Electrical Characteristics of MOSFETs

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References

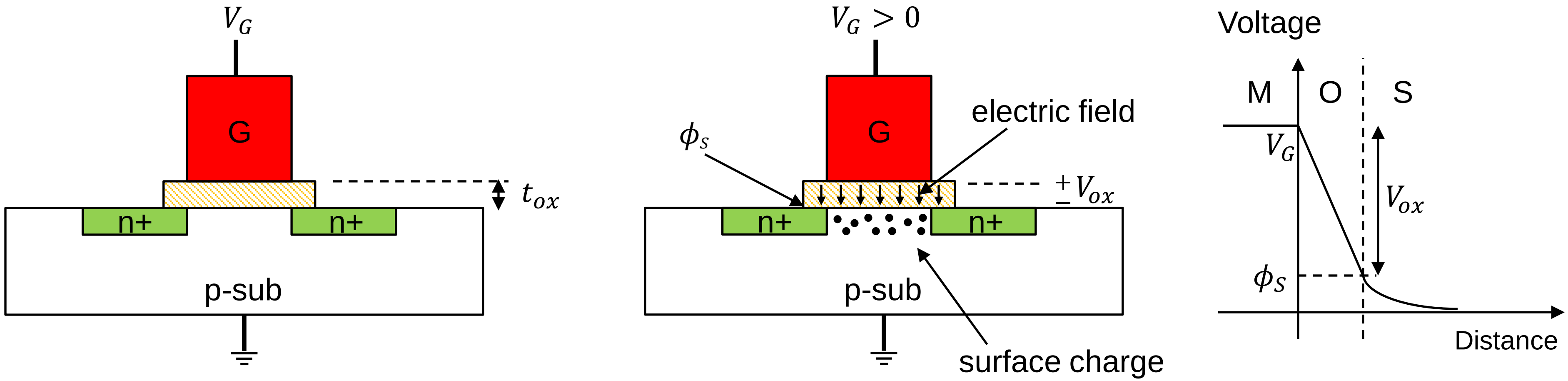
- John P. Uyemura, “Introduction to VLSI Circuits and Systems,” 2002.
  - Chapter 6
- Neil H. Weste and David M. Harris, “CMOS VLSI Design: A Circuits and Systems Perspective,” 2011.
  - Chapter 2

Goal

- Understand the electrical characteristics of MOSFETs.

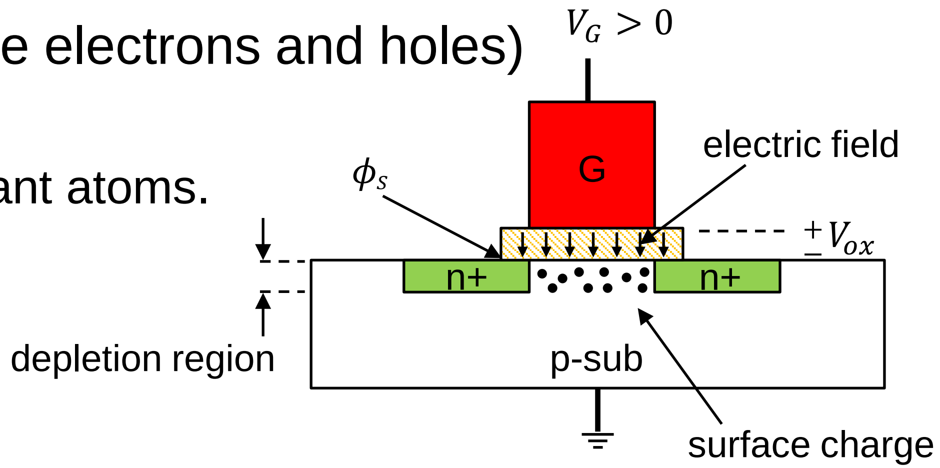
MOS Physics – Threshold Voltage (nFET)

- Oxide capacitance per unit area (F/m^2)
  - $c_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$
- Surface charge per unit area (C/m^2)
  - $Q_S = -c_{ox} V_G$
- $V_G = V_{ox} + \phi_S$
  - ϕ_S: surface potential



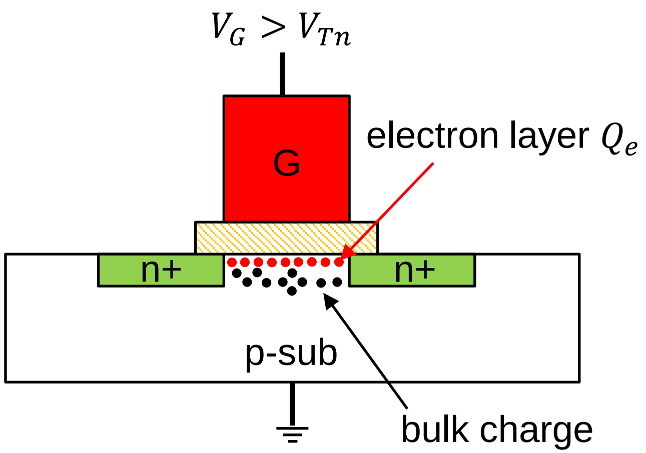
MOS Physics – Threshold Voltage (nFET)

- Force on a charged particle
  - $F = Q_{particle}E$
    - $F_e = -qE$ (for electrons)
    - $F_h = +qE$ (for holes)
- Bulk charge density (negative charge on the surface)
  - $Q_B = -\sqrt{2q\varepsilon_{si}N_a\phi_s}$
  - $Q_B = -c_{ox}V_{ox}$
    - $V_{ox} = \frac{1}{c_{ox}}\sqrt{2q\varepsilon_{si}N_a\phi_s}$
- Depletion region (depleted of free electrons and holes)
  - Holes: forced away
  - Electrons: absorbed by the dopant atoms.



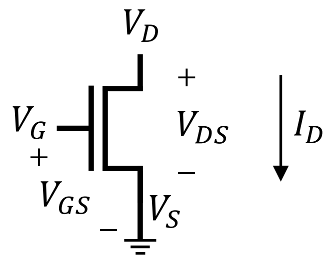
MOS Physics – Threshold Voltage (nFET)

- $V_G < V_{Tn}$
  - $Q_S = Q_B$
- $V_G > V_{Tn}$
  - $Q_S = Q_B + Q_e < 0$
  - The additional electrons are movable.
    - $Q_e = -c_{ox}(V_G - V_{Tn})$
- Surface potential
  - $\phi_S = 2|\phi_F|$
    - $|\phi_F|$: bulk Fermi potential
    - $|\phi_F| = \left(\frac{kT}{q}\right)\ln\left(\frac{N_a}{n_i}\right)$
- Threshold voltage for an ideal MOS structure
  - $V_{Tn} = V_{ox}|_{\phi_S=2|\phi_F|} + 2|\phi_F| = \frac{1}{c_{ox}}\sqrt{2q\varepsilon_{si}N_a(2|\phi_F|)} + 2|\phi_F|$
- A general expression
  - $V_{Tn} = \frac{1}{c_{ox}}\sqrt{2q\varepsilon_{si}N_a(2|\phi_F|)} + 2|\phi_F| + V_{FB} + \frac{qD_I}{c_{ox}}$
    - V_{FB}: flatband voltage
    - D_I: implant dose

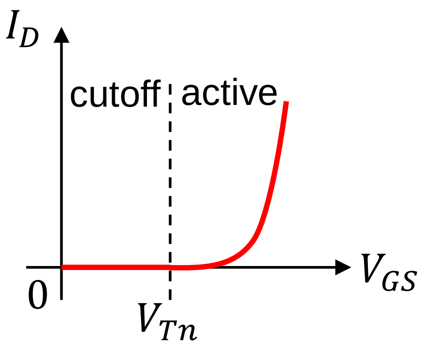


MOS Physics – I-V Characteristics (nFET)

- Cutoff
  - $V_{GS} < V_{Tn}$
  - $I_D = 0$
  - Open switch

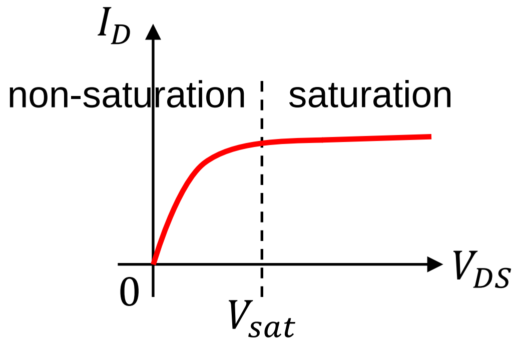


- Active
  - $V_{GS} > V_{Tn}$
  - If $V_{DS} = V_{DD}$
    - $I_D = \frac{1}{2}\mu_n c_{ox}\frac{W}{L}(V_{GS} - V_{Tn})^2 = \frac{1}{2}k_n{'}\frac{W}{L}(V_{GS} - V_{Tn})^2 = \frac{1}{2}\beta_n(V_{GS} - V_{Tn})^2$



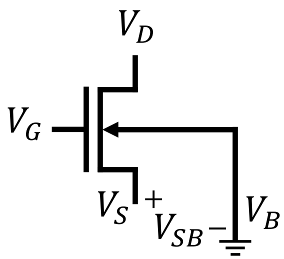
MOS Physics – I-V Characteristics (nFET)

- Active
  - $V_{GS} > V_{Tn}$
  - If V_{DS} varies
    - $I_D = \mu_n c_{ox} \frac{W}{L}\{(V_{GS} - V_{Tn})V_{DS} - \frac{1}{2}{V_{DS}}^2\} = \beta_n\{(V_{GS} - V_{Tn})V_{DS} - \frac{1}{2}{V_{DS}}^2\}$
    - The saturation occurs when $\frac{\partial I_D}{\partial V_{DS}} = 0.$
      - $V_{DS,sat} = V_{GS} - V_{Tn}$ (saturation voltage)
  - If $V_{DS} \geq V_{GS} - V_{Tn}$
    - Saturation
    - $I_D = \frac{1}{2}\beta_n(V_{GS} - V_{Tn})^2$
    - $I_D = \frac{1}{2}\beta_n(V_{GS} - V_{Tn})^2[1 + \lambda(V_{DS} - V_{sat})]$
      - λ: Channel-length modulation parameter

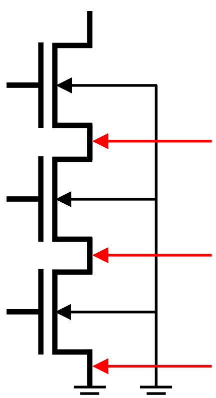


MOS Physics – I-V Characteristics (nFET)

- Body-bias effects
  - occurs when $V_{SB} > 0$.
    - V_B: bulk potential
  - $V_{Tn} = V_{T0n} + \gamma(\sqrt{2|\phi_F| + V_{SB}} - \sqrt{2|\phi_F|})$
    - γ: Body-bias coefficient
      - $\gamma = \frac{\sqrt{2q\varepsilon_{si}N_a}}{c_{ox}}$
    - $2|\phi_F|$: Bulk Fermi potential



- Example (NAND3)



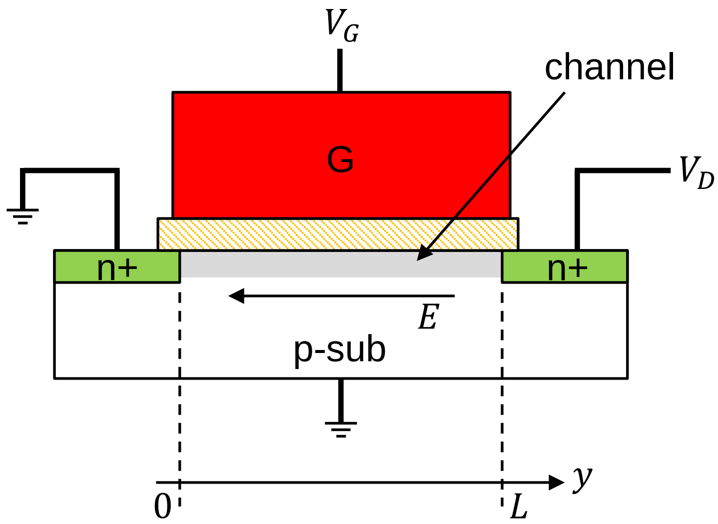
$V_{S3} > 0 \Rightarrow V_{SB3} > 0 \Rightarrow V_{Tn} > V_{T0n}$

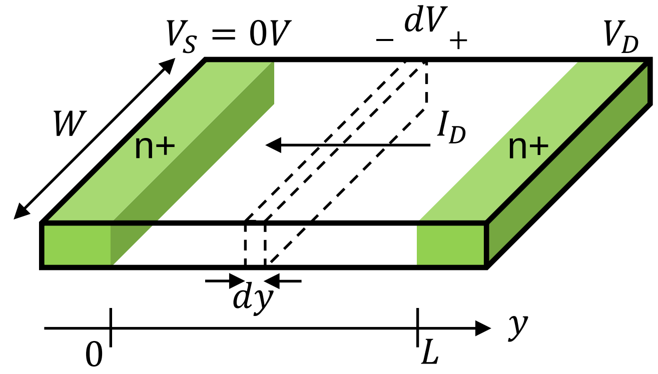
$V_{S2} > 0 \Rightarrow V_{SB2} > 0 \Rightarrow V_{Tn} > V_{T0n}$

$V_{S1} = 0 \Rightarrow V_{SB1} = 0 \Rightarrow V_{Tn} = V_{T0n}$

MOS Physics – I-V Characteristics (nFET)

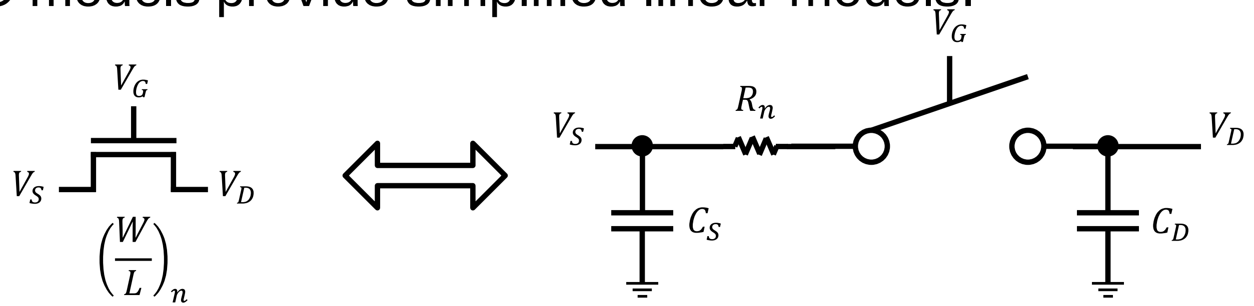
- Derivation
  - $E(y) = -\frac{dV}{dy}$
    - Boundary conditions
      - $V(0) = 0$
      - $V(L) = V_{DS}$
  - Charge
    - $Q_e(y) = -c_{ox}[V_{GS} - V_{Tn} - V(y)]$
  - $dV = I_D dR$
  - $dR = \frac{1}{\sigma_n} \cdot \frac{dy}{A_n} = \frac{1}{q \cdot u_n \cdot n_e} \cdot \frac{dy}{W \cdot x_e}$
    - x_e: channel thickness
  - Channel charge density
    - $Q_e = -qn_e x_e$
  - $dV = -\frac{I_D dy}{\mu_n W Q_e} = \frac{I_D dy}{\mu_n W c_{ox}(V_{GS} - V_{Tn} - V)}$
  - $I_D \int_0^L dy = \mu_n W c_{ox} \int_0^{V_{DS}} [V_{GS} - V_{Tn} - V] dV$
  - $I_D = \mu_n c_{ox} \frac{W}{L} [(V_{GS} - V_{Tn}) V_{DS} - \frac{1}{2} {V_{DS}}^2]$



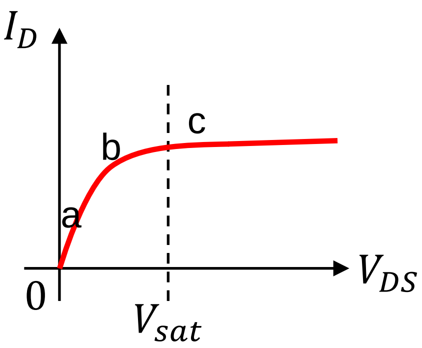


MOS Physics – FET RC Model

- FET RC models provide simplified linear models.

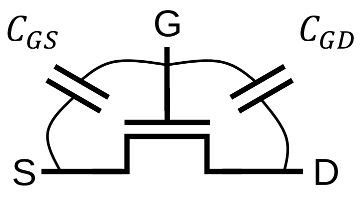


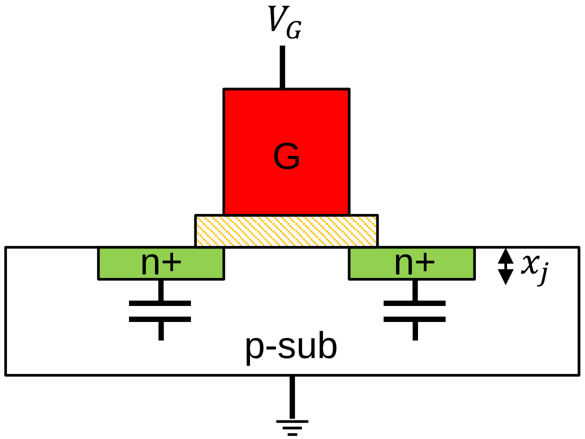
- R_n varies depending on V_{DS}.
  - $R_n = \frac{V_{DS}}{I_D}$
  - At a: $R_n \approx \frac{1}{\beta_n(V_{GS}-V_{Tn})}$
  - At b: $R_n = \frac{1}{\beta_n[(V_{GS}-V_{Tn})-\frac{1}{2}V_{DS}]}$
  - At c: $R_n = \frac{2V_{DS}}{\beta_n(V_{GS}-V_{Tn})^2}$
  - In general
    - $R_n = \frac{\eta}{\beta_n(V_{DD}-V_{Tn})}$ $(\eta = 1 \sim 6)$.

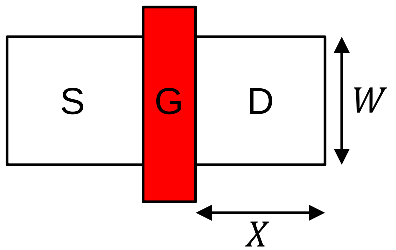


MOS Physics – FET RC Model

- Capacitance
  - MOS capacitance
    - $C_G = c_{ox} A_G$ (gate capacitance)
    - $C_{GS} \approx C_{GD} \approx \frac{1}{2} C_G$
  - Junction (depletion) capacitance
    - $C = \frac{C_0}{\left(1+\frac{V_R}{\phi_0}\right)^{m_j}}$
      - $C_0 = C_j A_{pn}$
        - » zero-bias capacitance
        - » C_j: given
        - » A_{pn}: pn junction area
      - ϕ_0: built-in potential
      - m_j: grading coefficient
    - $C_n = C_{bot} + C_{sw} = C_j XW + C_j x_j (2W + 2X)$
    - $C_n = \frac{C_j XW}{\left(1+\frac{V_R}{\phi_0}\right)^{m_j}} + \frac{C_j x_j (2W+2X)}{\left(1+\frac{V_R}{\phi_{0sw}}\right)^{m_{jsw}}}$

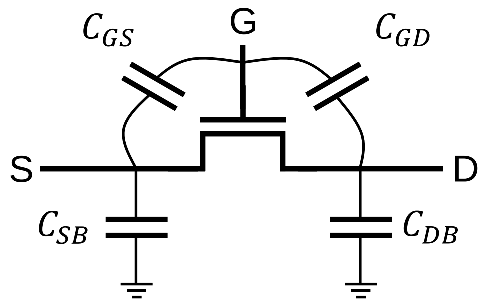




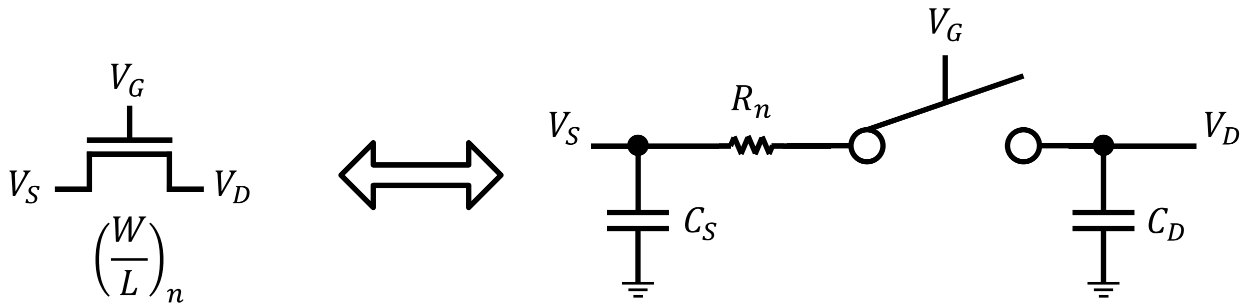


MOS Physics – FET RC Model

- FET RC model

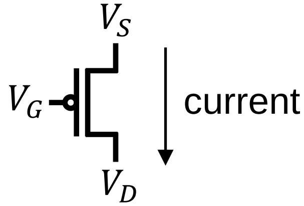


  - $C_S = C_{GS} + C_{SB}$
  - $C_D = C_{GG} + C_{DB}$



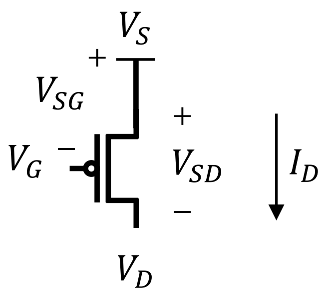
MOS Physics – pFET

- $V_{SG} < |V_{Tp}|$
  - $Q_h = 0$
- $V_{SG} > |V_{Tp}|$
  - $Q_h > 0$
- Threshold voltage
  - $V_{Tp} = -\frac{1}{c_{ox}}\sqrt{2q\varepsilon_{si}N_d\left(2\phi_{Fp}\right)} - 2\phi_{Fp} + V_{FBp} \mp \frac{qD_I}{c_{ox}}$
    - $2\phi_{Fp} = 2\left(\frac{kT}{q}\right)\ln\left(\frac{N_d}{n_i}\right)$: surface potential
    - V_{FBp}: flatband voltage

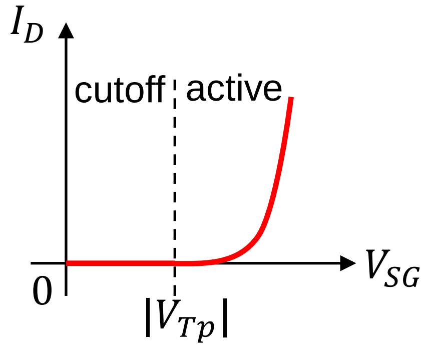


MOS Physics – pFET

- Cutoff
  - $V_{SG} < |V_{Tp}|$
  - $I_D = 0$
  - Open switch

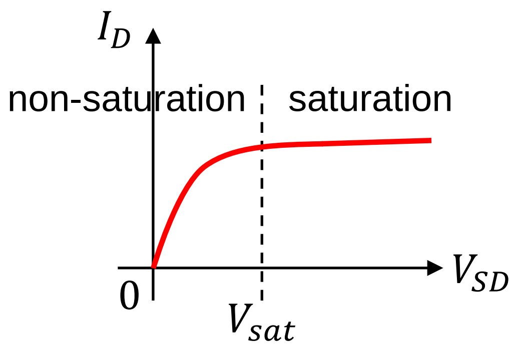


- Active
  - $V_{SG} > |V_{Tp}|$
  - If $V_{SD} = V_{DD}$
    - $I_D = \frac{1}{2}\mu_p c_{ox}\frac{W}{L}\left(V_{SG} - |V_{Tp}|\right)^2 = \frac{1}{2}k_p{}'\frac{W}{L}\left(V_{SG} - |V_{Tp}|\right)^2 = \frac{1}{2}\beta_p\left(V_{SG} - |V_{Tp}|\right)^2$



MOS Physics – pFET

- Active
  - $V_{SG} > |V_{Tp}|$
  - If V_{SD} varies
    - $I_D = \mu_p c_{ox} \frac{W}{L}\{(V_{SG} - |V_{Tp}|)V_{SD} - \frac{1}{2}{V_{SD}}^2\} = \beta_p\{(V_{SG} - |V_{Tp}|)V_{SD} - \frac{1}{2}{V_{SD}}^2\}$
    - The saturation occurs when $\frac{\partial I_D}{\partial V_{SD}} = 0.$
      - $V_{SD,sat} = V_{SG} - |V_{Tp}|$ (saturation voltage)
  - If $V_{SD} \geq V_{SG} - |V_{Tp}|$
    - Saturation
    - $I_D = \frac{1}{2}\beta_p(V_{SG} - |V_{Tp}|)^2$



- pFET resistance
  - $R_p = \frac{1}{\beta_p(V_{DD} - |V_{Tp}|)}$