbook
  - [illegible] depletion in R-G [illegible]

$$I = I_0(e^{\frac{qV}{kT}}-1) + A\frac{qn_iW_{dep}}{\tau_{dep}}(e^{\frac{qV}{2kT}}-1)$$

- charge storage $Q = I\tau_s$
- Discussion
  - dope → charge → $\mathcal{E}$ → V



→ $V_{bi} = \frac{1}{2}\mathcal{E}(0)\cdot W$ area

$$\#\text{ states} = \int_{E_1}^{E_2} D(E)\, dE$$

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D-N_A}{2}\right)^2 + n_i^2}$$

$$p = \frac{N_A - N_D}{2} + \quad ''$$

- Continuity Equation

e^- gen

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} + (G_n - R_n)$$

$$\frac{\partial p}{\partial t} = \frac{1}{q}\frac{\partial J_p}{\partial x} + (G_p - R_p)$$

- excess minority carrier transport

$$\frac{\partial(\Delta n)}{\partial t} = D_n\frac{\partial^2(\Delta n)}{\partial x^2}$$

- for p → $+\mu_n\mathcal{E}\frac{\partial(\Delta n)}{\partial x}$ $+\left(G_n - \frac{\Delta n}{\tau_n}\right)$

- excess minority diffusion
  - no $\mu_n\mathcal{E}$ term
- degenerate dope → no freeze out

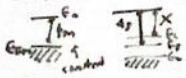
+ −
↓ ↑ energy levels
E E

☆ Fermi level diff equal to applied voltage

Matthew Tran
EE130
MT2

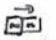
- Fabrication
  - SSI, MSI, LSI, VLSI, ULSI
    10^2 10^3 10^6
  - Foundry / fab - cleanroom main part
  - oxidation
    - dry: $Si + O_2 \to SiO_2$ thin
    - wet: $Si + 2H_2O \to SiO_2 + 2H_2$ thick
  - lithography
    - positive/negative photoresist
    - resolution limit R ≥ kλ diffraction
      - large aperture, quality lens
      - small field, step repeat w/ stepper
      - phase shift mask
      - optical proximity correction
  - etch
    - wet: isotropic
    - dry: anisotropic
  - doping
    - use mask w/ SiO_2, and anneal
    - Gas phase - $POCl_3$
    - Solid-Source Doping - ex. SiGe
    - In-Situ - for films
  - thin film deposition
    - crystalline, poly, amorphous
- MS Junction
  - 2 types:
    - light: Schottky diode
    - heavy: ohmic contact

  - Work Function - $E_0 - E_F = \phi$



$\phi_s = \chi + (E_c - E_F)$
doping!
in reality dipole forms

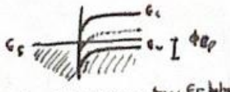
  - assume
    - MS ohmic contact
    - no oxide/charge at surface
    - no mixing at surface
  - $\phi_M > \phi_s$, n-type



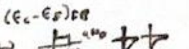
Schottky Barrier

$\phi_{Bn} = \phi_M - \chi$

  - $\phi_m < \phi_s$, p-type



  - Fermi level pinning - keeps E_F below E_c
  - $\phi_m > \phi_s$, n-type
    $qV_{bi} = \phi_B - (E_c - E_F)_{FB}$
  - Depletion region W



$$W = \sqrt{\frac{2\varepsilon_s V_{bi}}{qN_D}}$$

  - CV get ϕ_B

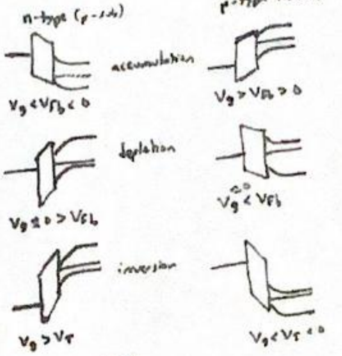
$$\frac{1}{C^2} = \frac{2(V_{bi} + V)}{qN_D\varepsilon_s A^2}$$

$qV_{bi} = \phi_m - kT\ln\frac{N_c}{N_d}$

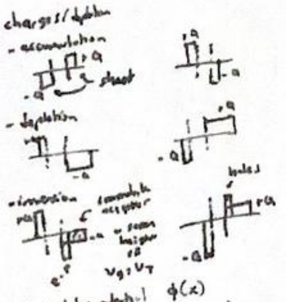
  - Current
    - Thermionic emission $\approx 120e^{-q\phi_B/kT}$ A/cm^2
      - cross if enough energy
        $I = I_s(e^{qV_a/kT} - 1)$, $I_s = AT^2J_s$
    - Tunneling (quantum)
    - Thermally activated Tunneling
  - Ohmic MS
    - ↓ ϕ_B Schottky barrier
    - ↓ W depletion barrier width
      - ↑ doping $E_c \cong E_F$ → $W = \sqrt{\frac{2\varepsilon_s\phi_{Bn}}{qN_D}}$
      - ↑ tunneling prob $P = e^{-H(\phi_{Bn} - V_a)/\sqrt{N_D}}$
  - Reduce Fermi level Pinning
    - thin interfacial oxide/nitride
    - 1D semiconductors $\phi_{Bn} = 0.7V + 0.2(\phi_m - 4.75)$
  - [illegible]
    $\phi_{Bn} + \phi_{Bp} \cong E_g$

- MOS Cap

  - assume
    - oxide 0 charge, no current
    - no charge oxide/interface
    - uniform type
    - $\phi_m = \phi_s$ → $V_{FB} = 0V$
  - bends oxide moves too
  - inversion = flip concentration
  - flatband = actual flat band, no charge
    → V_{FB} = Fermi diff (can be + or -)



  - charges/depletion



  - electrostatic potential $\phi(x)$
    $\phi(x) = \frac{1}{q}(E_i(\text{bulk}) - E_i(x))$
    ↑ far from surface
    ϕ_S $\phi(0) = \frac{1}{q}(E_i(\text{bulk}) - \phi_s)$ at surface
    $\phi_F = \frac{1}{q}(E_i(\text{bulk}) - \phi_F)$
    $\phi_F > 0$ → p-type $\phi_F < 0$ → n-type substrate
  ☆ $\phi_s = 2\phi_F$ → V_T, onset inversion
  - charge density
    - accumulation - δ function
    - depletion - $qN_A A W = Q_D$
      $W = \sqrt{\frac{2\varepsilon_s}{qN_A}\phi_s}$ $E_{max} = +\sqrt{\frac{2qN_A}{\varepsilon_{Si}}\phi_s}$
    - inversion - δ func for extra
      - max depletion width $W = W_T$
  - V_g relationship
    - Gauss's Law $\varepsilon_{ox}E_{ox} = \varepsilon_{Si}E_{Si}$
  - CV
    - DC + AC small
    - accumulation
      $C_g = C_{ox} = \frac{\varepsilon_{ox}A}{x_{ox}}$
    - depletion
      $C_s = \varepsilon_{Si}A/W$ C_{ox} C_s ─||─||─
      $C_g = \frac{C_{ox}C_s}{C_{ox} + C_s}$
    - inversion   "quasi-static"
      - high frequency → e^- don't move fast
        $W_T = \sqrt{\frac{2\varepsilon_{Si}}{qN_A}2\phi_F}$] same as depletion
      - low frequency → enough time
        $C = C_{ox}$

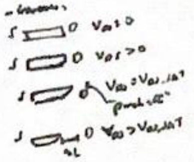
  - deep depletion
    ↑ ramp V_g
    → ↑W_T ↓C_g

- Nonideal MOSC
  - $V_{FB} = \phi_m - \phi_s$
  ☆ $V_g = V_{FB} + \Delta\phi_{semi} + \Delta\phi_{oxide}$
  $0 \le \phi_s \le 2\phi_F$ → $V_g = V_{FB} + \phi_s + x_{ox}\frac{\varepsilon_{Si}}{\varepsilon_{ox}}E_{Si}$
  - Poly-Si Depletion
    ↓V_g bc ϕ_{poly} → ↑x_{ox}

  - inversion layer thickness
  - Oxide charge → $V_{FB} = \phi_{MS} - \frac{Q_F}{C_{ox}}$
    - fixed oxide
    - mobile oxide ← shift CV
    - interface trap ← less sharp CV
- MOSFET

NMOS		PMOS
N+ poly/contact		P+ poly/contact
p-sub		n-sub
$V_g > 0$	enhancement	$V_T < 0$
$V_T < 0$	depletion	$V_T > 0$
	↑normally on	

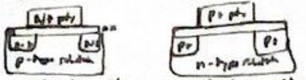
  - [illegible]



- [illegible]/Math
  $V_T = \phi_s + \sqrt{\frac{qN_A 2\varepsilon_s \phi_s}{C_{ox}}}$

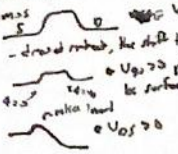
Matthew Tran
EE130
Final

- MOSFETs
  - NMOS
  - PMOS



enhancement $V_{GS} > V_T$ / enhancement $V_{GS} < V_T$
enhancement $V_T > 0$ / enhancement $V_T < 0$
depletion $V_T < 0$ / depletion $V_T > 0$
on at $V_G = 0$

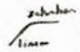
- band diagram



@ $V_{ds} = 0$, $V_{gs} = 0$
- draw at contact, the shift to match E_F & don't forget Flatband!!!
@ $V_{gs} > 0$ pushes bump down bc surface changes
@ $V_{DS} > 0$

- 3D

- Inversion charge $Q_{in} = C_{ox}(V_g - V_T - \phi)$
  - mainly drift current (no density diff?)



- Square Law . $C_{ox} = \frac{\varepsilon_{ox}}{x_{ox}}$
  - $0 < V_{DS} < V_{DS,sat}$; $V_G > V_T$

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

  - $V_{DS} > V_{DS,sat} = V_G - V_T$; $V_G > V_T$

$$I_{DS,sat} = \mu_n C_{ox}\frac{W}{2L}(V_G - V_T)^2$$

  - bulk
    $C_{ox} = \varepsilon_{ox}/x_{ox}$, $V_{FB} = \phi_M - \phi_S$

$$V_T = V_{FB} + 2\phi_F + x_{ox}\frac{\varepsilon_{Si}}{\varepsilon_{ox}}\sqrt{\frac{2qN_A}{\varepsilon_{Si}}2\phi_F}$$

- Effective mobility
  - ↓ surface scattering bc gate near it
    - interface roughness
    - phonon scattering
    - coulombic scattering

$$\mathcal{E}_{avg} = \frac{V_{GS} + V_T + 0.2V}{6T_{ox}}$$

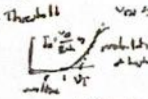
empirically, $\bar{\mu}_n = \frac{\mu_0}{1 + \theta(V_g - V_T)}$

- Bulk Charge Theory
  - account for depletion width

$$Q = -C_{ox}(V_g - V_T - \phi) + qN_a(W(\phi) - W_T)$$

$$I_D = -\mu_n C_{ox}\frac{W}{L}\left((V_g - V_T)V_D - \frac{V_D^2}{2} - \frac{4}{3}V_{ox}\phi_F\left(\left(1 + \frac{V_D}{2\phi_F}\right)^{3/2} - \left(1 + \frac{3V_D}{2\phi_F}\right)\right)\right)$$

- Threshold V_{DS} small



- Subthreshold Current
  - $V_{GS} = 0$, $V_{DS} = V_{DD}$
  - $I_{sub} \propto n_s = e^{q\psi_s/kT}$ surface inversion concentration

C_{ox}, C_{dep} $\quad \frac{d\psi_s}{dV_g} = \frac{C_{ox}}{C_{ox} + C_{dep}} = \frac{1}{\eta}$ $\quad \sqrt{\frac{2\varepsilon_{Si}}{qN_a}\phi_s}$

$$I_{ds} \propto e^{qV_{GS}/\eta kT} \quad \eta = 1 + \frac{C_{dep}}{C_{ox}} \leftarrow \varepsilon_{Si}/W_{dep}, \leftarrow \varepsilon_{ox}/x_{ox}$$

$$S = \underbrace{\eta \cdot \ln 10 \cdot \frac{kT}{q}}_{60mV} \frac{mV}{decade}$$

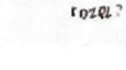
- Practical V_T when $I_{DS} = 100nA \cdot \frac{W}{L}$
  $\Rightarrow I_{off} = 100nA \cdot \frac{W}{L} \cdot 10^{-V_T/S}$

- Velocity saturation
  - max $\mathcal{E}_{sat}$ $\quad v = \frac{\mu_s \mathcal{E}}{1 + \frac{\mathcal{E}}{\mathcal{E}_{sat}}}$
  - bad esp w/ small L bc ET, $<1\mu m$ bad — but before saturation $V_G - V_T$

$$I_{DS,sat} \approx W C_{ox}(V_G - V_T)v_{sat}$$

- Ballistic Device
  - small L (below mean free path) → no scattering → $> v_{sat}$ exceeded
  - able to hit 40% of limit
- Series Resistance of D and S
- V_T roll off if ↓L, ↓V_T bc no hard to hill bump

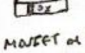
$$V_T = V_{FB} + 2\phi_B + \frac{2\varepsilon_r \cdot 2\phi_B}{C_{ox}W_{dep}}$$



- reduce leakage
  ↑N_{sub}, should ↑C_{ox} keep V_T same
- lower X_{ox} (T_{ox})
  ↑C_{ox} → ↑I_{on}
  ↓S
  better V_T roll off
  - too thin bad bc
    - breakdown from $\mathcal{E}$
    - leakage current (tunneling)
      <1.5nm in SiO_2 bad
      ↑ HfO_2 better
  - high-k dielectric
    - HfO_2 thicker (but lower) tunnel barrier
  - metal gate
    - no poly depletion!!

challenges
insert SiO_2 layer? →
- chemical reaction
- lower surface mobility
- too low V_T for PMOS (+ charge)

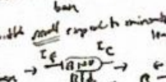
- Ultra Thin Body (UTB) MOSFET
  - most current leaks beyond surface
  - SOI, no for leakage!
  - BOX buried oxide



at expense of
$x_{Si} < L_g/4$
to benefit

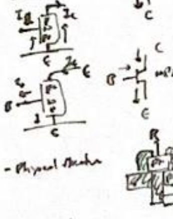
- Multigate MOSFET or FINFET
  - Tall, short, nanowire

- Bipolar Junction Transistor (BJT)
  - PNP
  - NPN



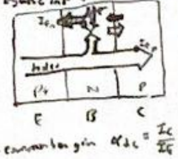
  - base width small compared to minority diff length

common base →
common emitter
common collector



- Physical Sketch

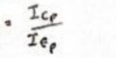
- BJT design
  - injected minority don't recombine in neutral base
  - emitter current mostly carriers injected into base (not emitter)
  - ↓W_{base} ⇒ ↑β
  - emitter efficiency



$$\gamma = \frac{I_{Ep}}{I_{Ep} + I_{En}}$$

  - Base transport Factor $\quad \alpha_T = \frac{I_{Cp}}{I_{Ep}}$
  - common base gain $\alpha_{dc} = \frac{I_C}{I_E} = \gamma\alpha_T$
  - common emitter $\beta_{dc} = \frac{I_C}{I_B} = \frac{\alpha_{dc}}{1 - \alpha_{dc}}$

- Current
  - Assume low level injection (majority carrier concentration change little)
    $\Delta p \ll p_0$, $\Delta n \ll n_0$



- emitter diffusion $\Delta n_E(x''=0) = n_{E0}(e^{qV_{EB}/kT} - 1)$
- base diff $\Delta p_B(0) = p_{B0}(e^{qV_{EB}/kT} - 1)$
  $\Delta p_B(W) = p_{B0}(e^{qV_{CB}/kT} - 1)$
- collector $\Delta n_C(x'=0) = n_{C0}(e^{qV_{CB}/kT} - 1)$

$N_E = N_{A_E}$	$N_B = N_{D_B}$	$N_C = N_{AC}$
$D_E = D_N$	$D_B = D_P$	$D_C = D_N$
$\tau_E = \tau_n$	$\tau_B = \tau_p$	$\tau_E = \tau_n$
$L_E = L_N$	$L_B = L_P$	$L_E = L_N$
$n_{E0} = \frac{n_i^2}{N_E}$	$p_{B0} = \frac{n_i^2}{N_B}$	$n_{C0} = \frac{n_i^2}{N_C}$

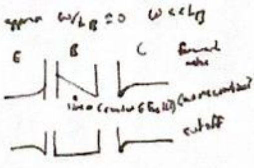
$$I_{En} = -qA\frac{D_E}{L_E}n_{E0}\left(e^{qV_{EB}/kT} - 1\right)$$

$$I_{Cn} = -qA\frac{D_C}{L_C}n_{C0}\left(e^{qV_{CB}/kT} - 1\right)$$

I_{Ep}, I_{Cp} just no ∴

- approx $W/L_B \approx 0$ $\quad W \ll L_B$

$$\gamma = \frac{1}{1 + \frac{D_E}{D_B}\frac{N_B}{N_E}\frac{W}{L_E}}$$

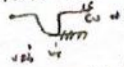


$$\alpha_T = \frac{1}{1 + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$

$$\alpha_{dc} = \frac{1}{1 + \frac{D_E}{D_B}\frac{N_B}{N_E}\frac{W}{L_E} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$

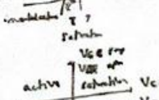
$$\beta_{dc} = \frac{1}{\frac{D_E}{D_B}\frac{N_B}{N_E}\frac{W}{L_E} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$

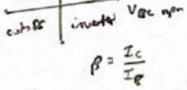
- Extra
- MOSFET has no hopping/mean ideal



- ϕ_s is a quadratic! ϕ_s, $\sqrt{\phi_s}$
  x^2, x $x \ge 0$
- at flatband, $\phi_s = 0$
  - V_g changes ϕ_s
- prefer light doped drain bc hot carrier effects (impact ionization) at high V_D
- ↓V_T rolloff ↓S = ↓ L
  ⇒ ↑C_{ox} to match, high-k same for thicker, low leakage

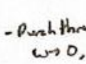
- Modes of Operation
  - Cutoff - base diode off $V_{BE} < 0.6V$
  - Saturation - on, I_c limited by low V_{CE}
  - Active - I_c controlled by I_B, V_{CE} ...





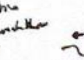
$$\beta = \frac{I_C}{I_B}$$

- base width modulation
  ↑$W_{dep,CB}$ ⇒ ↓W ⇒ ↑I_C "Early effect"

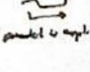


$r_o = \frac{V_A}{I_C}$
- reduce?
  ↑W base
  ↑N_B
  ↓N_C

- Punch through
  W → 0, ↑↑I_C



- Avalanche Multiplication
  - may occur before punchthrough
  - wide & gap between
  ↑↑I_C



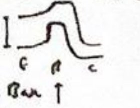
e⁻ generated & amplified as extra I_B?

- Emitter Bandgap Narrowing

$\beta \propto \frac{N_E}{N_B}\cdot\frac{n_{iB}^2}{n_{iE}^2}$ $\quad n_{iE}^2 > n_i^2$ heavy doping ⇓ ↓E_g by ΔE_g

$n_{iE}^2 = n_i^2 e^{\Delta E_{gE}/kT}$
negligible $<10^{18}$

- Heterojunction BJT
  - wide bandgap emitter $\beta \propto \frac{N_E}{N_B}\cdot\frac{n_{iB}^2}{n_{iE}^2}$



- Narrow Bandgap Base ↑
  - further ↑β