Chapter 5

Field Effect Transistors

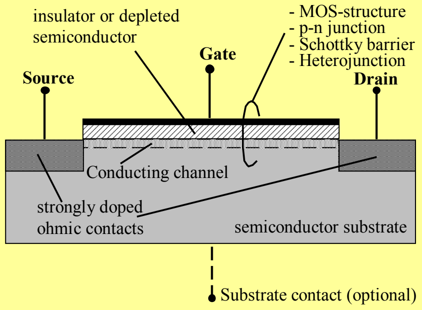
T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Contents

- ***Principle of operation of FETs:***
  - Basic structure and properties
  - Introduction of various types of FETs (MOSFET, MESFET, HFET, TFT)
- ***Basic FET modeling:***
  - Gradual channel approximation
  - Basic FET models: Threshold voltage, charge control models, velocity saturation
  - SPICE implementation and examples

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Principle of FET Operation



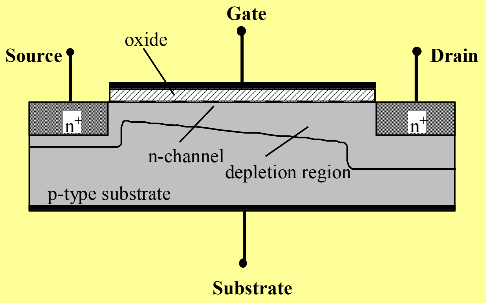
T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Principle of FET Operation (Cont.)

- Conducting semiconductor channel between two ohmic contacts – source and drain
- The gate terminal controls the channel current
- The gate structure acts as a two-terminal device:
  - MOS-structure (MOSFET)
  - *p-n* junction (JFET)
  - Schottky barrier (MESFET)
  - Heterojunction (HFET)
- The gate is a very high-impedance terminal

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Basic MOSFET Operation



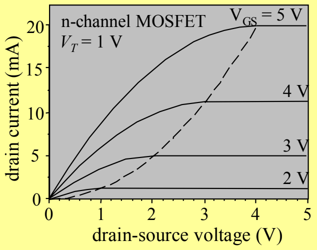
T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Basic MOSFET Operation (Cont.)

- The **channel current** is carried by inversion charge at the semiconductor/oxide interface. This charge is controlled by the gate voltage
- The **threshold voltage** V_T defines the onset of strong inversion in the channel
- The channel current saturates at a sufficiently high drain-source voltage. Mechanisms: **Pinch-off** ($V_{SAT} = V_{GS} - V_T$) or **velocity saturation**

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

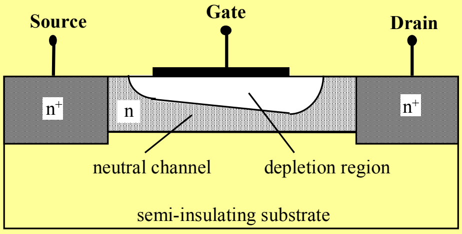
Long-Channel MOSFET Characteristics



- Saturation by pinch-off for *n*-channel MOSFET
- The broken line indicates where the characteristics saturate

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Basic MESFET Operation

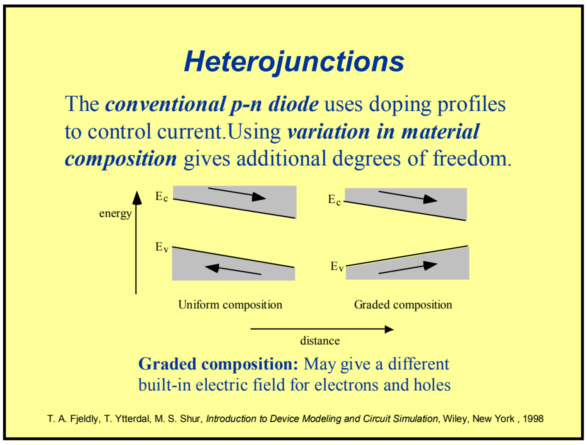


T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Basic MESFET Operation (Cont.)

- The **channel** is defined by the neutral part of the doped n-type layer. The gate voltage controls the width of the Schottky barrier depletion region
- The **threshold voltage** is defined by full depletion of the channel
- The current saturates because of **saturation** of the electron velocity near drain
- MESFETs are typically made from **GaAs** because of its low effective electron mass and the velocity overshoot effect

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

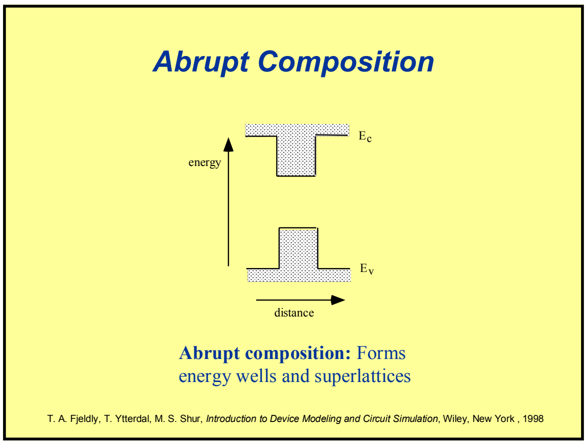


Heterojunctions

The ***conventional p-n diode*** uses doping profiles to control current.Using ***variation in material composition*** gives additional degrees of freedom.

Graded composition: May give a different built-in electric field for electrons and holes

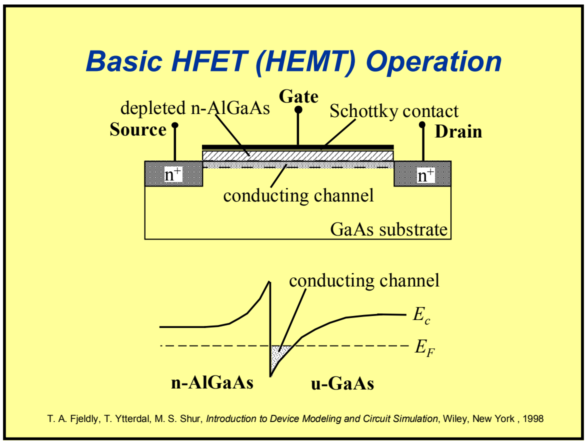
T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998



Abrupt Composition

Abrupt composition: Forms energy wells and superlattices

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998



Basic HFET (HEMT) Operation

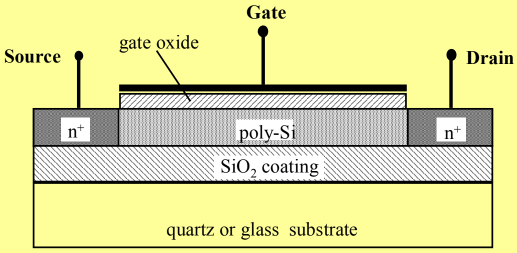
T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Basic HFET Operation (Cont.)

- **Material system:** Typically GaAs/AlGaAs
- **Channel:** Defined by electrons populating the quantum well at the GaAs/AlGaAs interface
- **Operation:** Similar to MOSFET
- Very **fast** device: $f_T > 300$ GHz

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Poly-Si TFT Operation

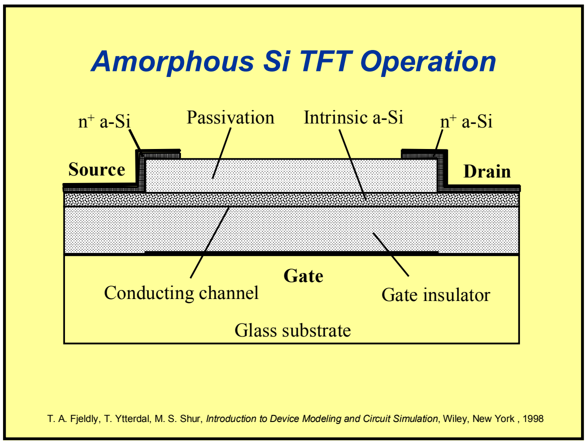


T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Poly-Si TFT Operation (Cont.)

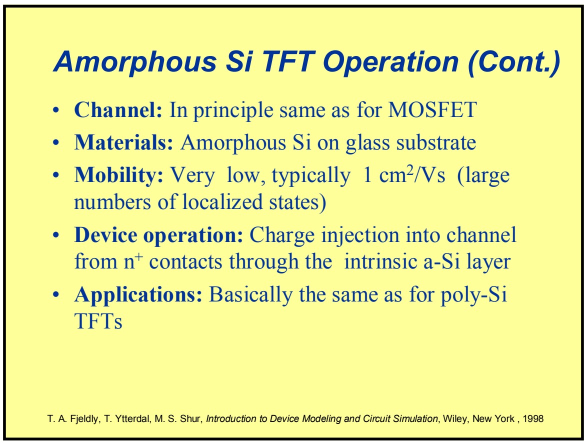
- **Channel:** In principle same as for MOSFET
- **Materials:** Polycrystalline Si on glass or quartz substrate
- **Mobility:** 30 – few hundred cm^2/Vs (electron scattering on grain boundaries)
- **Applications:** Large area flat panel displays, printers, scanners

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998



Amorphous Si TFT Operation

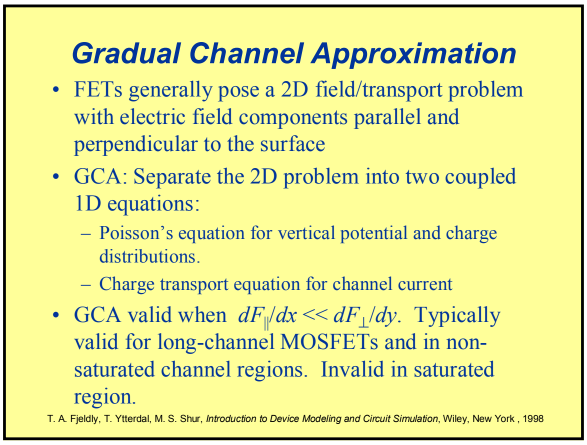
T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998



Amorphous Si TFT Operation (Cont.)

- **Channel:** In principle same as for MOSFET
- **Materials:** Amorphous Si on glass substrate
- **Mobility:** Very low, typically 1 cm^2/Vs (large numbers of localized states)
- **Device operation:** Charge injection into channel from n$^+$ contacts through the intrinsic a-Si layer
- **Applications:** Basically the same as for poly-Si TFTs

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

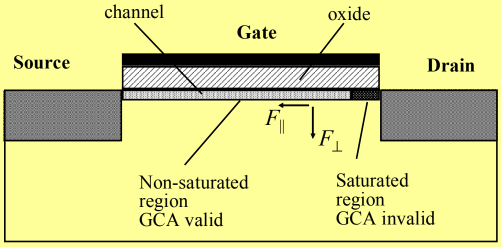


Gradual Channel Approximation

- FETs generally pose a 2D field/transport problem with electric field components parallel and perpendicular to the surface
- GCA: Separate the 2D problem into two coupled 1D equations:
  - Poisson's equation for vertical potential and charge distributions.
  - Charge transport equation for channel current
- GCA valid when $dF_{\parallel}/dx << dF_{\perp}/dy$. Typically valid for long-channel MOSFETs and in non-saturated channel regions. Invalid in saturated region.

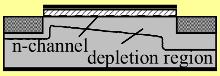
T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Gradual Channel Approximation (Cont.)



T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

The Meyer MOSFET Model



Use results from the MIS capacitor. Add connections between channel and source and drain.

Total charge per unit area in the semiconductor: $q_s = -c_i\left[V_{GS} - V_{FB} - 2\varphi_b - V(x)\right]$

Depletion charge per unit area:

$$q_{dep} = -qN_a d_{dep} = -\sqrt{2\varepsilon_s qN_a\left[2\varphi_b + V(x)\right]}$$

⇒ Inversion (electronic) charge per unit area:

$$q_i = -qn_s = -c_i\left[V_{GS} - 2\varphi_b - V_{FB} - V(x)\right] + \sqrt{2\varepsilon_s qN_a\left[2\varphi_b + V(x)\right]}$$

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Meyer I-V Characteristics

$$I_d = \frac{W\mu_n c_i}{L}\left\{\left(V_{GS} - V_{FB} - 2\varphi_b - \frac{V_{DS}}{2}\right)V_{DS} - \frac{2\sqrt{2\varepsilon_s qN_a}}{3c_i}\left[\left(V_{DS} + 2\varphi_b\right)^{3/2} - \left(2\varphi_b\right)^{3/2}\right]\right\}$$

Saturation voltage ($n_s(L) = 0$)

$$V_{SAT} = V_{GS} - 2\varphi_b - V_{FB} + \frac{\varepsilon_s qN_a}{c_i^2}\left[1 - \sqrt{1 + \frac{2c_i^2\left(V_{GS} - V_{FB}\right)}{\varepsilon_s qN_a}}\right]$$

Note : $V_{GS} - V_T \equiv V_{GT} = V_{SAT}$ for small N_a

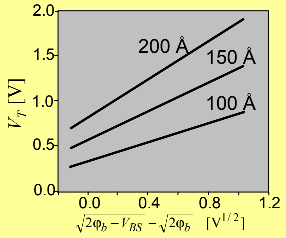
T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

MOSFET Threshold Voltage

For MIS capacitor: $V_T = V_{FB} + 2\varphi_b + \sqrt{4\varepsilon_s q N_a \varphi_b} / c_i$

For MOSFET (with source and drain connected) and substrate bias:

$$V_T = V_{FB} + 2\varphi_b + \sqrt{2\varepsilon_s q N_a (2\varphi_b - V_{BS})} / c_i$$



Body plot

Slope: $\gamma = \sqrt{2\varepsilon_s q N_a} / c_i$

(Body effect parameter)

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Simple Charge Control I-V Model

Parallel plate capacitor model for inversion charge:
(neglect variation in depletion charge along the channel)

$$qn_s = c_i [V_{GT} - V(x)]$$

I–V characteristics (constant mobility):

$$I_d = W\mu_n q n_s F = W\mu_n c_i (V_{GT} - V)\frac{dV}{dx}$$

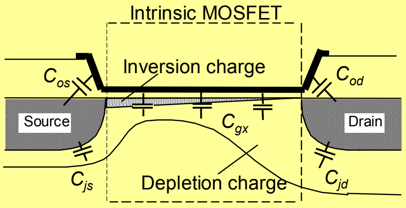
$$\Rightarrow I_d = \frac{W\mu_n c_i}{L} \times \begin{cases} V_{GT}V_{DS} - V_{DS}^2/2, & \text{for } V_{DS} \le V_{SAT} = V_{GT} \\ V_{GT}^2/2, & \text{for } V_{DS} > V_{SAT} \end{cases}$$

Transconductance:

$$g_m = \left.\frac{\partial I_d}{\partial V_{GS}}\right|_{V_{DS}} = \frac{W\mu_n c_i}{L} \times \begin{cases} V_{DS}, & \text{for } V_{DS} \le V_{SAT} \\ V_{GT}, & \text{for } V_{DS} > V_{SAT} \end{cases}$$

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

MOSFET Capacitances



T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

MOSFET Capacitances (Cont.)

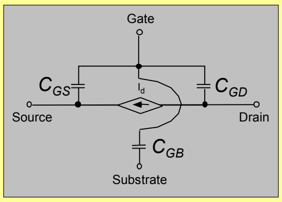
Note: Intrinsic semiconductor charge consists of *inversion charge* and *depletion charge*. In general, these are non-uniformly distributed along the channel.

Capacitance models:

- ***Meyer****:* Derivatives of intrinsic gate charge with respect to terminal voltages.
- ***Ward-Dutton****:* Assign inversion charge to source and drain terminals, and depletion charge to substrate terminal.

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Meyer Capacitance Model



$$C_{GS} = \left.\frac{\partial Q_G}{\partial V_{GS}}\right|_{V_{GD},V_{GB}}$$

$$C_{GD} = \left.\frac{\partial Q_G}{\partial V_{GD}}\right|_{V_{GS},V_{GB}}$$

$$C_{GB} = \left.\frac{\partial Q_G}{\partial V_{GB}}\right|_{V_{GS},V_{GD}}$$

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Meyer Capacitance Model (Cont.)

Gate charge in *strong inversion* (inversion charge dominant):

$$Q_G \approx -Q_i = qW\int_0^L n_s\,dx \approx \tfrac{2}{3}C_i\frac{(V_{GD}-V_T)^3-(V_{GS}-V_T)^3}{(V_{GD}-V_T)^2-(V_{GS}-V_T)^2}$$

Gate charge in *weak inversion* (depletion charge dominant):

$$Q_G \approx -Q_{dep} \approx WL\sqrt{2\varepsilon_s qN_a\psi_s} \approx \gamma C_i\left(\sqrt{\gamma^2/4+V_{GB}-V_{FB}}-\gamma/2\right)$$

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Meyer Capacitances

Strong inversion:

$$C_{GS} = \tfrac{2}{3} C_i \left[1 - \left(\frac{V_{SAT} - V_{DS}}{2V_{SAT} - V_{DS}} \right)^2 \right]$$

$$C_{GD} = \tfrac{2}{3} C_i \left[1 - \left(\frac{V_{SAT}}{2V_{SAT} - V_{DS}} \right)^2 \right]$$

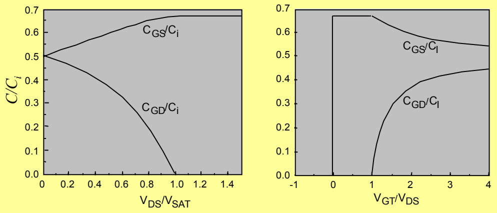
$$C_{GB} = 0$$

Weak inversion:

$$C_{GS} = C_{GD} = 0, \qquad C_{GB} = C_i \Big/ \sqrt{1 + 4\left(V_{GB} - V_{FB}\right)/\gamma^2}$$

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Meyer Capacitances (Cont.)



T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Velocity Saturation in MOSFETs

Must be included in short-channel devices

Velocity-field relationships used in MOSFET modeling:

$$v(F) = \frac{\mu F}{\left[1 + \left(\mu F / v_s\right)^m\right]^{1/m}}$$

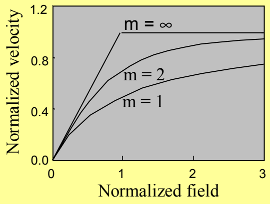
Two-piece v–F model ($m = \infty$):

$$v(F) = \begin{cases} \mu F & \text{for } F < F_s \\ v_s & \text{for } F \geq F_s \end{cases}$$

where $F_s = v_s/\mu$

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Velocity Saturation in MOSFETs II



$m = 1$ for p-channel MOSFET
$m = 2$ for n-channel MOSFET
$m = \infty$ two-piece v–F model

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Simple Velocity Saturation I–V Model

- Use two-piece v–F relationship
- Current saturation occurs when $F(L) = F_s$
- Use simple charge control model below saturation

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Simple Velocity Saturation I–V Model (Cont.)

⇒ I–V characteristics:

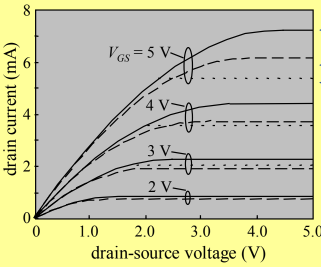
$$I_d = \frac{W\mu_n c_i}{L} \times \begin{cases} V_{GT}V_{DS} - V_{DS}^2/2 & \text{for } V_{DS} \le V_{SAT} \\ V_L^2\left[\sqrt{1+(V_{GT}/V_L)^2} - 1\right] & \text{for } V_{DS} > V_{SAT} \end{cases}$$

Saturation voltage:

$$V_{SAT} = V_{GT} - V_L\left[\sqrt{1+\left(\frac{V_{GT}}{V_L}\right)^2} - 1\right] \quad \text{where } V_L = F_s L$$

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Comparison of Basic MOSFET Models



<– Simple Charge Control Model (constant µ)
<– Meyer Model
<– Velocity Saturation Model

L = 2 µm
V_T = 0.43 V
$N_a = 10^{22}$ m^{-3}

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

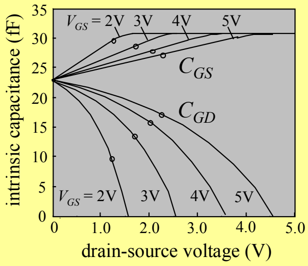
Comparison of Basic MOSFET Models (Cont.)

Conclusion

- SCCM overestimates the saturation current (neglects velocity saturation and variation in depletion charge)
- MM shows effect of including variation in depletion charge
- VSM shows effect of including velocity saturation

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Meyer C–V Model with Velocity Saturation



T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Meyer C–V Model with Velocity Saturation

At $V_{DS} = V_{SAT}$:

$$C_{GSs} = \tfrac{2}{3} C_i \left[1 - \left(\frac{V_{SAT}}{2 V_L} \right)^2 \right]$$

$$C_{GDs} = \tfrac{2}{3} C_i \left[1 - \left(1 - \frac{V_{SAT}}{2 V_L} \right)^2 \right]$$

However, $C_{GS} \Rightarrow 2/3 C_i$ and $C_{GD} \Rightarrow 0$ when $V_{DS} > V_{SAT}$, so basic Meyer C–V model is also applicable for short-channel MOSFET.

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

MOSFET Level 1 SPICE Model

(Simple Charge Control Model)

Threshold voltage:

$$V_T = \mathbf{VTO} + \mathbf{GAMMA}\left(\sqrt{\mathbf{PHI} - V_{BS}} - \sqrt{\mathbf{PHI}}\right)$$

VTO = $V_T(V_{BS} = 0)$ (Threshold voltage at zero substrate bias)

GAMMA = $\sqrt{2\varepsilon_s q N_a} / c_i$ (Body effect parameter)

PHI = $2\varphi_b = 2V_{th}\ln(N_a/n_i)$ (Surface potential)

(Alternatively, specify **TOX** = d_i , **NSUB** = N_a , **UO** = μ_n)

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

SPICE Level 1 Model (Cont.)

I–V characteristics:

$$I_d = \frac{\mathbf{W} \cdot \mathbf{KP}(1 + \mathbf{LAMBDA} \cdot V_{DS})}{\mathbf{L} - 2\mathbf{LD}} \times \begin{cases} V_{GT} V_{DS} - V_{DS}^2 / 2, & V_{DS} \le V_{GT} \\ V_{GT}^2 / 2, & V_{DS} > V_{GT} \\ 0, & V_{GT} < 0 \end{cases}$$

L, W (Gate length and with, specified on the device line)
LD (Lateral diffusion)
KP = $\mu_n c_i$ (Transconductance coefficient)
LAMBDA (Channel length modulation parameter)

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

MOSFET Level 2 SPICE Model

(Modified Meyer Model)

Threshold voltage: Same as Level 1, but can define **VTO** in terms of type of gate (**TPG**), substrate doping (**NSUB**), and surface density of states (**NSS**)

Saturation voltage:

$$V_{SAT} = V_{GS} - \mathbf{PHI} - V_{FB} + \frac{\mathbf{GAMMA}^2}{2}\left[1 - \sqrt{1 + \frac{4(V_{GS} - V_{FB})}{\mathbf{GAMMA}^2}}\right]$$

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

SPICE Level 2 Model (Cont.)

I–V characteristics (above threshold, below saturation):

$$I_d = \frac{\mathbf{W}}{\mathbf{L} - 2\mathbf{LD}}\,\frac{\mathbf{KP}}{1 - \mathbf{LAMBDA}\cdot V_{DS}}\left\{\left(V_{GS} - V_{FB} - \mathbf{PHI} - \frac{V_{DS}}{2}\right)V_{DS} - \tfrac{2}{3}\mathbf{GAMMA}\left[(V_{DS} - V_{BS} + \mathbf{PHI})^{3/2} - (-V_{BS} + \mathbf{PHI})^{3/2}\right]\right\}$$

TPG determines V_{FB}. **LAMBDA** can be modeled in terms of **NSUB**.

Additional modeling features: Field (bias) dependent mobility (**UCRIT**, **UTRA**, **UEXP**), velocity saturation (**VMAX**), Subthreshold current (**NFS**)

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

MOSFET Level 3 SPICE Model

(Modified Velocity Saturation Model)

I–V characteristics (above threshold, below saturation):

$$I_d = \frac{\mathbf{W}}{\mathbf{L} - 2\mathbf{LD}}\mathbf{KP}\left[V_{GT}V_{DS} - \frac{1 + F_B}{2}V_{DS}^2\right]$$

F_B accounts for short and narrow channel effects, enters into V_T and V_{SAT}. V_T also includes effects of static feedback from drain to channel (**ETA**).

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

SPICE Level 3 Model (Cont.)

Saturation voltage:

$$V_{SAT} = \frac{V_{GT}}{1+F_B} + \frac{\mathbf{VMAX(L-2LD)}}{\mathbf{U0}} - \sqrt{\left(\frac{V_{GT}}{1+F_B}\right)^2 + \left(\frac{\mathbf{VMAX(L-2LD)}}{\mathbf{U0}}\right)^2}$$

Mobility model: $\mu = \frac{\mathbf{UO}}{1+\mathbf{THETA}\cdot V_{GT}}$

UO : Mobility at threshold

THETA : Parameter for dependence on V_{GT}

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Basic MOSFET SPICE Models: Conclusion

- **Level 1:** Simple charge control model – a long channel model, only good for rough estimates. Uses Meyer's capacitance model. Does not include the subthreshold regime.
- **Level 2:** Modified Meyer model. Includes velocity saturation. Uses Meyer's capacitance model. This model is quite complex (includes many semi-empirical corrections to describe short-channel effects), and may sometimes have difficulties with convergence.

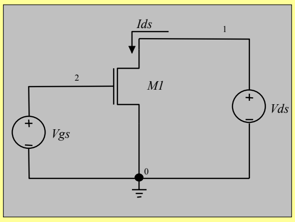
T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Basic MOSFET SPICE Models: Conclusion (Cont.)

- **Level 3:** Modified velocity saturation model. Also quite complex, but more efficient than Level 2. Short channel effects are introduced through the correction factor F_B (in the I–V characteristics and in V_T) and through velocity saturation. Contains both the Meyer and the Ward-Dutton capacitance models.

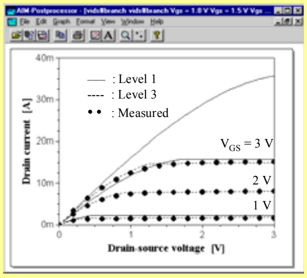
T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Example: MOSFET I–V Characteristics



T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

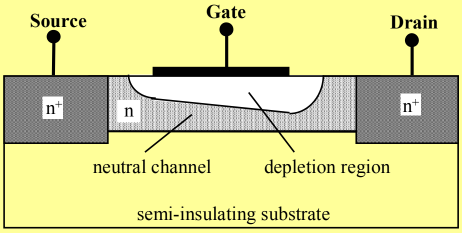
Short-Channel MOSFET Characteristics



L = 0.6 µm
W= 50 µm
V_{To} = 0.51 V

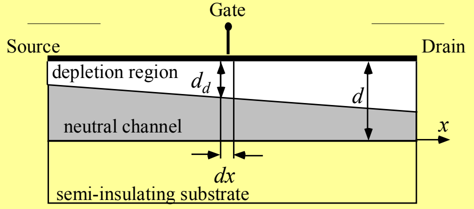
T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Basic MESFET Model



T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Basic MESFET Model (Cont.)



Use results from the Schottky (metal-semiconductor) diode.
Depletion width (Gradual Channel Approximation):

$$d_d(x) = \sqrt{\frac{2\varepsilon_s}{qN_d}\left[V_{bi} - V_{GS} + V(x)\right]}$$

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Basic MESFET Model (Cont.)

Threshold voltage:

$$V_T = V_{bi} - V_{po}$$

Pinch-off voltage:

$$V_{po} = \frac{qN_d d^2}{2\varepsilon_s}$$

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

The Shockley Model

Assume a constant mobility

I–V characteristics ($g_o = qN_d\mu_n Wd/L$):

$$I_d = qN_d W\left[d - d_d(x)\right]\mu_n \frac{dV}{dx}$$

$$\Rightarrow \quad I_d = g_o\left\{V_{DS} - \frac{2}{3V_{po}^{1/2}}\left[\left(V_{DS} + V_{bi} - V_{GS}\right)^{3/2} - \left(V_{bi} - V_{GS}\right)^{3/2}\right]\right\}$$

Pinch-off condition:

$$d_d(L) = d$$

Saturation voltage (Pinch-off):

$$V_{SAT} = V_{GS} - V_T = V_{GT}$$

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

MESFET C-V Model

Because of the similarity between the MESFET Shockley model and the simple MOSFET models, a Meyer-type capacitance model may be used.

Total gate charge ($V_{DS} = 0$):

$$|Q_{Go}| = qN_d WLd_d = qN_d WLd\sqrt{1 - V_{GT}/V_{po}}$$

Corresponding gate-channel capacitance ($C_o = \varepsilon_s WL/d$):

$$C_{ch} = \left.\frac{\partial Q_{Go}}{\partial V_{GT}}\right|_{V_{DS}} = \frac{C_o}{\sqrt{1 - V_{GT}/V_{po}}}$$

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

MESFET C-V Model (Cont.)

"Meyer" capacitances:

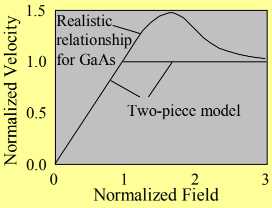
$$C_{GS} = \frac{2}{3}C_{ch}\left[1 - \left(\frac{V_{SAT} - V_{DS}}{2V_{SAT} - V_{DS}}\right)^2\right]$$

$$C_{GD} = \frac{2}{3}C_{ch}\left[1 - \left(\frac{V_{SAT}}{2V_{SAT} - V_{DS}}\right)^2\right]$$

In saturation: $C_{GS} = \frac{2}{3}C_{ch}, C_{GD} = 0$

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

MESFET Velocity Saturation Model



Two-piece linear *v*–*F* model:

$$v(F) = \begin{cases} \mu F, & \text{for } F < F_s \equiv v_s/\mu \\ v_s, & \text{for } F \ge F_s \end{cases}$$

Below saturation – same as for Shockley model

Saturation (approximately):

$$V_{SAT} \approx \left(\frac{1}{V_L} + \frac{1}{V_{GT}}\right)^{-1}$$

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Additional MESFET Models

Square-law model: $I_{sat} = \beta V_{GT}^2$

Curtice model (1980): $I_d = I_{sat}(1+\lambda V_{DS})\tanh(\alpha V_{DS})$

Statz model (1987): $I_{sat} = \dfrac{\beta V_{GT}^2}{1+\alpha V_{GT}}$

Shur (1987): $\beta = \dfrac{2\varepsilon_s v_s W}{d(V_{po}+3V_L)}$

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Basic SPICE MESFET Model

The Statz model – Level 1 in AIM-Spice, Level 2 in PSpice

Linear regime ($V_{DS} < 3/\mathbf{ALPHA}$):

$$I_d = (1+\mathbf{LAMBDA}\cdot V_{DS})\frac{\mathbf{BETA}\cdot V_{GT}^2}{1+\mathbf{B}\cdot V_{GT}}\left[1-\left(1-\frac{\mathbf{ALPHA}\cdot V_{DS}}{3}\right)^3\right]$$

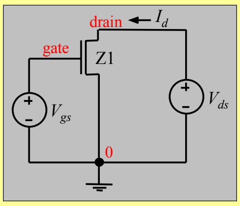
Saturation regime ($V_{DS} \geq 3/\mathbf{ALPHA}$):

$$I_d = (1+\mathbf{LAMBDA}\cdot V_{DS})\frac{\mathbf{BETA}\cdot V_{GT}^2}{1+\mathbf{B}\cdot V_{GT}}$$

VTO = V_{bi} - V_{po} (Threshold voltage)
ALPHA = g_{ch}/I_{sat} (Saturation parameter)
BETA : (Transconductance parameter)
LAMBDA : (Channel length modulation parameter)
B : (Doping tail extention parameter)

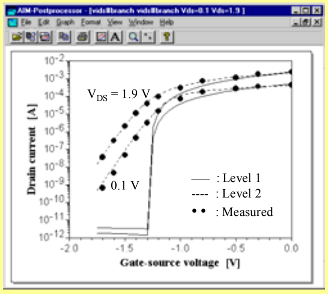
T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Example: MESFET Subthreshold Characteristics



T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

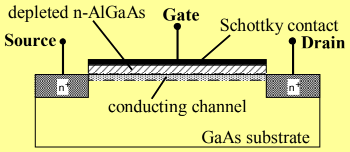
MESFET Subthreshold Characteristics



L = 1 µm
V_{To} = -1.3 V

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

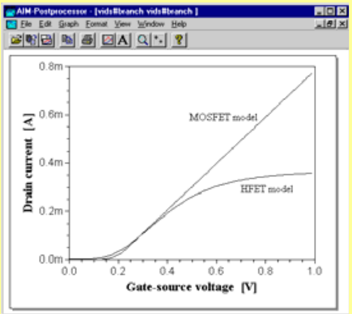
Basic HFET Model



Can use a MOSFET model as a first approximation because of the similarities between HFET and MOSFET.

T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

HFET Transfer Characteristics



T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998