Digital Integrated Circuit
Lecture 7 MOS Transistor Theory

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Review of Previous Lecture

Lecture 6

- Long-channel IV
  - Input and output characteristics
- Capacitance
  - Area and perimeter dependence of diffusion capacitance
- Nonideal IV
  - ON current and OFF current
  - Various device options

2.4 Nonideal IV

2.4. Nonideal IV (4)

- Intel 22 nm transistor

Table I. 22nm modular SoC transistor options and device characteristics

Transistor Type	High Speed Logic		Low Power Logic		High Voltage	
Options	High Performance (HP)	Standard Perf./ Power (SP)	Low Power (LP)	Ultra Low Power (ULP)	1.8 V	3.3 V
Vdd (Volt)	0.75 / 1	0.75 / 1	0.75 / 1	0.75/1.2	1.5/1.8/3.3	3.3 / >5
Gate Pitch (nm)	90	90	90	108	min. 180	min. 450
Lgate (nm)	30	34	34	40	min. 80	min. 280
N/PMOS Idsat/Ioff (mA/um)	1.08/ 0.91 @ 0.75 V, 100 nA/um	0.71 / 0.59 @ 0.75 V, 1 nA/um	0.41 / 0.37 @ 0.75 V 30 pA/um	0.35 / 0.33 @ 0.75 V 15 pA/um	0.92 / 0.8 @ 1.8 V 10 pA/um	1.0 / 0.85 @ 3.3 V 10 pA/um

(Intel’s 2012 IEDM abstract)

2.4. Nonideal IV (5)

- Mobility degradation due to the verteic E-field
  - Collisions with oxide interface

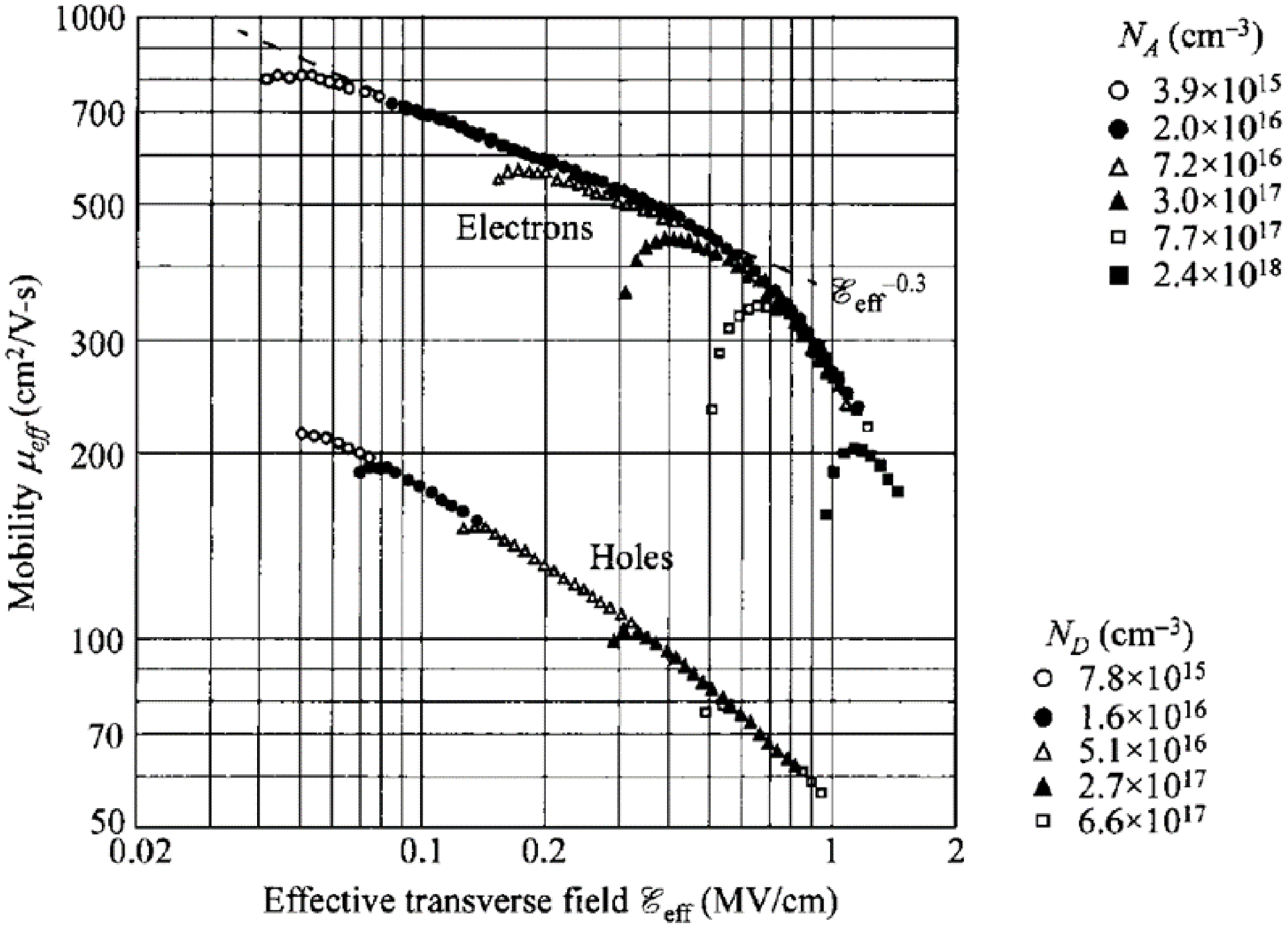
$$\mu_{\text{eff}-n} = \frac{540 \frac{\text{cm}^2}{\text{V}\cdot\text{s}}}{1 + \left(\frac{V_{gs} + V_t}{0.54 \frac{\text{V}}{\text{nm}} t_{\text{ox}}} \right)^{1.85}} \qquad \mu_{\text{eff}-p} = \frac{185 \frac{\text{cm}^2}{\text{V}\cdot\text{s}}}{1 + \frac{\left| V_{gs} + 1.5 V_t \right|}{0.338 \frac{\text{V}}{\text{nm}} t_{\text{ox}}}}$$

Calculate the mobilties at $|V_{gs}|$ = 1.0 V. Assume that t_{ox} = 1.05 nm and $|V_t|$ = 0.3 V.

  - Why do we have different behaviors for electrons and holes?

2.4. Nonideal IV (6)

- Experimental data ("Universal" mobility curve)



Inversion layer mobility (Sze's book)

2.4. Nonideal IV (7)

- Velocity saturation
  - Saturation velocity (Canali model)
  - Electrons: 1.07 X 10^7 cm/sec
  - Holes: 8.37 X 10^6 cm/sec
  - A simple model

$$v = \begin{cases} \dfrac{\mu_{\mathrm{eff}} E}{1 + \dfrac{E}{E_c}} & E < E_c \\ v_{\mathrm{sat}} & E \geq E_c \end{cases}$$

$$E_c = \frac{2 v_{\mathrm{sat}}}{\mu_{\mathrm{eff}}}$$

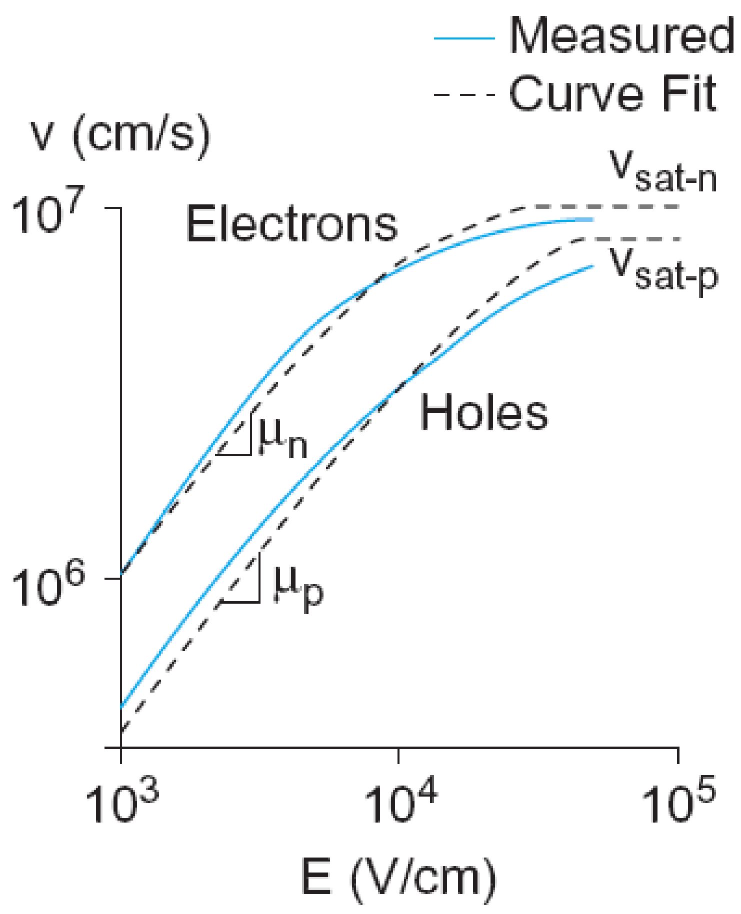


Fig. 2.15

2.4. Nonideal IV (8)

- When the electric field is lower than E_c,

$$E = \frac{I_d}{\mu_n C_{OX} W \left(V_g - V_t - V_c \right) - \frac{I_d}{E_c}} = \frac{dV_c}{dx}$$

  - (Note that the sign is not correct but understood.)
  - Then, the integration gives

$$LI_d = \int_{V_s}^{V_d} \left[\mu_n C_{OX} W \left(V_g - V_t - V_c \right) - \frac{I_d}{E_c} \right] dV_c$$

$$= \mu_n C_{OX} W \left[\left(V_g - V_t \right) V_{ds} - \frac{1}{2} V_{ds}^2 \right] - \frac{I_d}{E_c} V_{ds}$$

2.4. Nonideal IV (9)

- Drain current with the velocity saturation

$$I_d = \frac{1}{L + \frac{V_{ds}}{E_c}} \mu_n C_{OX} W \left[\left(V_g - V_t\right) V_{ds} - \frac{1}{2} V_{ds}^2 \right]$$

  - With $V_c = E_c L$,

$$I_d = \frac{1}{1 + \frac{V_{ds}}{V_c}} \mu_n C_{OX} \frac{W}{L} \left[\left(V_g - V_t\right) V_{ds} - \frac{1}{2} V_{ds}^2 \right]$$

  - The factor, $\frac{1}{1+\frac{V_{ds}}{V_c}}$, describes the velocity saturation.
  - Then, when do we have the saturation?

2.4. Nonideal IV (10)

- Condition for saturation, $E = E_c$ @ $x = L$
  - In this case, $V_d = V_{dsat}$ and $I_d = I_{dsat}$

$$E_c = \frac{I_{dsat}}{\mu_n C_{OX} W\left(V_g - V_t - V_{dsat}\right) - \frac{I_{dsat}}{E_c}}$$

  - The saturation current becomes

$$I_{dsat} = \frac{1}{2}\mu_n C_{OX} W\left(V_g - V_t - V_{dsat}\right)E_c$$

  - What is V_{dsat}?

2.4. Nonideal IV (11)

- Equating two expressions,

$$I_{dsat} = \frac{1}{2}\mu_n C_{OX} W \left(V_g - V_t - V_{dsat}\right) E_c$$

$$I_{dsat} = \frac{1}{1 + \frac{V_{dsat}}{V_c}} \mu_n C_{OX} \frac{W}{L} \left[\left(V_g - V_t\right) V_{dsat} - \frac{1}{2} V_{dsat}^2\right]$$

  - With the gate overdrive voltage, $V_{GT} \equiv V_g - V_t$, we can find

$$V_{dsat} = \frac{V_{GT} V_c}{V_{GT} + V_c}$$

$$I_{dsat} = C_{OX} W \frac{V_{GT}^2}{V_{GT} + V_c} v_{sat}$$

  - Two extreme cases, $V_{GT} \ll V_c$ and $V_{GT} \gg V_c$

Homework#2

- Due: AM08:00, September 21
- Problem#1
  - Compare three modes for the velocity saturation:
  - 1) The one studied in this lecture.
  - 2) $v_{sat} = \frac{\mu_{eff}E}{\sqrt{1+\left(\frac{E}{E_c}\right)^2}}$
  - 3) $v_{sat} = \frac{\mu_{eff}E}{1+\frac{E}{E_c}}$ for any E value
  - Draw the velocity-field graph in the semi-logarithmic scale. μ_{eff} is 710 cm^2/V sec and E_c is 11 kV/cm. The electric field varies from 100 V/cm to 100 kV/cm.

Homework#2

- Problem#2
  - Draw the output characteristics of an NMOSFET, by using two IV models. Compare them.
  - 1) Long-channel IV
  - 2) The one studied in this lecture.
  - Parameters are: W is 100 µm. L is 1 µm. t_{ox} is 25 nm. The effective mobility is assumed to be a constant of 500 cm^2/V sec, for simplicity. E_c is 11 kV/cm. Consider five values of V_{GT}: 0.5 V, 1.0 V, 1.5 V, 2.0 V, and 2.5 V. Increase the drain voltage up to 3.0 V.

2.4. Nonideal IV (12)

- Threshold voltage (Body effect)
  - It is given by

$$V_t = \frac{\sqrt{2\epsilon_{si} q N_A}}{C_{ox}} \sqrt{\phi_s + V_{sb}} + V_{FB} + \phi_s$$

$$\phi_s = 2 v_T \log \frac{N_A}{n_i}$$

  - At zero V_{sb},

$$V_{t0} = \gamma \sqrt{\phi_s + V_{sb}} + V_{FB} + \phi_s$$

  - Therefore,

$$V_t = V_{t0} + \gamma \left(\sqrt{\phi_s + V_{sb}} - \sqrt{\phi_s} \right)$$

2.4. Nonideal IV (13)

- Leakage
  - Subthreshold slope
  - Drain-induced barrier lowering
  - Gate-induced drain leakage

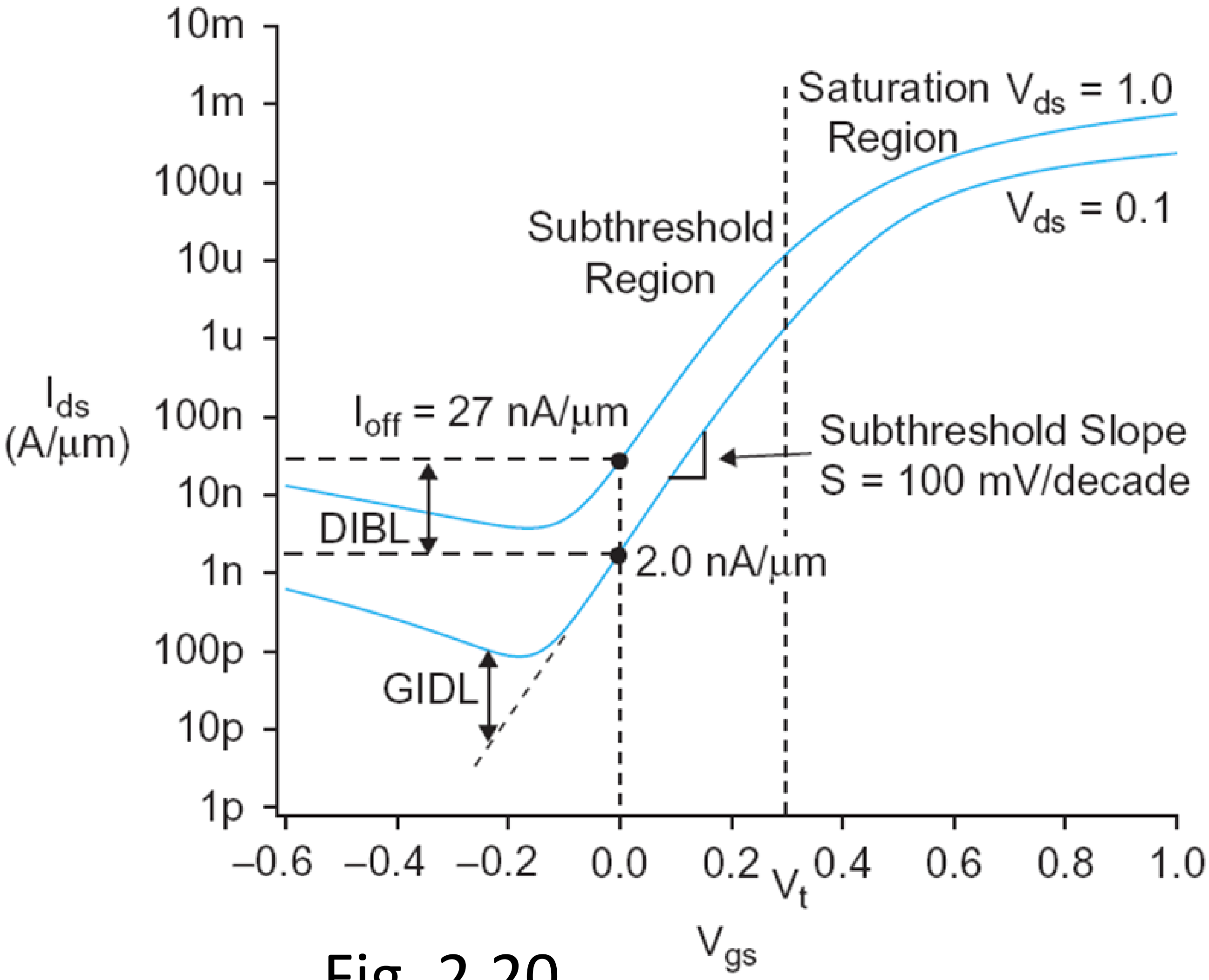


Fig. 2.20

Thank you!