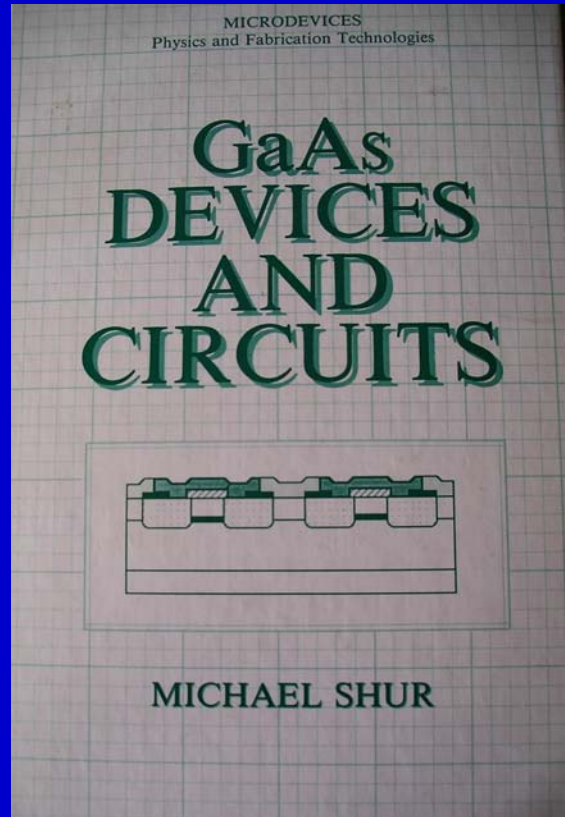
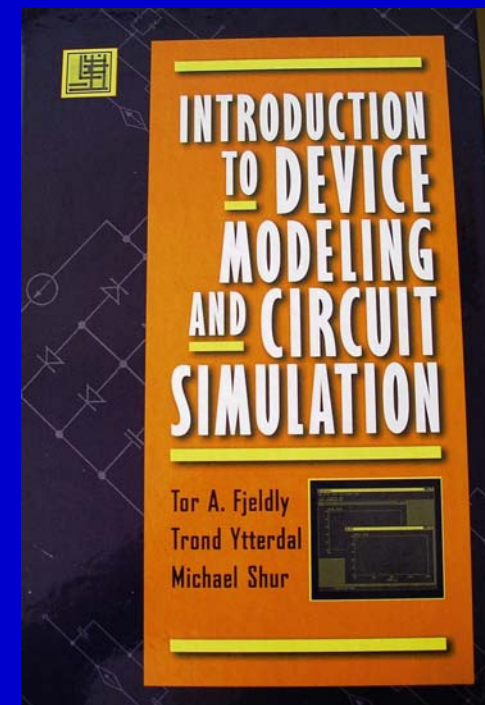


# Metal Semiconductor Field Effect Transistors



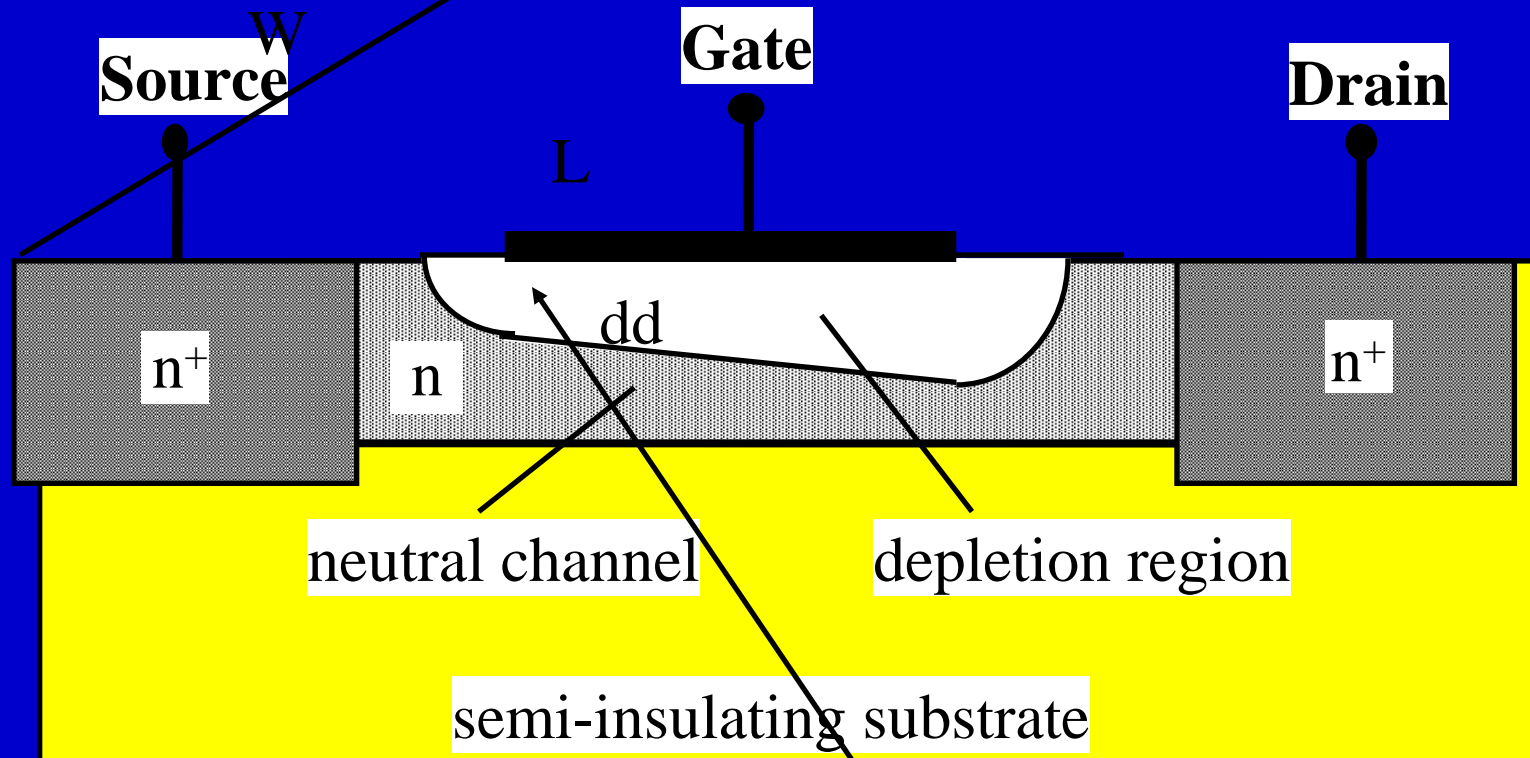
Many slides in this section are from  
T. A. Fjeldly, T. Ytterdal,  
M. S. Shur, Introduction to Device  
Modeling and Circuit  
Simulation for VLSI, Wiley, 1998



# Outline

- **Principle of operation**
- **MESFET modeling**
- **MESFET design**
- **Gate leakage in MESFETs**
- **MESFET characterization.**
- **MESFET technology -**
- **Digital and microwave applications**

# Basic MESFET Operation



$$C_{dep} = \epsilon / dd$$

$$C_{edge} = \epsilon W$$

$$S = W L$$

Capacitance per unit area ( $F/m^2$ )    Capacitance (F)

## 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

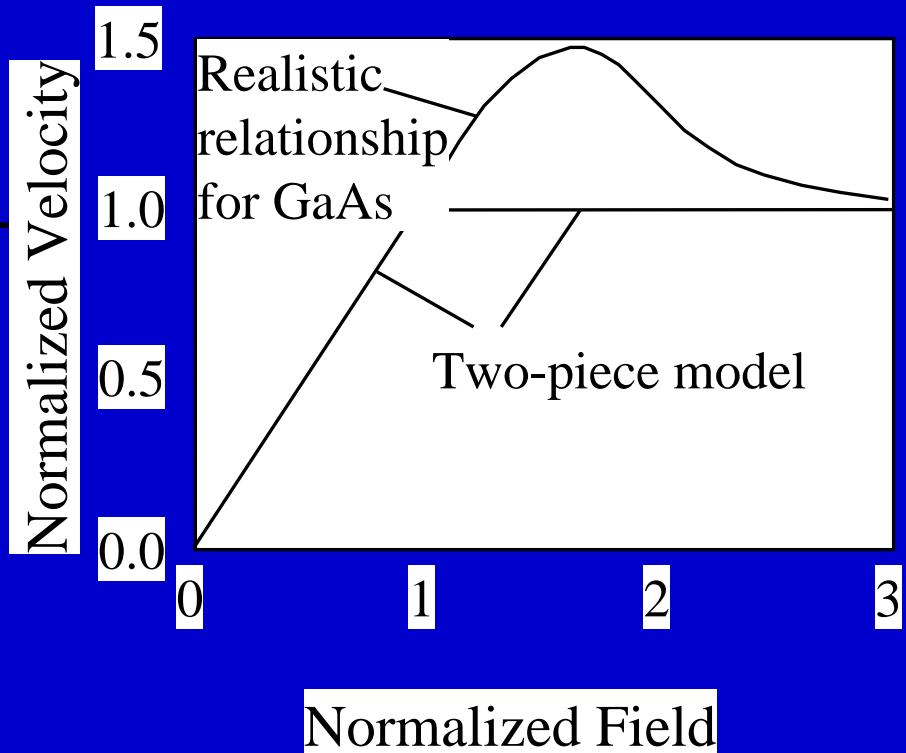
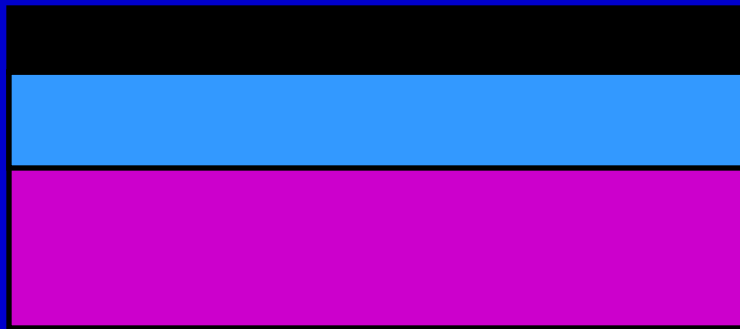
The threshold voltage is defined by the total depletion of the channel

The current saturates because of saturation of the electron velocity near drain

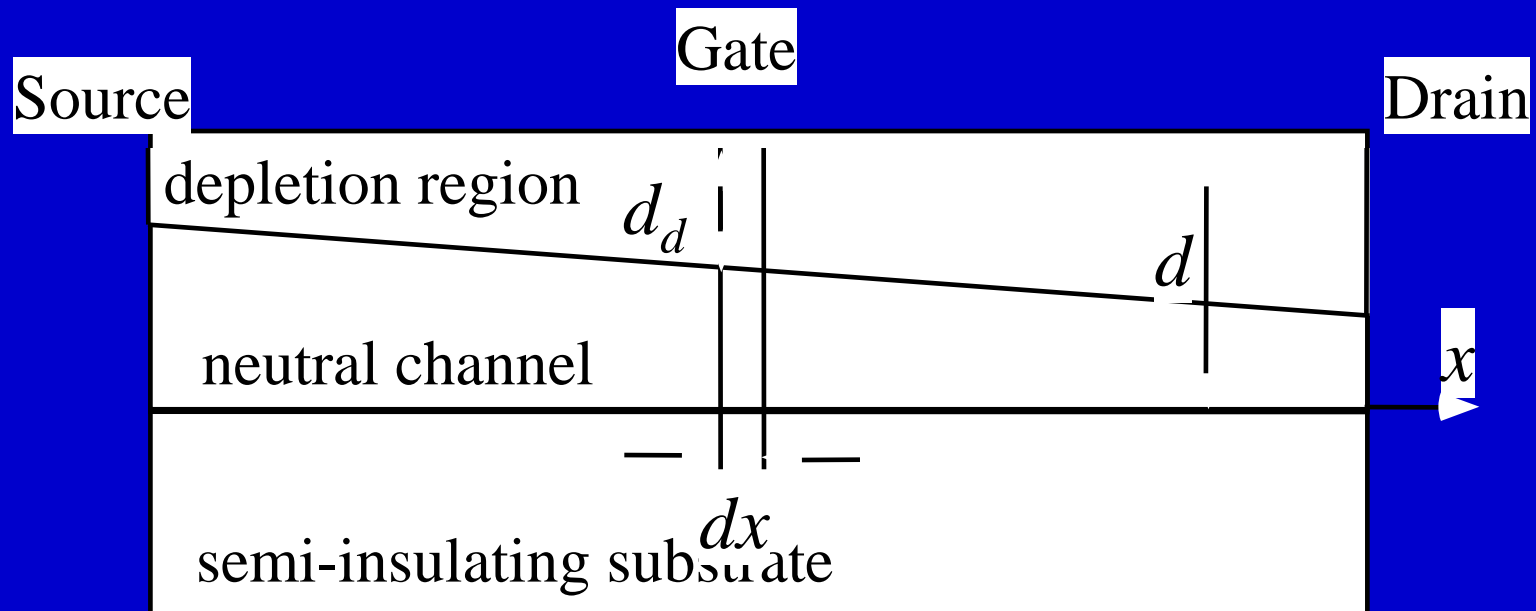
MESFETs are typically made from GaAs because of its low effective electron mass and the velocity overshoot effect

# Saturation velocity region under the gate (at the drain side of the channel)

Gate



# Basic MESFET Model



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

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

# Basic MESFET Model (Cont.)

Threshold voltage:

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

Pinch-off voltage:

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

# The Shockley Model

Assume a constant mobility

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

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

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

*Pinch-off condition:*

$$d_d(L) = d$$

*Saturation voltage* (Pinch-off):

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

## 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 ( $V_{DS} = 0$ ):*

$$|Q_{Go}| = qN_dWLd_d = qN_dWLd\sqrt{1 - V_{GT}/V_{po}}$$

*Corresponding gate-channel capacitance*

*( $C_o = \epsilon_s WL/d$ ):*

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

# Meyer's Model

$$|Q_G| = \int q N_d W L d_d(x) dx$$

Differentiate QG with respect to  $V_{GS}$  and  $V_{DS}$

# MESFET C-V Model (Cont.)

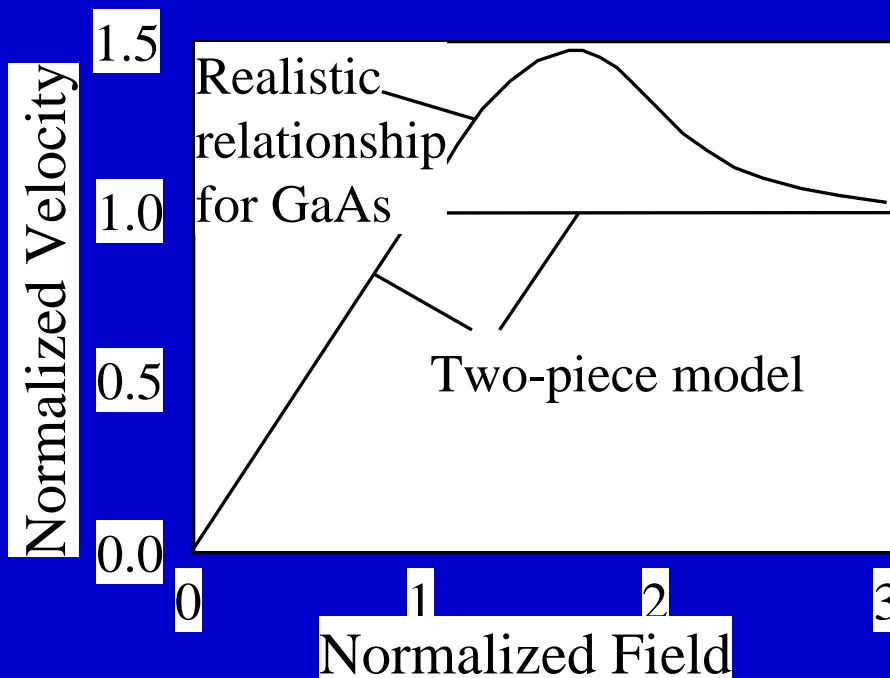
“Meyer” capacitances:

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

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

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

# MESFET Velocity Saturation Model



Two-piece linear  $v$ - $F$  model:

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

Below saturation – same as for Shockley model

Saturation (approximately):

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

$$V_L = F_s L$$

# 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):**

$$I_{sat} = \frac{\beta V_{GT}^2}{1 + \alpha V_{GT}}$$

**Shur (1987):**

$$\beta = \frac{2\varepsilon_s v_s W}{d(V_{po} + 3V_L)}$$

# Basic SPICE MESFET Model

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

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

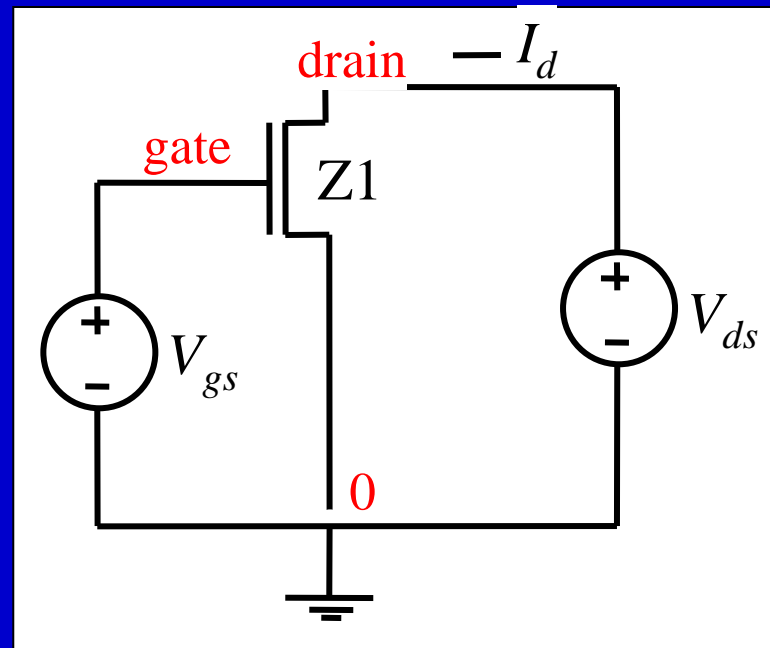
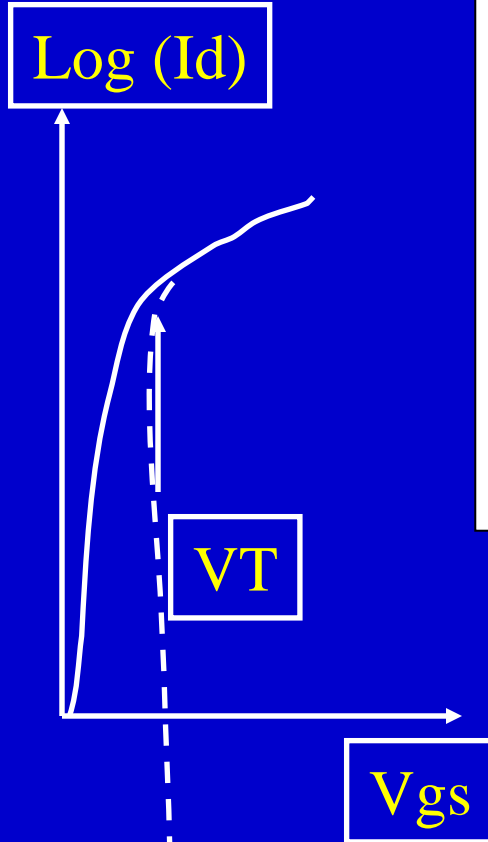
$$I_d = (1 + \text{LAMBDA} \cdot V_{DS}) \frac{\text{BETA} \cdot V_{GT}^2}{1 + \text{B} \cdot V_{GT}} \left[ 1 - \left( 1 - \frac{\text{ALPHA} \cdot V_{DS}}{3} \right)^3 \right]$$

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

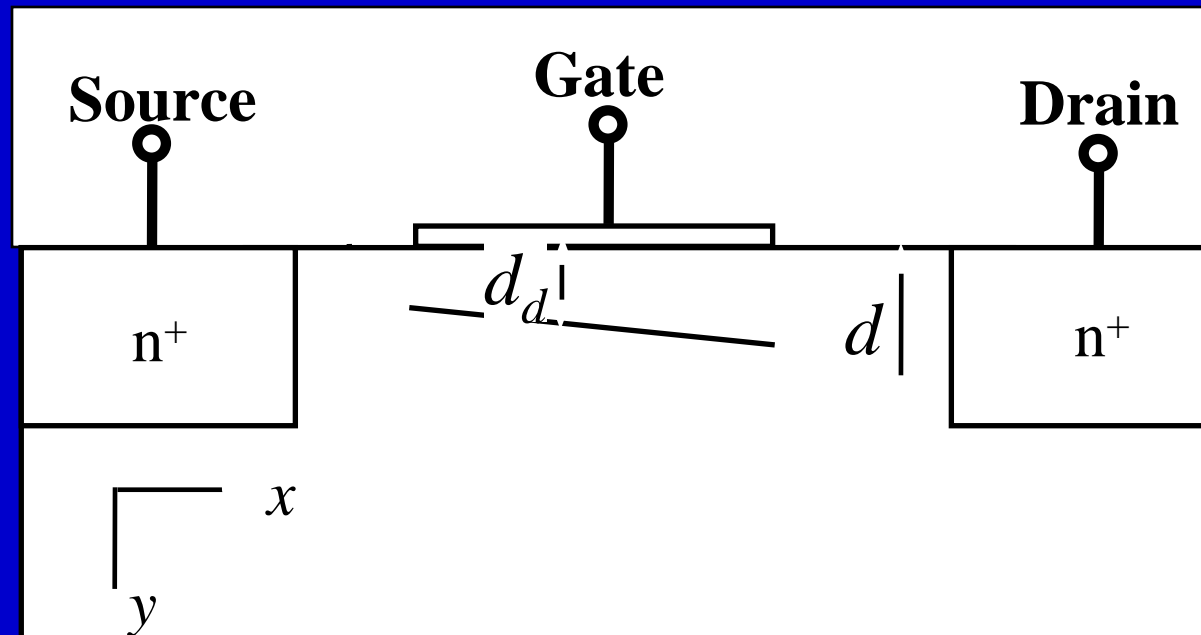
$$I_d = (1 + \text{LAMBDA} \cdot V_{DS}) \frac{\text{BETA} \cdot V_{GT}^2}{1 + \text{B} \cdot V_{GT}}$$

**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)

# MESFET Subthreshold Characteristics



# Universal MESFET Model



To calculate  $g_{ch}$  and  $I_{sat}$  we need an expression for  $n_s$  :

Above threshold (uniform doping):

$$n_{sa} = \int_{d_d}^d N(y) dy = N_d d \left[ 1 - \sqrt{1 - \frac{V_{GT} - V(x)}{V_{po}}} \right]$$

# UCCM for MESFETs

Below threshold:

$$n_{sb} \approx n_0 \exp\left(\frac{V_{GT} - V_F}{\eta V_{th}}\right)$$

Unified charge density expression:

$$n_s \approx \frac{n_{sa} n_{sb}}{n_{sa} + n_{sb}} = \left[ \frac{1}{N_d d} \left( 1 - \sqrt{1 - \frac{V_{gte}}{V_{po}}} \right)^{-1} + \frac{1}{n_0} \exp\left(-\frac{V_{gt}}{\eta V_{th}}\right) \right]^{-1}$$

Use same expression for  $V_{gte}$  as for MOSFETs

# MESFET Saturation Current

Combine above- and below- threshold expressions:

$$I_{sat} \approx \frac{I_{sata} I_{satb}}{I_{sata} + I_{satb}}$$

where

$$I_{sata} = \frac{2\beta V_{gte}^2}{\left(1 + 2\beta V_{gte} R_s + \sqrt{1 + 4\beta V_{gte} R_s}\right) \left(1 + t_c V_{gte}\right)}$$

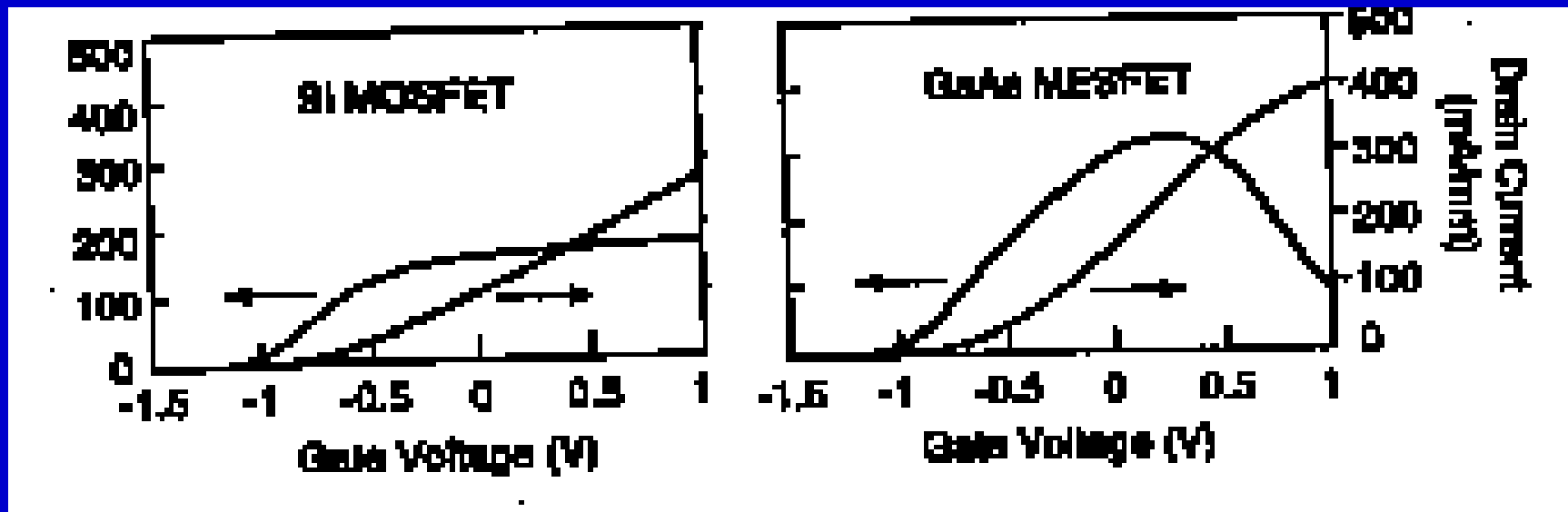
$$I_{satb} = \frac{qn_o \eta D_n W}{L} \exp\left(\frac{V_{GT}}{\eta V_{th}}\right)$$

MESFET transconductance parameter:  $\beta = \frac{2W\epsilon_s v_s}{d(V_{po} + 3V_L)}$

# MESFET-MOSFET I-V comparison

Transconductance (mS/mm)

Drain current (mA/mm)



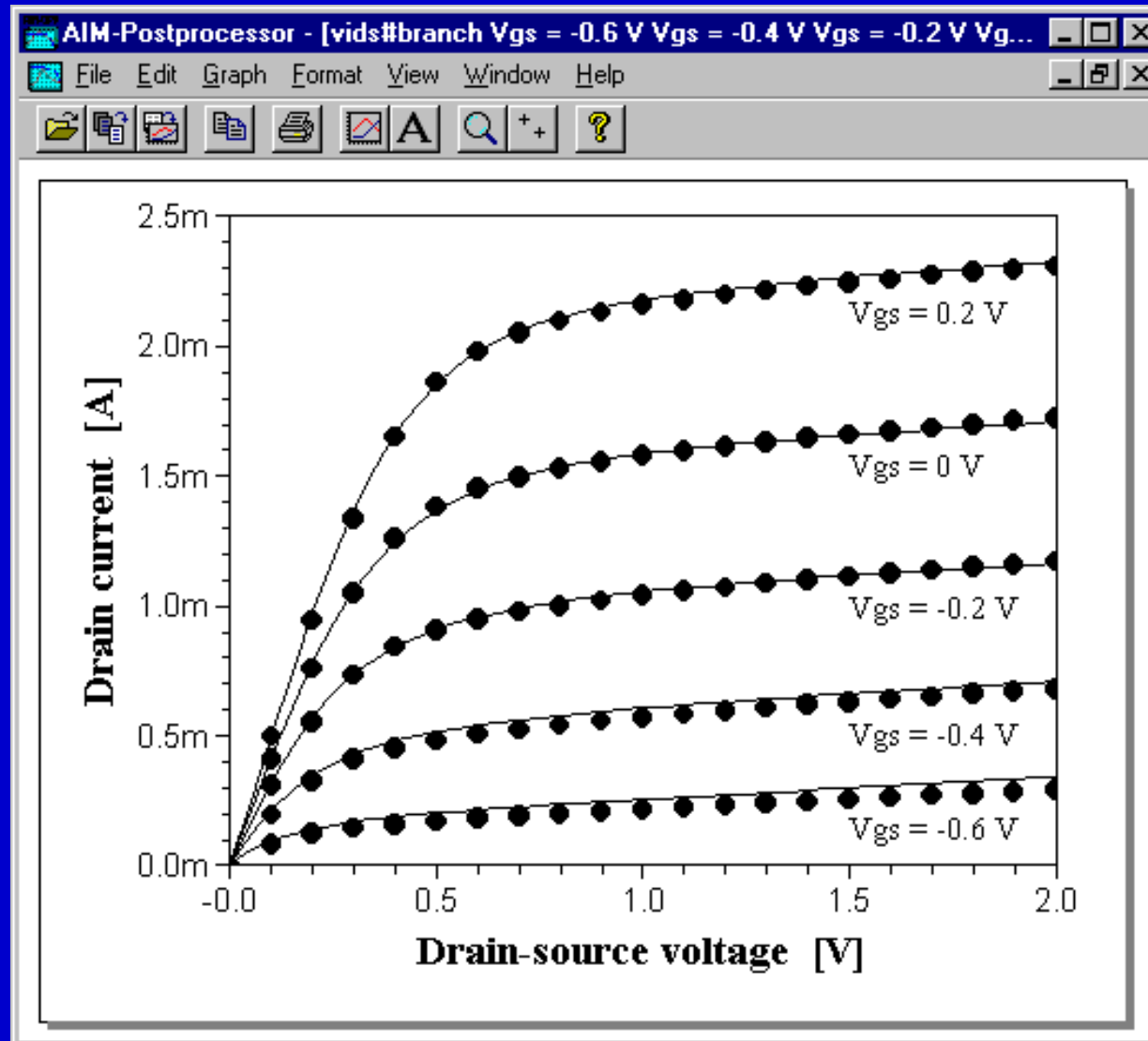
"Haste still pays haste,  
and leisure answers leisure;  
Like doth quit doth,  
and Measure still for Measure."

William Shakespeare

# MESFET I–V Characteristics

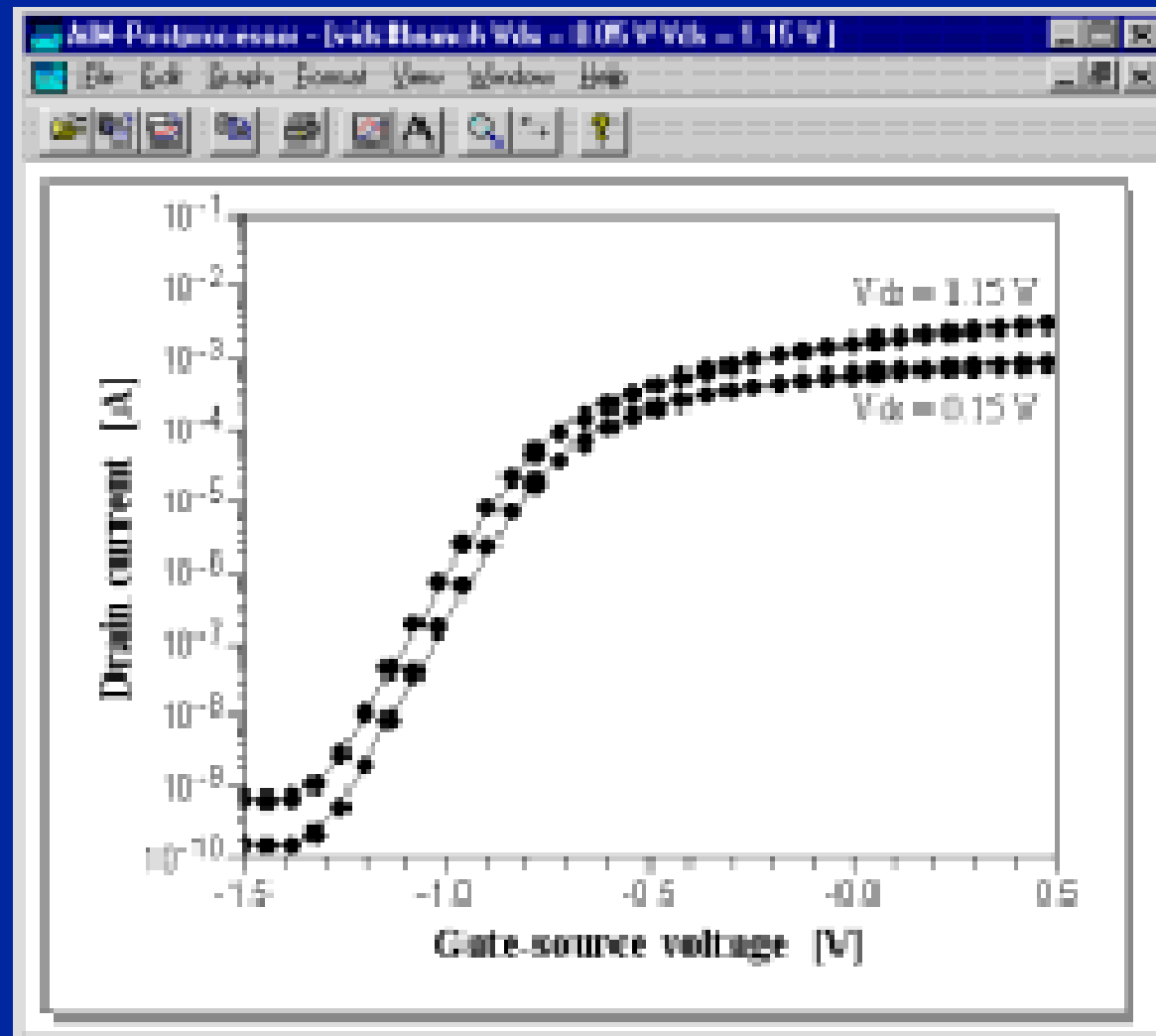
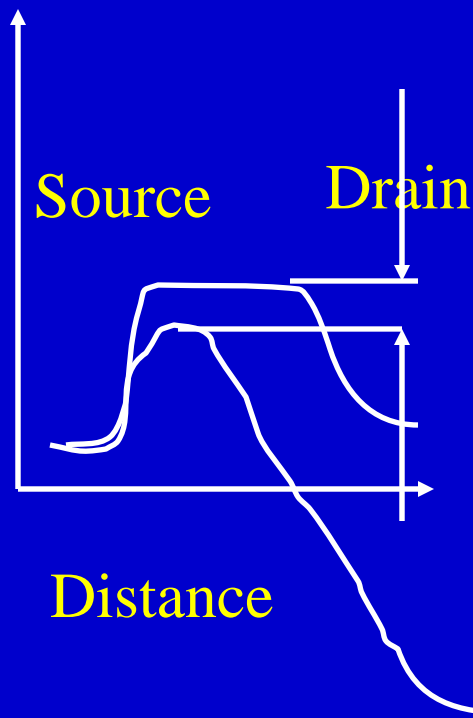
0.5  $\mu\text{m}$  MESFET from Vitesse modeled with the universal MESFET model, implemented as MESFET Level 2 in AIM-Spice.

I-V



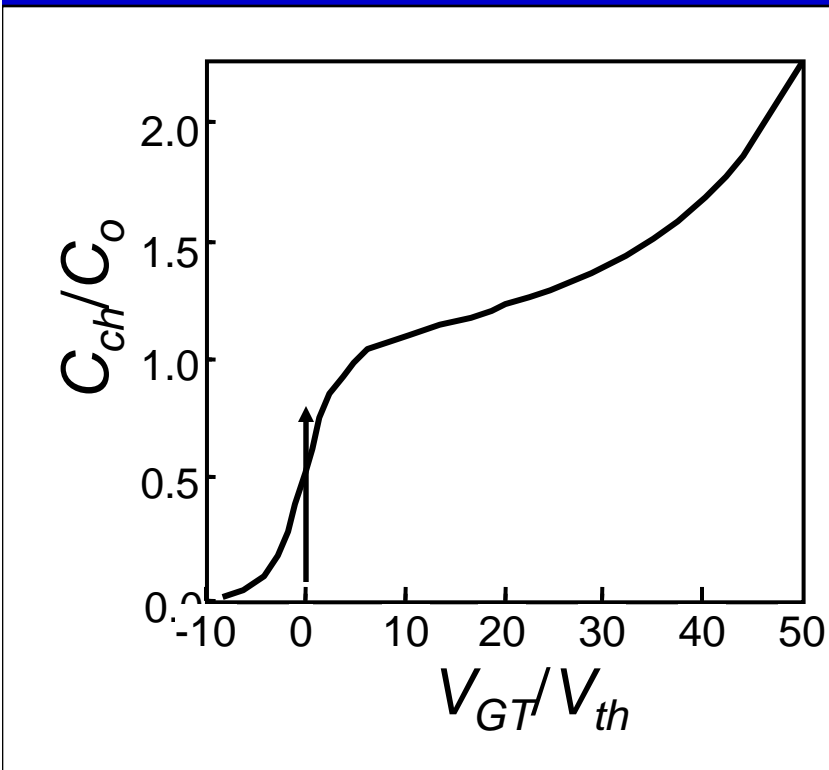
# $I_d$ - $V_g$

Drain Induced  
Barrier  
Lowering  
Potential



# Unified MESFET C-V Model

Unified channel capacitance:



$$C_a = qWL \frac{dn_{sa}}{dV_{gt}} = \frac{WL\epsilon_s}{d\sqrt{(1 - V_{gt} / V_{po})}}$$

$$C_b = qWL \frac{dn_{sb}}{dV_{gt}} = WL \frac{qn_o}{\eta V_{th}} \exp\left(\frac{V_{gt}}{\eta V_{th}}\right)$$

Combine below- and above-threshold expressions ( $V_{ds} = 0$ ):

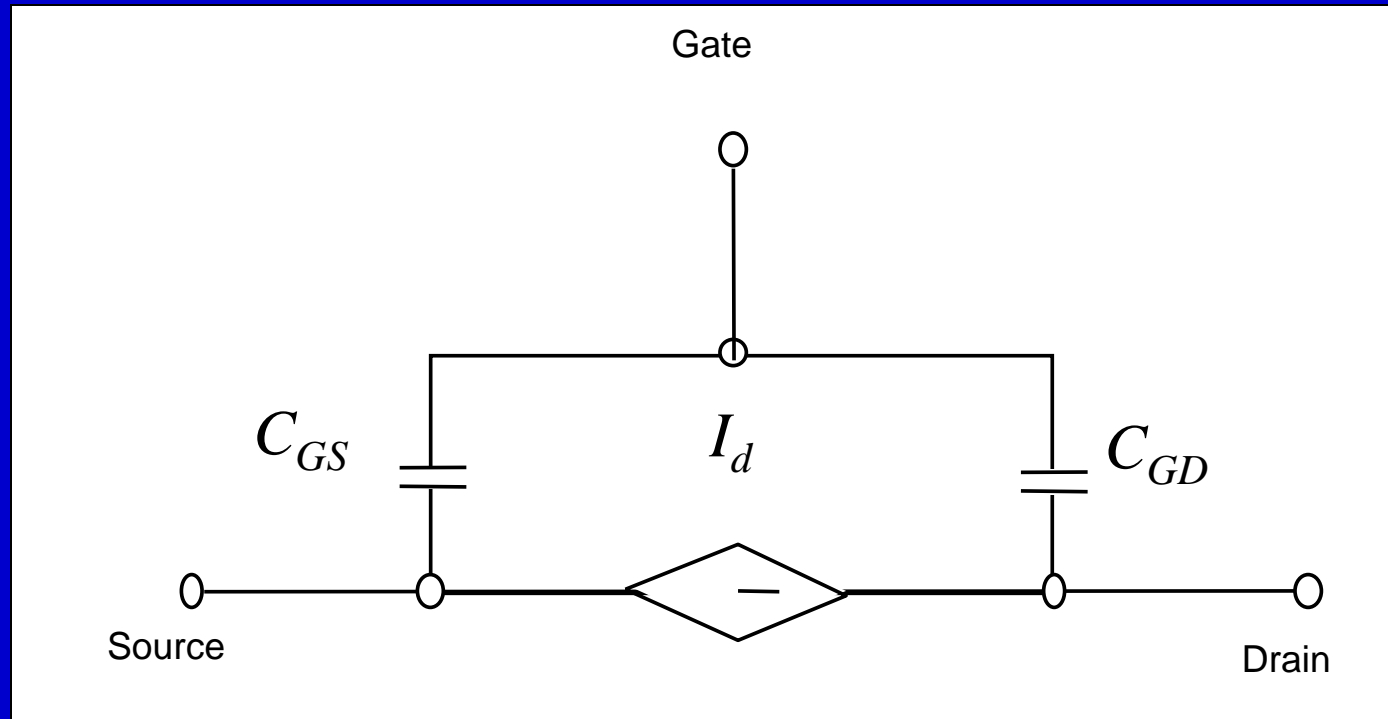
$$C_{ch} = \frac{C_a C_b}{C_a + C_b}$$

Below threshold

Above threshold



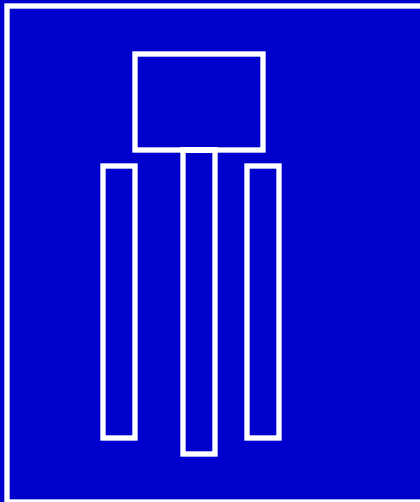
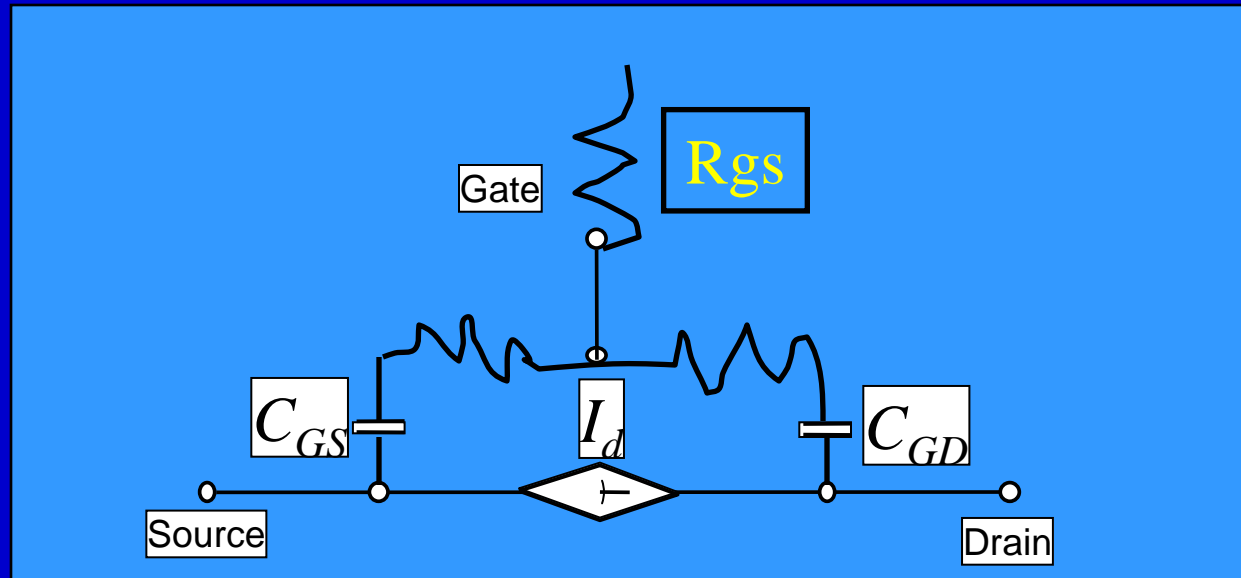
## Meyer-Like Capacitance Model for MESFETs



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

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

# Improved Equivalent Circuit



The gate series resistance limits the gate finger width

# Universal MESFET AIM-Spice Model

## Level 2

Threshold voltage:

$$V_T = \mathbf{VTO} - \sigma V_{ds}$$

$\mathbf{VTO} = V_T(V_{ds} = 0)$  (Threshold voltage at zero drain bias)

I-V characteristics:

$$I_d = \frac{g_{ch} V_{ds} (1 + \mathbf{LAMBDA} \cdot V_{ds})}{\left[ 1 + (g_{ch} V_{ds} / I_{sat})^{\mathbf{M}} \right]^{1/\mathbf{M}}}$$

$\mathbf{M} = m$  (Knee shape parameter)

$\mathbf{LAMBDA} = \lambda$  (Channel length modulation parameter)

# MESFET Level 2 (Cont.)

Channel charge density:

$$n_s = \left[ \frac{1}{\mathbf{ND} \cdot \mathbf{D}} \left( 1 - \sqrt{1 - \frac{V_{gte}}{V_{po}}} \right)^{-1} + \frac{1}{n_o} \exp\left( -\frac{V_{gt}}{\mathbf{ETA} V_{th}} \right) \right]^{-1}$$

Linear channel conductance:

$$g_{chi} = \frac{qn_s \mathbf{MU} \cdot \mathbf{W}}{\mathbf{L}}, \quad g_{ch} = \frac{g_{chi}}{1 + g_{chi}(\mathbf{RS} + \mathbf{RD})}$$

# MESFET Level 2

## (Cont.)

Saturation current:

$$I_{sat} = \frac{I_{sata} I_{satb}}{I_{sata} + I_{satb}}$$

$$I_{sata} = \frac{2\beta V_{gte}^2}{\left(1 + 2\beta V_{gte} \mathbf{RS} + \sqrt{1 + 4\beta V_{gte} \mathbf{RS}}\right) \left(1 + \mathbf{TC} \cdot V_{gte}\right)}$$

$$I_{satb} \approx \frac{qn_o V_{th} \mathbf{ETA} \cdot \mathbf{MU} \cdot \mathbf{W}}{\mathbf{L}} \exp\left(\frac{V_{gt}}{\mathbf{ETA} \cdot V_{th}}\right)$$

$$\beta = \frac{2\varepsilon_s \mathbf{VS} \cdot \mathbf{W}}{\mathbf{D} \cdot \left(V_{po} + 3\mathbf{VS} \cdot \mathbf{L}/\mathbf{MU}\right)}$$

$$n_o = \frac{\varepsilon_s \mathbf{ETA} \cdot V_{th}}{q\mathbf{D}}$$

$$V_{po} = \frac{q\mathbf{ND} \cdot \mathbf{D}^2}{2\varepsilon_s}$$

# MESFET Level 2 (Cont.)

Effective gate voltage overdrive:

$$V_{gte} = V_{th} \left[ 1 + \frac{V_{gt}}{2V_{th}} + \sqrt{\mathbf{DELTA}^2 + \left( \frac{V_{gt}}{2V_{th}} - 1 \right)^2} \right]$$

<b>RS, RD</b>	(Series resistances)
<b>MU = <math>\mu</math></b>	(Low-field mobility)
<b>L, W</b>	(Gate length and width)
<b>D</b>	(Active region thickness)
<b>TC = <math>t_c</math></b>	(Transconductance compression)
<b>VS = <math>v_s</math></b>	(Saturation velocity)
<b>DELTA = <math>\delta</math></b>	(Threshold transition width)
<b>ETA = <math>\eta</math></b>	(Ideality factor)

## MESFET Level 2 (Cont.)

The I–V model also contains expressions for:

Gate leakage current

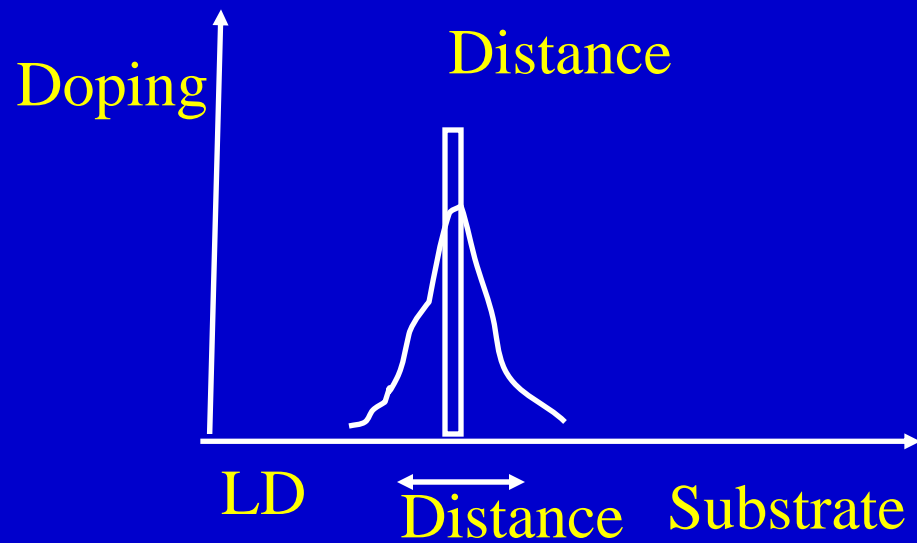
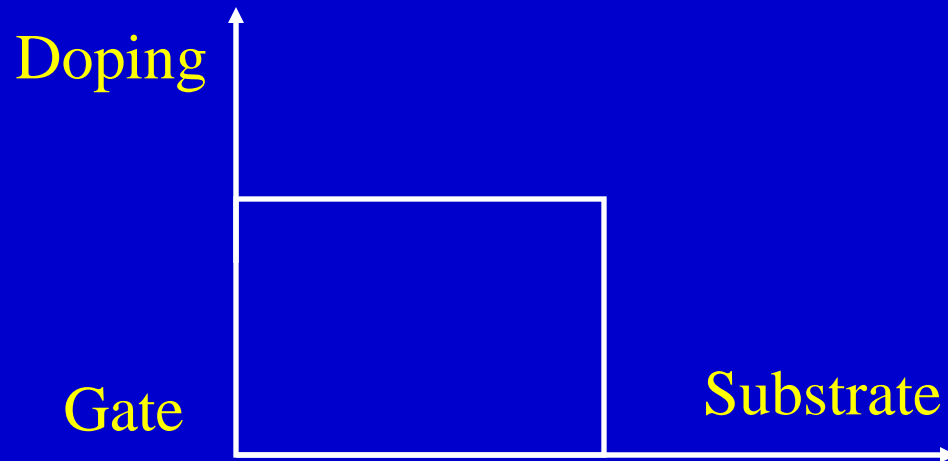
Temperature dependencies of key parameters

Frequency dependencies of key parameters

Sidegating and backgating

Separate model for delta-doped MESFET  
(Level 3)

# Delta Doped MESFET



## MESFET Level 2 (Cont.)

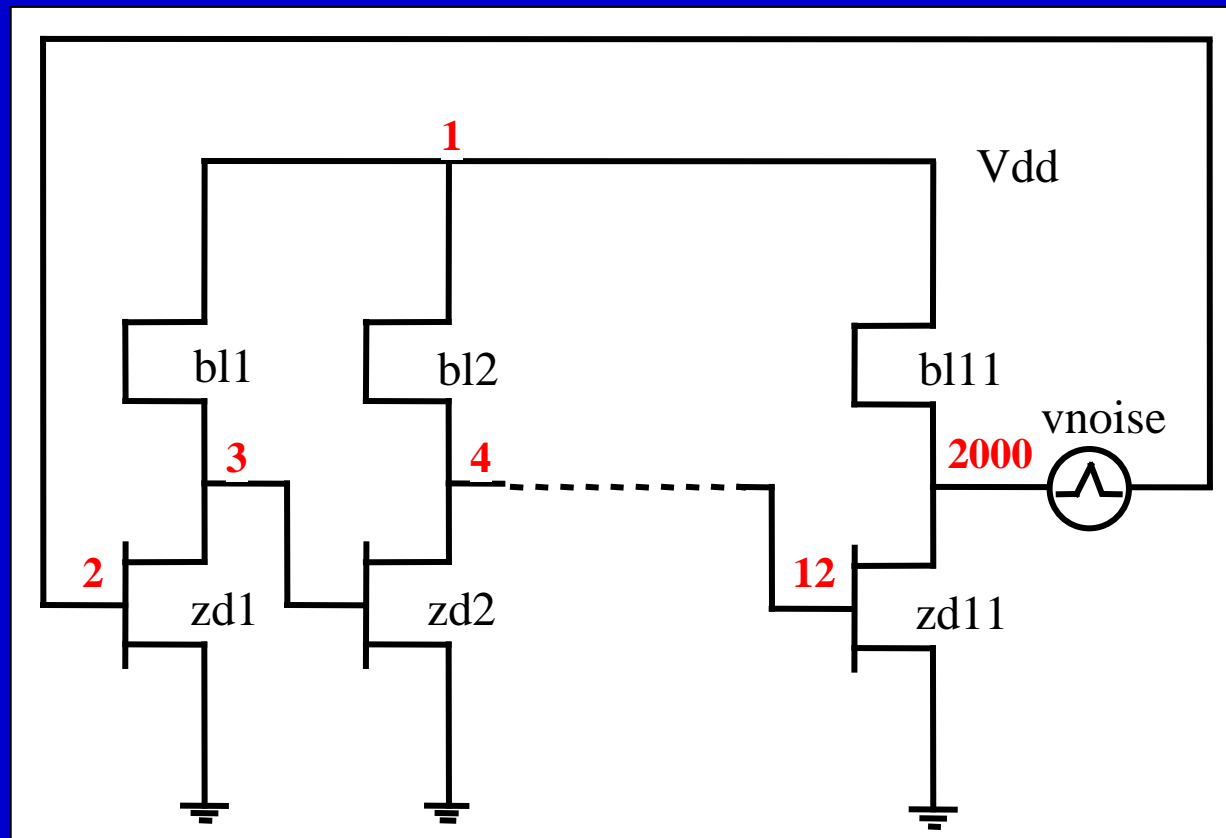
*MESFET gate-channel capacitance*  
(contained in Meyer's capacitance model):

$$C_{ch} \approx \frac{\epsilon_s \mathbf{W} \cdot \mathbf{L}}{\mathbf{D}} \left[ \sqrt{1 - \frac{V_{gte}}{V_{po}}} + \exp\left(-\frac{V_{gt}}{\mathbf{ETA} V_{th}}\right) \right]^{-1}$$

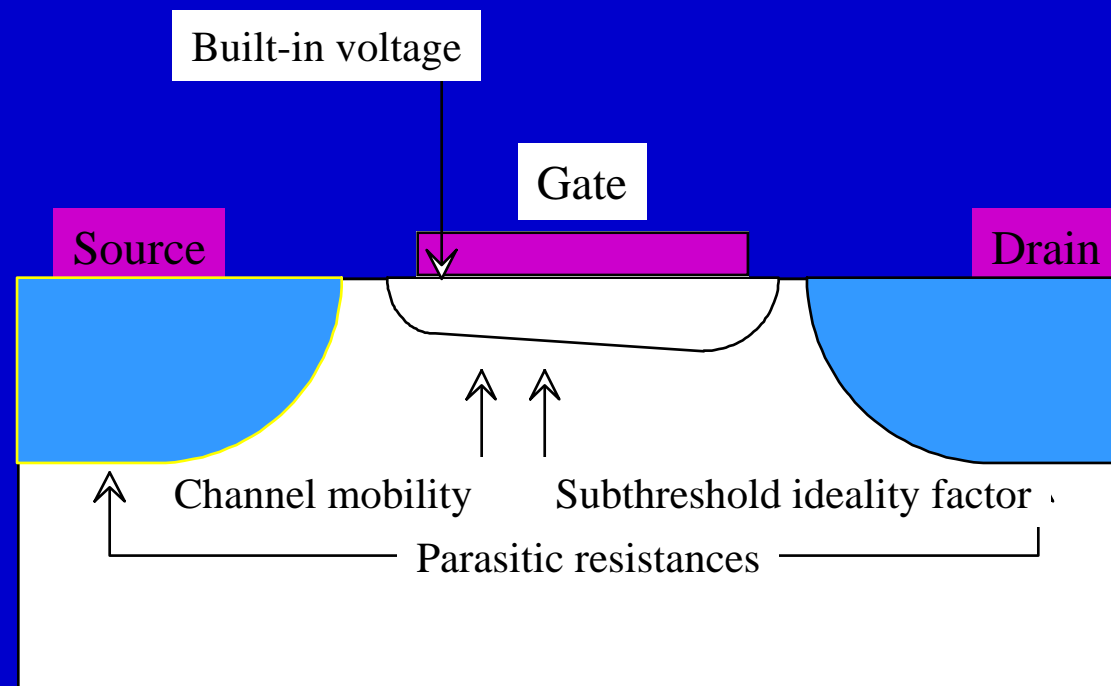
# MESFET Ring Oscillator

MESFET inverters with ungated load:

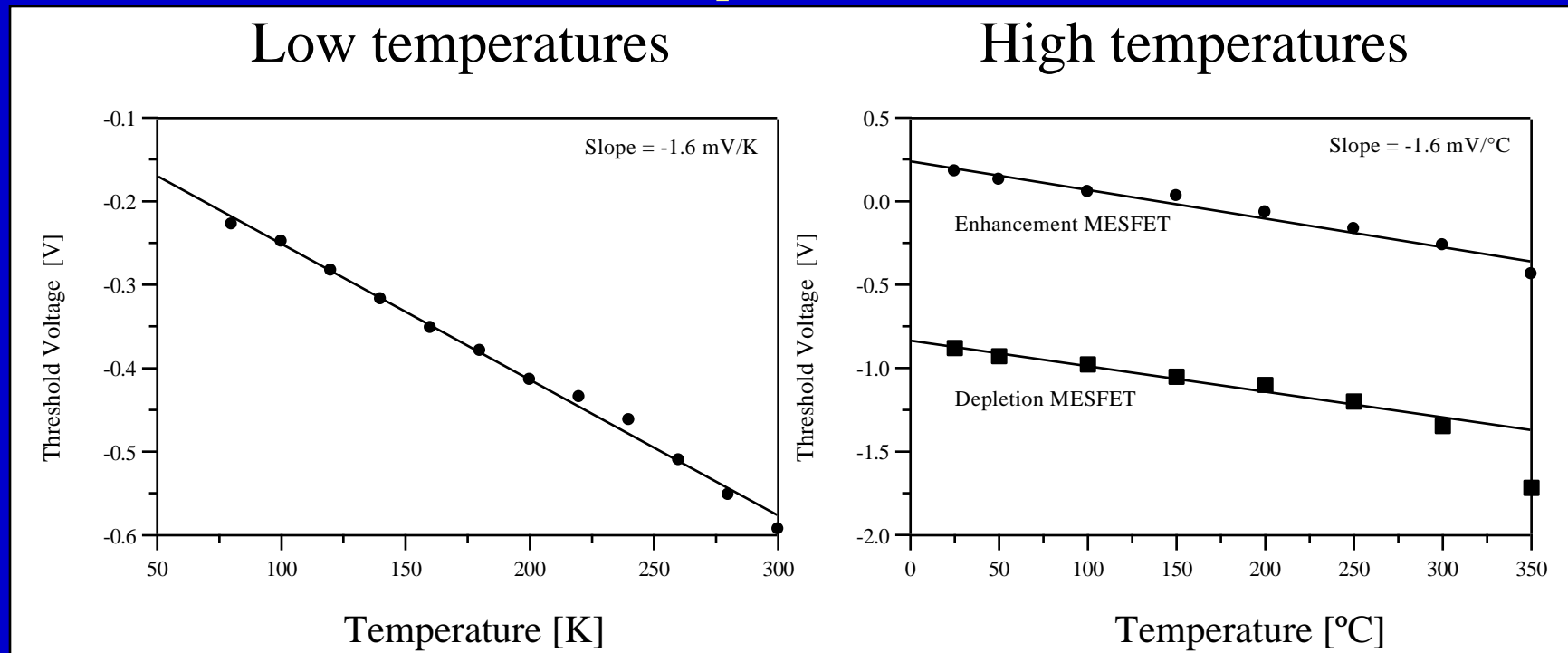
$$I_L = I_{Lsw} \tanh(V_L / V_{Lss})(1 + \lambda_L V_L)$$



# Temperature dependent Model Parameters



# Threshold voltage versus Temperature



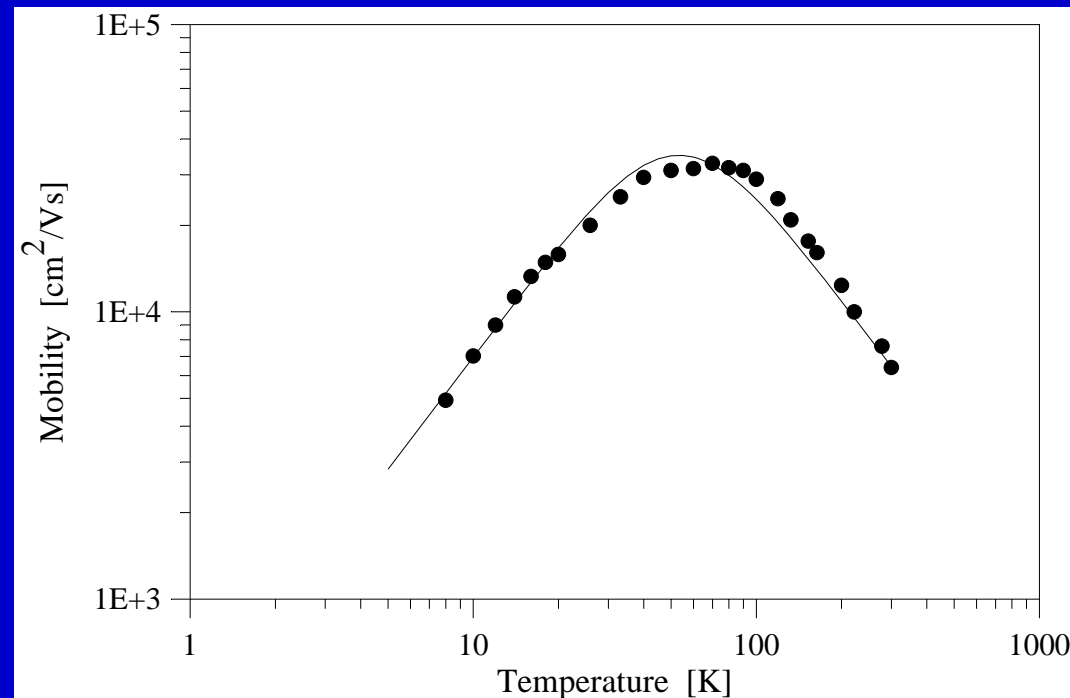
Enhancement

$$V_T = V_{T0} - K_{VT} (T - T_0)$$



Depletion

# Mobility



Impurity scattering:

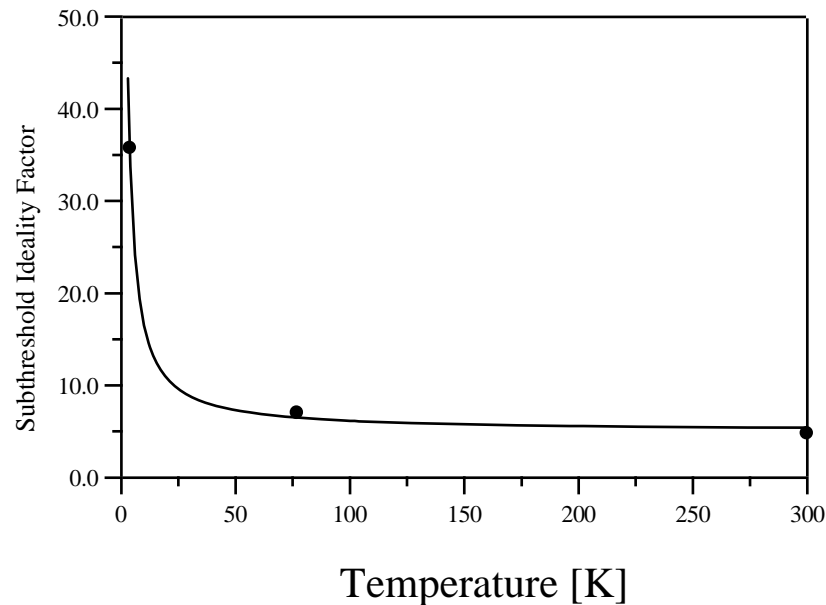
$$\mu_{imp} = \mu_0(T/T_\mu)^{XTM0}$$

Polar optical phonon scattering:  $\mu_{po} = \mu_1(T_\mu/T)^{XTM1} + \mu_2(T_\mu/T)^{XTM2}$

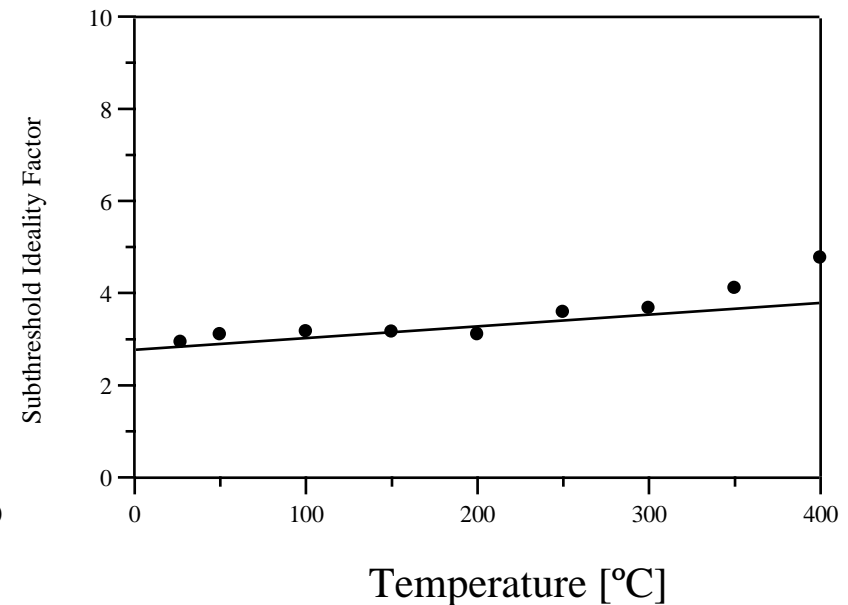
$$1/\mu_{n0} = 1/\mu_{imp} + 1/\mu_{po}$$

# Subthreshold Ideality Factor

## Low temperatures



## High temperatures



$$\eta = \eta_0(1 + T/T_{\eta 0}) + T_{\eta 1}/T$$

## Additional T-dependent parameters

Saturation velocity:

$$v_s = 0.6v_{s0} \left( 1 + \frac{\mu_{n0}}{\mu_{vs}} - \frac{\mu_{n0}^2}{3\mu_{vs}^2} \right)$$

Schottky barrier height:

$$\Phi_b = \Phi_{b0} - \phi_{b1}(T - T_0)$$

Reverse Schottky conductances:

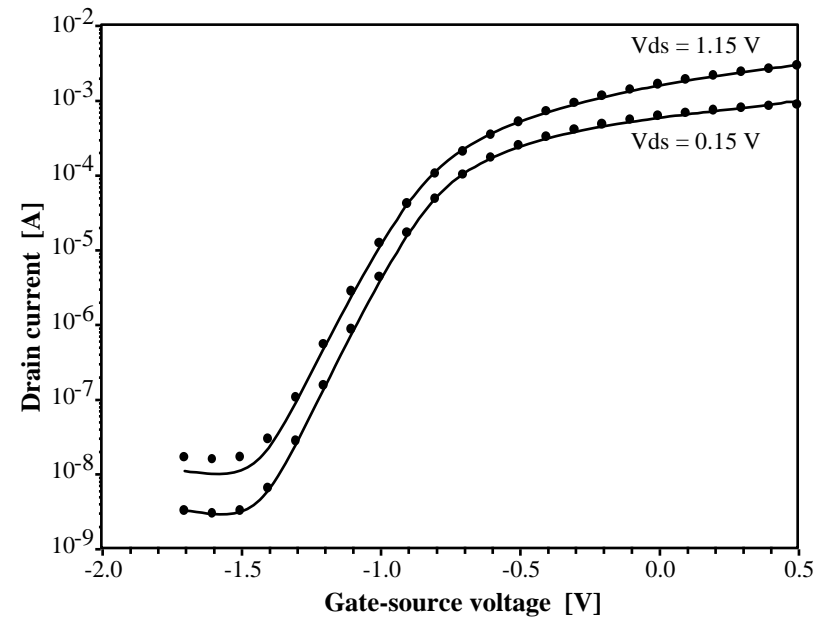
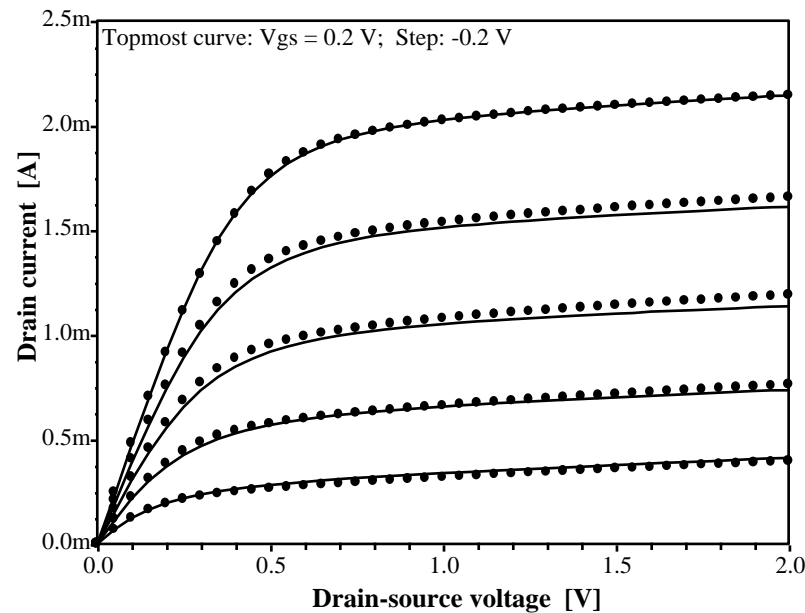
$$g_g = g_{g0} \exp[\xi(T - T_0)]$$

Series resistances:

$$R = R_0 \left[ 1 + r_1(T - T_0) + r_2(T - T_0)^2 \right]$$

# I-V Characteristics at 120 °C

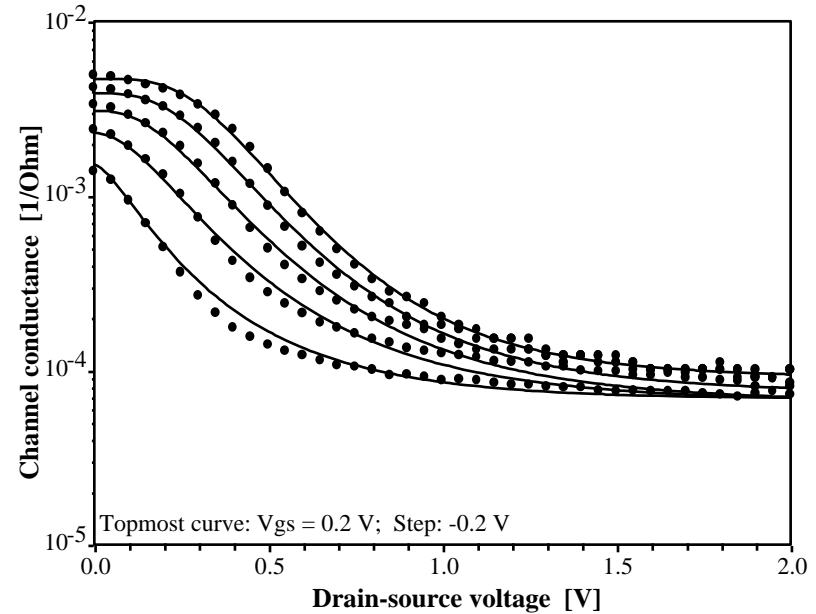
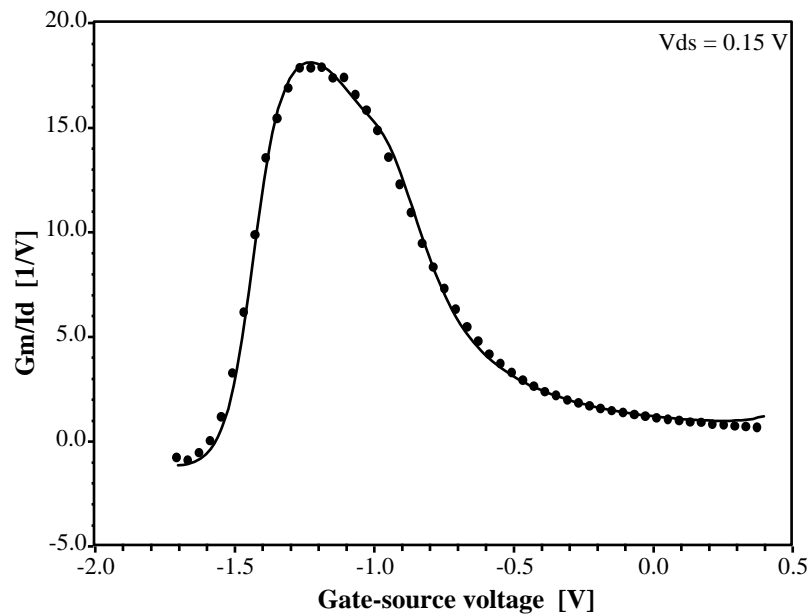
Vitesse BPLDD process,  $L_{eff} = 0.515 \mu\text{m}$



$T = 120 \text{ }^\circ\text{C}$

# $G_m/I_d$ and $G_d$ at 120 °C

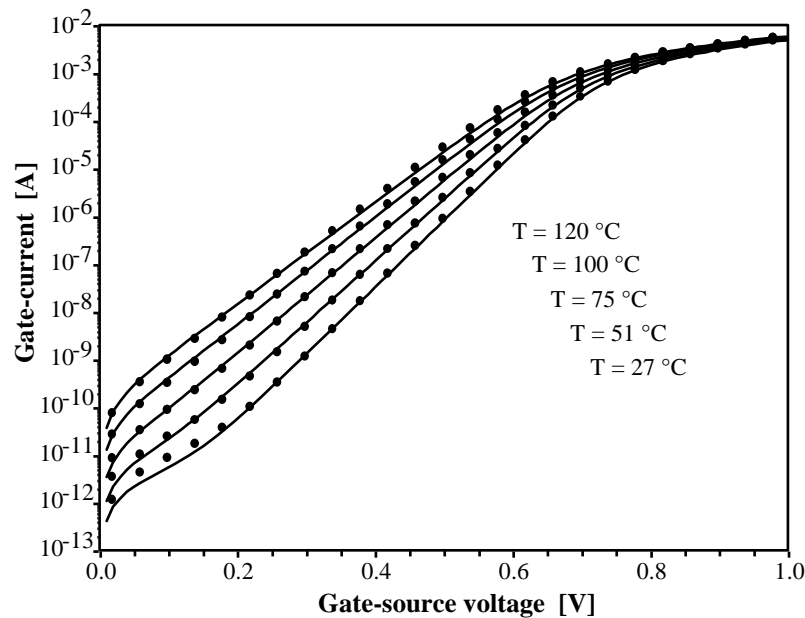
Vitesse BPLDD process,  $L_{eff} = 0.515 \mu\text{m}$



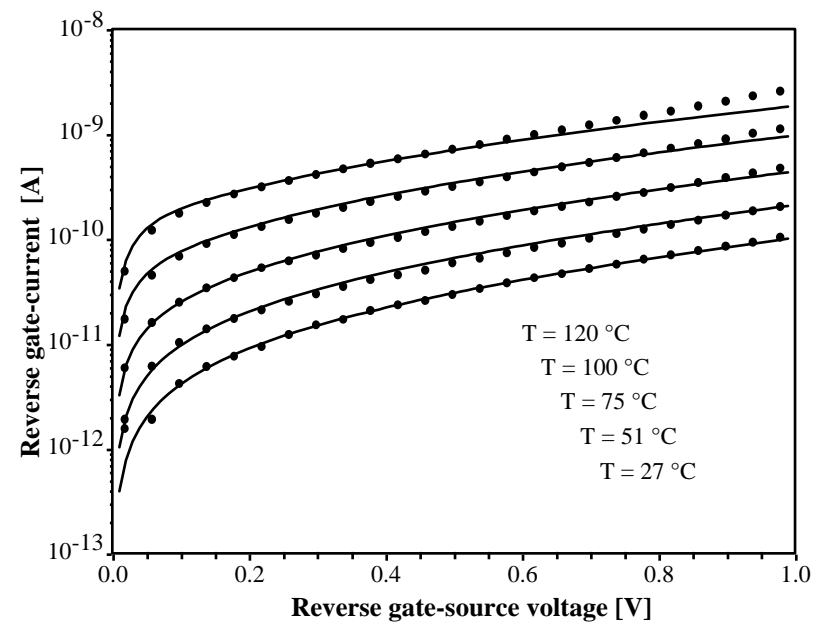
$T = 120 \text{ }^\circ\text{C}$

# Gate Leakage Current

Vitesse BPLDD process,  $L_{eff} = 0.515 \mu\text{m}$



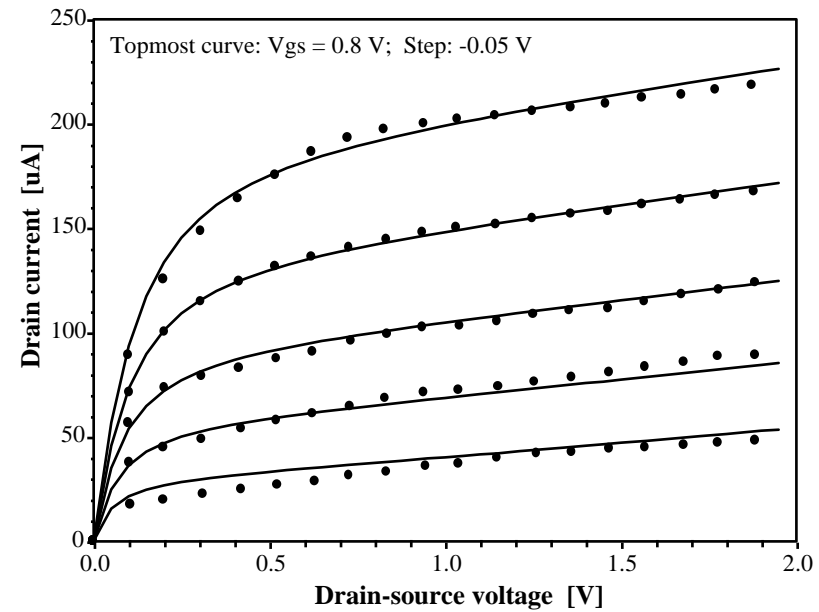
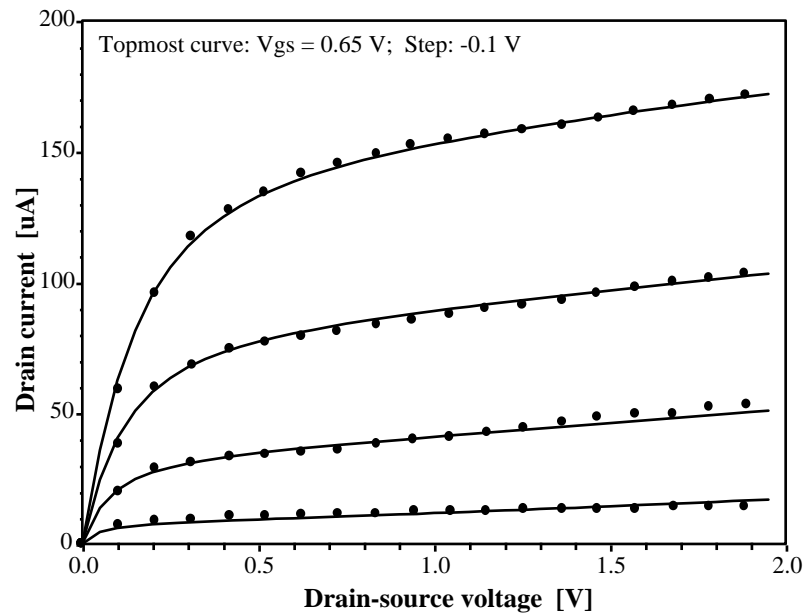
Forward direction



Reverse direction

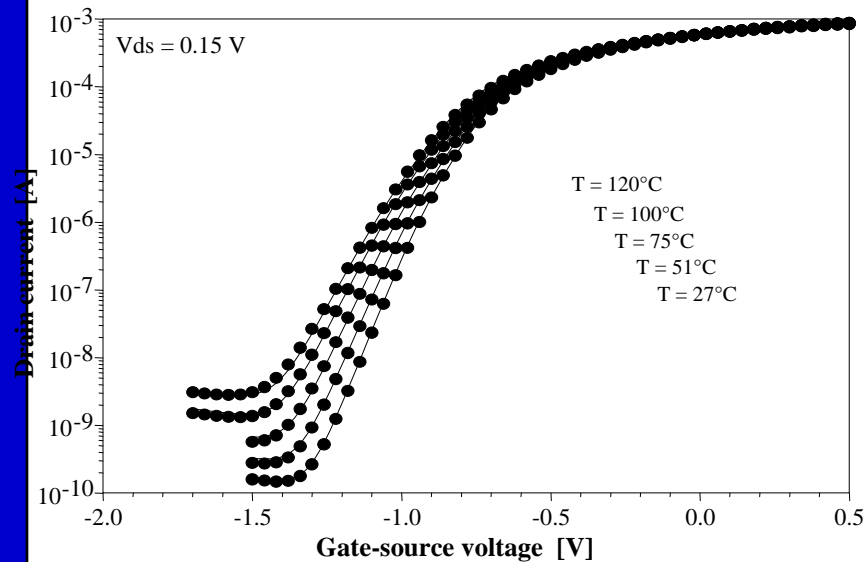
# I-V Characteristics at Room Temperature and 77 K

Triquint process,  $L_{eff} = 1 \mu\text{m}$



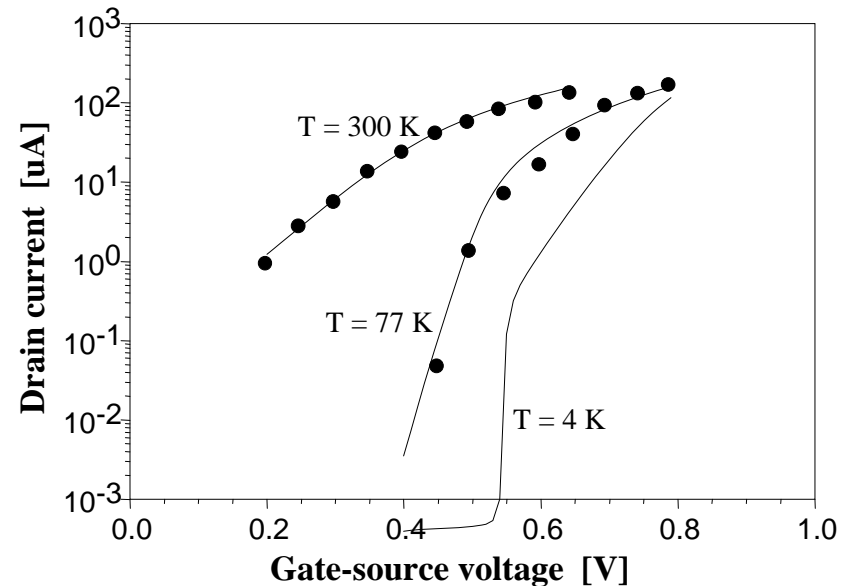
# Subthreshold Characteristics

Vitesse BPLDD process,  $L_{eff} = 0.515 \mu\text{m}$



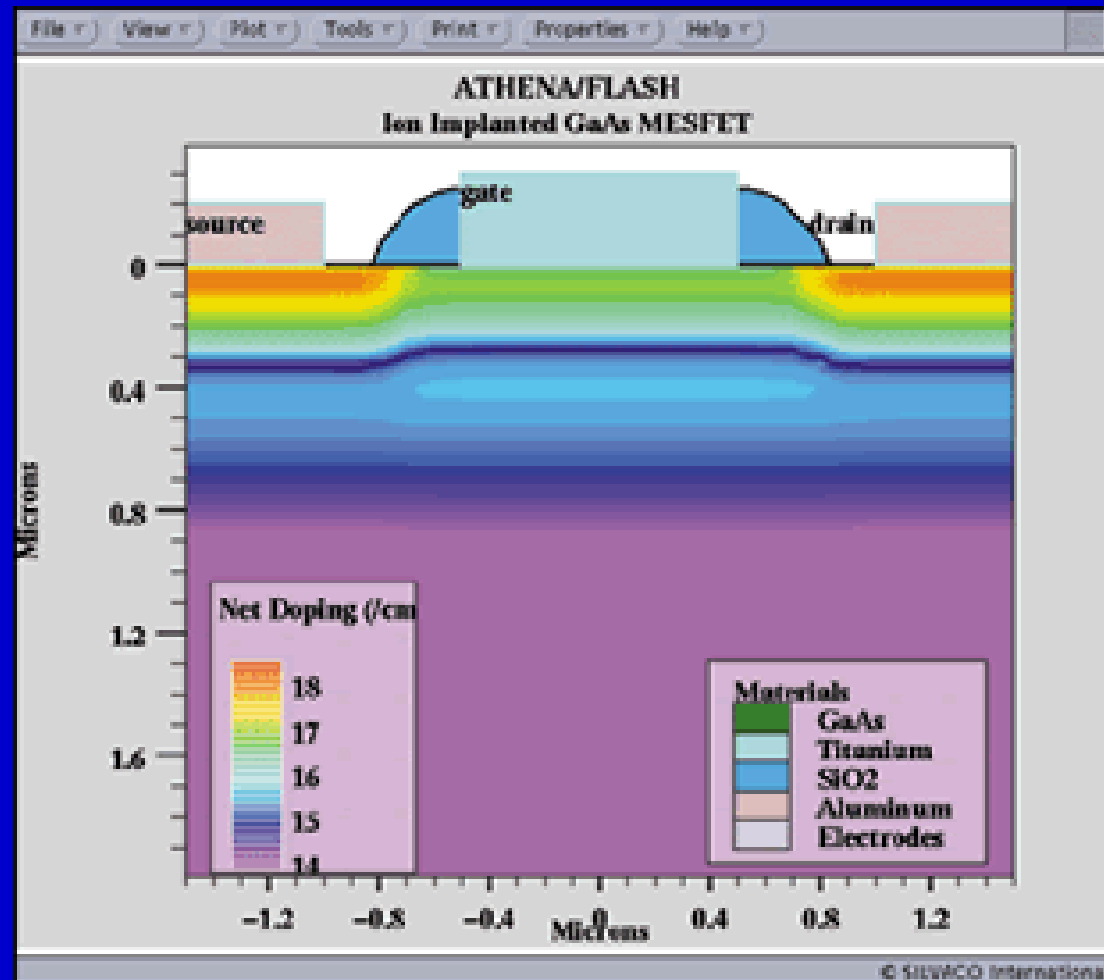
$T = 27\text{-}120 \text{ }^\circ\text{C}$

Triquint process,  $L_{eff} = 1 \mu\text{m}$



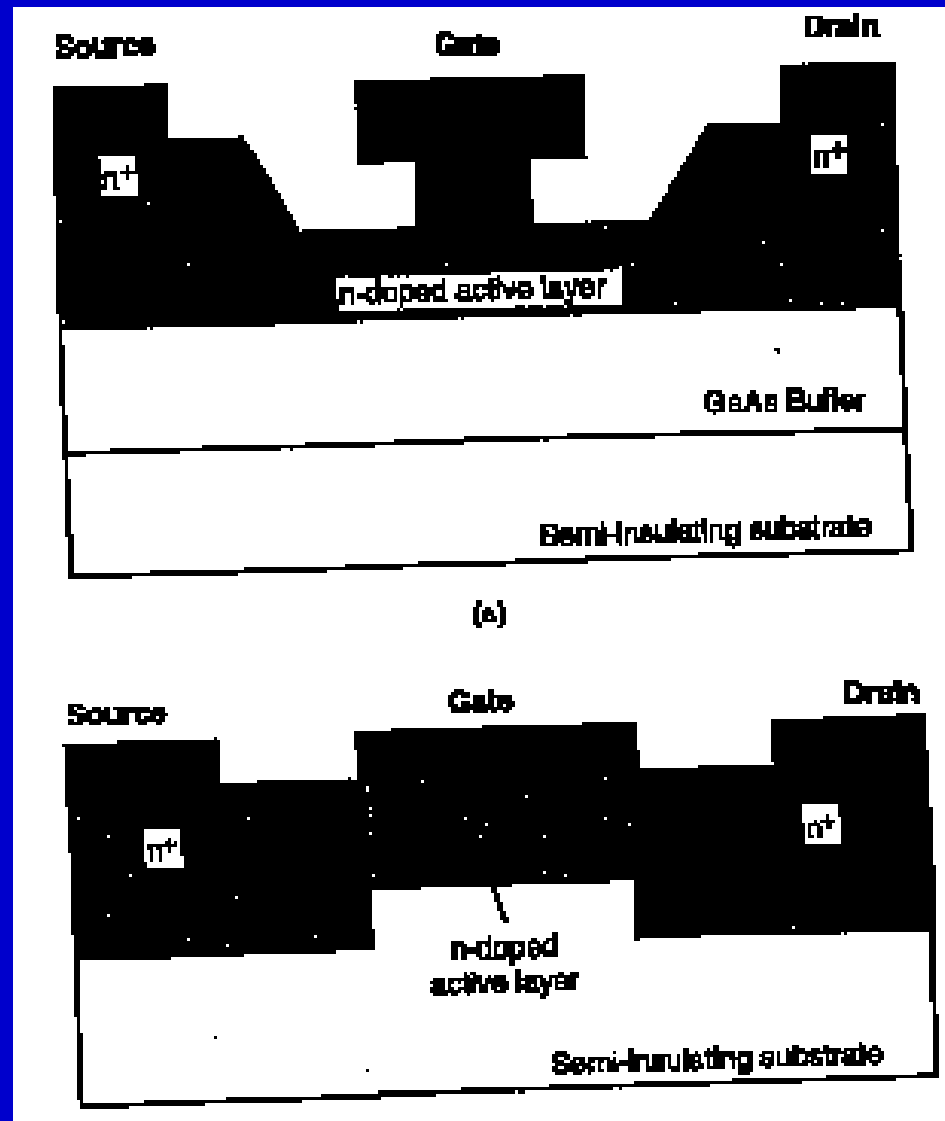
$T = 4, 77, 300 \text{ K}$

# 2D Simulation (Silvaco FLASH)

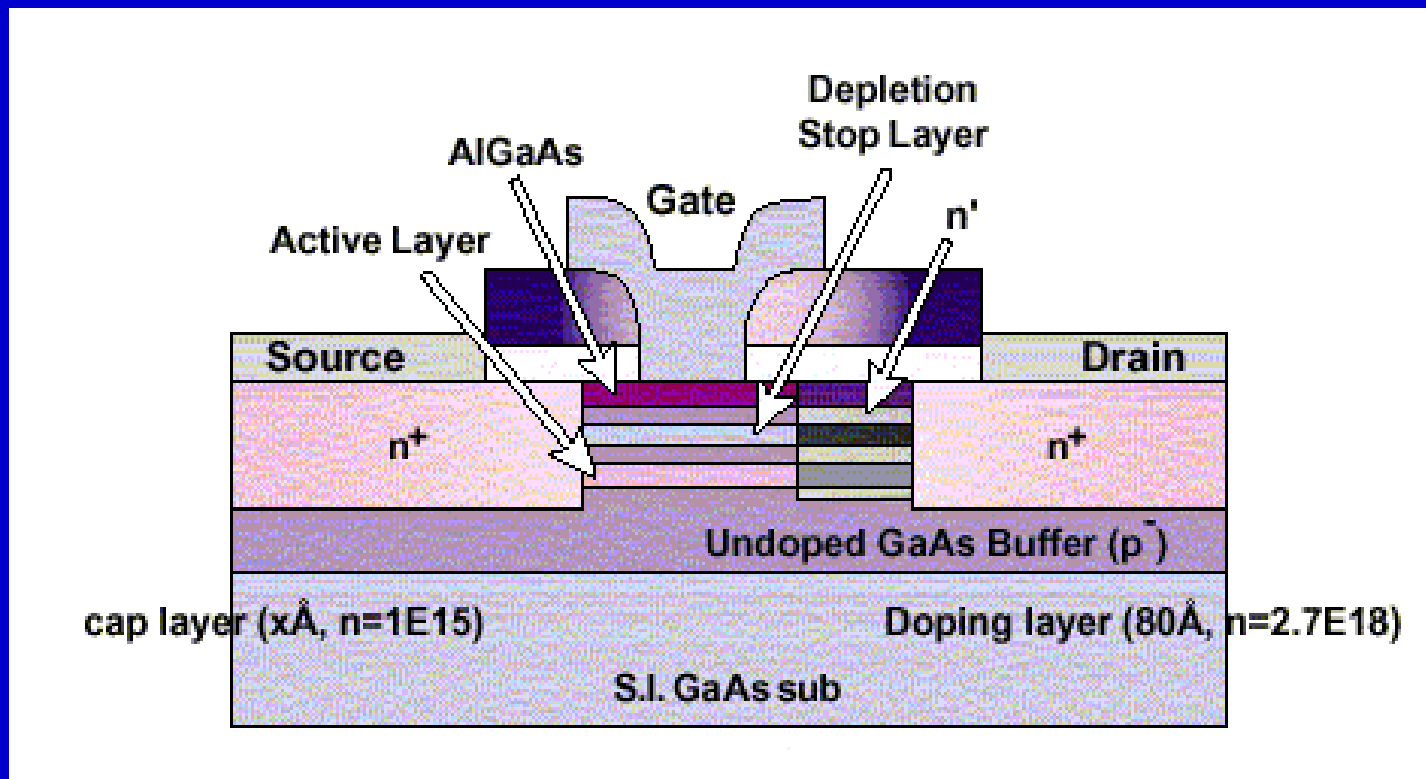


Courtesy of Silvaco, International

# T-gate and regular gate

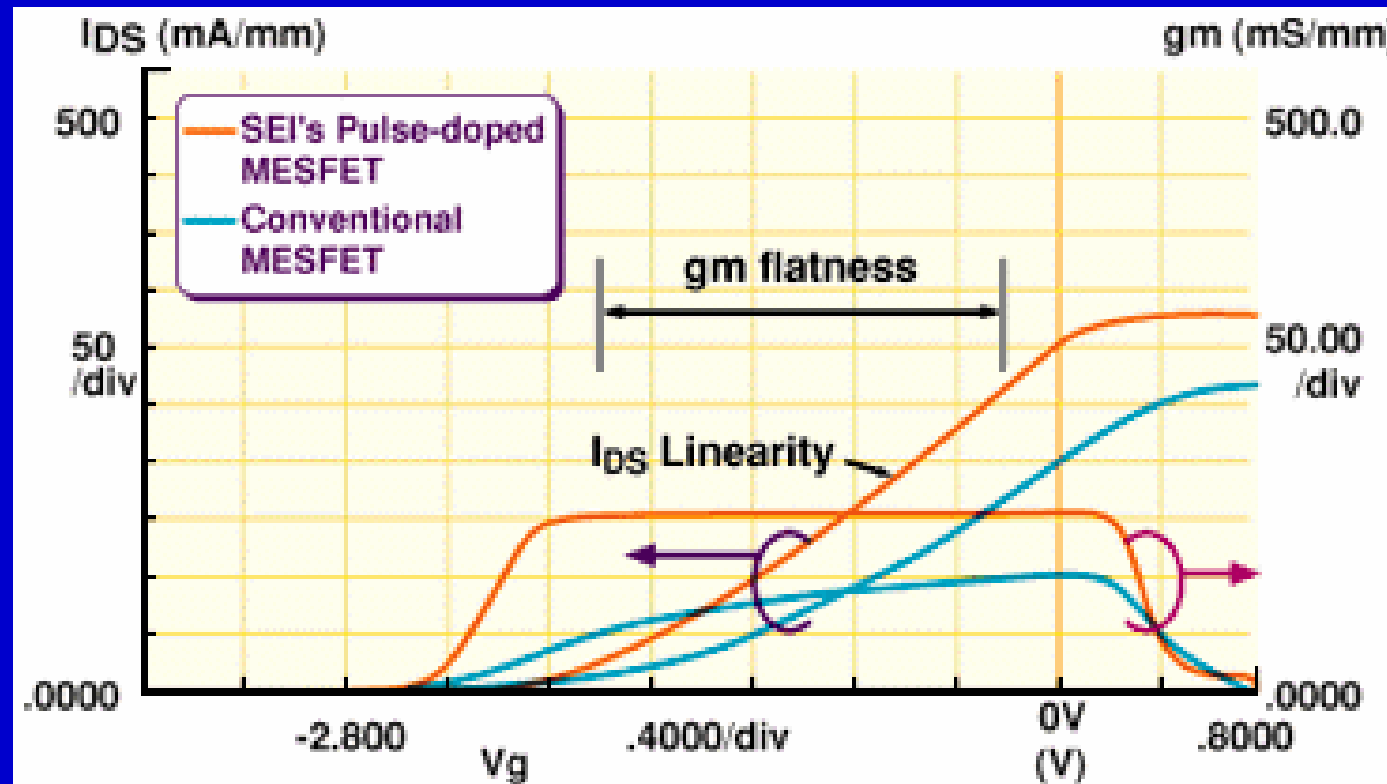


# Advanced Pulsed Doped GaAs MESFET



From [www.atnjapan.com/SEI\\_GaAsIC/](http://www.atnjapan.com/SEI_GaAsIC/)

# Comparison of Performance



From [www.atnjapan.com/ SEI\\_GaAsIC/](http://www.atnjapan.com/SEI_GaAsIC/)

## Power GaAs MESFET Performance

Type No. (MHz)	P1dB (dBm)	IP3 (dBm)	IDS (mA)	gm (mS)	Freq
P0110002P	24	39	80	90	~DC-2.5GHz
P0110003P	28	43	220	250	~DC-2.5GHz
P0110004P	30	45	400	450	~DC-2.5GHz

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