MOS Model 20

-- a versatile LDMOS model --

A.C.T. Aarts * and D.B.M. Klaassen **

** Eindhoven University of Technology*

*** Philips Research Laboratories*

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The Netherlands

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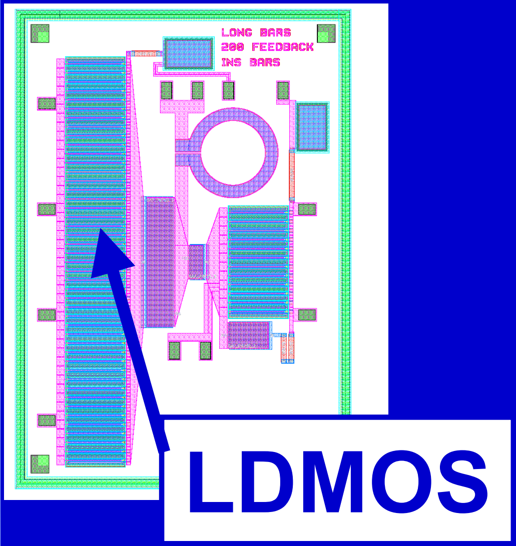
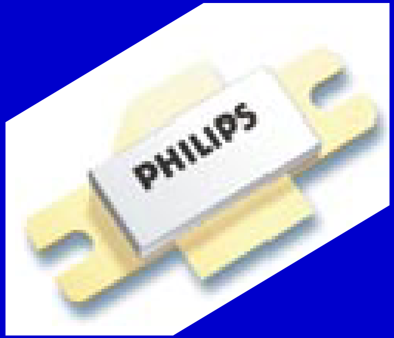
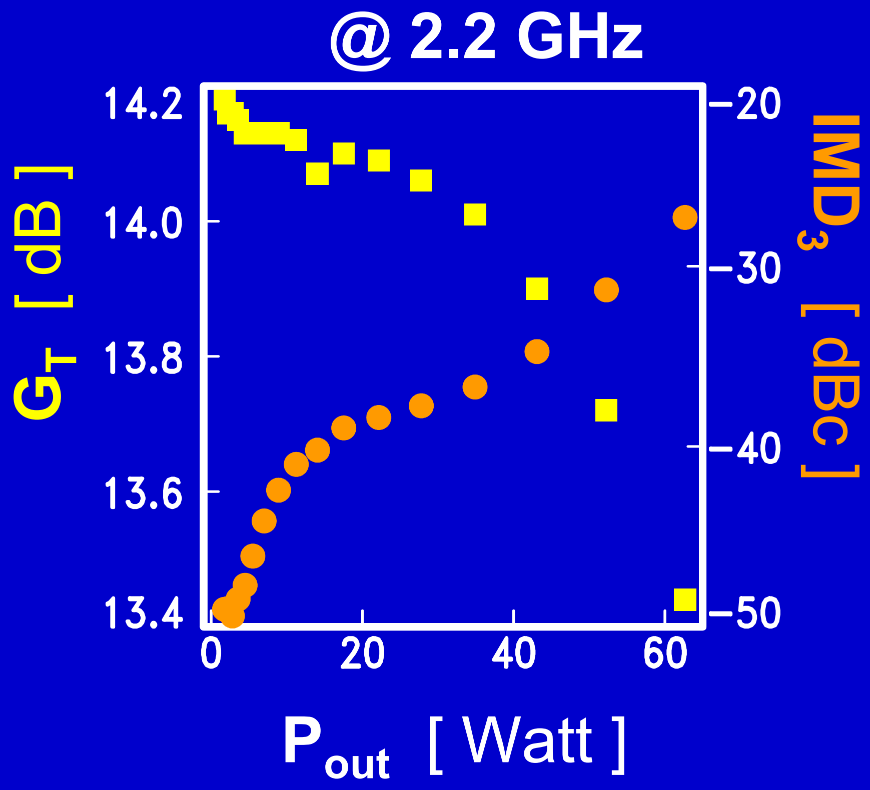
introduction: LDMOS devices



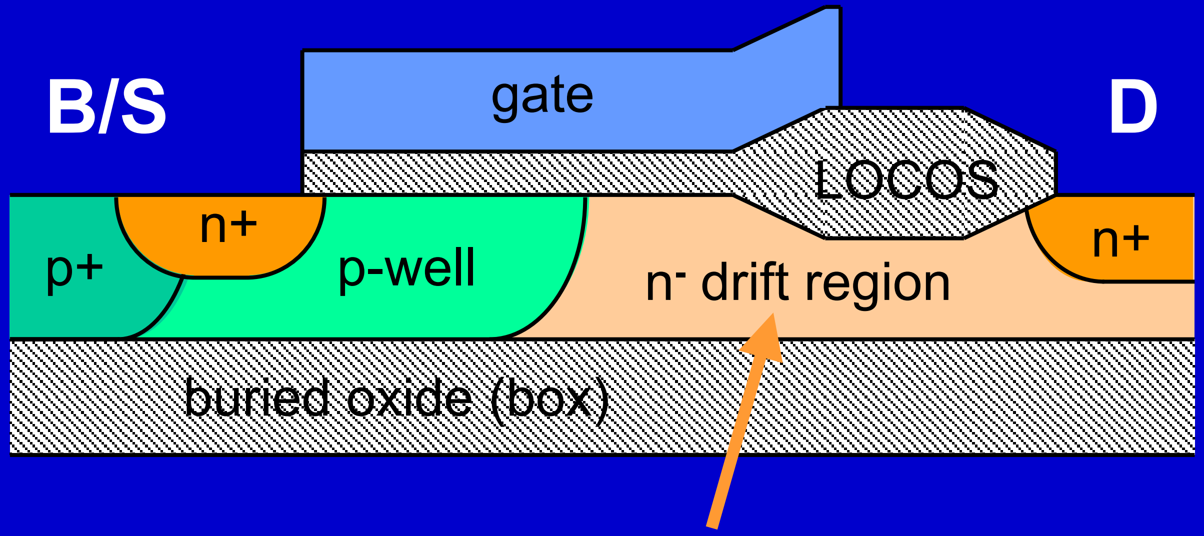


RF-power amplifiers



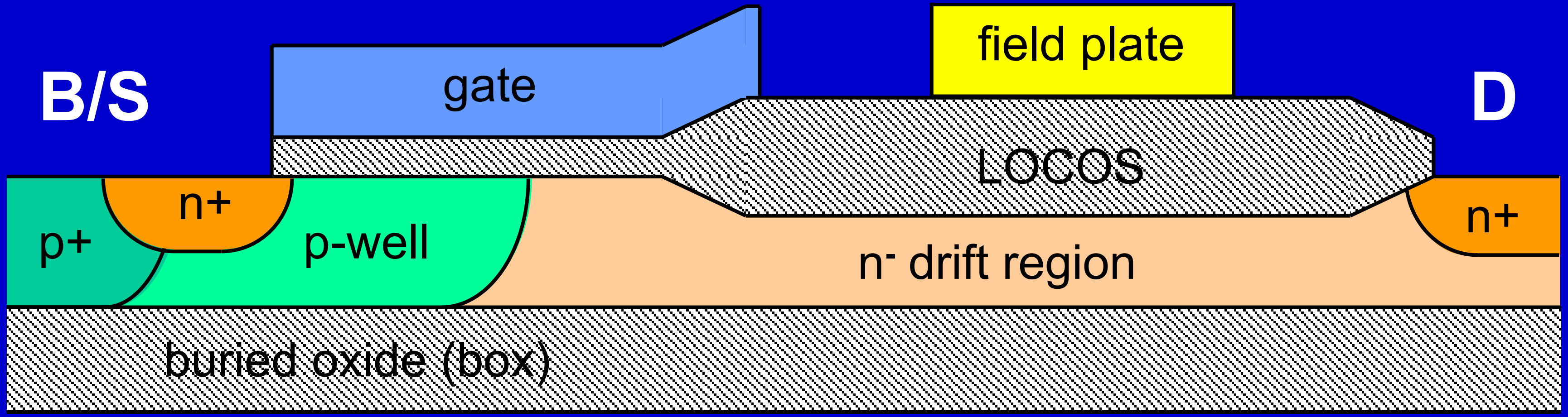
LDMOS applications ⇒ accurate modelling important

introduction: LDMOS devices



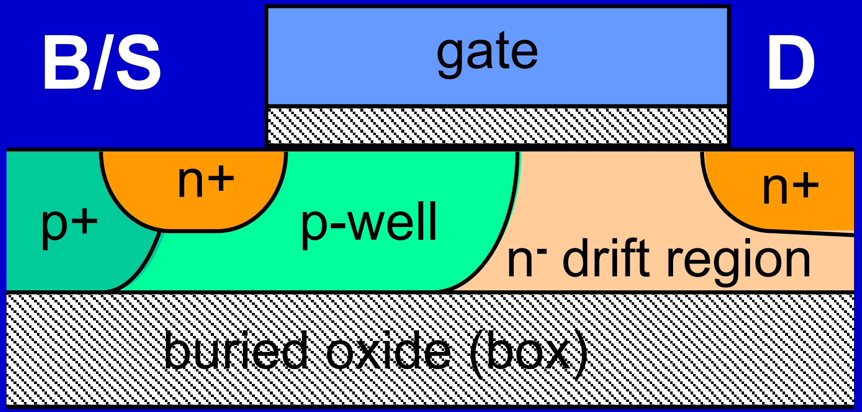
to withstand high voltages

introduction: LDMOS devices



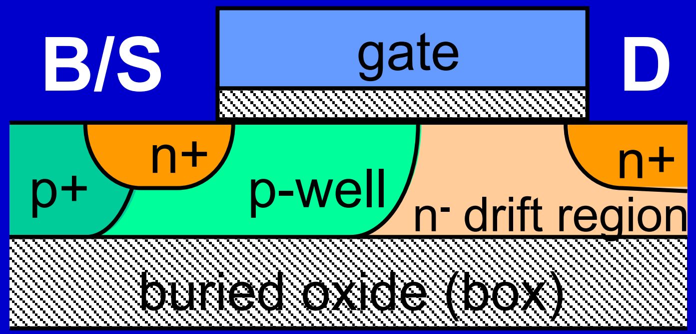
drain voltages can be as high as 1200V ….

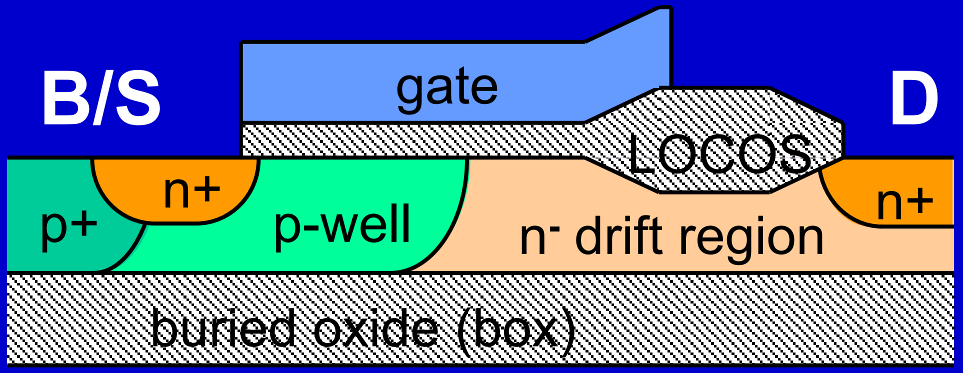
introduction: LDMOS devices

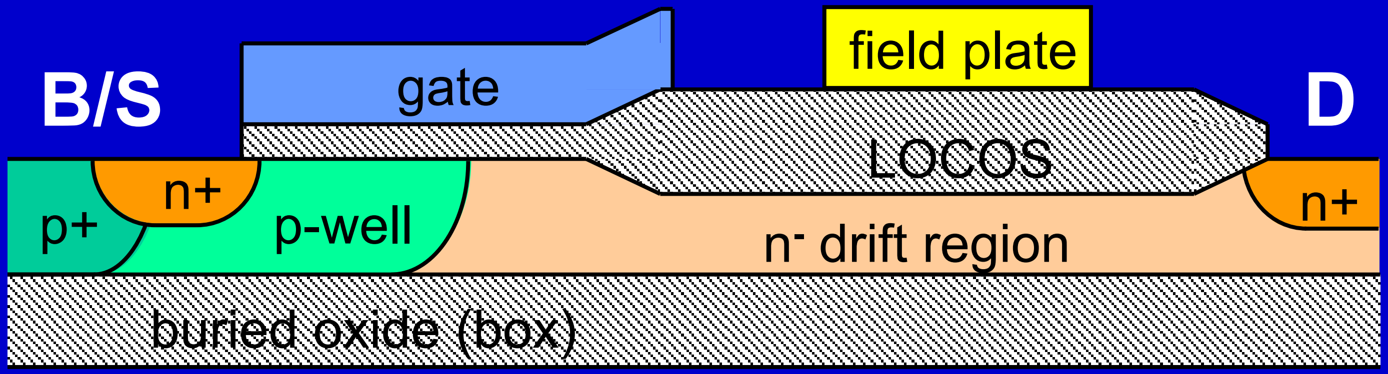


…. or drain voltages can be as low as 12V

introduction: LDMOS devices

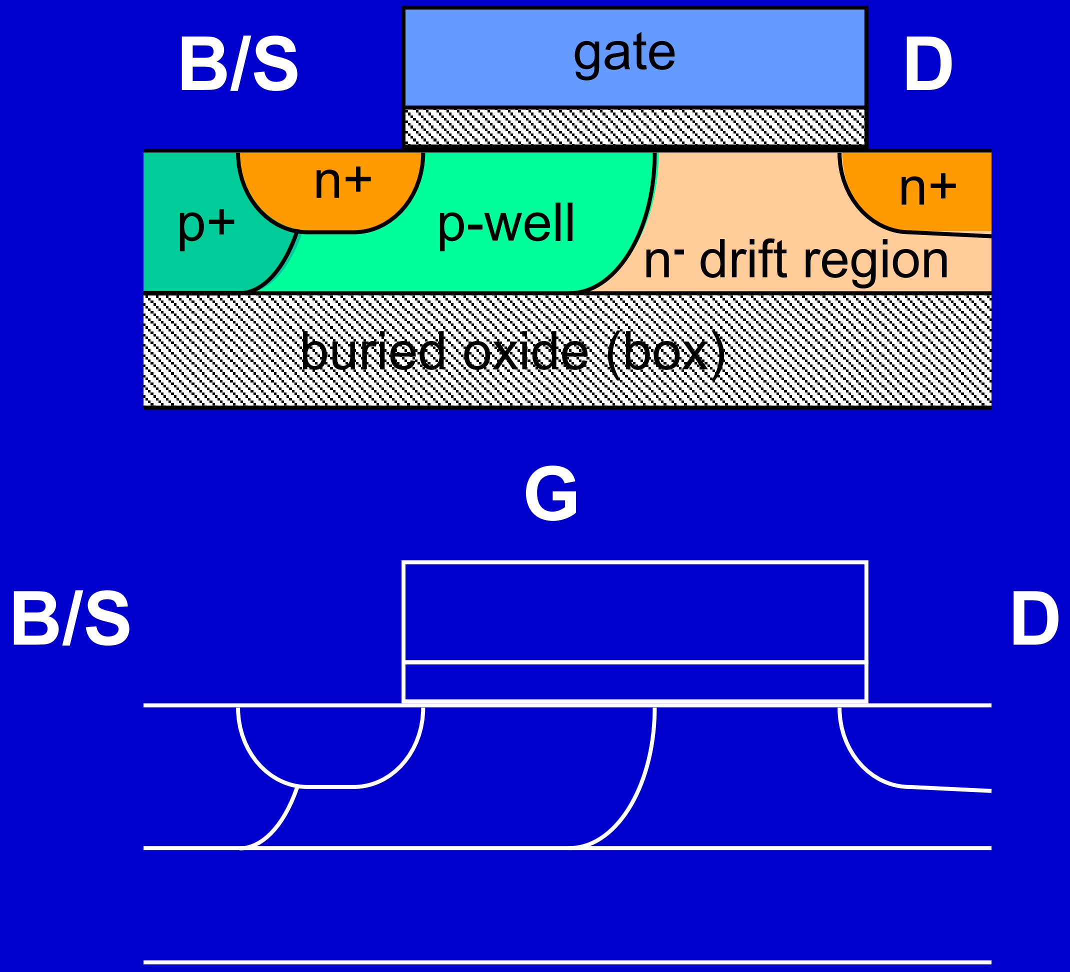






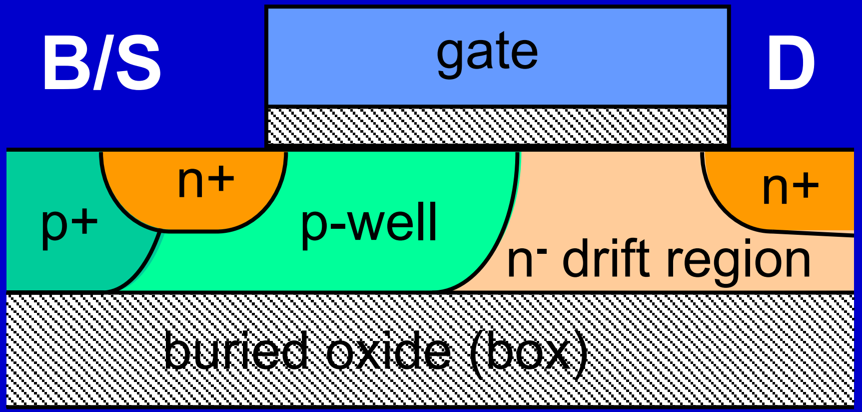
drain voltages vary between 12 and 1200V

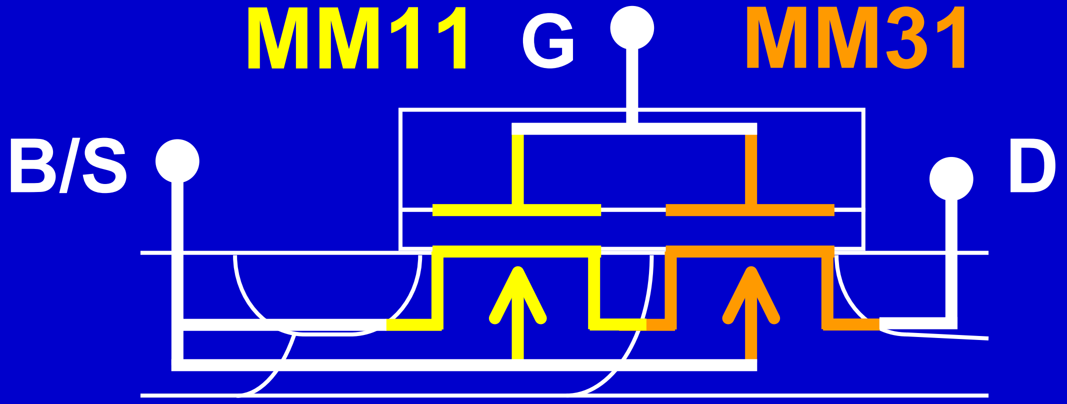
introduction: LDMOS devices



low-voltage LDMOS device

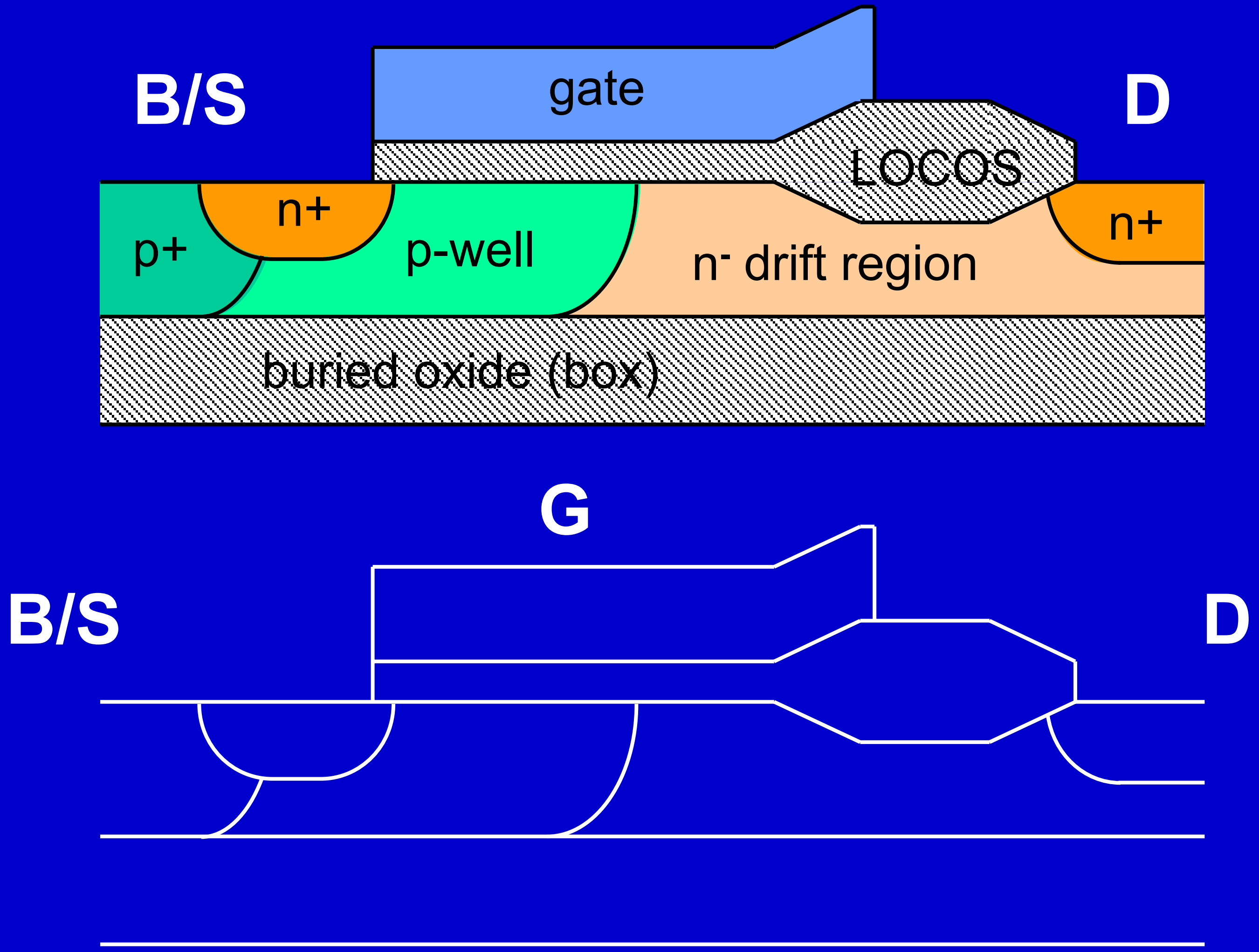
introduction: LDMOS devices





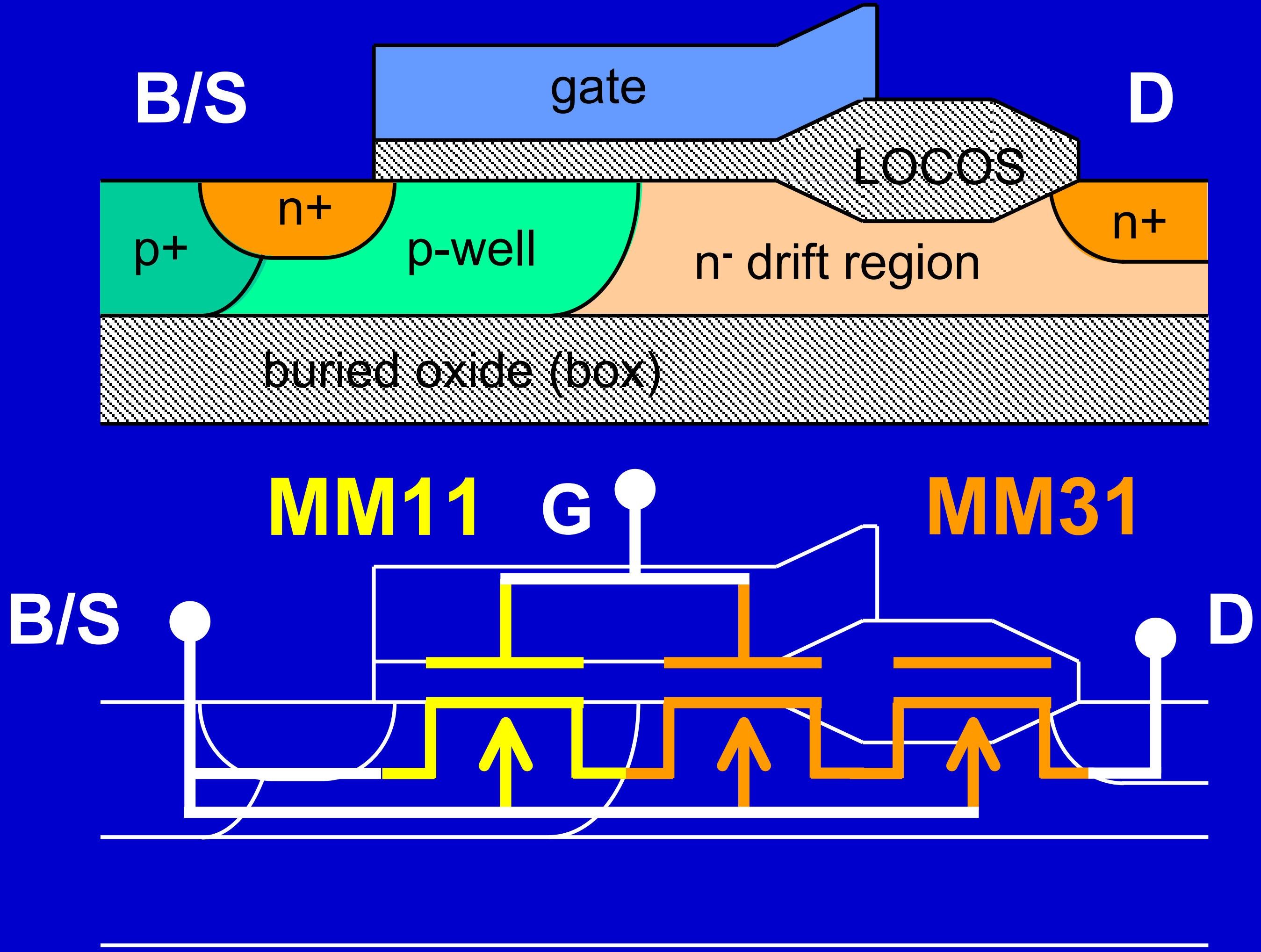
low-voltage LDMOS device

introduction: LDMOS devices



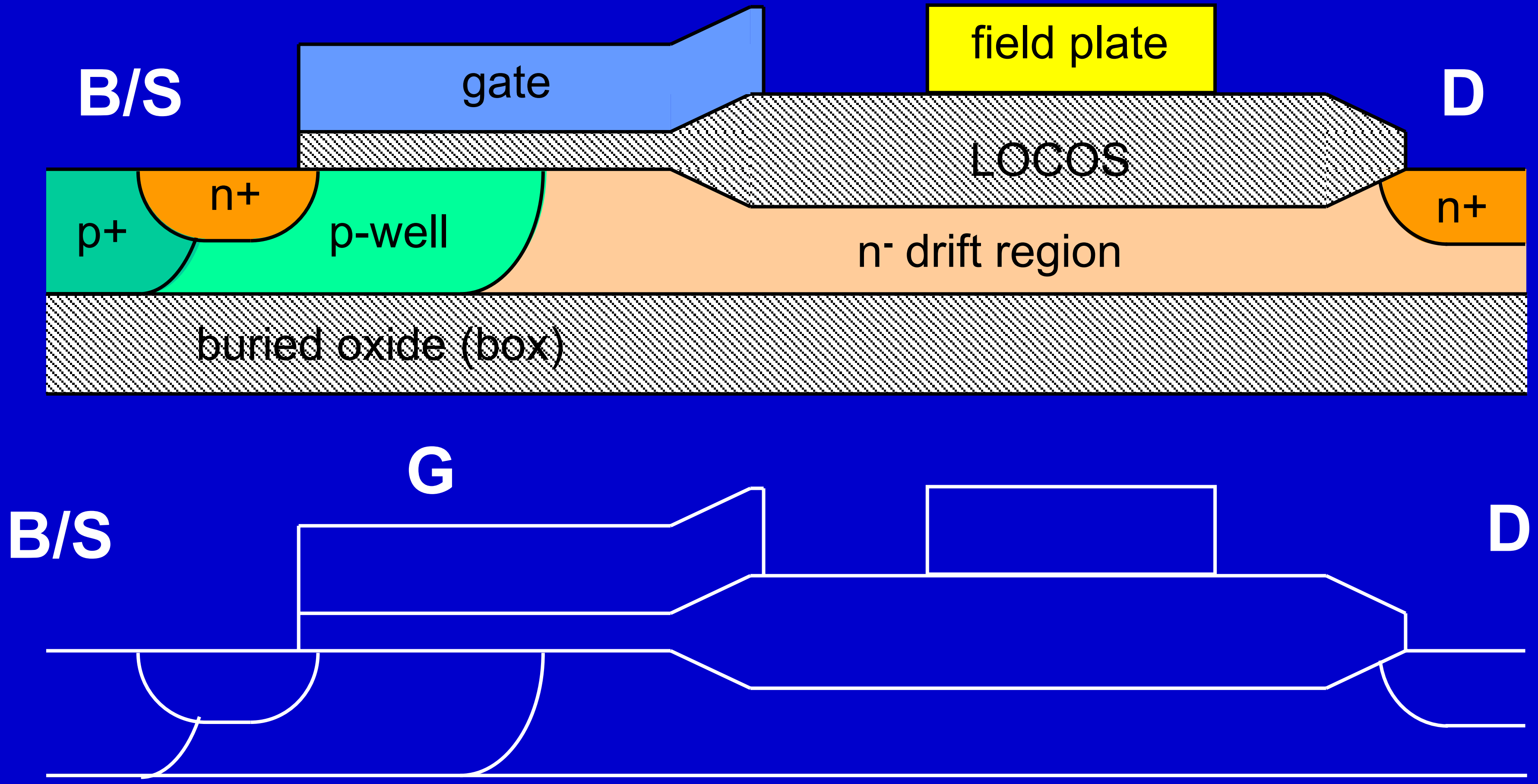
medium-voltage LDMOS device

introduction: LDMOS devices



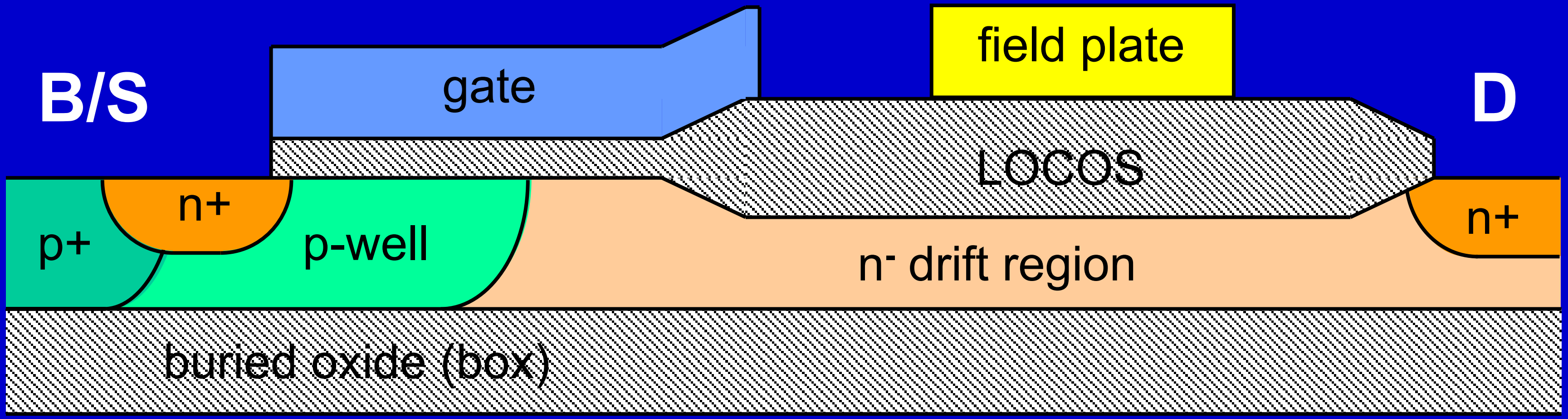
medium-voltage LDMOS device

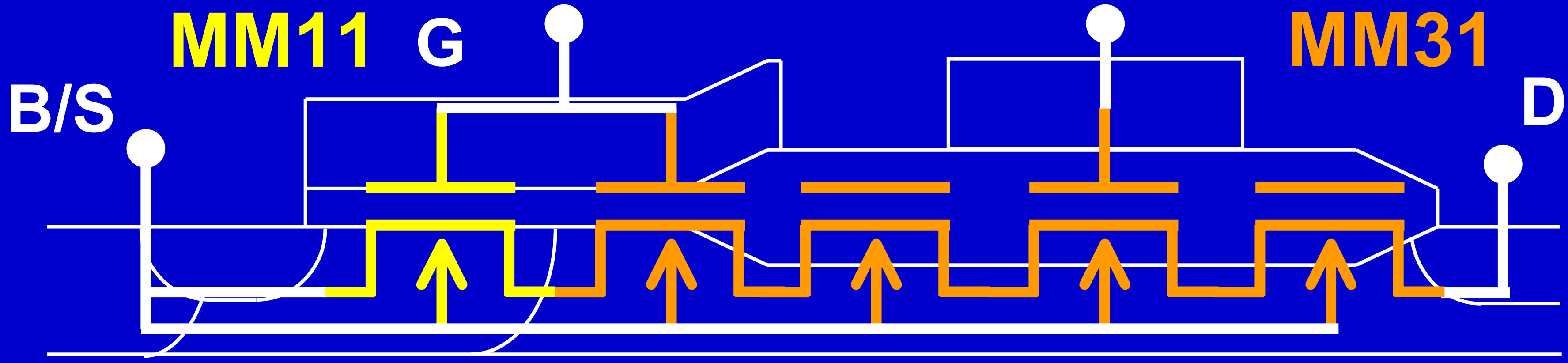
introduction: LDMOS devices



high-voltage LDMOS device

introduction: LDMOS devices



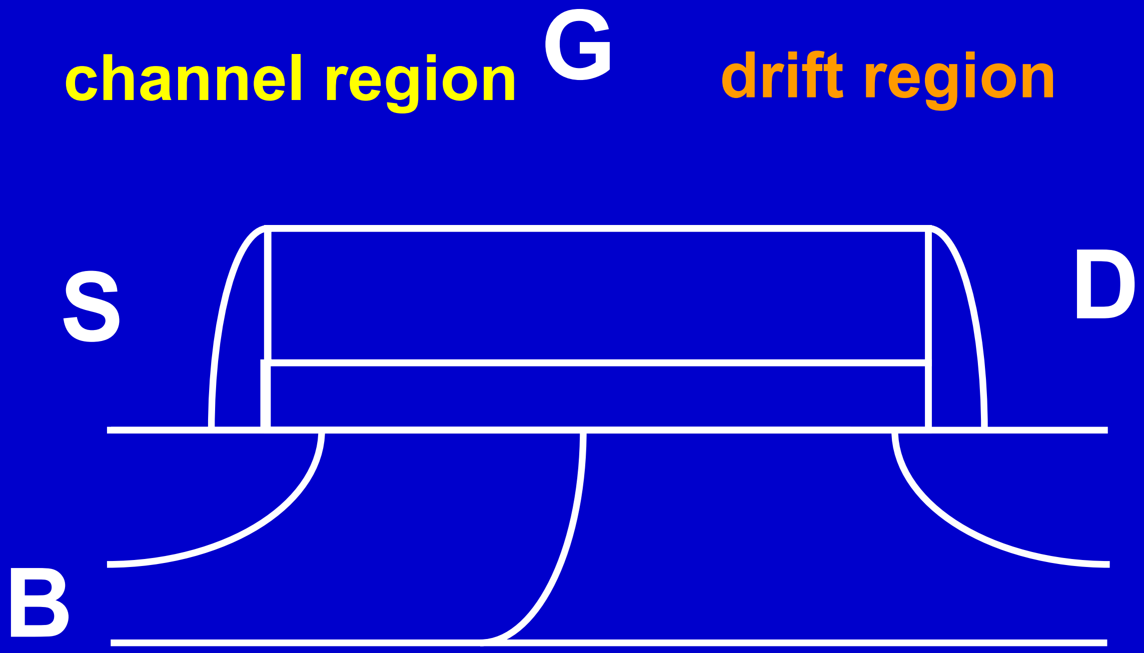


high-voltage LDMOS device

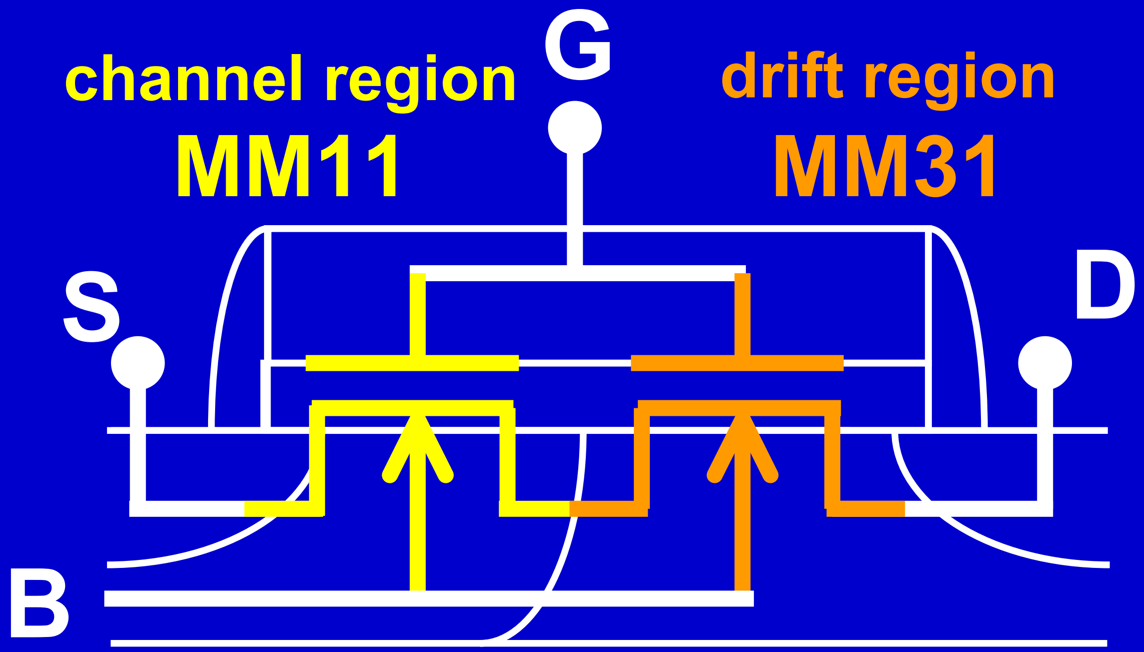
outline

- introduction
    - LDMOS devices
    - ➡ modelling approaches
- MOS Model 20
    - basic model
    - additional model features
- summary

modelling approach: sub-circuit models



modelling approach: sub-circuit models



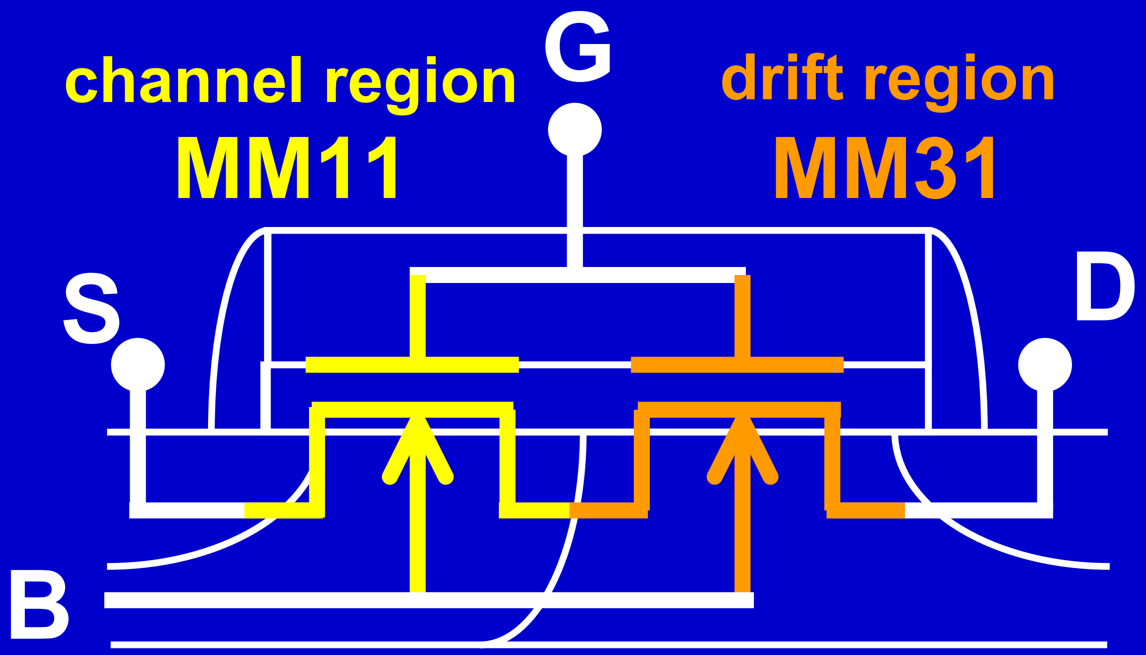
channel region

MM11

drift region

MM31

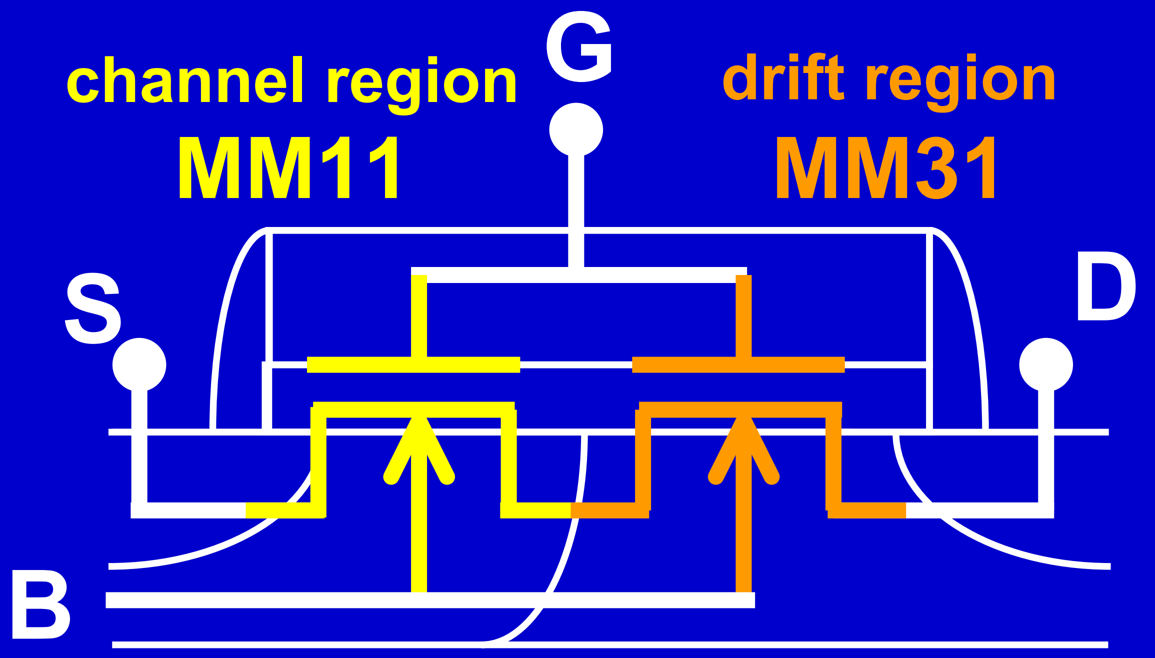
modelling approach: sub-circuit models



pro's

- flexible
- charge partitioning
  channel / drift region

modelling approach: sub-circuit models



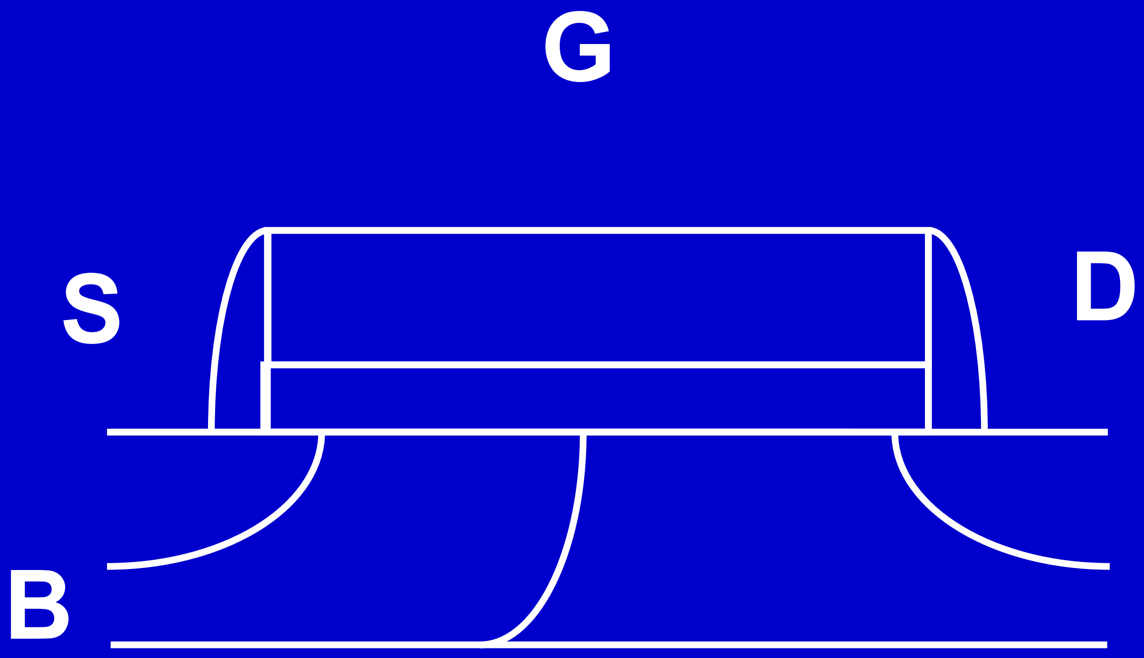
pro’s

- flexible
- charge partitioning
  channel / drift region

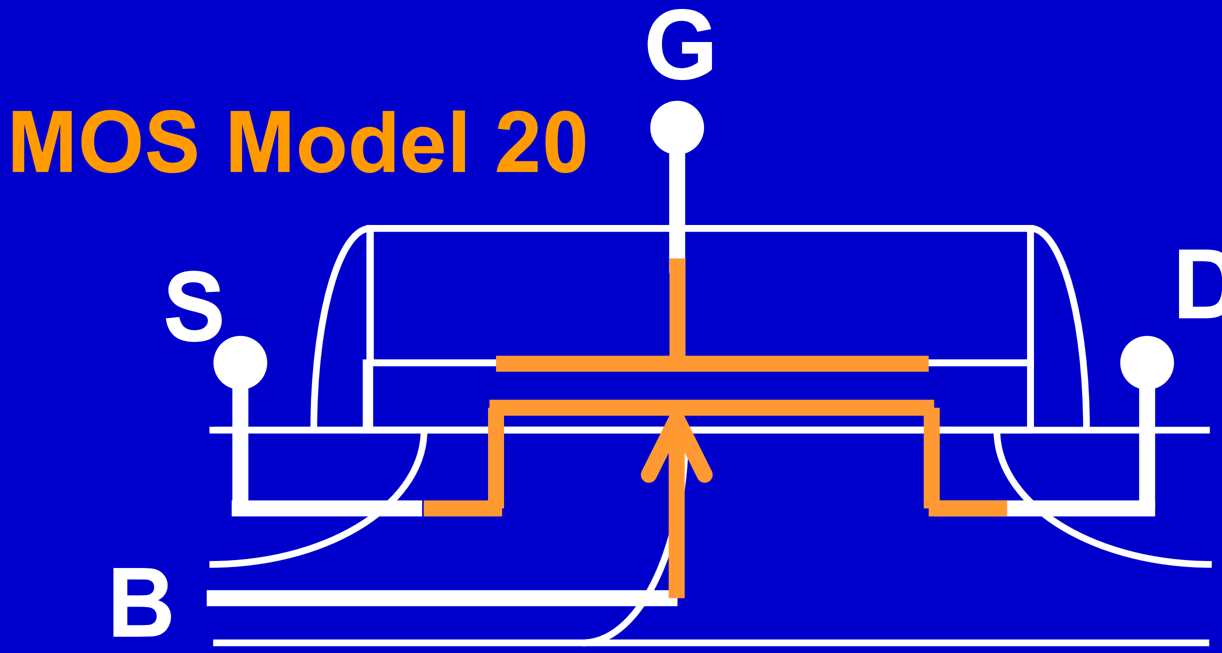
con’s

- uncontrolled node
- computation time /
  convergence

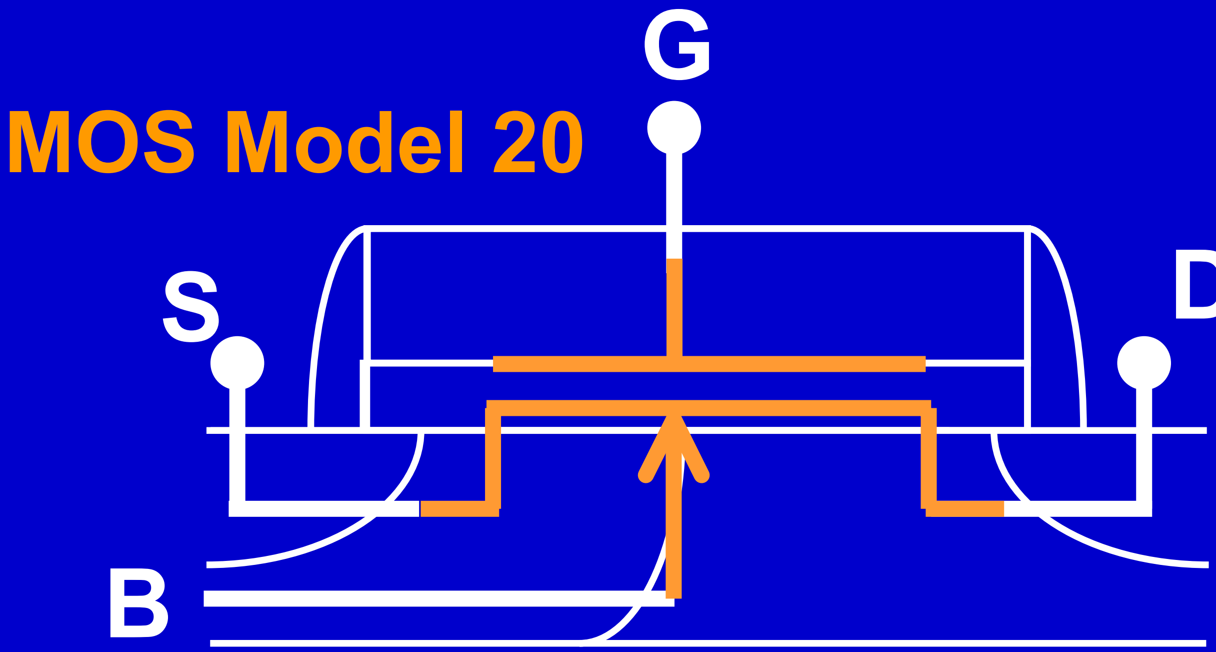
modelling approach: single models



modelling approach: single models



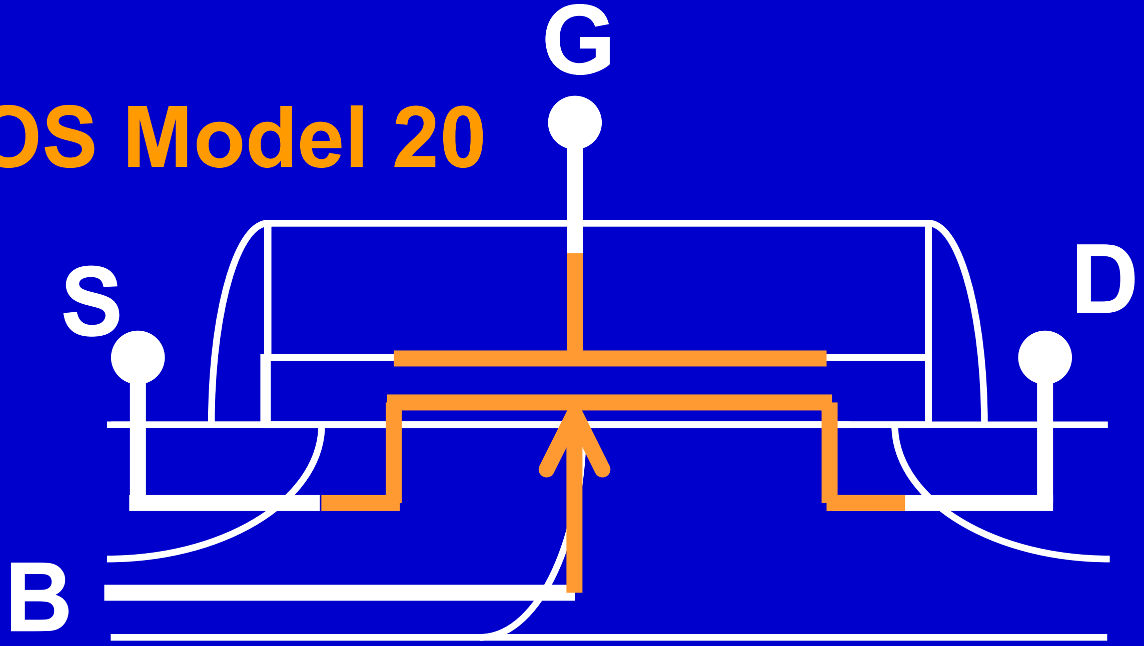
modelling approach: single models



pro's

- no uncontrolled node
- convergence

modelling approach: single models



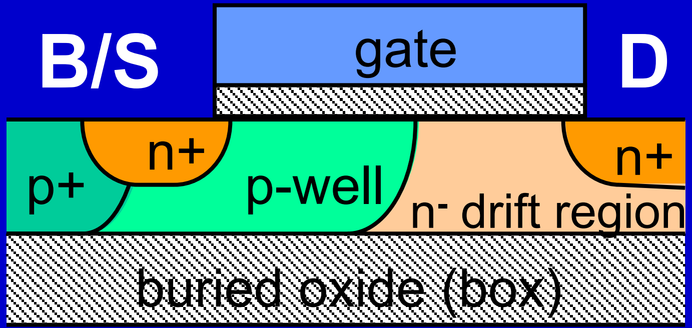
pro’s

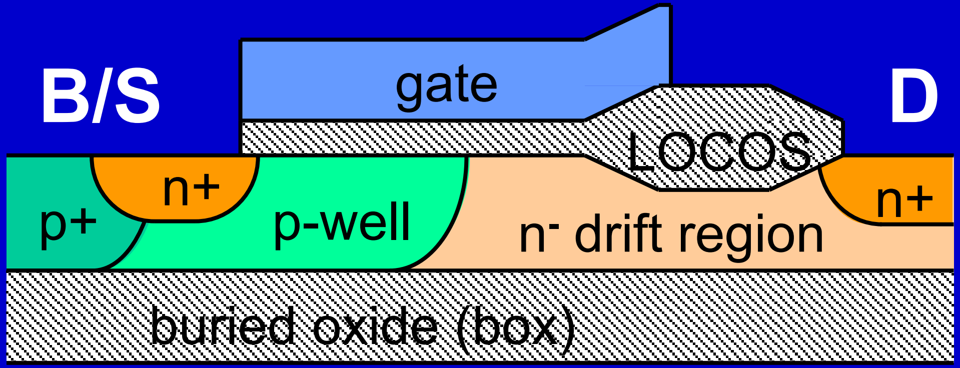
- no uncontrolled node
- convergence

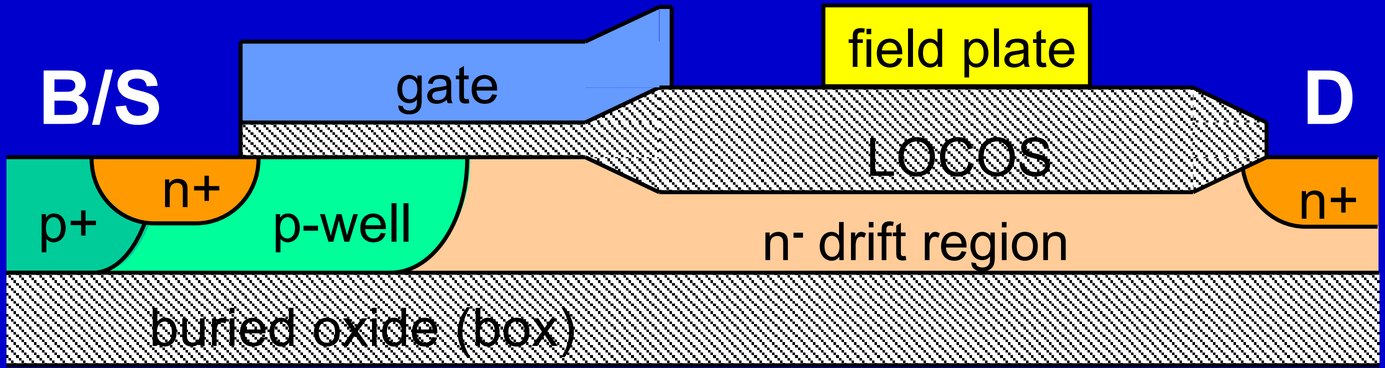
con’s

- charge partitioning
  channel / drift region

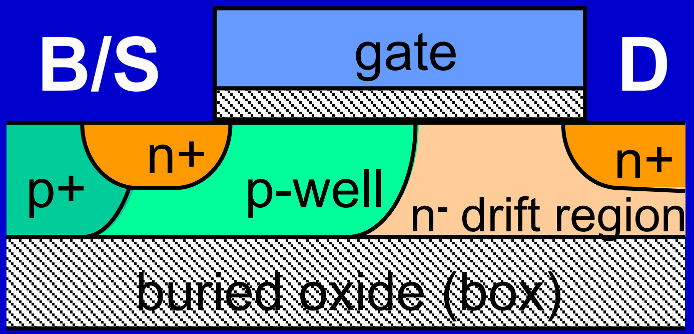
modelling approach: target

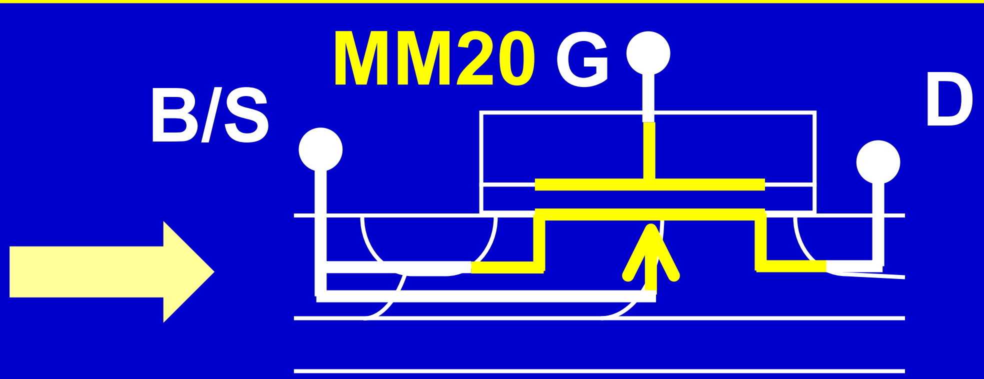


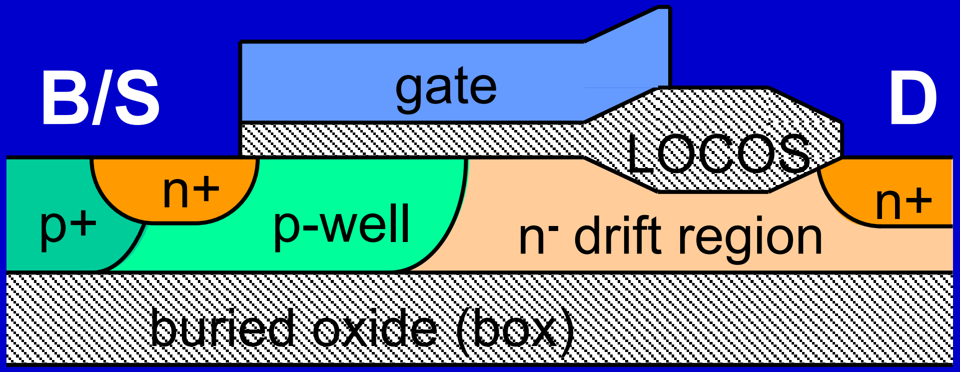


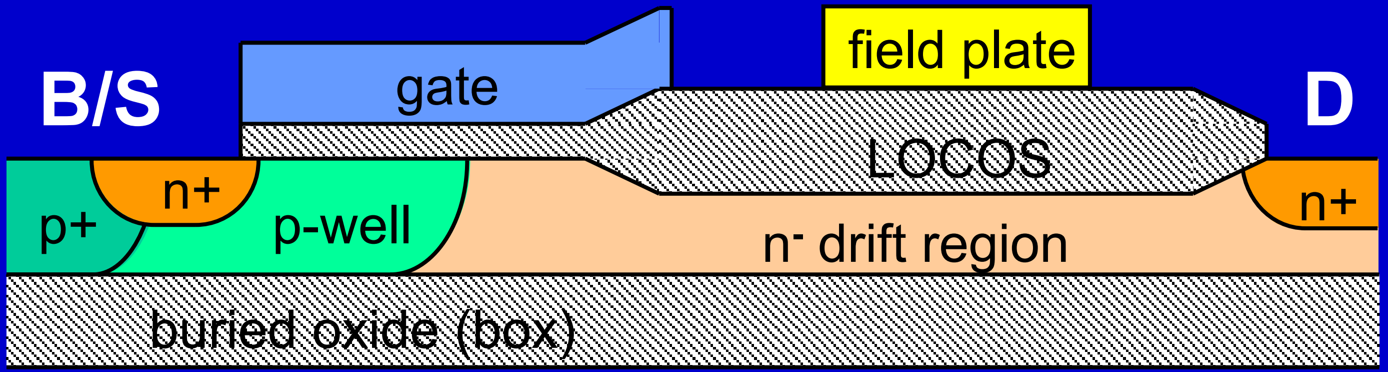


modelling approach: target

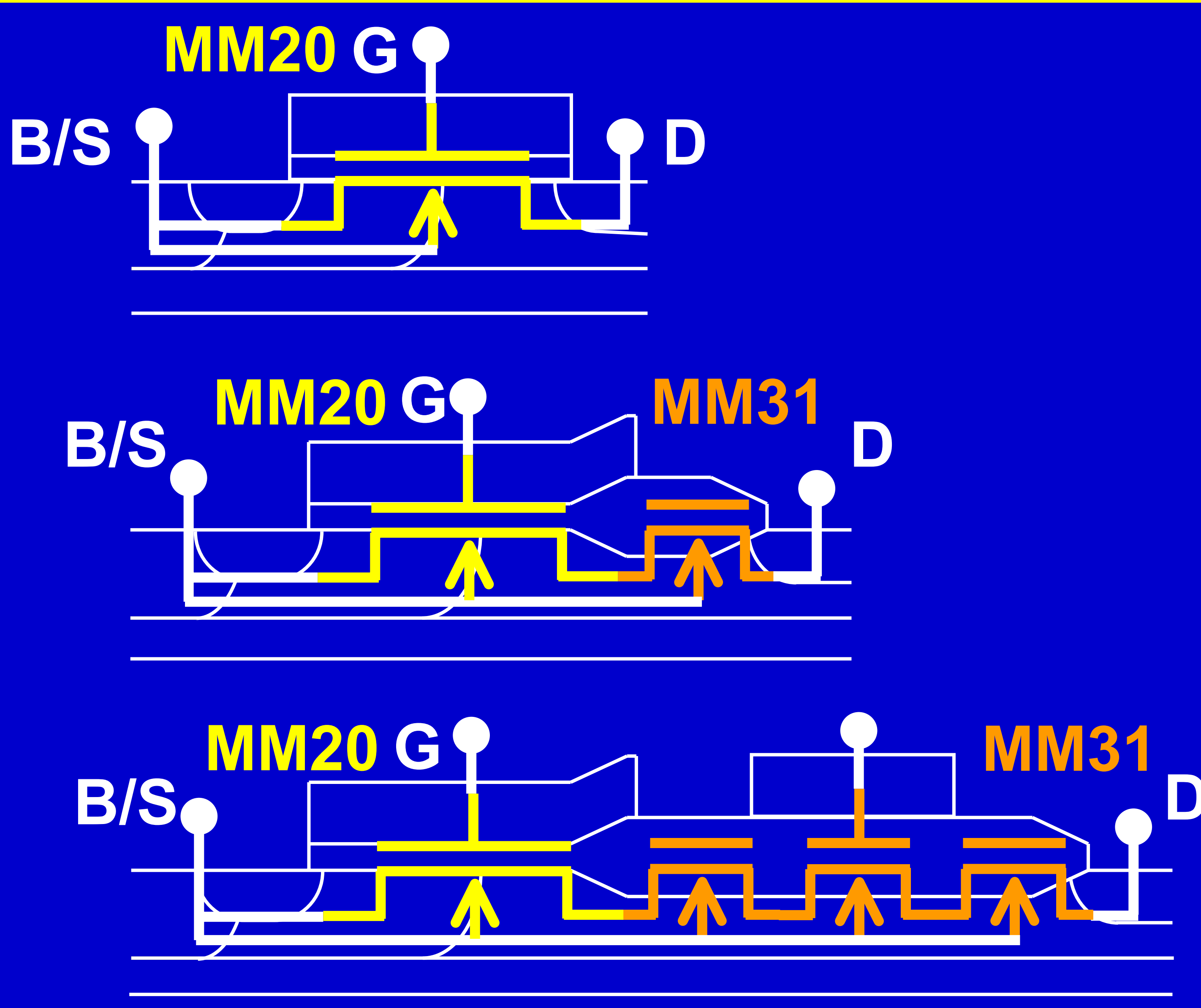




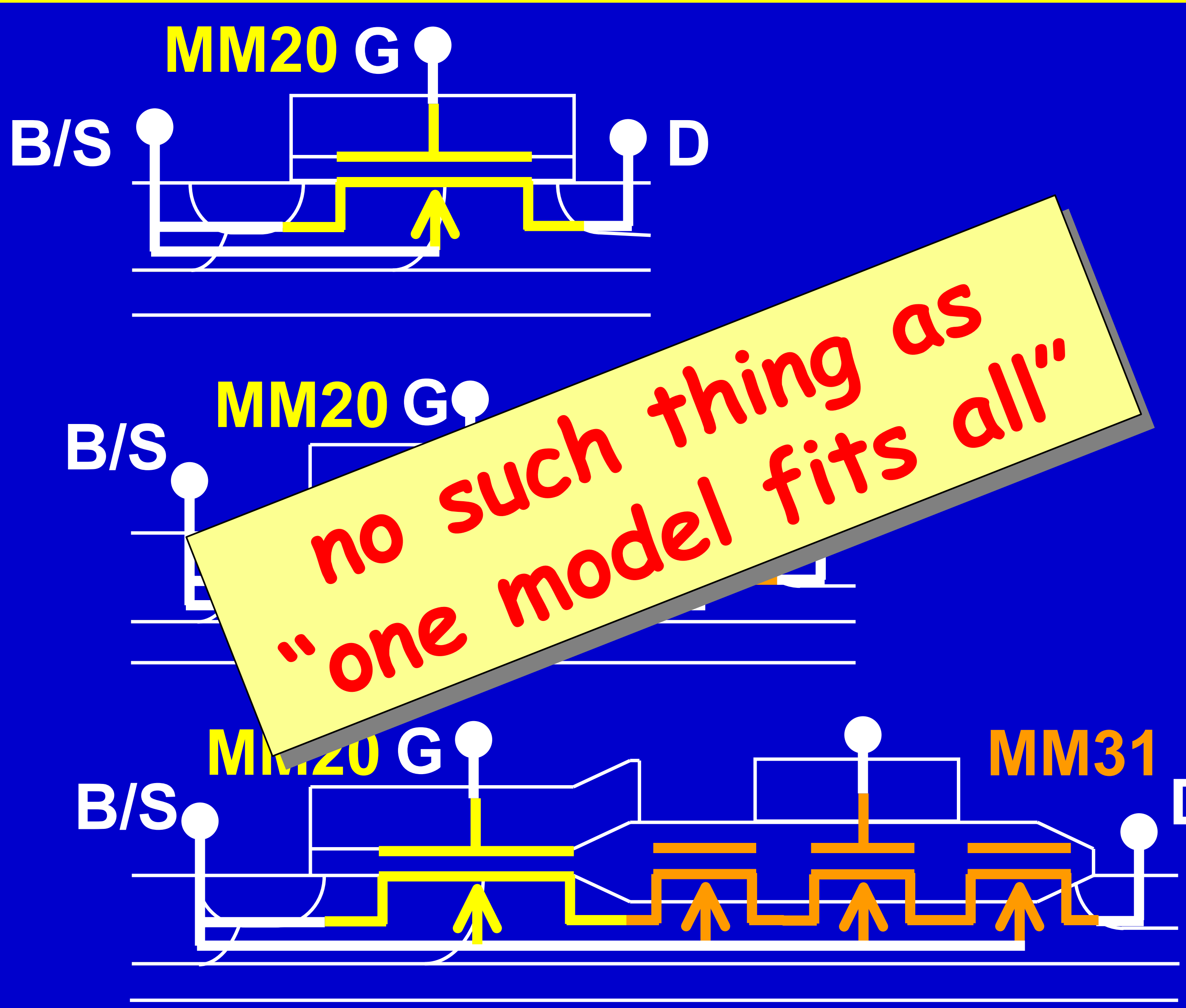




modelling approach: target



modelling approach: target

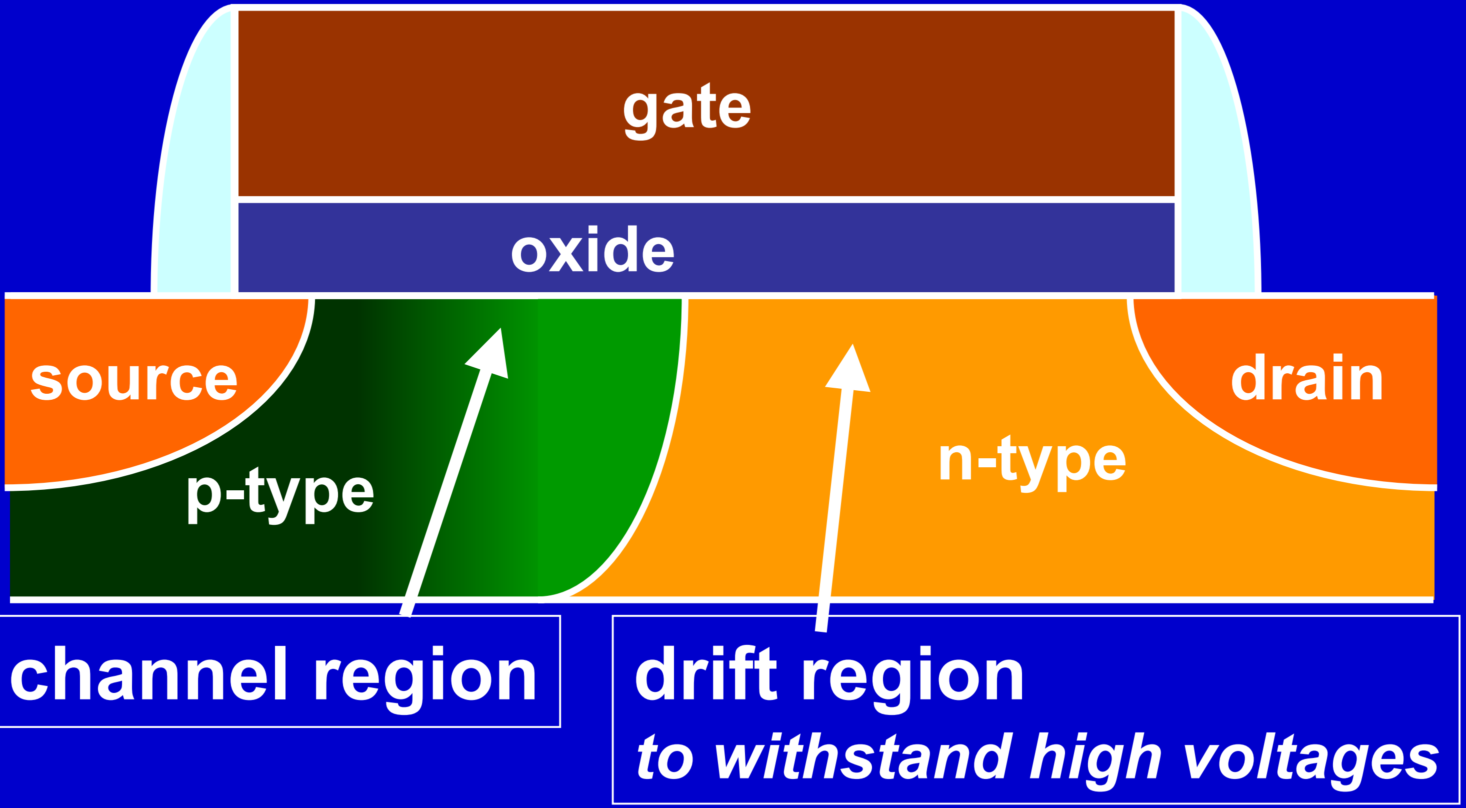


no such thing as "one model fits all"

outline

- introduction
- MOS Model 20
  - ➡ basic model
    - DC-model
    - nodal charge model
  - additional model features
- summary

MOS Model 20: challenges

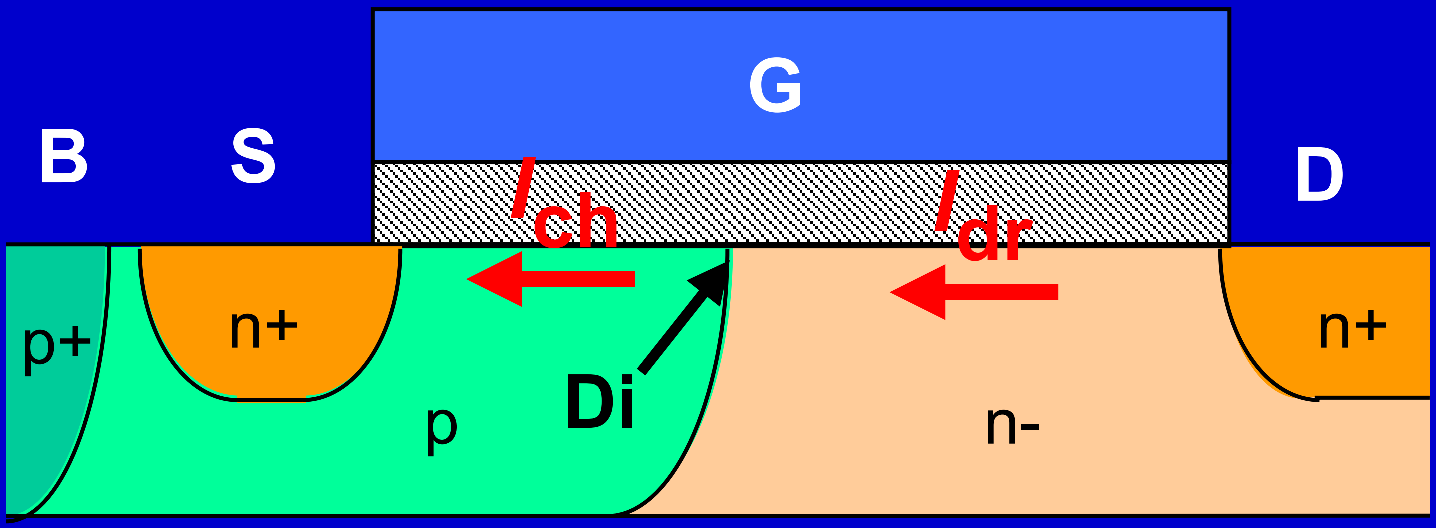


channel region

drift region
to withstand high voltages

lateral non-uniformity: 1. both p- and n-type
2. diffused p-well doping

MOS Model 20: DC-model

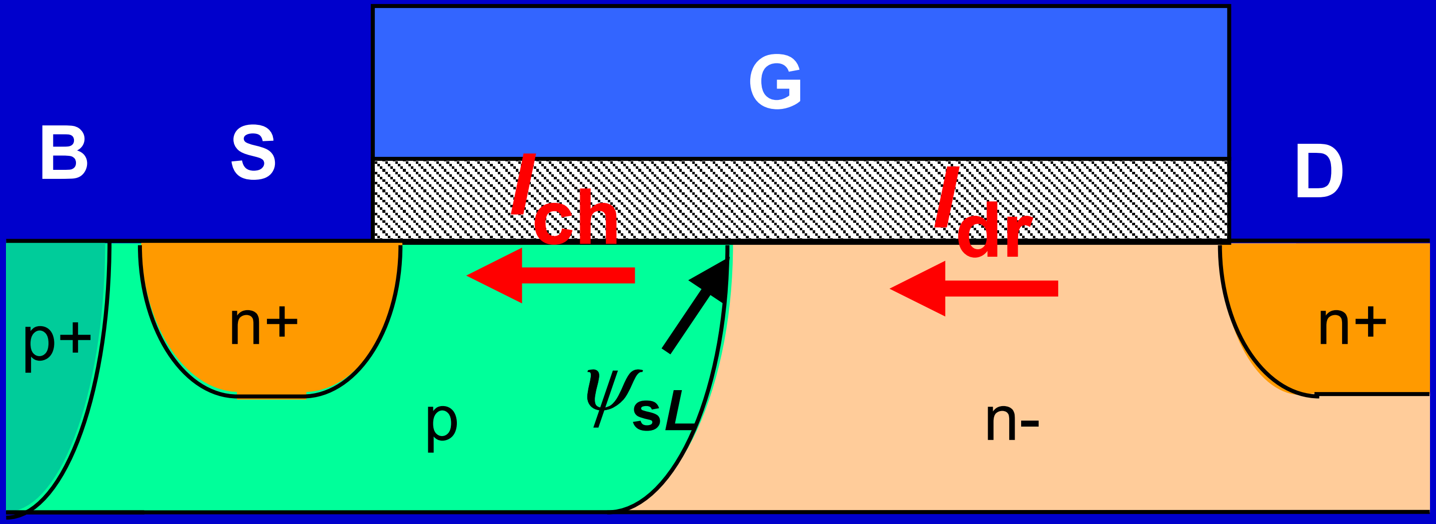


approach: 1. determine V_{Di} :

Kirchhoff's current law (KCL): $I_{ch} = I_{dr}$

2. DC-current: $I_{DS} = I_{ch}$

MOS Model 20: DC-model

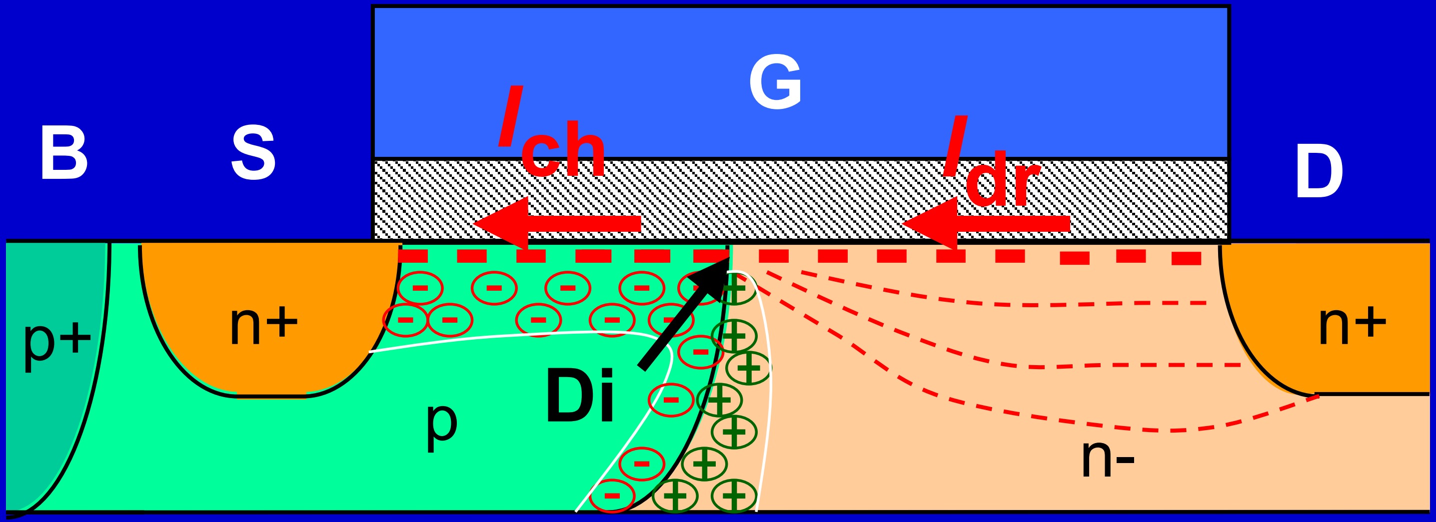


essential to first determine V_{Di} since

$$I_{DS} = I_{ch} = I_{ch}\,(\psi_{sL},\ \psi_{s0})$$

$$\psi_{sL} = \psi_{sL}\,(\underline{V_{DiS}},\ V_{GS},\ V_{SB}\ )$$

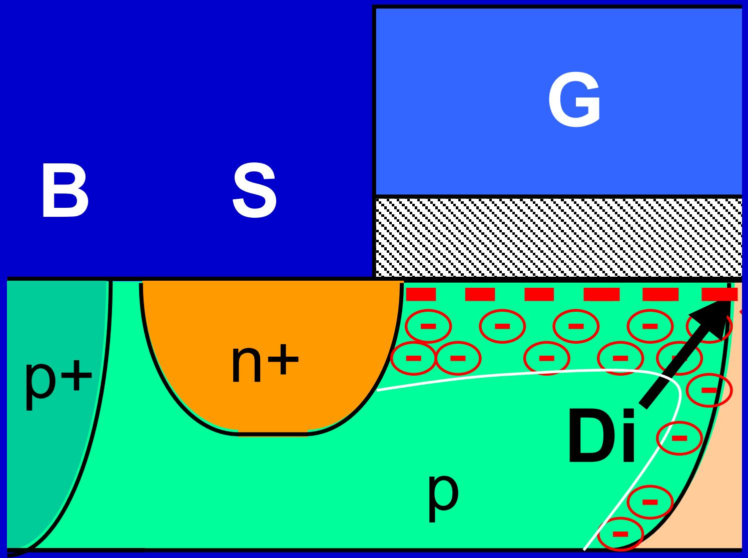
MOS Model 20: internal drain potential



1. determine V_{Di} from:

$$I_{ch}\,(\underline{V_{DiS}},\ V_{GS},\ V_{SB}) = I_{dr}\,(\underline{V_{DDi}},\ \underline{V_{GDi}},\ \underline{V_{DiB}})$$

MOS Model 20: internal drain potential



determine:

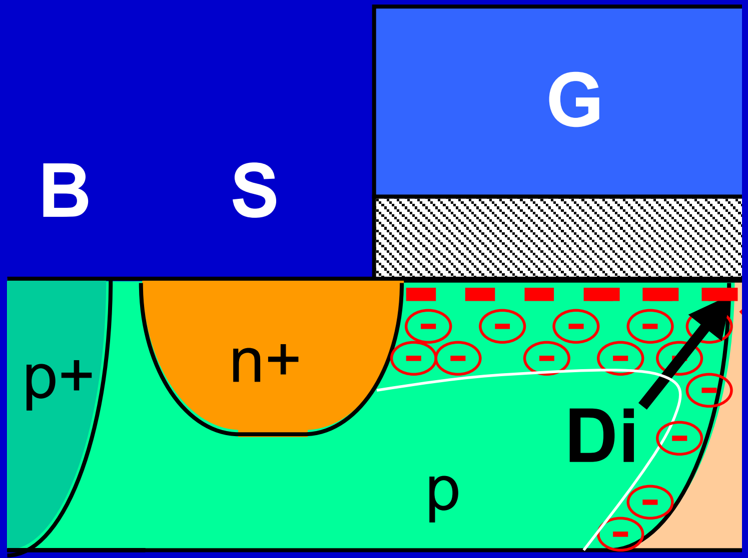
$$I_{ch} = I_{ch}\,(V_{DiS}, V_{GS,} V_{SB})$$

include:

- strong inversion
- mobility reduction due to vertical field
- velocity saturation

neglect 2nd-order effects

MOS Model 20: internal drain potential



include strong inversion

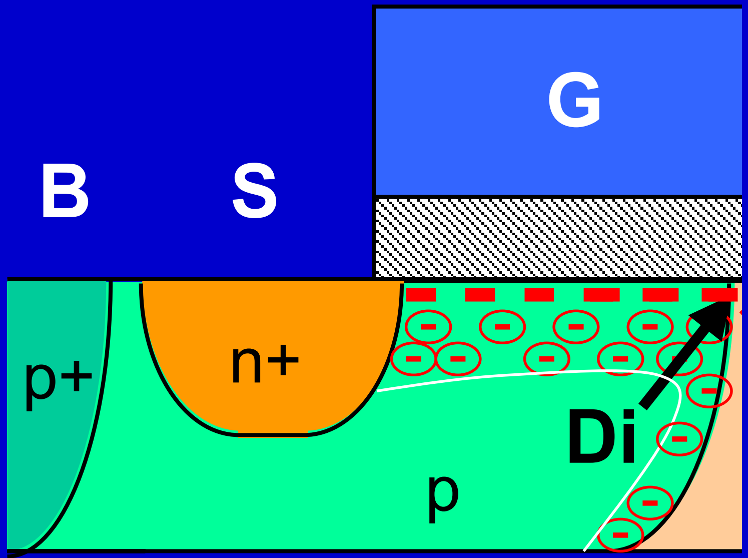
$$I_{\mathrm{ch}} = \frac{W\mu_{\mathrm{ch}}}{L_{\mathrm{ch}}} \int_{\psi_{\mathrm{s0}}}^{\psi_{\mathrm{s}L}} -Q_{\mathrm{inv}} d\psi_{\mathrm{s}}$$

approximation: $Q_{\mathrm{inv}} \cong -C_{\mathrm{ox}} \left[\underbrace{V_{\mathrm{inv0}}} - \xi\left(\psi_{\mathrm{s}} - \psi_{\mathrm{s0}}\right) \right]$

inversion charge at source

$$\xi = 1 + \frac{0.5 k_0}{\sqrt{\psi_{\mathrm{s0}} + 1}}$$

MOS Model 20: internal drain potential



include strong inversion

$$I_{\mathrm{ch}} = \frac{W\mu_{\mathrm{ch}}}{L_{\mathrm{ch}}} \int_{\psi_{s0}}^{\psi_{sL}} -Q_{\mathrm{inv}} d\psi_s$$

approximation: $Q_{\mathrm{inv}} \cong -C_{\mathrm{ox}} \left[\underbrace{V_{\mathrm{inv}0}}_{} - \xi \left(\psi_s - \psi_{s0} \right) \right]$

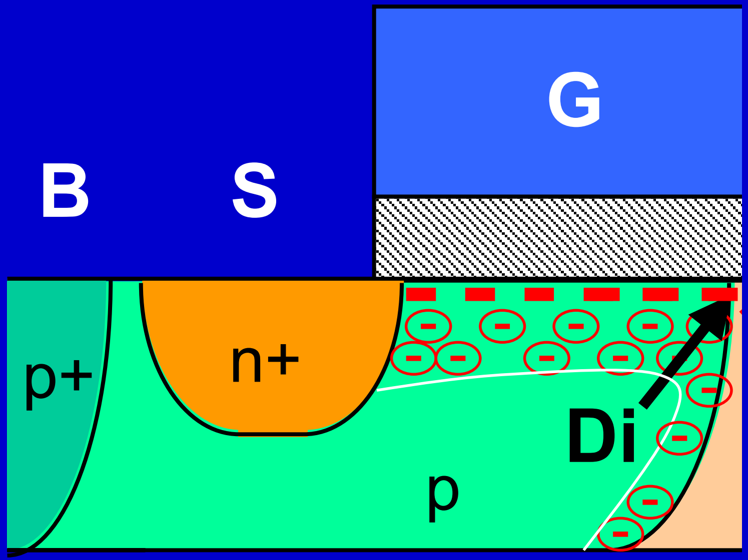
inversion charge at source

$$\xi = 1 + \frac{0.5 k_0}{\sqrt{\psi_{s0} + 1}}$$

➡ $$I_{\mathrm{ch}} = \frac{W\mu_{\mathrm{ch}} C_{\mathrm{ox}}}{L_{\mathrm{ch}}} \left(V_{\mathrm{inv}0} - \frac{\xi}{2} \Delta\psi_s \right) \Delta\psi_s$$

$$\Delta\psi_s = \psi_{sL} - \psi_{s0}$$

MOS Model 20: internal drain potential



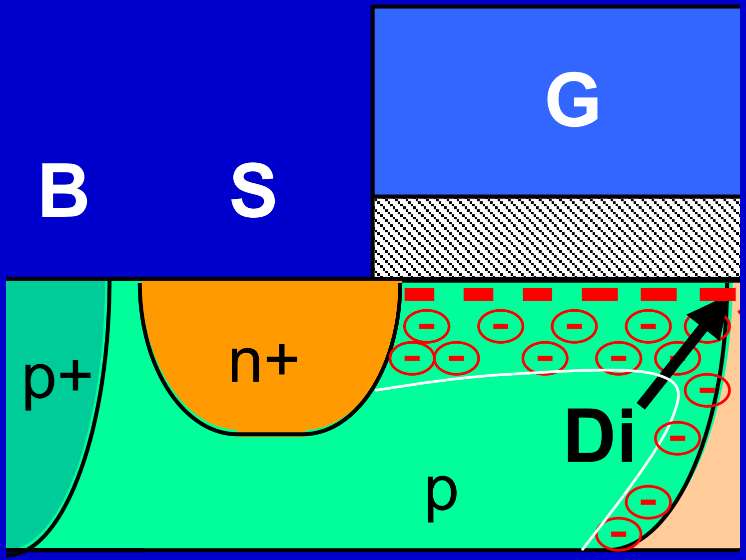
include

- **velocity saturation**

$$\mu_{\mathbf{ch}} = \frac{\mu_{\mathbf{eff}}}{1 + \theta_3 \Delta \psi_{\mathbf{s}}}$$

$$\theta_3 = \frac{\mu_{\mathbf{0}}}{L_{\mathbf{ch}}\, v_{\mathbf{sat}}}$$

MOS Model 20: internal drain potential



include

- **velocity saturation**

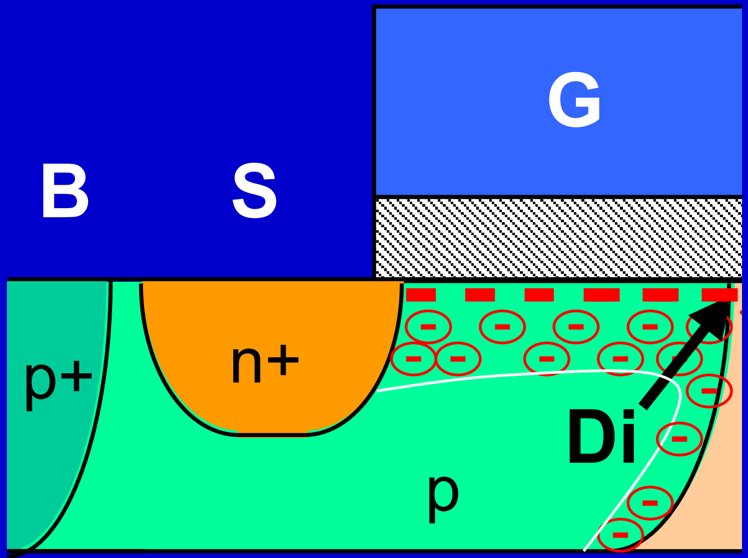
$$\mu_{ch} = \frac{\mu_{eff}}{1 + \theta_3 \Delta\psi_s}$$

$$\theta_3 = \frac{\mu_0}{L_{ch}\, v_{sat}}$$

- **mobility reduction** (surface scattering)

$$\mu_{eff} = \frac{\mu_0}{1 + \theta_1 V_{inv0} + \theta_2\left(\sqrt{\psi_{s0}} - \sqrt{\psi_{s0}\big|_{V_{SB}=0}}\right)} = \frac{\mu_0}{F_{mob}}$$

MOS Model 20: internal drain potential



approximate: $\Delta\psi_s \cong V_{DiS}$

$$I_{ch} = \beta \frac{\left(V_{inv0} - 0.5\xi\, V_{DiSeff}\right) V_{DiSeff}}{F_{mob}\left(1 + \theta_3\, V_{DiSeff}\right)}$$

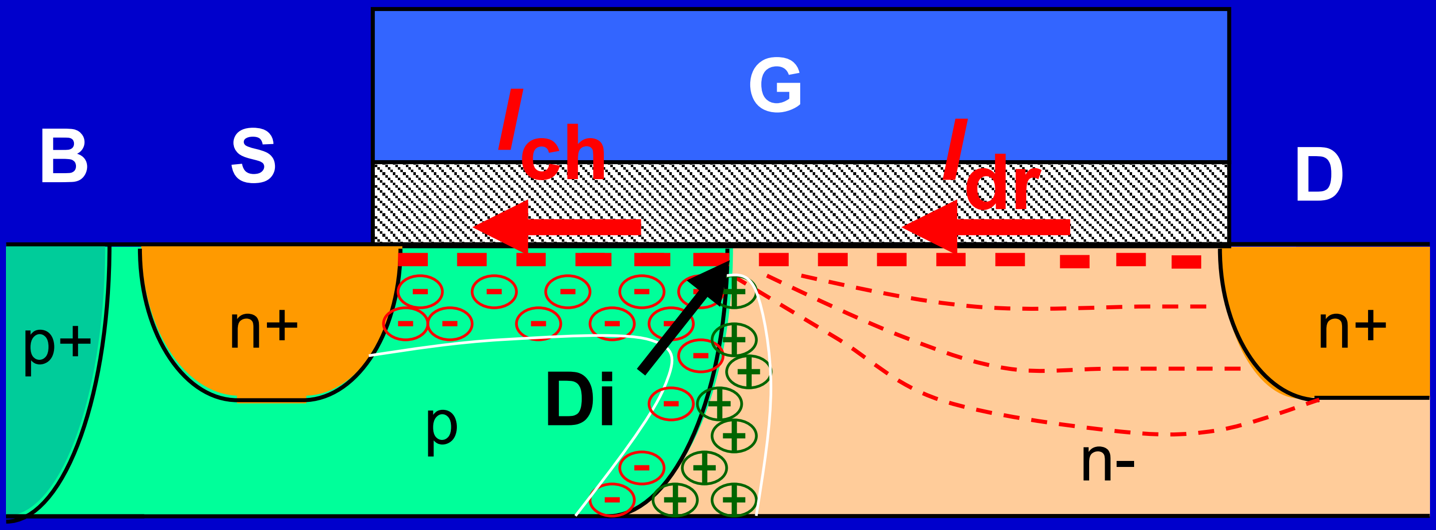
$$\beta = \frac{W \mu_0 C_{ox}}{L_{ch}}$$

$$V_{DiSeff} = \min\left(V_{DiS}, V_{DiSsat}\right)$$

$$V_{DiSsat} = \frac{2V_{inv0}/\xi}{1 + \sqrt{1 + 2\theta_3\, V_{inv0}/\xi}}$$

$I_{ch} = I_{ch}\,(V_{DiS}, V_{GS}, V_{SB})$

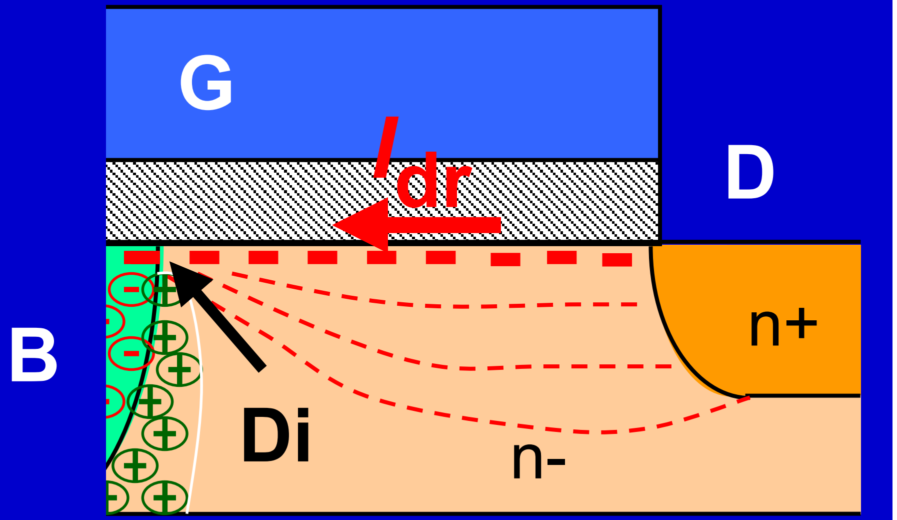
MOS Model 20: internal drain potential



1. determine V_{Di} from:

$$I_{ch}\,(\underline{V_{DiS}},\ V_{GS},\ V_{SB}) = I_{dr}\,(\underline{V_{DDi}},\ \underline{V_{GDi}},\ \underline{V_{DiB}})$$

MOS Model 20: internal drain potential



determine:

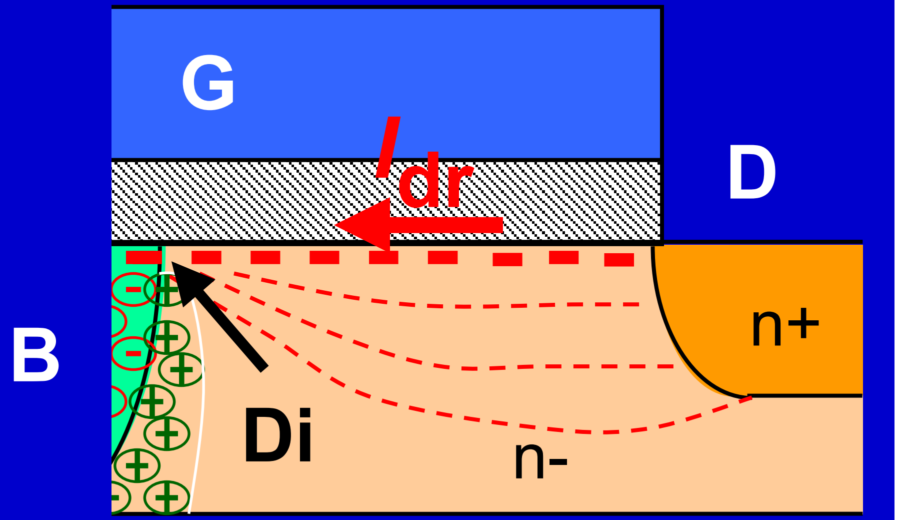
$$I_{dr} = I_{dr}\,(V_{DDi}\,,\; V_{GDi}\,,\; V_{DiB})$$

include:

- accumulation
- depletion
- bulk current
- mobility reduction due to vertical field
- velocity saturation
- pinch-off

MOS Model 20: internal drain potential

$$I_{\text{dr}} = \frac{W\mu_{\text{dr}}}{L_{\text{dr}}} \int_{V_{\text{Di}}}^{V_{\text{D}}} -Q_{\text{n}}^{\text{dr}}\, dV_{\text{C}}$$



$$Q_{\text{n}}^{\text{dr}} = \underbrace{qN_D t_{\text{Si}}^{\text{eff}}}_{\text{bulk current}} - \underbrace{Q_{\text{acc}}^{\text{dr}}}_{\text{accumu-lation}} - \underbrace{Q_{\text{dep}}^{\text{dr}}}_{\text{depletion}}$$

approximation:

$$Q_{\text{n}}^{\text{dr}} \equiv -C_{\text{ox}} V_{\text{n}}^{\text{dr}} \cong -C_{\text{ox}} \left(V_{\text{n}}^{\text{dr}} \Big|_{V_{\text{C}} = V_{\text{Di}}} - \left(V_{\text{C}} - V_{\text{Di}} \right) \right)$$

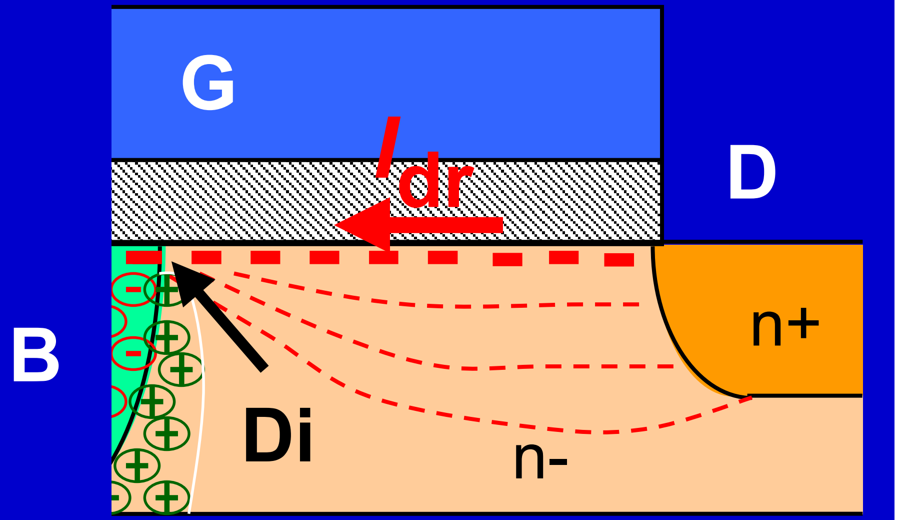
MOS Model 20: internal drain potential

include

- **velocity saturation:**

$$\mu_{\mathrm{dr}} = \frac{\mu_{\mathrm{eff}}^{\mathrm{dr}}}{1+\theta_3^{\mathrm{dr}} V_{\mathrm{DDi}}}$$

$$\theta_3^{\mathrm{dr}} = \frac{\mu_0}{L_{\mathrm{dr}}\, v_{\mathrm{sat}}}$$



Quasi-Saturation

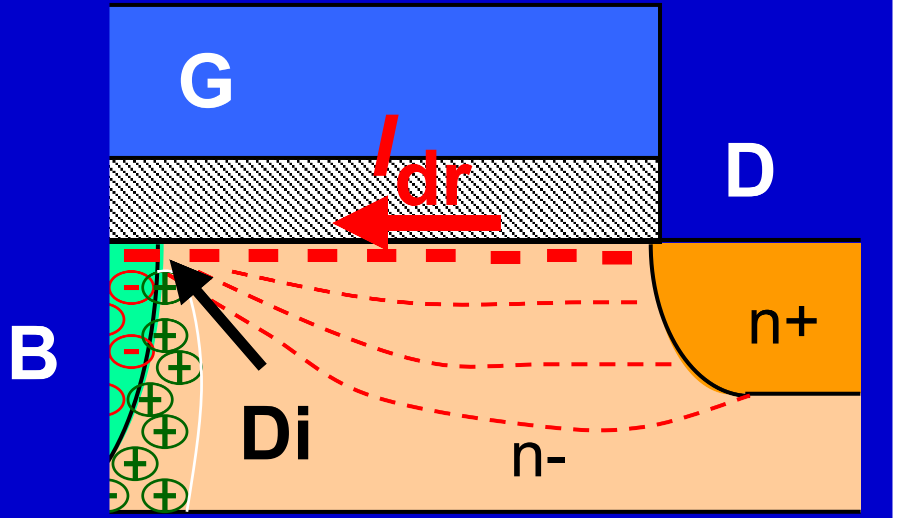
MOS Model 20: internal drain potential

include

- **velocity saturation:**

$$\mu_{\mathbf{dr}} = \frac{\mu_{\mathbf{eff}}^{\mathbf{dr}}}{1 + \theta_3^{\mathbf{dr}} V_{\mathbf{DDi}}}$$

$$\theta_3^{\mathbf{dr}} = \frac{\mu_0}{L_{\mathbf{dr}}\ v_{\mathbf{sat}}}$$



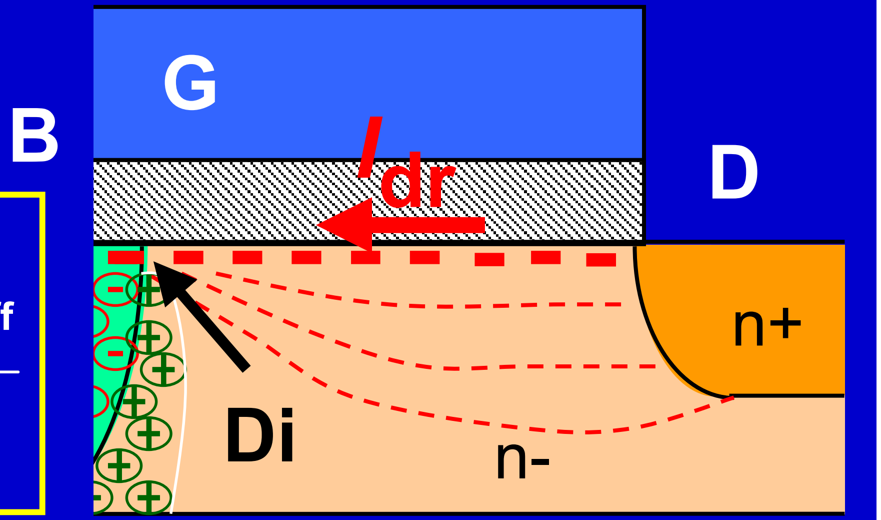
Quasi-Saturation

- **mobility reduction** (surface scattering):

$$\mu_{\mathbf{eff}}^{\mathbf{dr}} = \frac{\mu_0}{1 + 0.5\,\theta_{1\mathbf{acc}}\left(V_{\mathbf{GS}}^* + V_{\mathbf{GD}}^*\right)} = \frac{\mu_0}{F_{\mathbf{mobacc}}}$$

MOS Model 20: internal drain potential

$$I_{\mathrm{dr}} = \beta_{\mathrm{acc}} \frac{\left(V_{\mathrm{n}}^{\mathrm{dr}}\Big|_{V_{\mathrm{C}}=V_{\mathrm{Di}}} - 0.5\, V_{\mathrm{DDi,eff}}\right) V_{\mathrm{DDi,eff}}}{F_{\mathrm{mobacc}}\left(1+\theta_3^{\mathrm{dr}}\, V_{\mathrm{DDi,eff}}\right)}$$



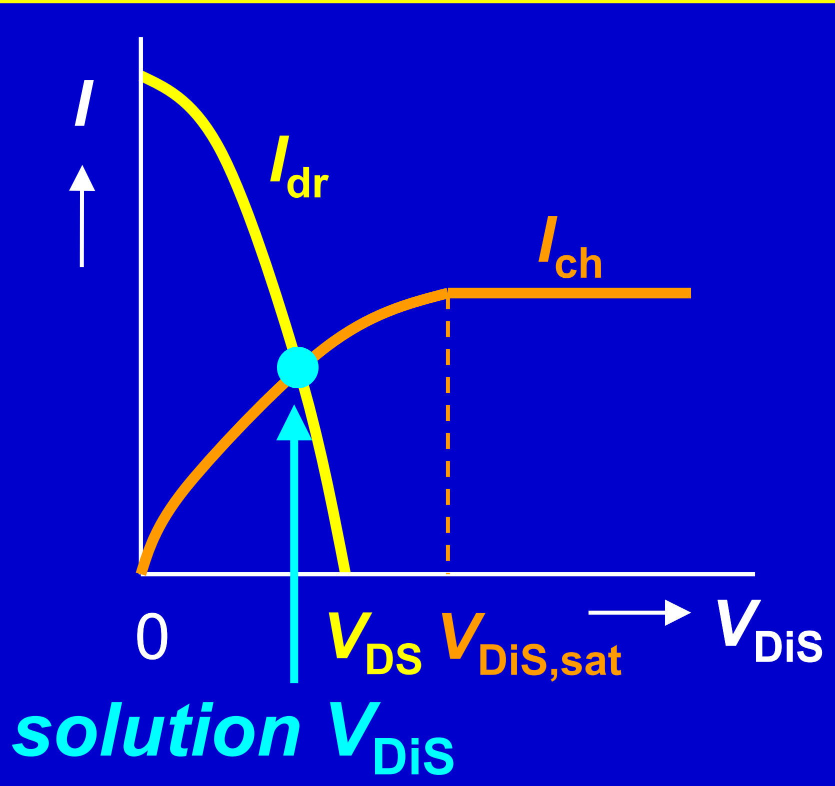
$$\beta_{\mathrm{acc}} = \frac{W \mu_0 C_{\mathrm{ox}}}{L_{\mathrm{dr}}}$$

$$V_{\mathrm{DDi,eff}} = \min\left(V_{\mathrm{DDi}}, V_{\mathrm{DDi,sat}}\right)$$

$$V_{\mathrm{DDi,sat}} = \frac{2\, V_{\mathrm{n}}^{\mathrm{dr}}\Big|_{V_{\mathrm{C}}=V_{\mathrm{Di}}}}{1+\sqrt{1+2\,\theta_3^{\mathrm{dr}}\, V_{\mathrm{n}}^{\mathrm{dr}}\Big|_{V_{\mathrm{C}}=V_{\mathrm{Di}}}}}$$

$$I_{\mathrm{dr}} = I_{\mathrm{dr}}\left(V_{\mathrm{DDi}}, V_{\mathrm{GDi}}, V_{\mathrm{DiB}}\right)$$

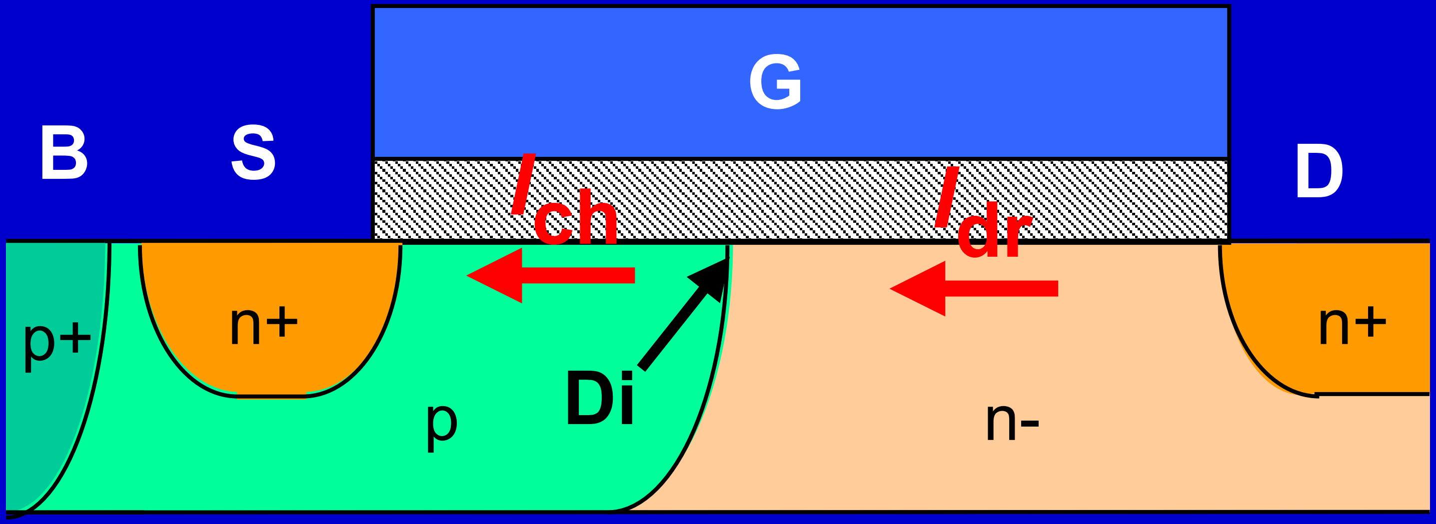
MOS Model 20: internal drain potential



numerical iteration:

$$\underbrace{V_{DiS}}_{\text{current + charges}} \qquad \underbrace{\frac{\partial V_{DiS}}{\partial V_{GS}},\ \frac{\partial V_{DiS}}{\partial V_{DS}},\ \frac{\partial V_{DiS}}{\partial V_{SB}}}_{\text{conductances + capacitances}}$$

MOS Model 20: DC-model

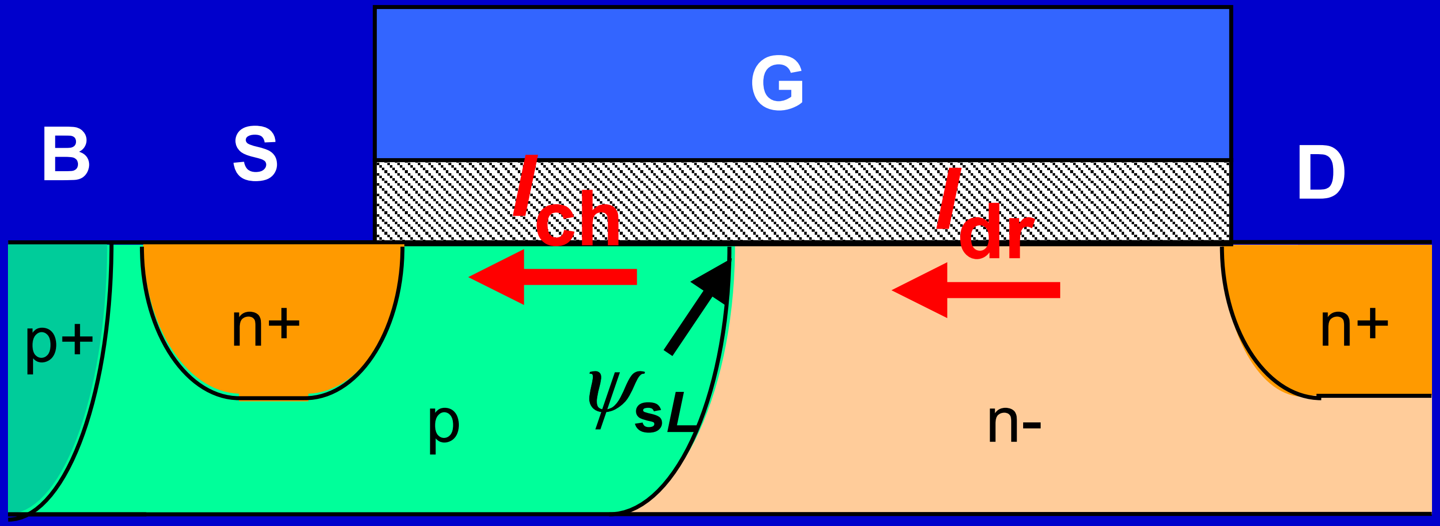


approach: 1. determine V_{Di} :

Kirchhoff's current law (KCL): $I_{ch} = I_{dr}$

2. DC-current: $I_{DS} = I_{ch}$

MOS Model 20: DC-current



surface-potential-based: $I_{DS} = I_{ch}\,(\psi_{sL},\ \psi_{s0})$

$$\psi_{s0} = \psi_s\,(V_{SB},\ V_{GB},\ )$$

$$\psi_{sL} = \psi_s\,(V_{SB} + \underline{V_{DiSeff}},\ V_{GB}\ )$$

also include 2^{nd}-order effects

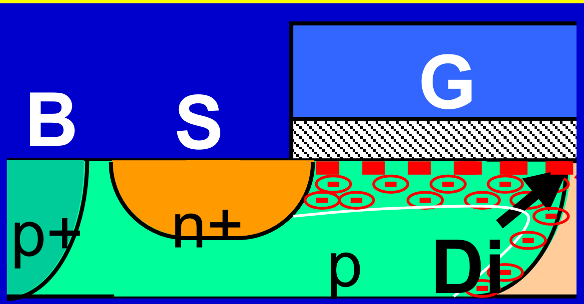
MOS Model 20: DC-current

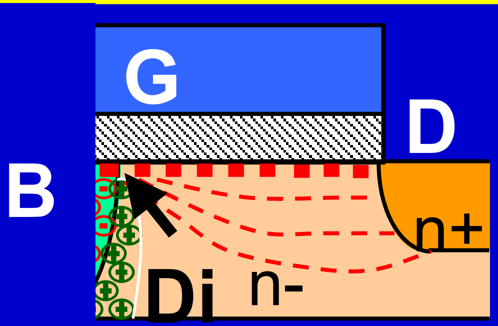
$$I_{\mathrm{DS}} = \frac{W\mu_{\mathrm{ch}}}{L_{\mathrm{ch}}}\left[\underbrace{\int_{\psi_{\mathrm{s}0}}^{\psi_{\mathrm{s}L}} -Q_{\mathrm{inv}}\,d\psi_{\mathrm{s}}}_{\text{drift}} + \underbrace{\phi_T\left(Q_{\mathrm{inv}L} - Q_{\mathrm{inv}0}\right)}_{\text{diffusion}}\right]$$

- DIBL & static feedback: $\Delta V_G = D_{\mathrm{dibl,sf}}\dfrac{V_{\mathrm{DS}}^4}{\left(\left(4\phi_T\right)^2 + V_{\mathrm{DS}}^2\right)^{3/2}}$
- channel length modulation: $G_{\Delta .L} = 1 - \alpha\ln\left(\dfrac{2\left(V_{\mathrm{DS}} - V_{\mathrm{DiSeff}}\right)}{V_{\mathrm{P}}}\right)$

$$\boxed{I_{\mathrm{DS}} = \beta\frac{\left(V_{\mathrm{inv}0} - \frac{\xi}{2}\Delta\psi_{\mathrm{s}}\right)\Delta\psi_{\mathrm{s}} + \phi_T\left(V_{\mathrm{inv}0} - V_{\mathrm{inv}L}\right)}{G_{\Delta L}\;F_{\mathrm{mob}}\;\left(1 + \theta_3\Delta\psi_{\mathrm{s}}\right)}}$$

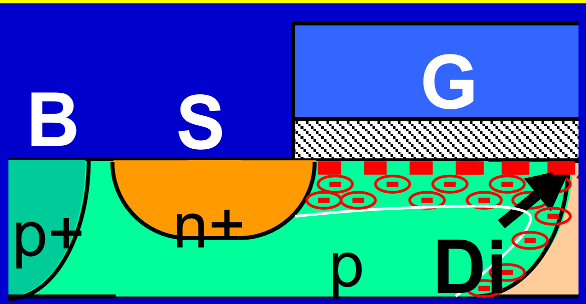
MOS Model 20: DC-model

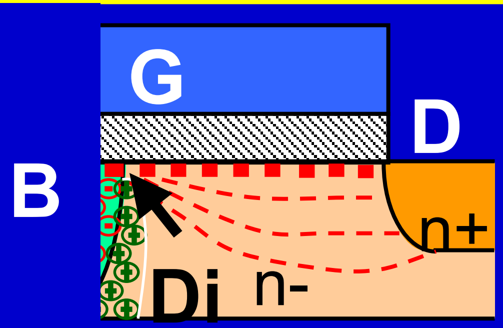




- **surface-potential-based (MM11)**
- **mobility reduction due to vertical field (MM9)**
- **velocity saturation (MM9)**
- **channel length modulation (MM11)**
- **DIBL (MM11)**
- **static feedback (MM11)**

MOS Model 20: DC-model





- surface-potential-based (MM11)
- mobility reduction due to vertical field (MM9)
- velocity saturation (MM9)
- channel length modulation (MM11)
- DIBL (MM11)
- static feedback (MM11)

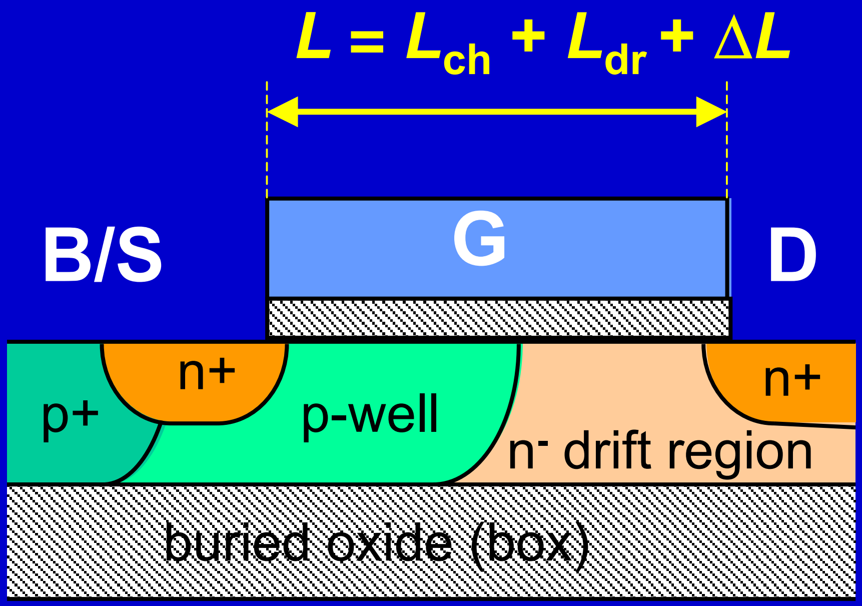
- accumulation
- depletion
- bulk current
- mobility reduction due to vertical field
- velocity saturation

outline

- introduction
- MOS Model 20
  - basic model
    - DC-model
    - ➡ comparison with experimental data
    - nodal charge model
  - additional model features
- summary

MOS Model 20: experimental data

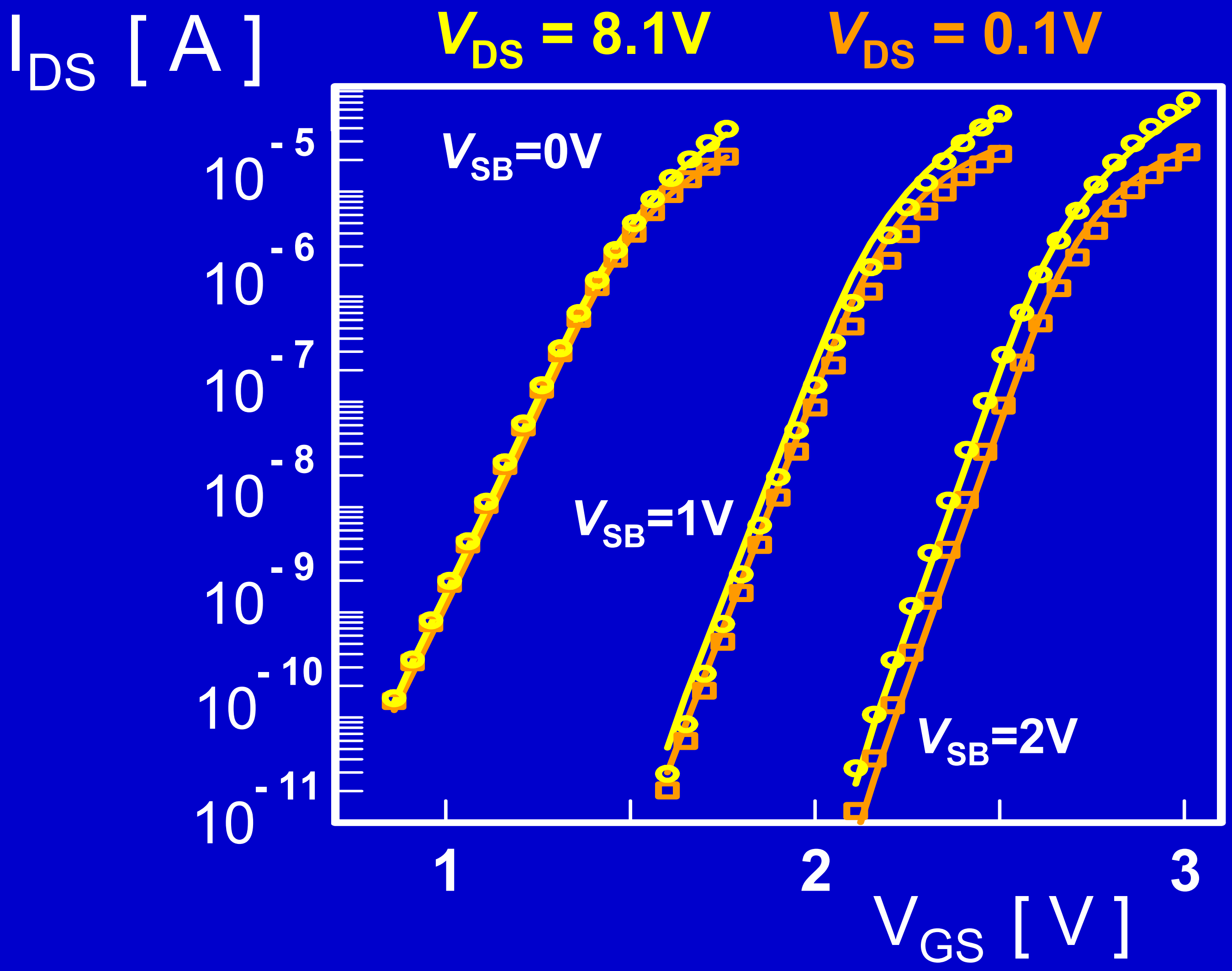
low-voltage



12V SOI-LDMOS: $L = 1.6\ \mu m$

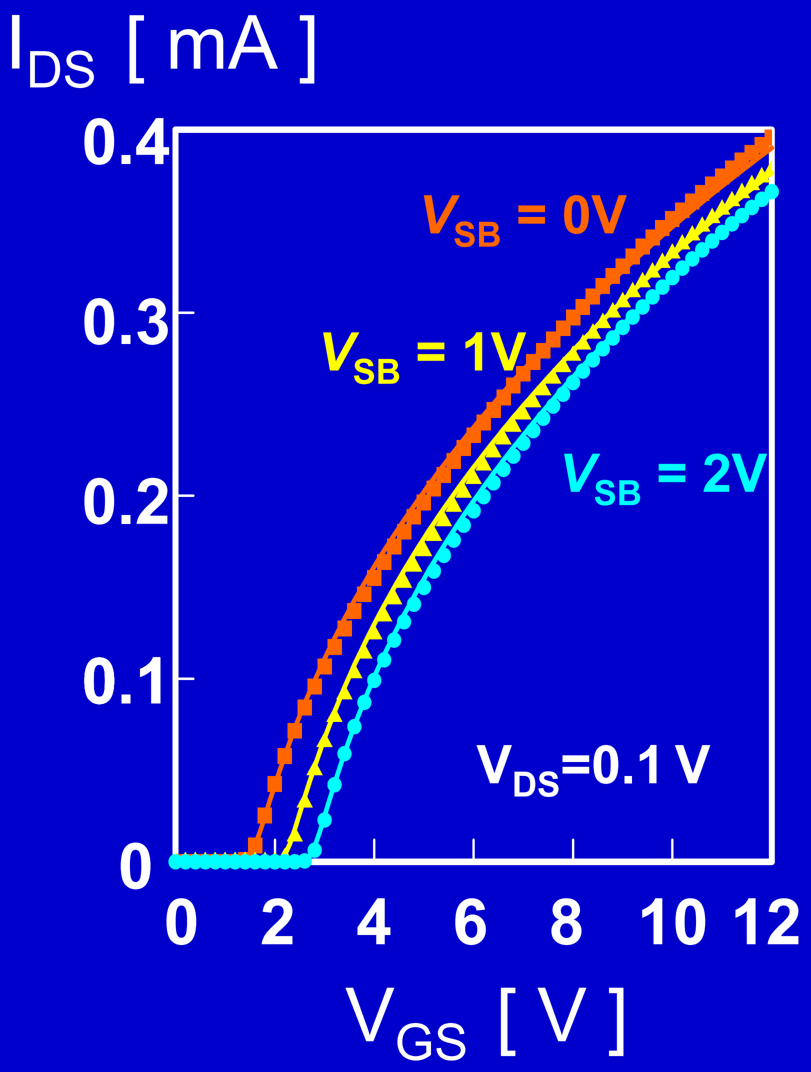
MOS Model 20: experimental data

12V SOI-LDMOS: T_{ox}= 38 nm, W = 17 μm, L = 1.6 μm, T = 25 °C



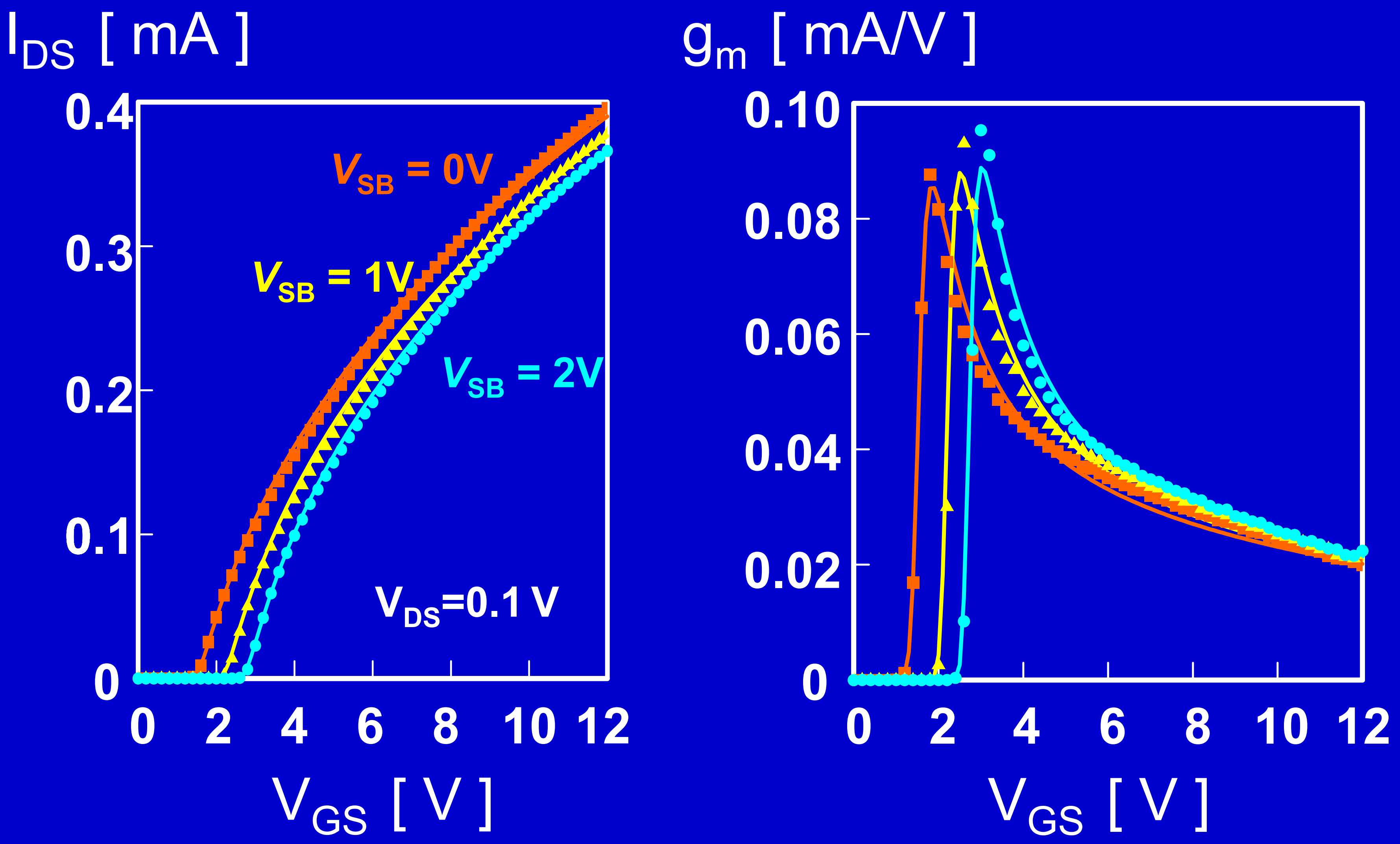
MOS Model 20: experimental data

12V SOI-LDMOS: T_{ox}= 38 nm, W = 17 μm, L = 1.6 μm, T = 25 °C



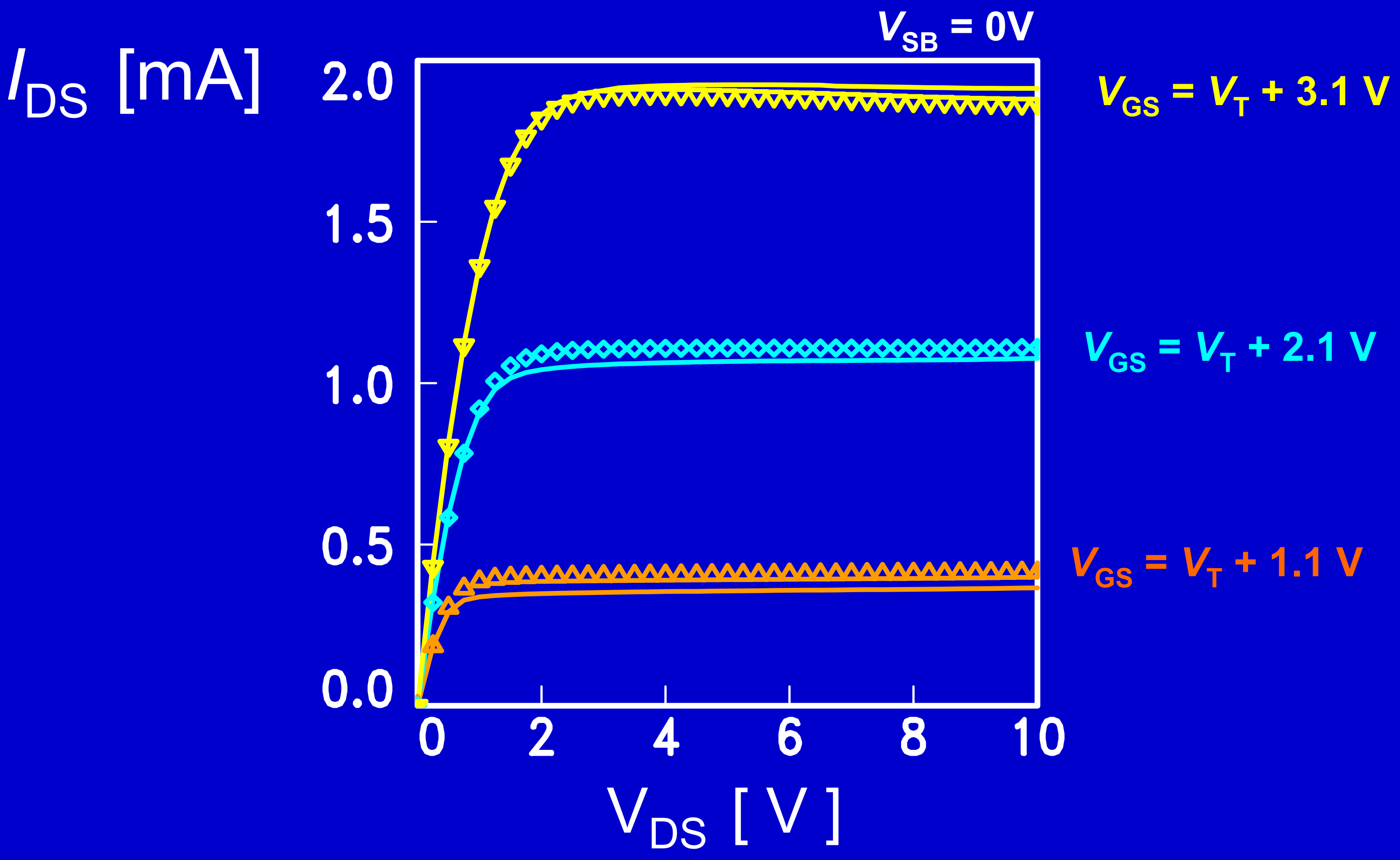
MOS Model 20: experimental data

12V SOI-LDMOS: T_{ox}= 38 nm, W = 17 μm, L = 1.6 μm, T = 25 ºC



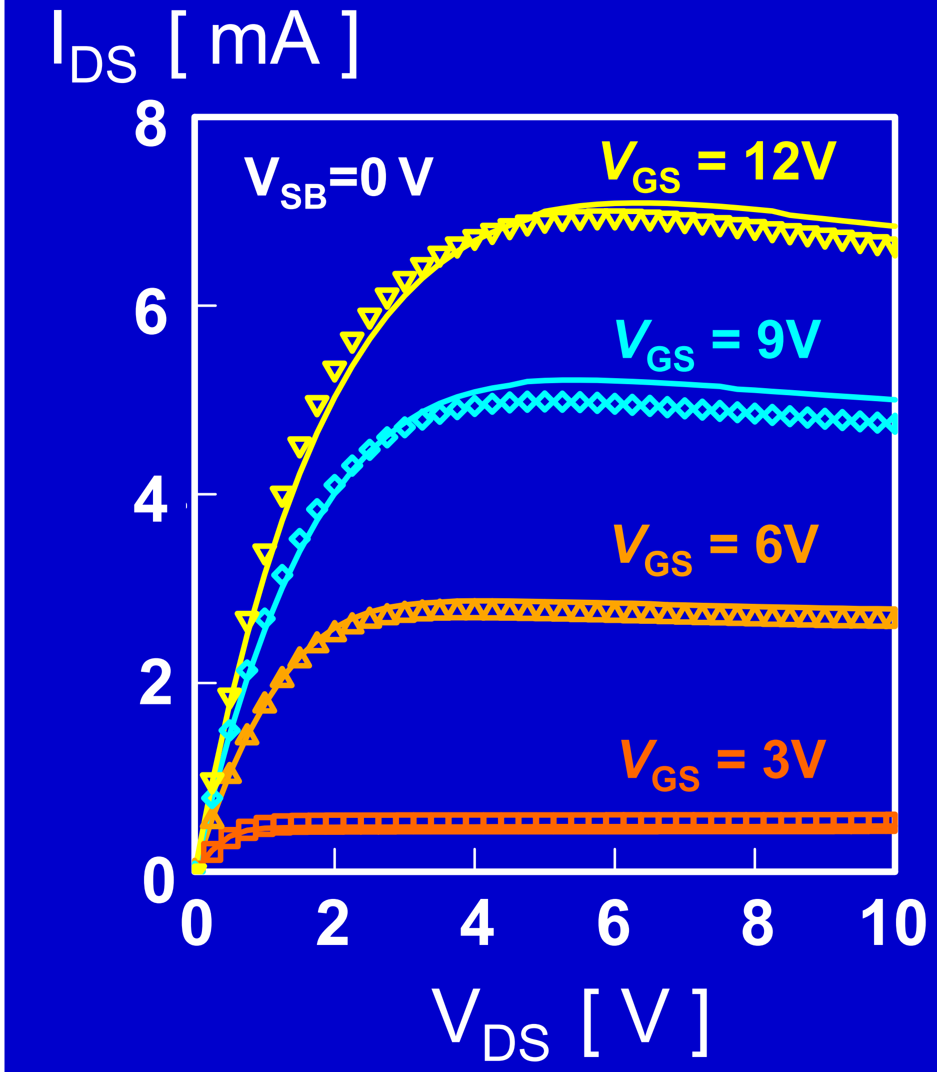
MOS Model 20: experimental data

12V SOI-LDMOS: T_{ox}= 38 nm, W = 17 μm, L = 1.6 μm, T = 25 ºC



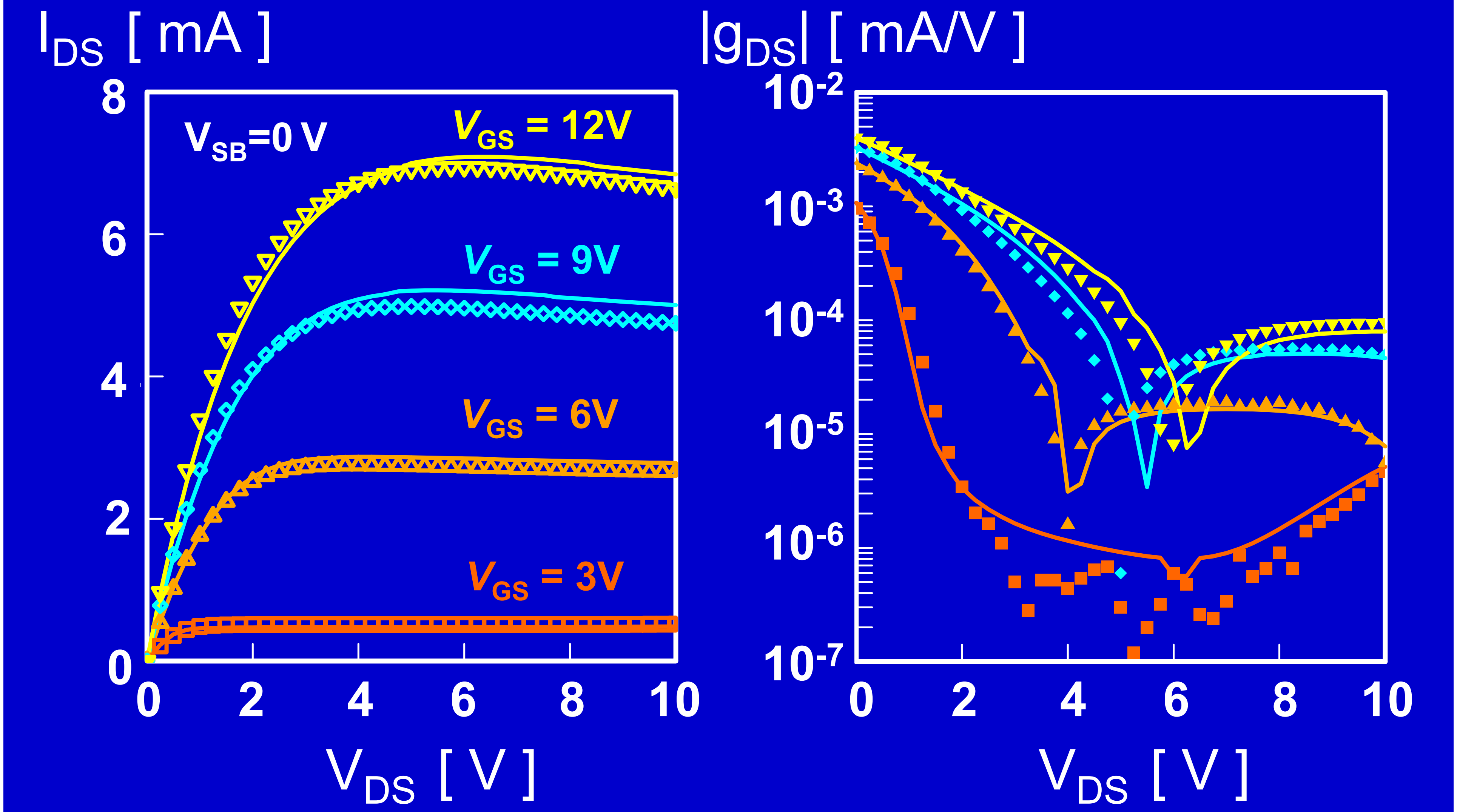
MOS Model 20: experimental data

12V SOI-LDMOS: T_{ox}= 38 nm, W = 17 μm, L = 1.6 μm, T = 25 ºC



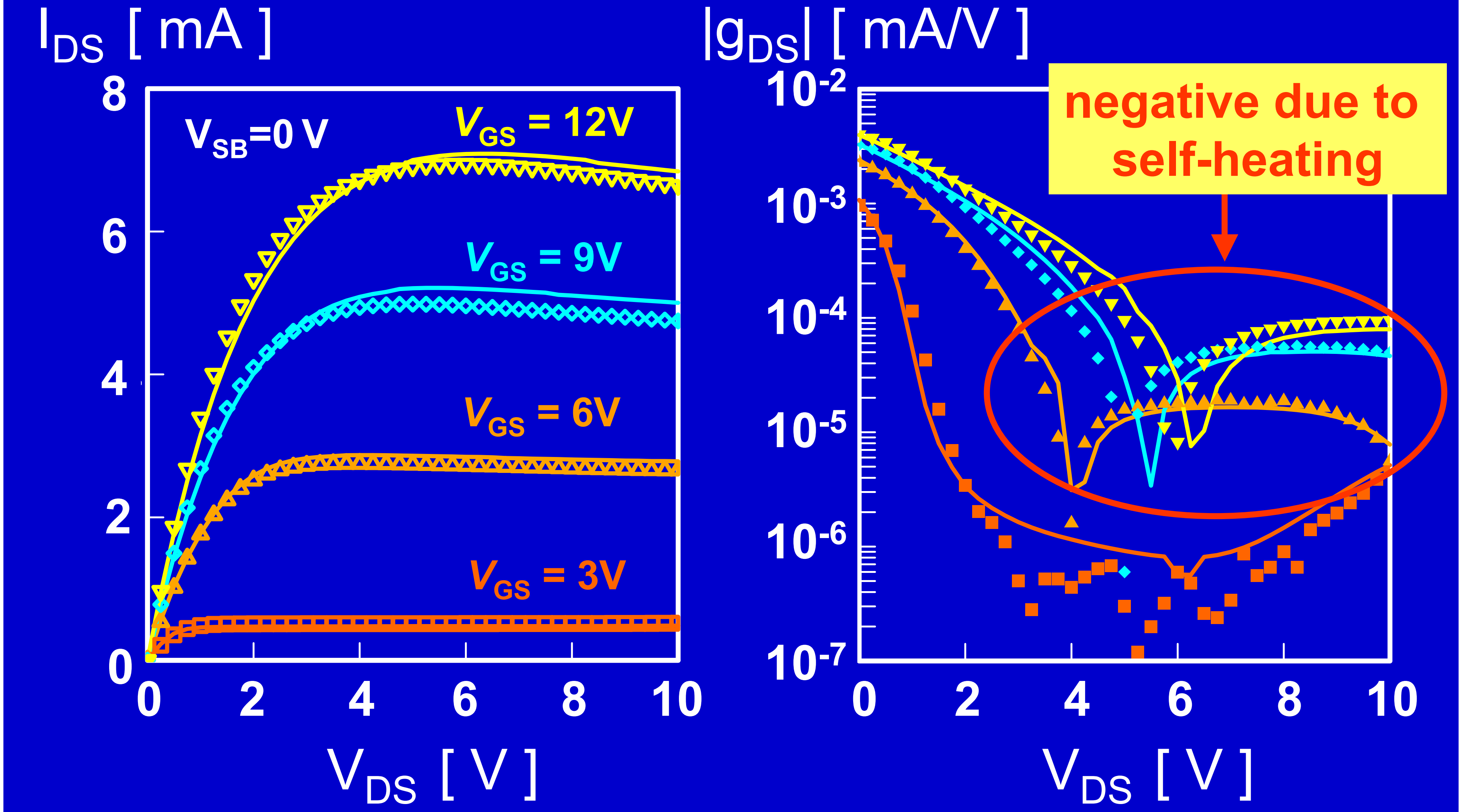
MOS Model 20: experimental data

12V SOI-LDMOS: T_{ox}= 38 nm, W = 17 μm, L = 1.6 μm, T = 25 °C



MOS Model 20: experimental data

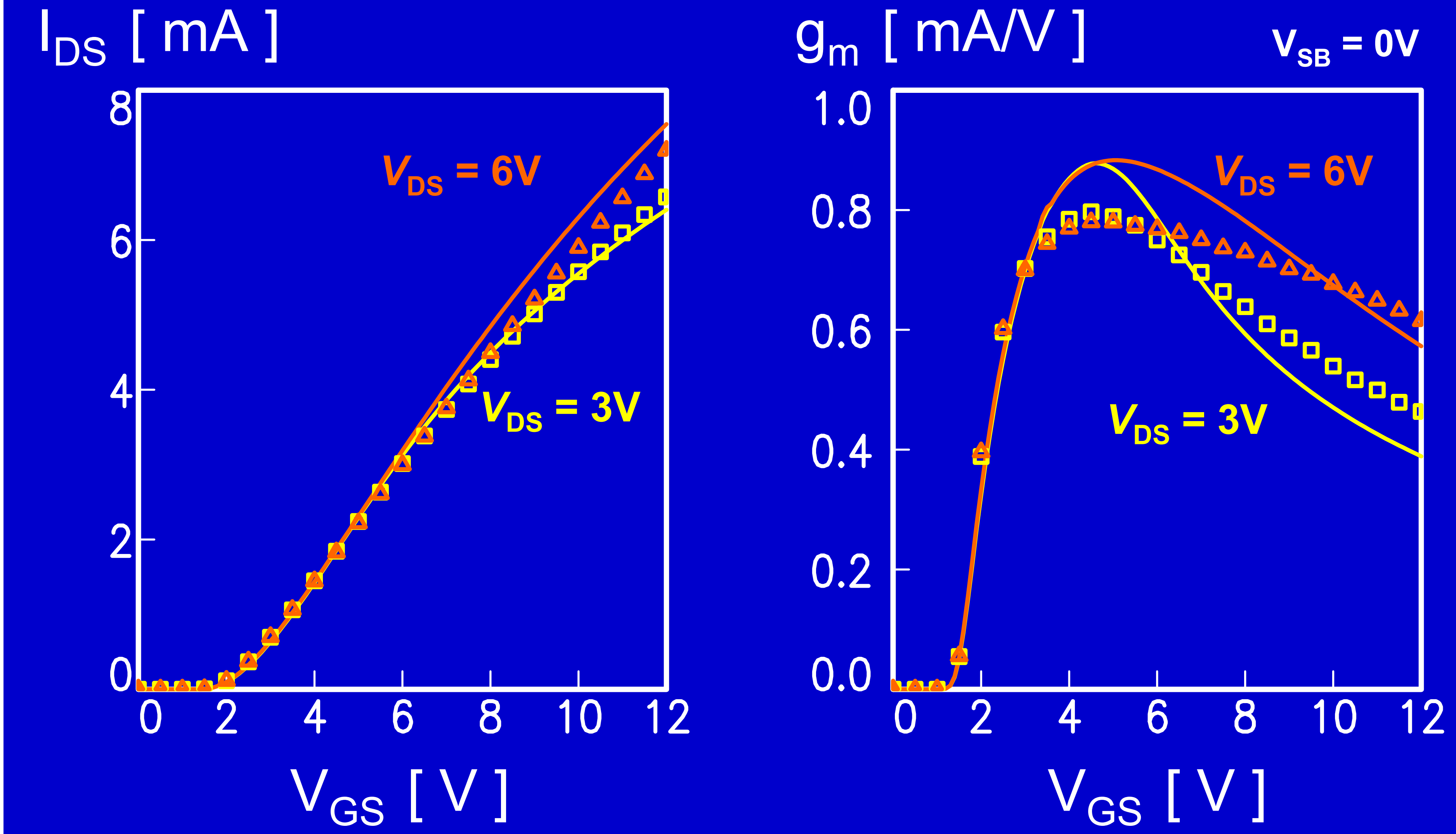
12V SOI-LDMOS: T_{ox}= 38 nm, W = 17 μm, L = 1.6 μm, T = 25 ºC



negative due to self-heating

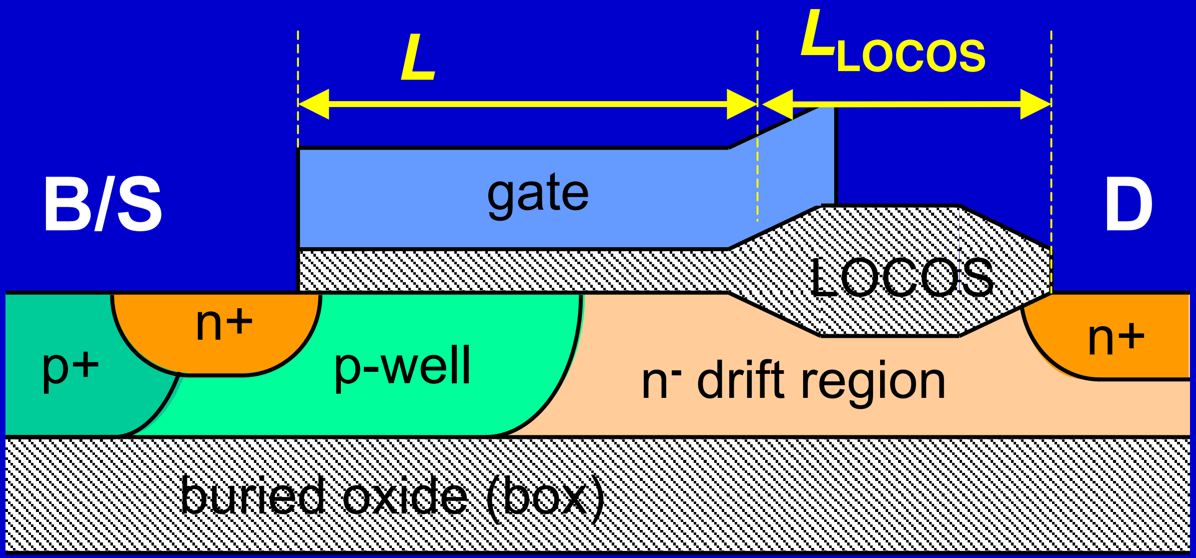
MOS Model 20: experimental data

12V SOI-LDMOS: T_{ox} = 38 nm, W = 17 μm, L = 1.6 μm, T = 25 °C



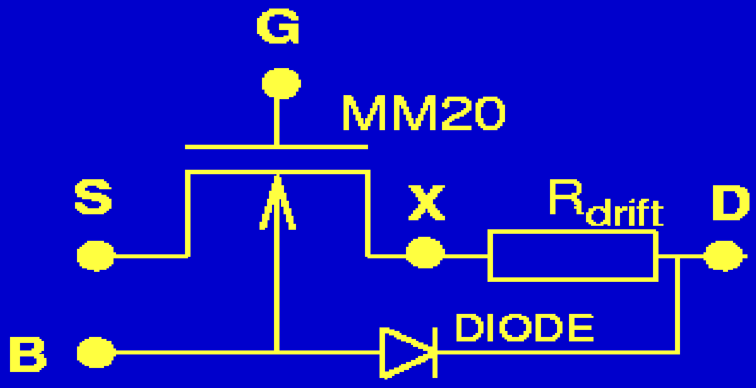
MOS Model 20: quasi-saturation

high-voltage



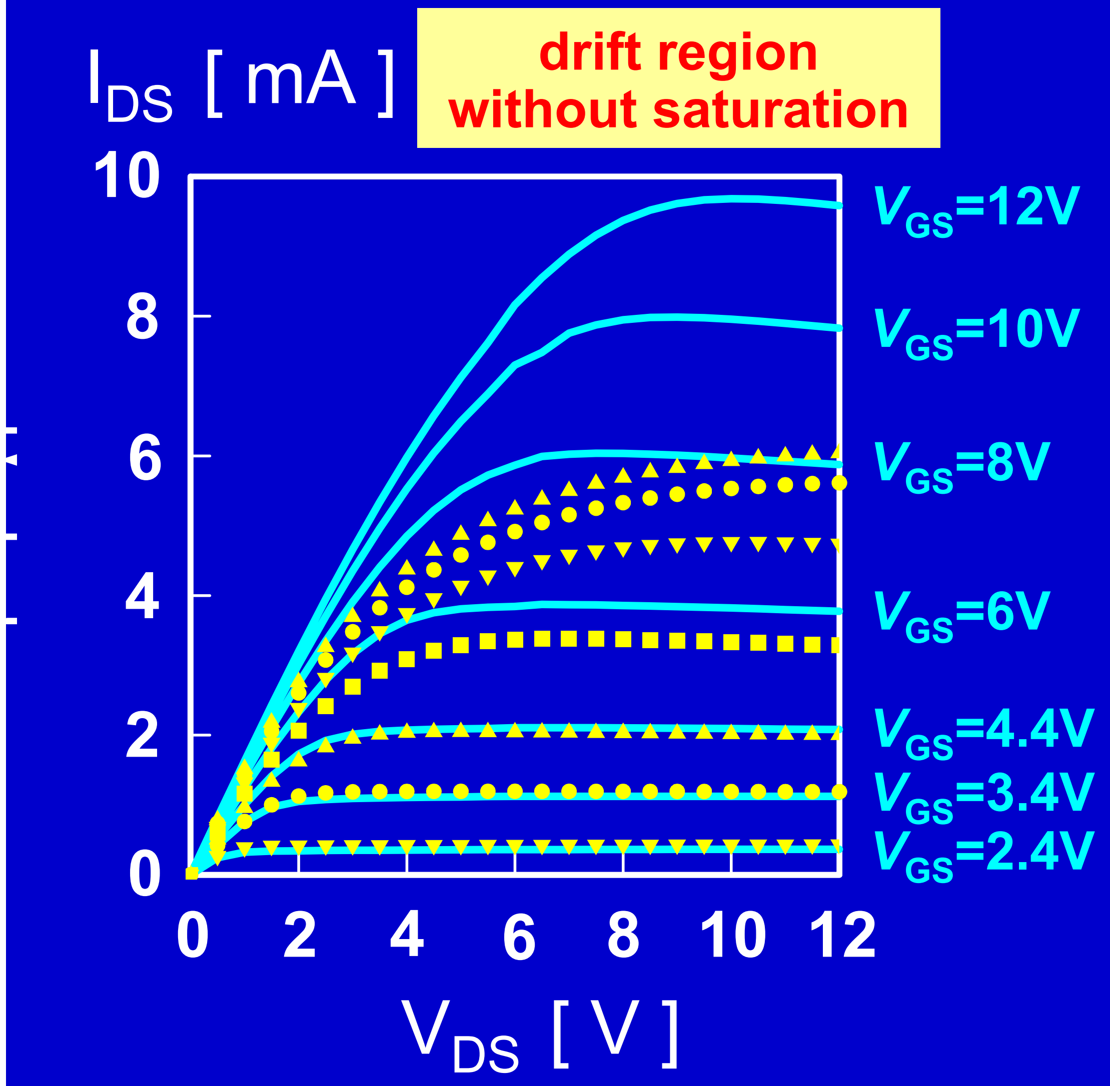
60V SOI-LDMOS: T_{ox} = 38 nm, L = 2.6 μm, L_{LOCOS} = 3.5 μm

sub-circuit



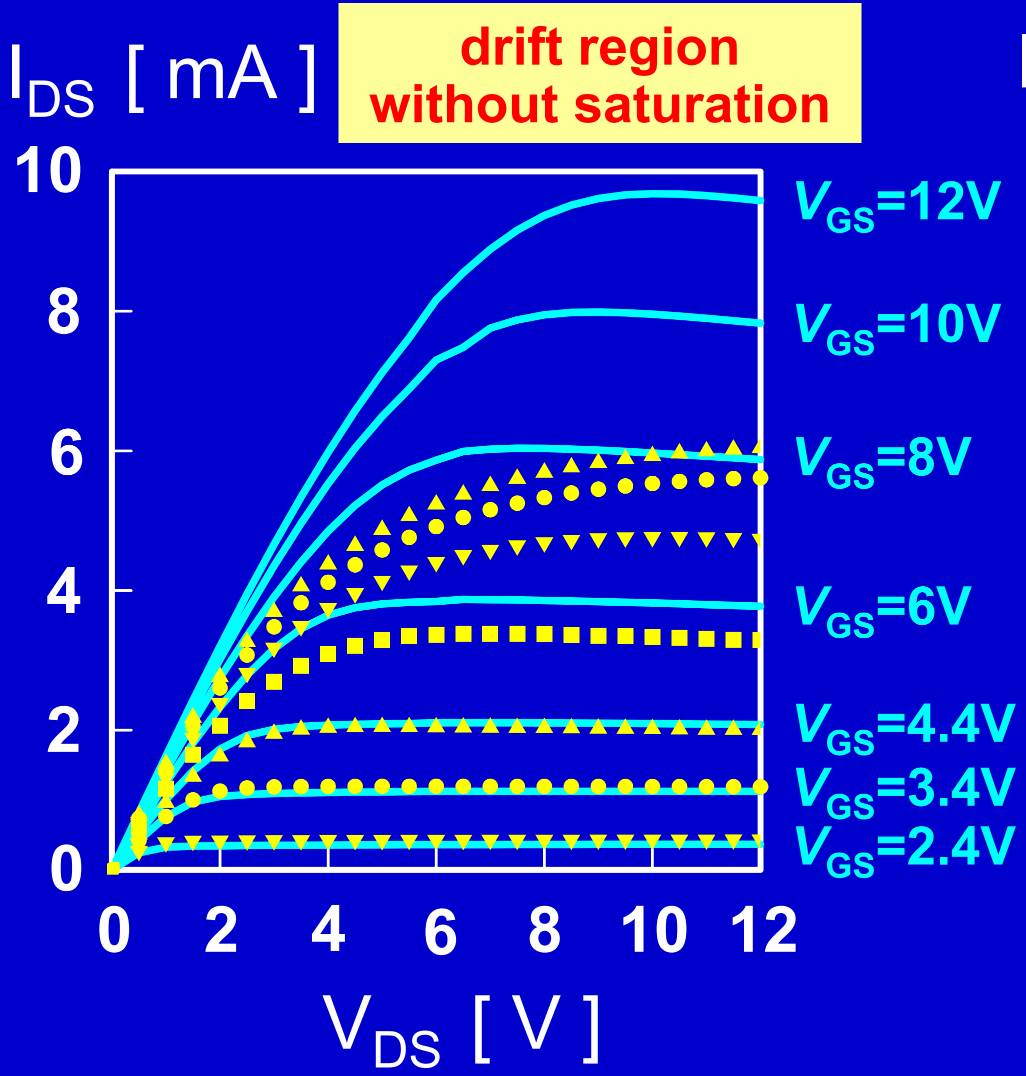
MOS Model 20: quasi-saturation

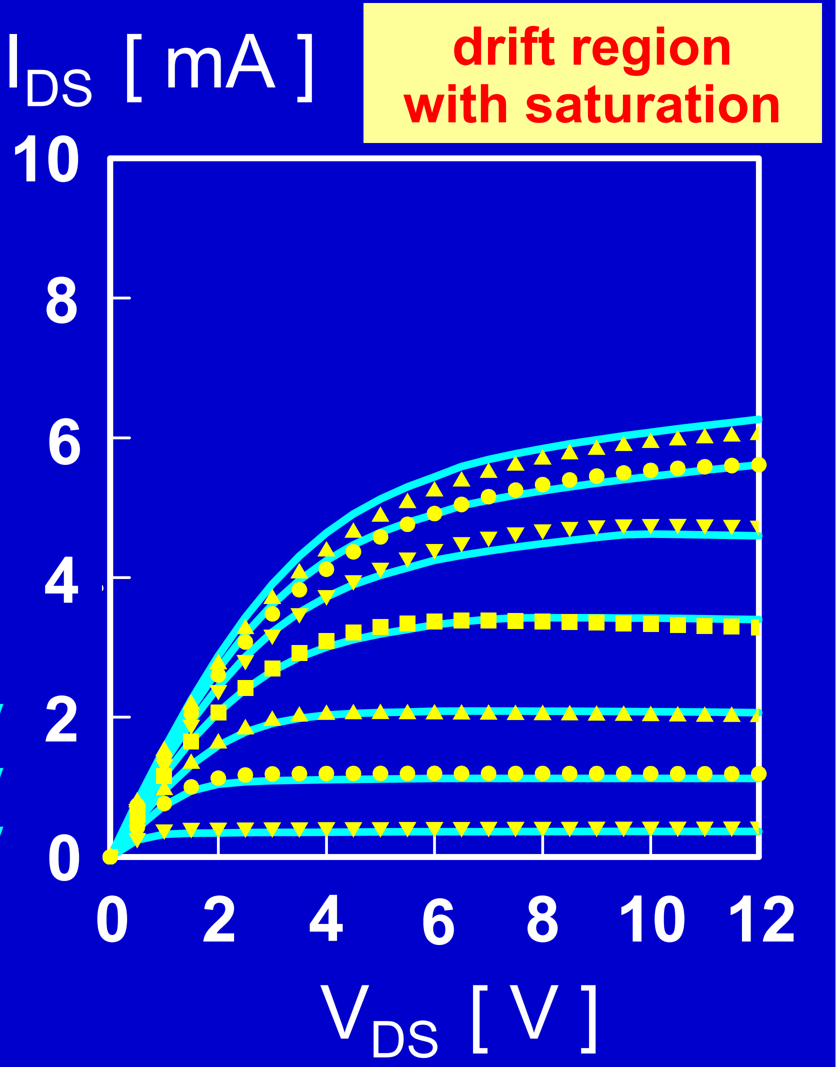
60V SOI-LDMOS: T_{ox}= 38nm, W = 20µm, L = 2.6µm, L_{locos}= 3.5µm, T= 25 °C



MOS Model 20: quasi-saturation

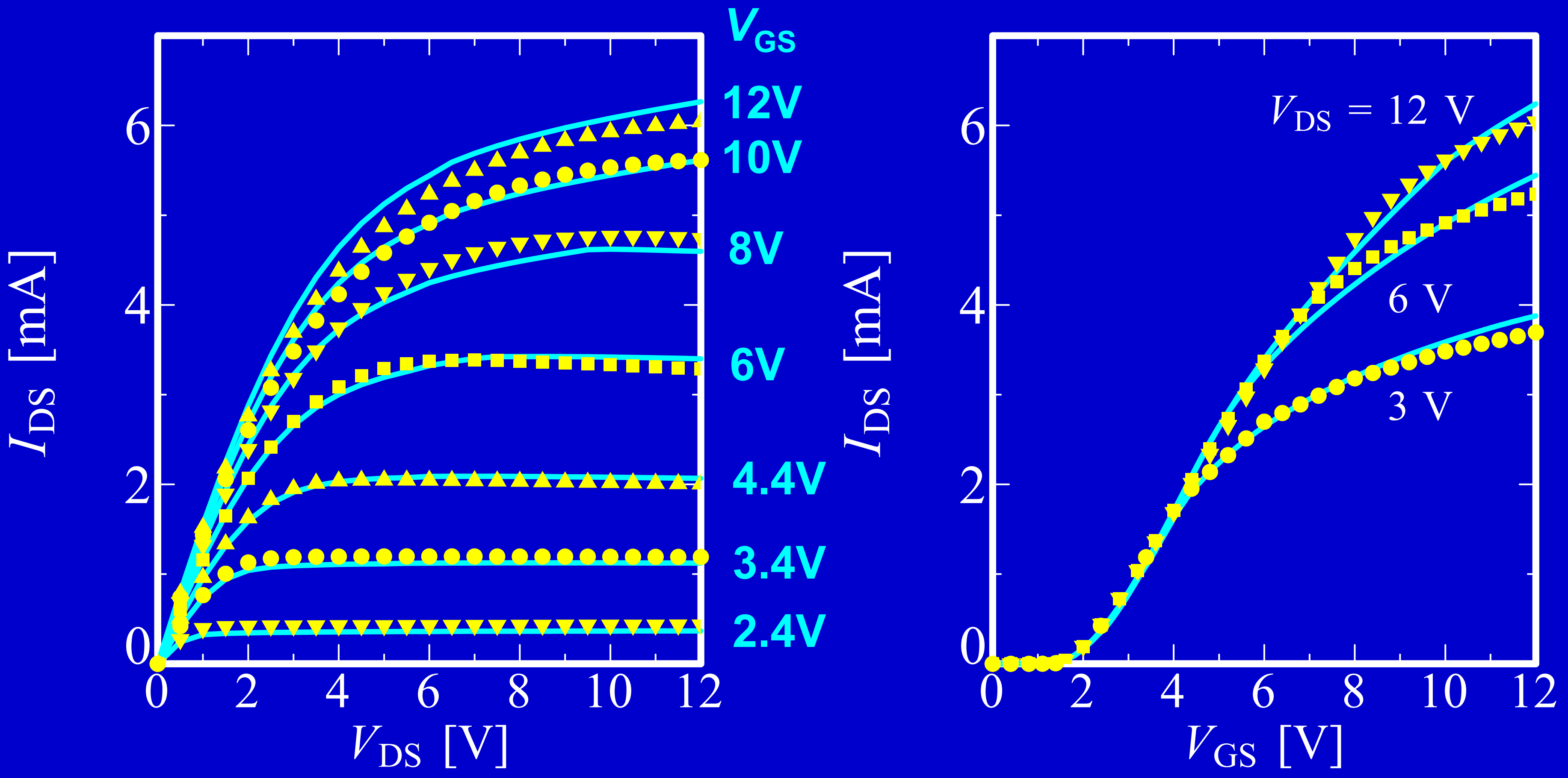
60V SOI-LDMOS: T_{ox}= 38nm, W = 20μm, L = 2.6μm, L_{locos}= 3.5μm, T= 25 °C





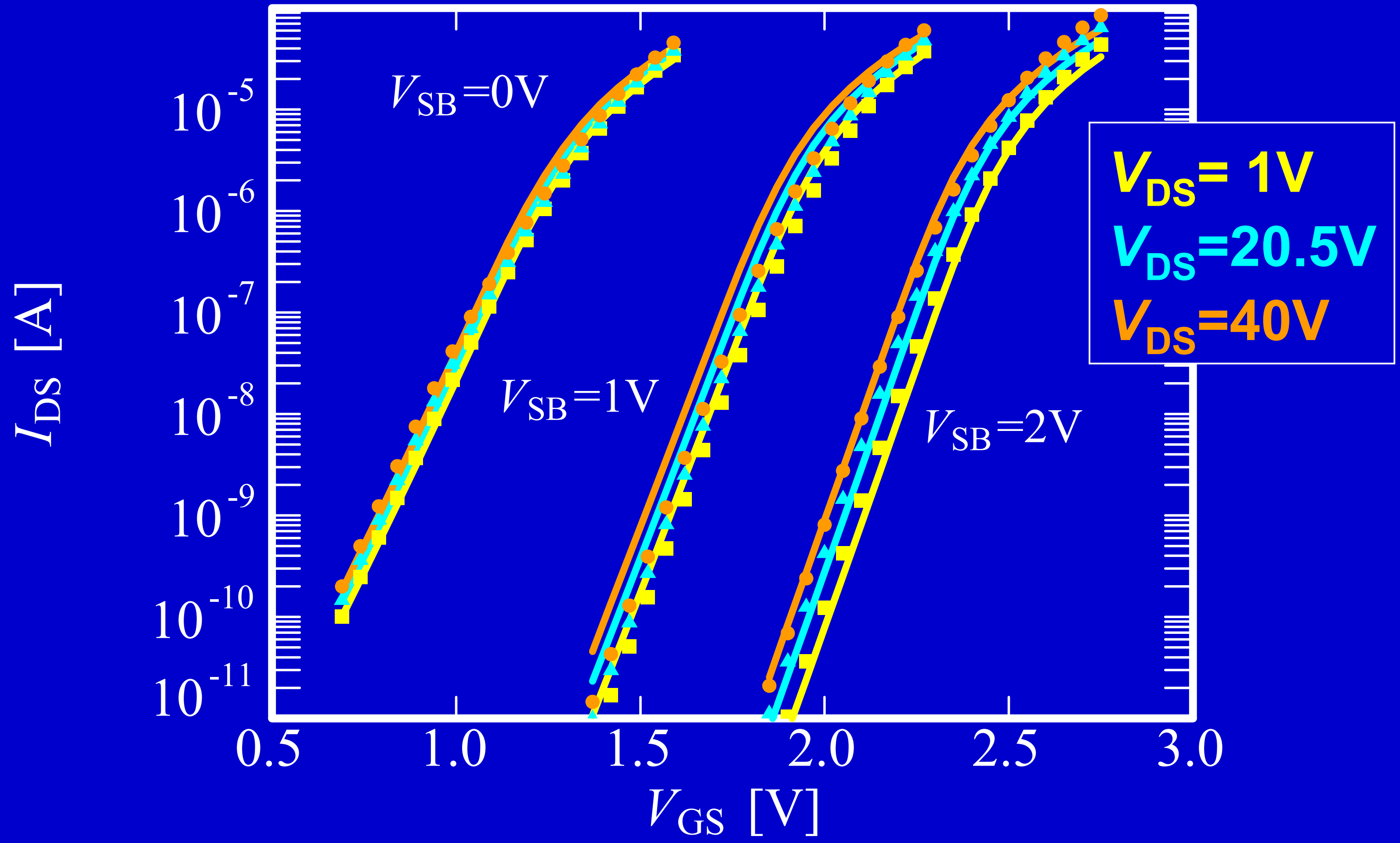
MOS Model 20: quasi-saturation

60V SOI-LDMOS: T_{ox}= 38nm, W = 20μm, L = 2.6μm, L_{locos}= 3.5μm, T= 25 °C



MOS Model 20: quasi-saturation

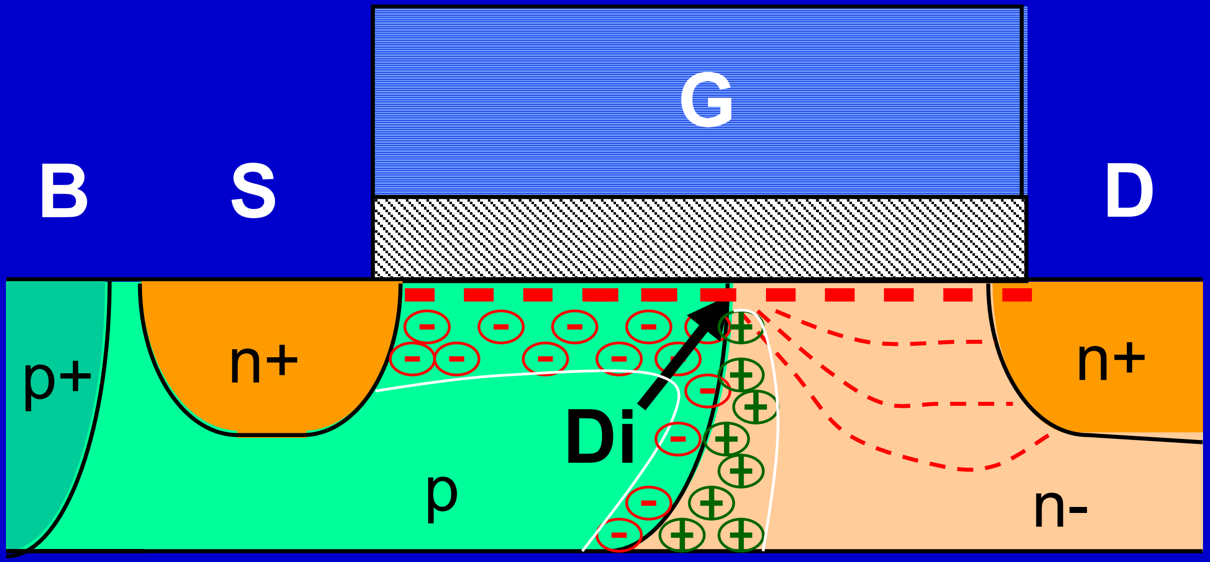
60V SOI-LDMOS: T_{ox}= 38nm, W = 20μm, L = 2.6μm, L_{locos}= 3.5μm, T= 25 °C



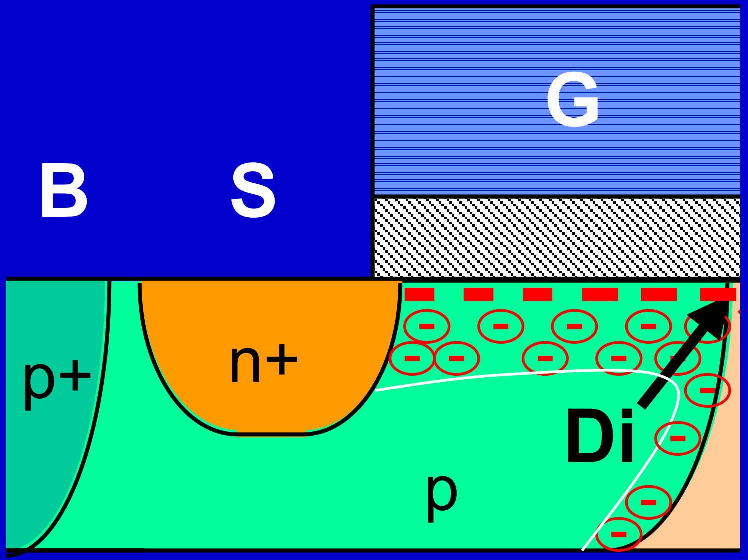
outline

- introduction
- MOS Model 20
  - basic model
    - DC-model
    - ➡ nodal charge model
  - additional model features
- summary

MOS Model 20: nodal charge model



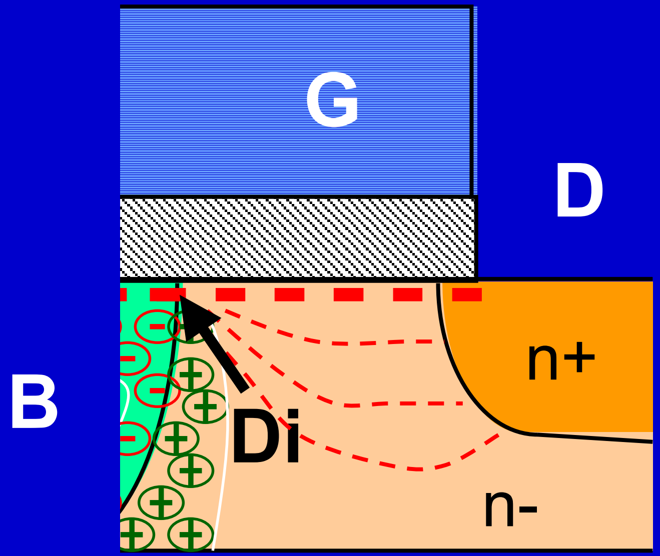
MOS Model 20: gate and bulk charges



$$Q_{\mathrm{G,\,channel}} = -W\int_0^L \left(Q'_{\mathrm{inv}} + Q'_{\mathrm{dep}} + Q'_{\mathrm{acc}}\right)\cdot dx$$

$$Q_{\mathrm{B,\,channel}} = W\int_0^L \left(Q'_{\mathrm{dep}} + Q'_{\mathrm{acc}}\right)\cdot dx$$

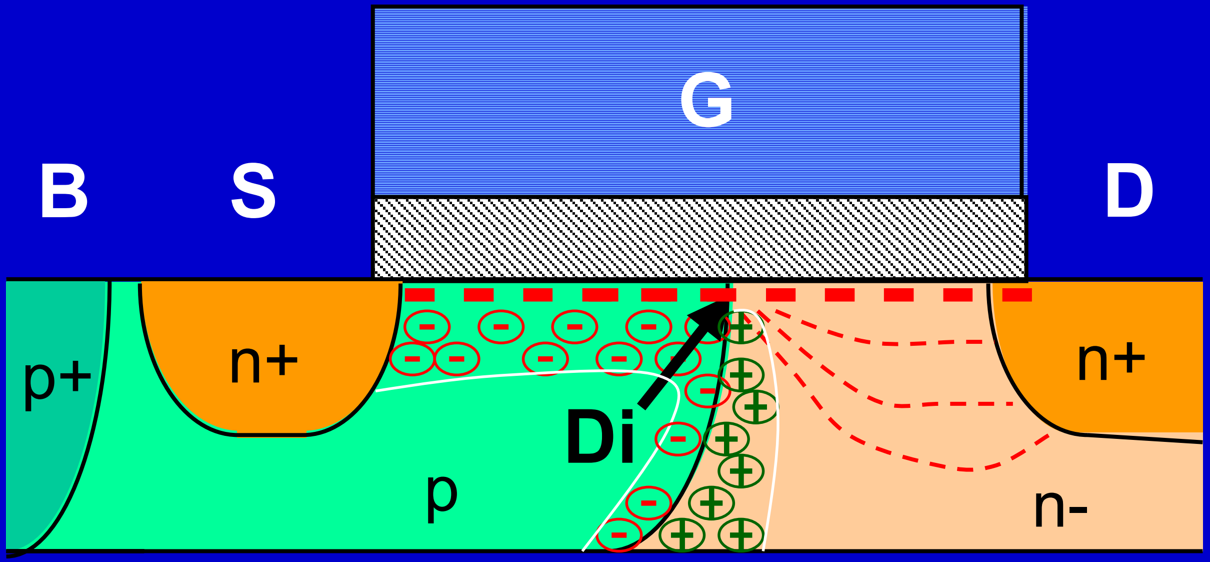
MOS Model 20: gate and bulk charges



$$Q_{\text{G, drift region}} = -W \int_0^{L_{dr}} \left(Q'_{inv} + Q'_{dep} + Q'_{acc} \right) \cdot dx$$

$$Q_{\text{B, drift region}} = W \int_0^{L_{dr}} Q'_{inv} \cdot dx$$

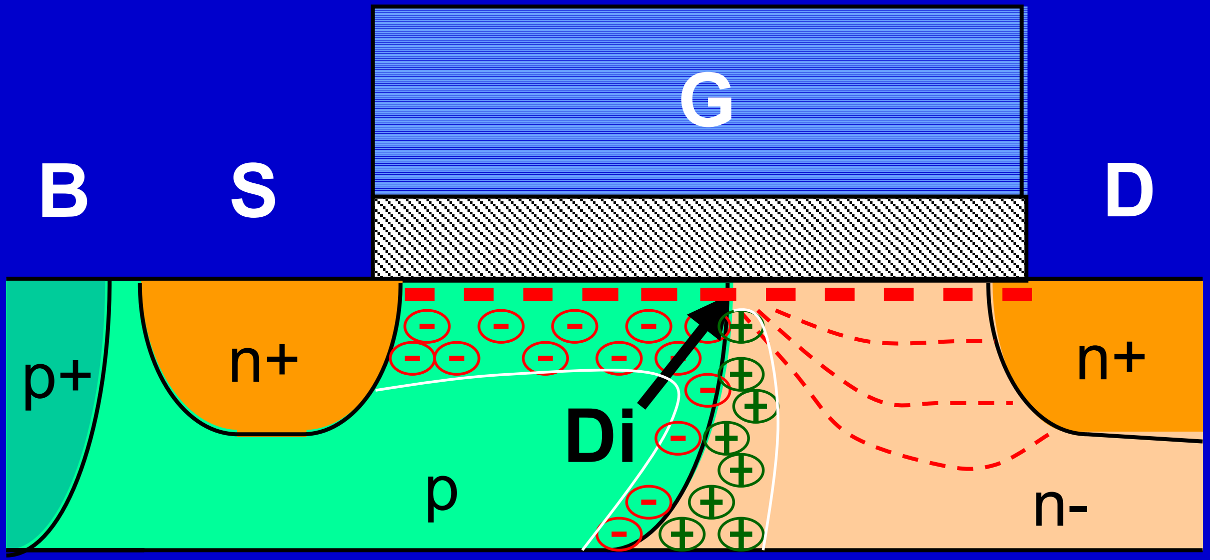
MOS Model 20: gate and bulk charges



$$Q_{\text{G, LDMOS}} = Q_{\text{G, channel}} + Q_{\text{G, drift region}}$$

$$Q_{\text{B, LDMOS}} = Q_{\text{B, channel}} + Q_{\text{B, drift region}}$$

MOS Model 20: gate and bulk charges



$$Q_{\text{G, LDMOS}} = Q_{\text{G, channel}} + Q_{\text{G, drift region}}$$

$$C_{ij} = \left(2 \cdot \delta_{ij} - 1\right) \cdot \frac{\partial Q_i}{\partial V_j}$$

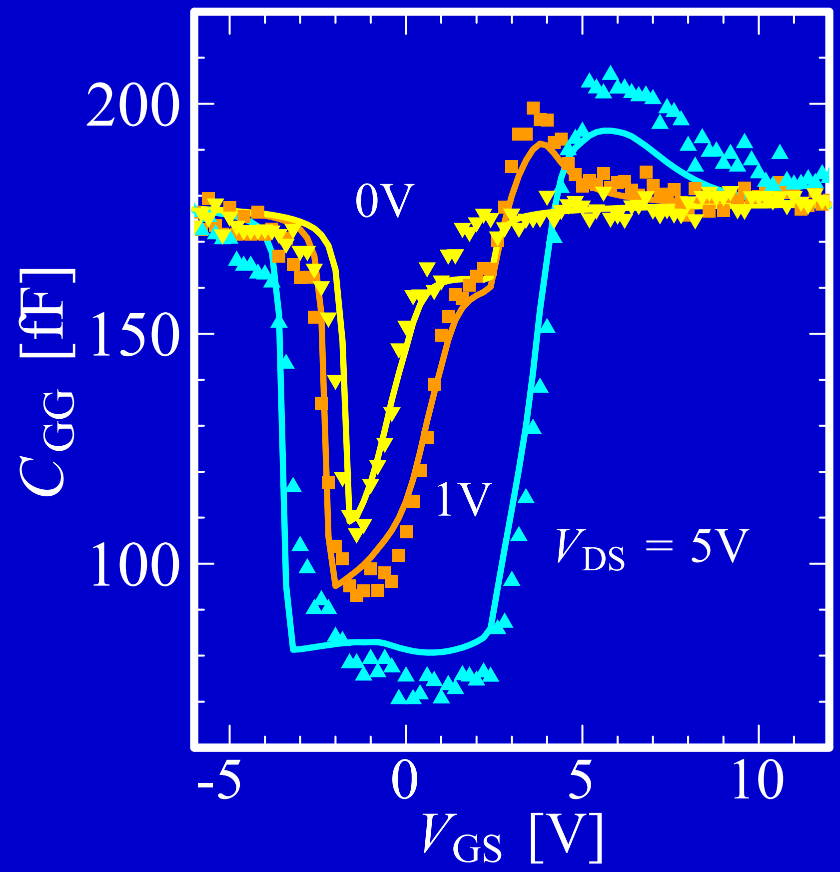
$$Q_{\text{B, LDMOS}} = Q_{\text{B, channel}} + Q_{\text{B, drift region}}$$

outline

- introduction
- MOS Model 20
  - basic model
    - DC-model
    - nodal charge model
  - → comparison with experimental data
  - additional model features
- summary

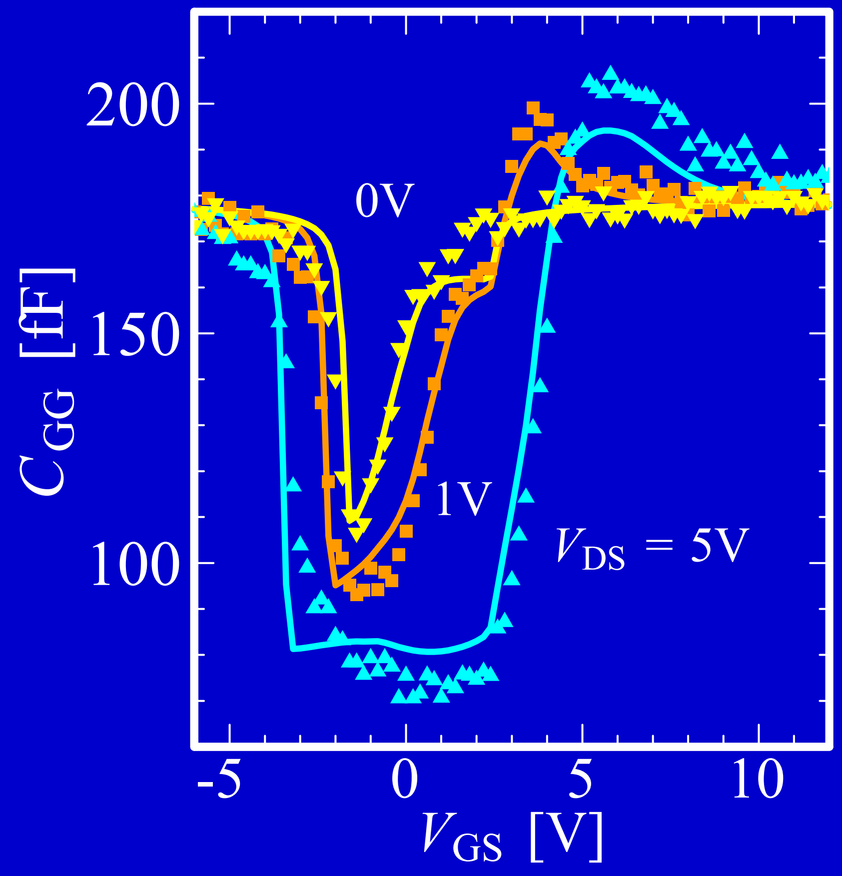
MOS Model 20: experimental data

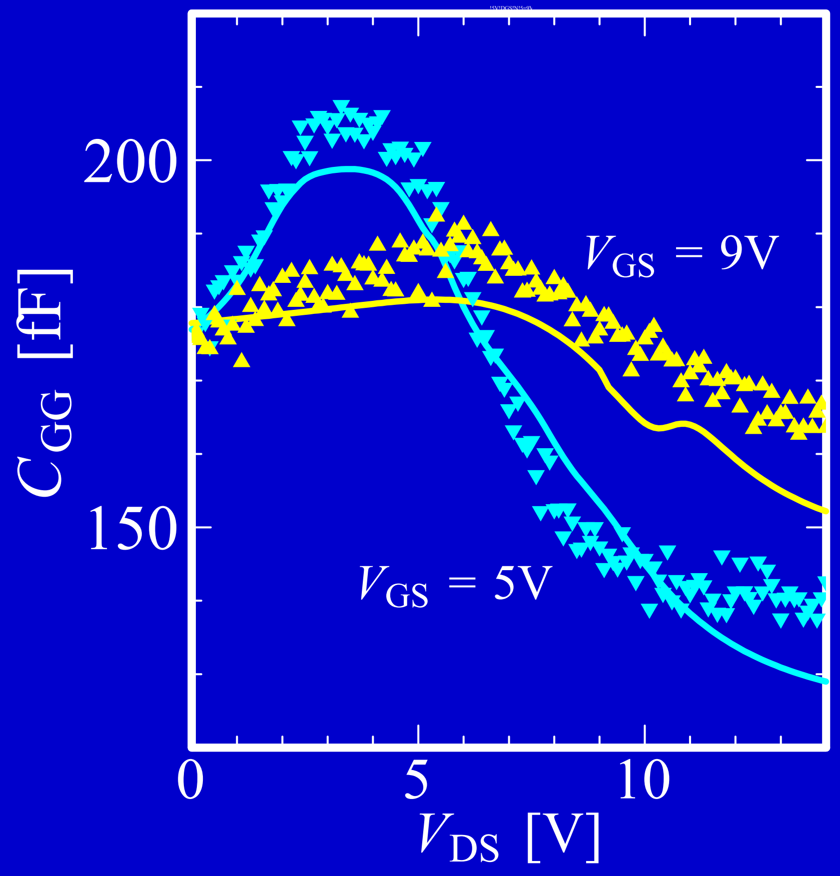
14V SOI-LDMOS: T_{ox} = 60 nm, W = 50 μm, L = 5 μm, T = 25 °C



MOS Model 20: experimental data

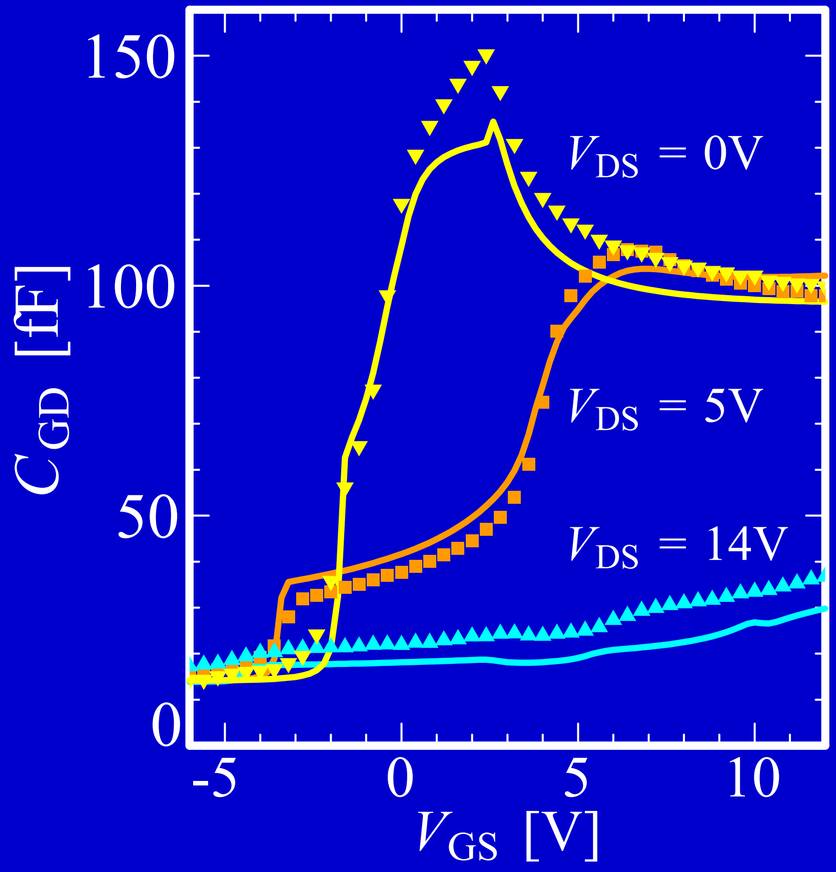
14V SOI-LDMOS: T_{ox} = 60 nm, W = 50 μm, L = 5 μm, T = 25 °C





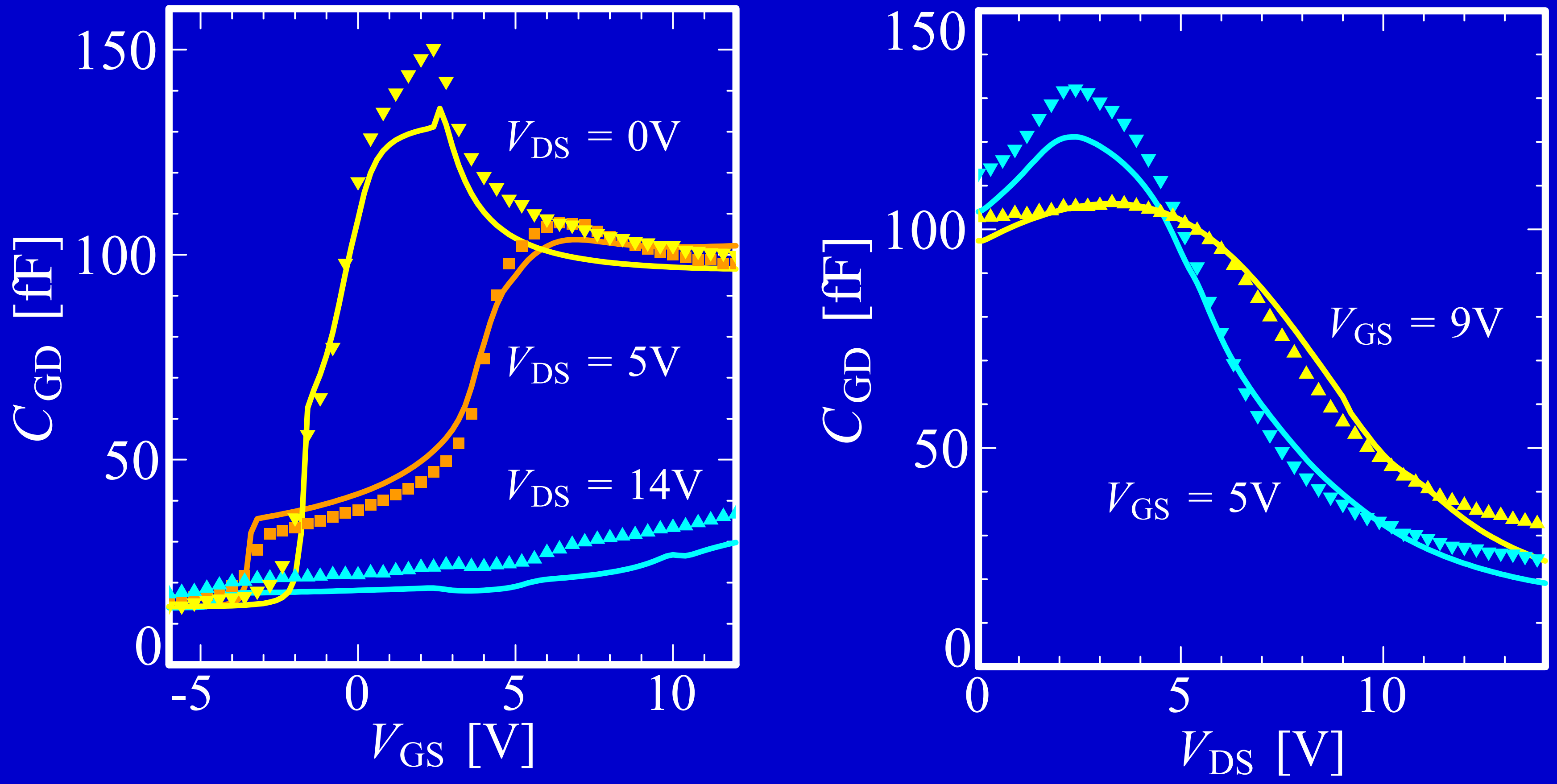
MOS Model 20: experimental data

14V SOI-LDMOS: T_{ox} = 60 nm, W = 50 μm, L = 5 μm, T = 25 °C



MOS Model 20: experimental data

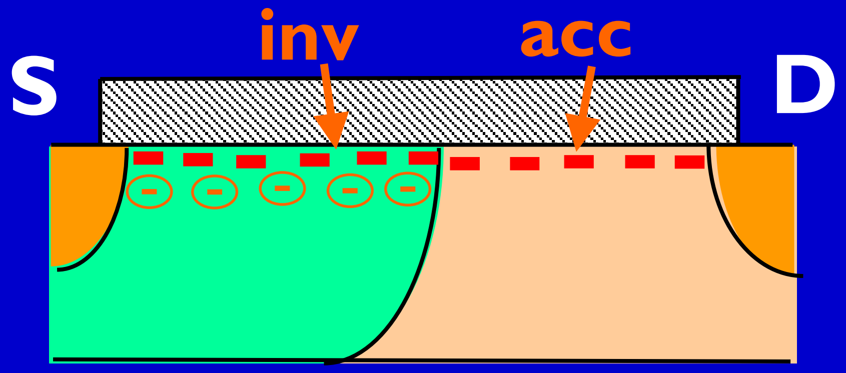
14V SOI-LDMOS: T_{ox} = 60 nm, W = 50 μm, L = 5 μm, T = 25 °C



outline

- introduction
- MOS Model 20
  - basic model
    - DC-model
    - nodal charge model
  - additional model features
- summary

MOS Model 20: source and drain charges



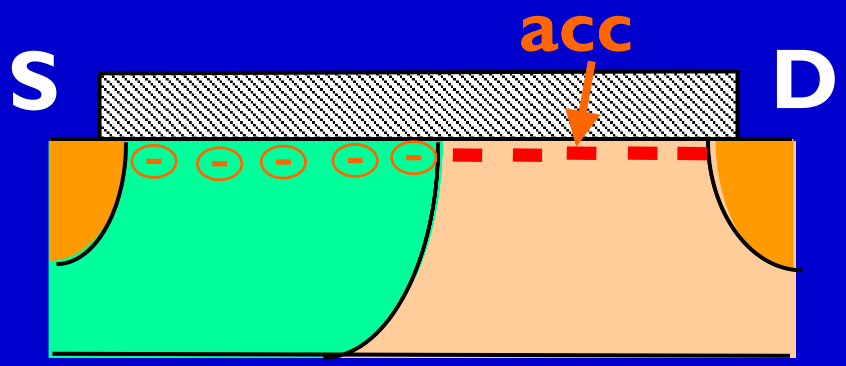
channel region in strong inversion

Ward-Dutton (uniform MOSFET)

$$Q_{\mathrm{D,\,LDMOS}} = W\int_{0}^{L} \frac{x}{L+L_{\mathrm{dr}}} Q'_{\mathrm{inv}}\,dx + W\int_{L}^{L+L_{\mathrm{dr}}} \frac{x}{L+L_{\mathrm{dr}}} Q'_{\mathrm{acc}}\,dx$$

$$Q_{\mathrm{S,\,LDMOS}} = W\int_{0}^{L} \frac{L+L_{\mathrm{dr}}-x}{L+L_{\mathrm{dr}}} Q'_{\mathrm{inv}}\,dx + W\int_{L}^{L+L_{\mathrm{dr}}} \frac{L+L_{\mathrm{dr}}-x}{L+L_{\mathrm{dr}}} Q'_{\mathrm{acc}}\,dx$$

MOS Model 20: source and drain charges



channel region in
weak inversion

all charge in the drift region attributed to the drain

$$Q_{\mathrm{D,\,LDMOS}} = W \int_{L}^{L+L_{\mathrm{dr}}} Q'_{\mathrm{acc}}\, dx$$

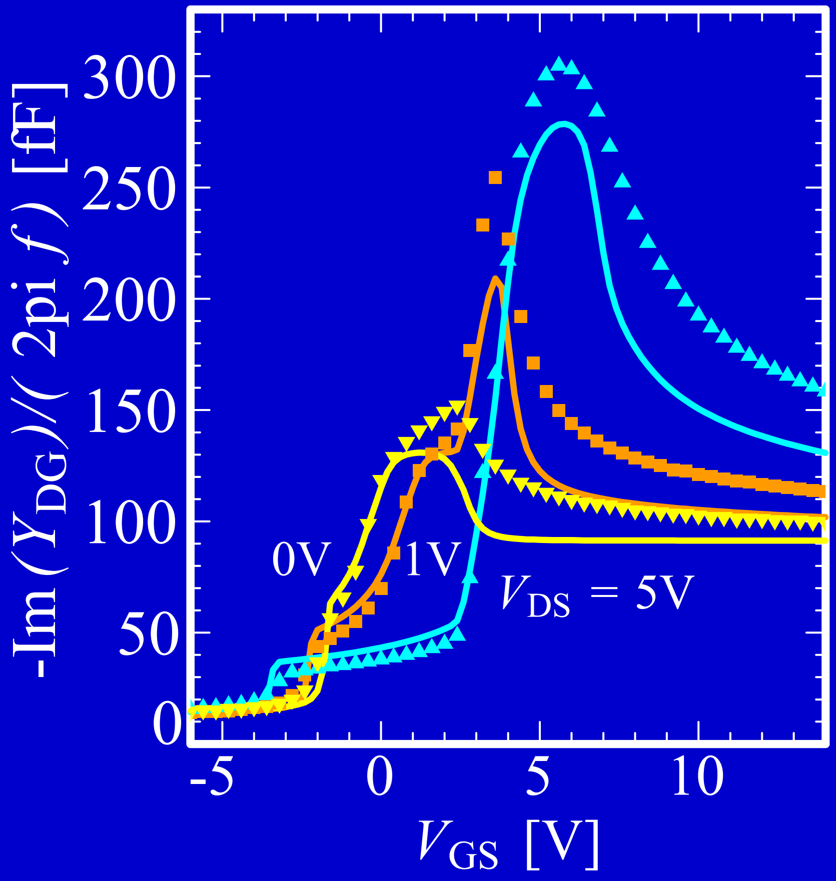
$$Q_{\mathrm{S,\,LDMOS}} = 0$$

outline

- introduction
- MOS Model 20
  - basic model
    - DC-model
    - nodal charge model
    - ➡ comparison with experimental data
  - additional model features
- summary

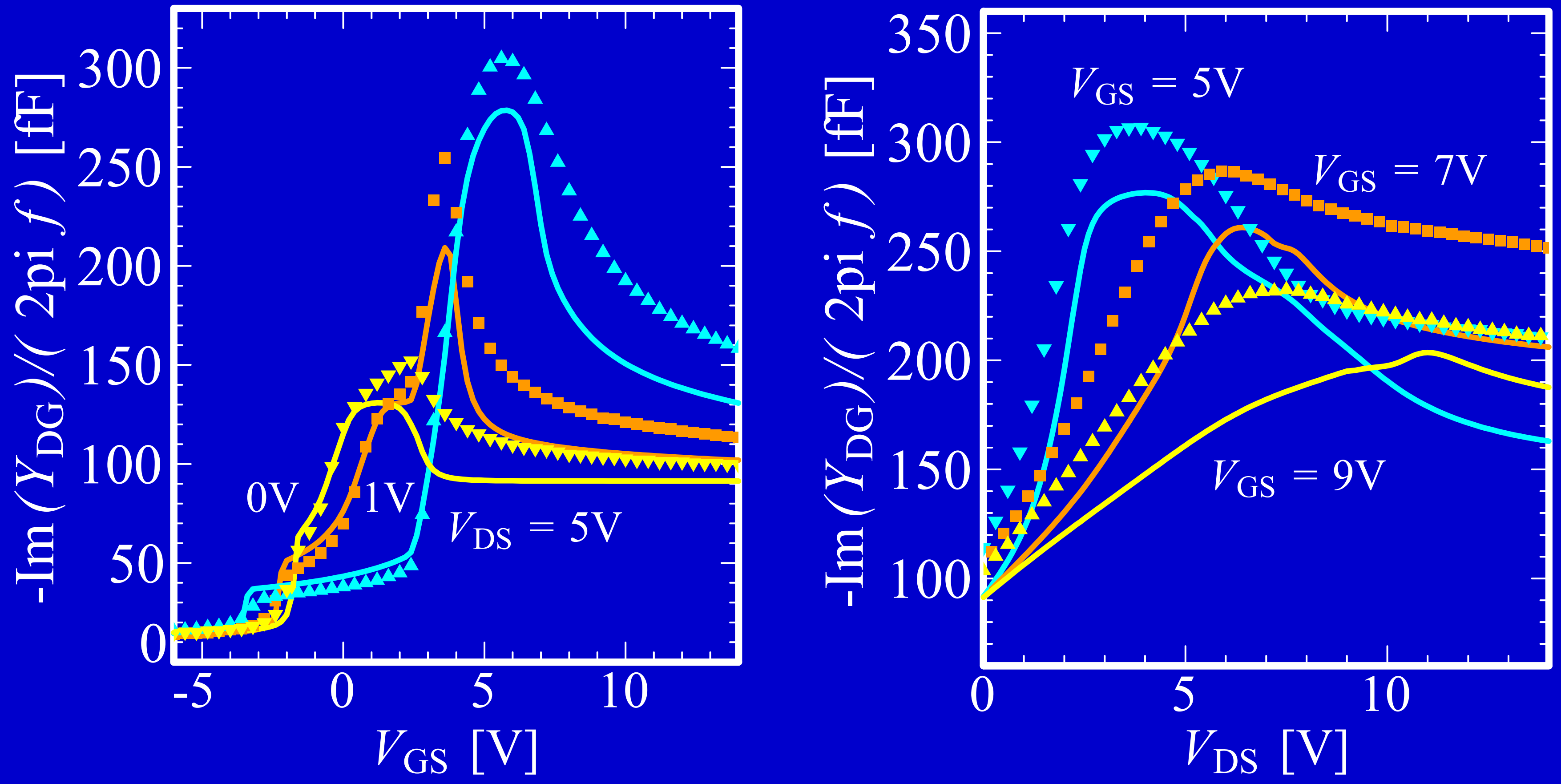
MOS Model 20: experimental data

14V SOI-LDMOS: T_{ox}= 60 nm, W = 50 µm, L = 5 µm, T = 25 ºC



MOS Model 20: experimental data

14V SOI-LDMOS: T_{ox}= 60 nm, W = 50 μm, L = 5 μm, T = 25 ºC



MOS Model 20: experimental data

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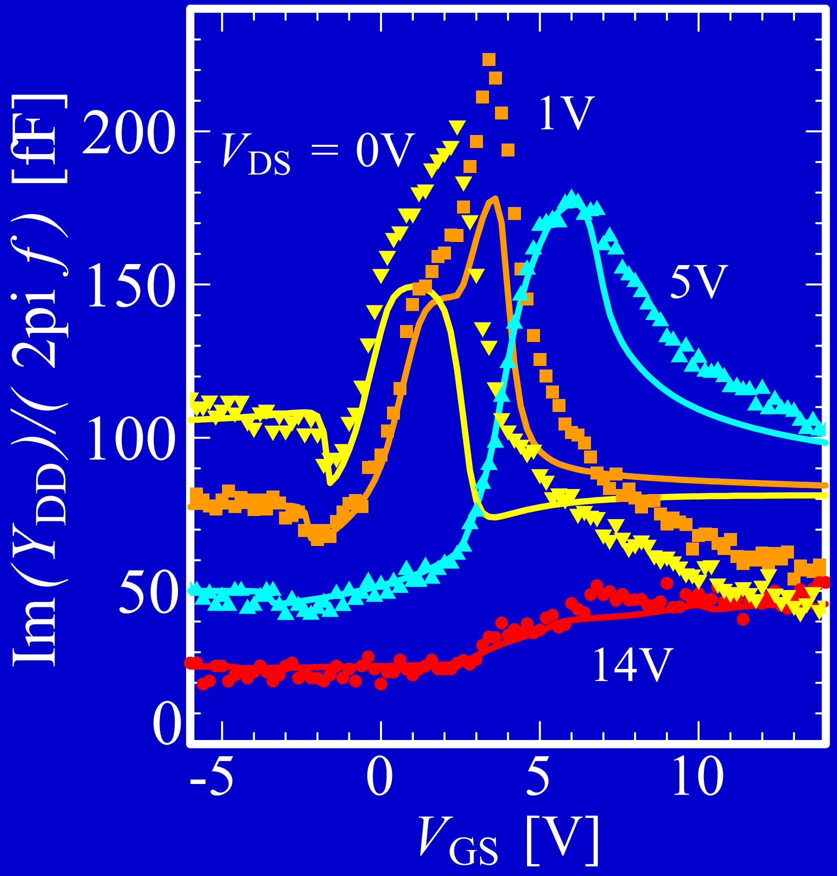
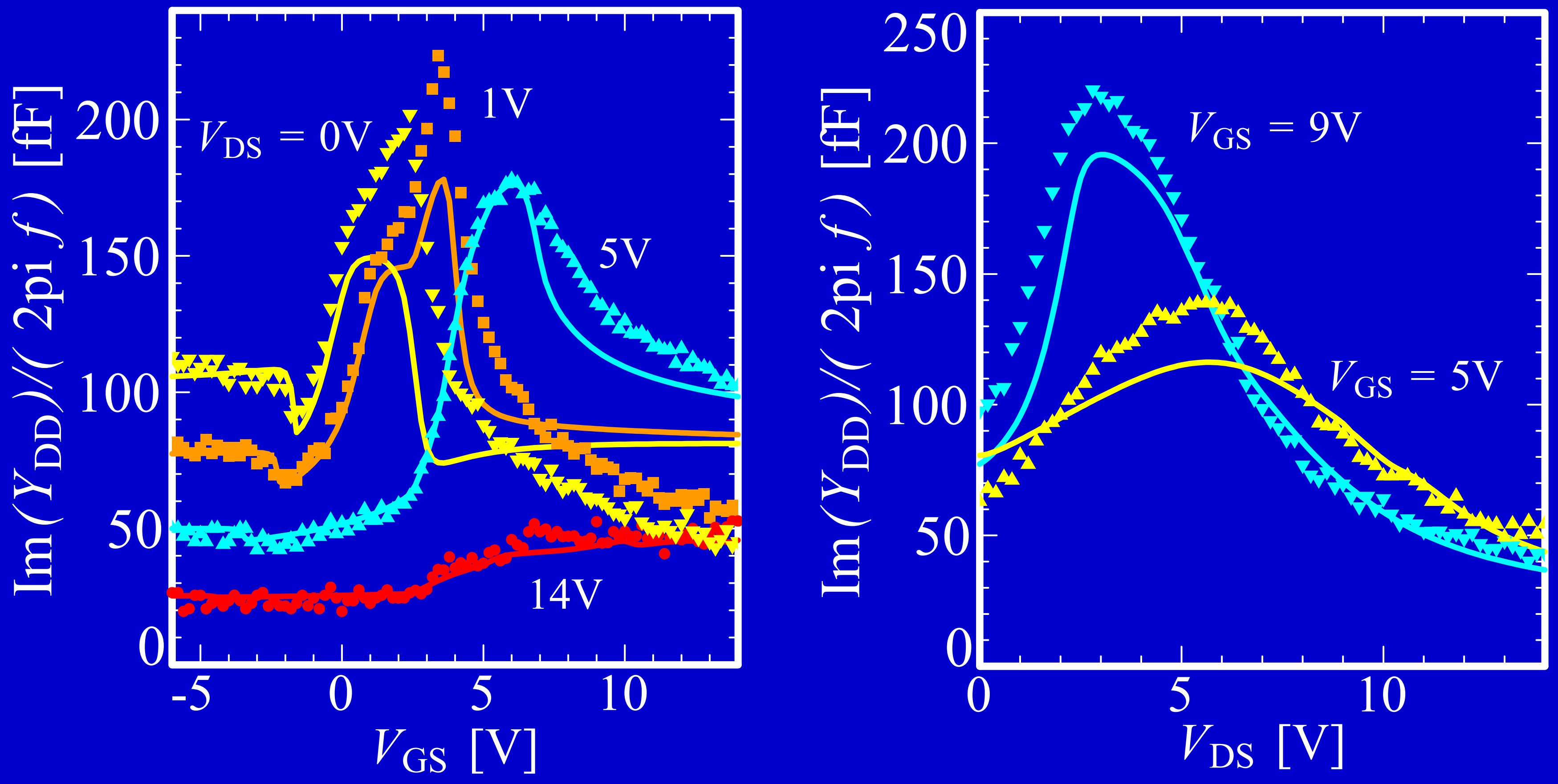


MOS Model 20: experimental data

14V SOI-LDMOS: T_{ox}= 60 nm, W = 50 μm, L = 5 μm, T = 25 ºC



interpretation of h.f. measurements

$$Y_{\mathrm{GG}} = \frac{j \cdot \omega \cdot C_{\mathrm{GG}}}{1 + j \cdot \omega \cdot R_{\mathrm{g}} \cdot C_{\mathrm{GG}}} \approx j \cdot \omega \cdot C_{\mathrm{GG}}$$

$$Y_{\mathrm{GD}} = \frac{-j \cdot \omega \cdot C_{\mathrm{GD}}}{1 + j \cdot \omega \cdot R_{\mathrm{g}} \cdot C_{\mathrm{GG}}} \approx -j \cdot \omega \cdot C_{\mathrm{GD}}$$

$$Y_{\mathrm{DG}} = \frac{g_{\mathrm{m}} - j \cdot \omega \cdot C_{\mathrm{DG}}}{1 + j \cdot \omega \cdot R_{\mathrm{g}} \cdot C_{\mathrm{GG}}} \approx g_{\mathrm{m}} - j \cdot \omega \cdot \left(C_{\mathrm{DG}} + g_{\mathrm{m}} \cdot R_{\mathrm{g}} \cdot C_{\mathrm{GG}}\right)$$

$$Y_{\mathrm{DG}} = g_{\mathrm{DS}} + j \cdot \omega \cdot C_{\mathrm{DD}} + \left(g_{\mathrm{m}} - j \cdot \omega \cdot C_{\mathrm{DG}}\right) \cdot \frac{j \cdot \omega \cdot R_{\mathrm{g}} \cdot C_{\mathrm{GD}}}{1 + j \cdot \omega \cdot R_{\mathrm{g}} \cdot C_{\mathrm{GG}}}$$

$$\longrightarrow \quad Y_{\mathrm{DG}} \approx g_{\mathrm{DS}} + j \cdot \omega \cdot \left(C_{\mathrm{DD}} + g_{\mathrm{m}} \cdot R_{\mathrm{g}} \cdot C_{\mathrm{GD}}\right)$$

retain only terms of O(ω)

interpretation of h.f. measurements

$$C_{\mathrm{GG}} = \frac{\Im\left(Y_{\mathrm{GG}}\right)}{\omega}$$

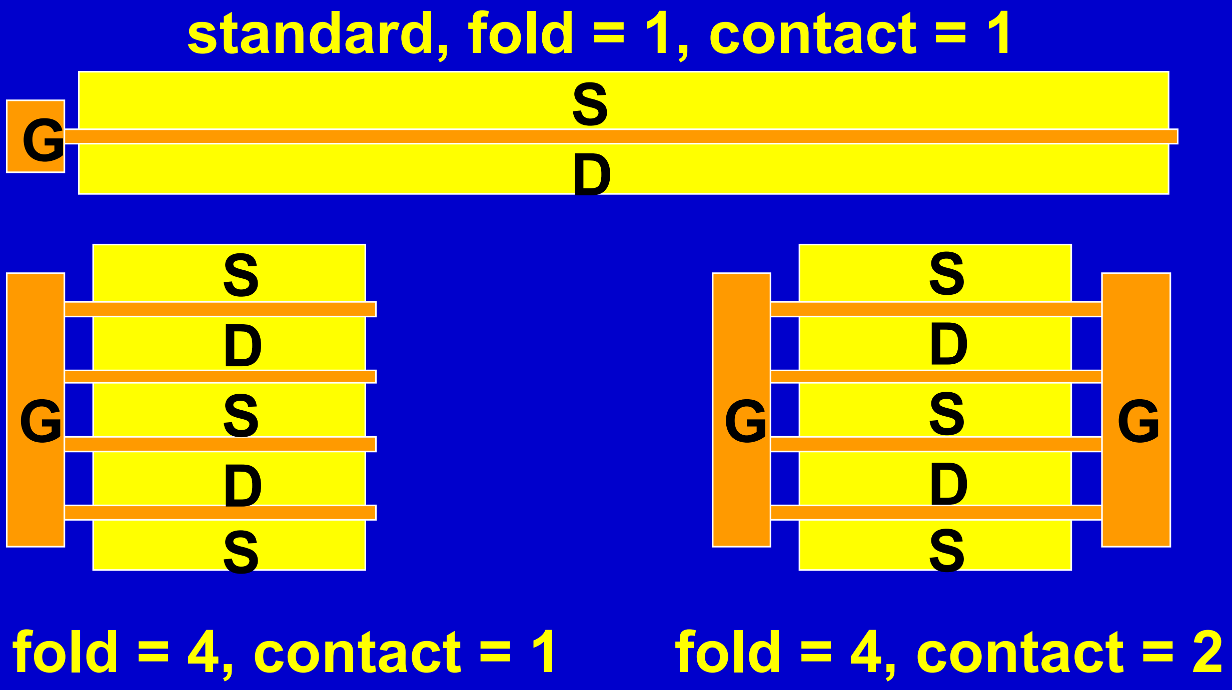
$$C_{\mathrm{GD}} = -\frac{\Im\left(Y_{\mathrm{GD}}\right)}{\omega}$$

$$g_{\mathrm{m}} = \Re\left(Y_{\mathrm{DG}}\right)$$

$$C_{\mathrm{DG}} = -\frac{\Im\left(Y_{\mathrm{DG}}\right)}{\omega} - R_{\mathrm{g}} \cdot \Re\left(Y_{\mathrm{DG}}\right) \cdot \frac{\Im\left(Y_{\mathrm{GG}}\right)}{\omega}$$

$$C_{\mathrm{DD}} = \frac{\Im\left(Y_{\mathrm{DD}}\right)}{\omega} + R_{\mathrm{g}} \cdot \Re\left(Y_{\mathrm{DG}}\right) \cdot \frac{\Im\left(Y_{\mathrm{GD}}\right)}{\omega}$$

interpretation of h.f. measurements

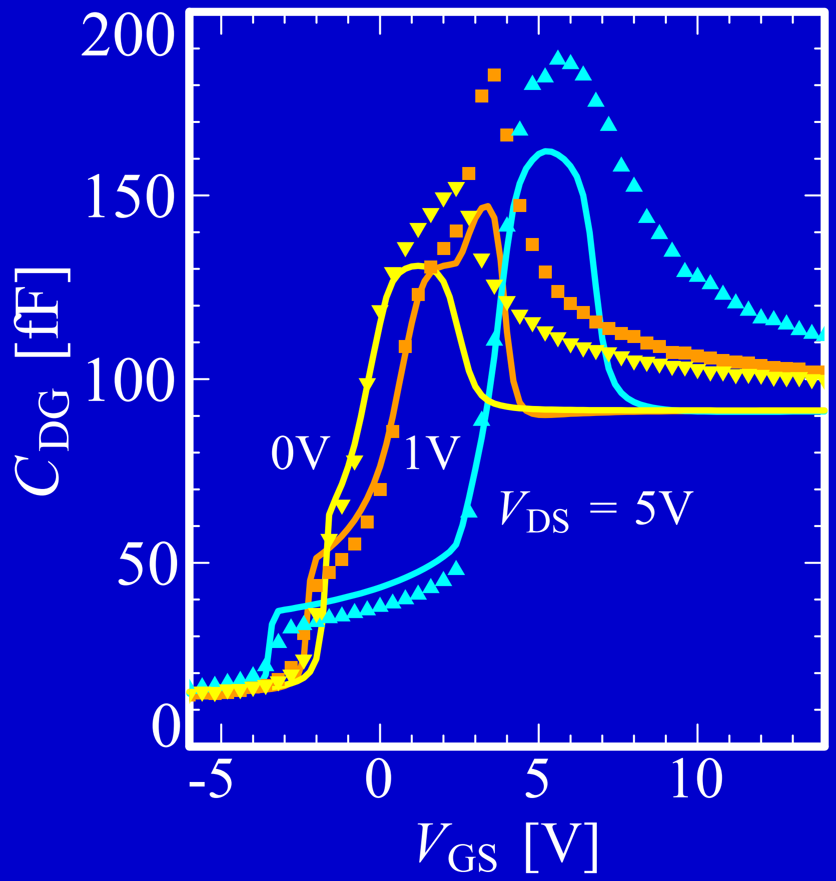


$$R_{\text{gate}} = \frac{W_{\text{g}} \cdot R_{\text{sheet}}}{3 \cdot fold^2 \cdot contact^2 \cdot L_{\text{g}}} + \frac{R_{\text{contact}}}{W_{\text{g}} \cdot L_{\text{g}}}$$

$$R_{\text{gate}} = 340\Omega$$

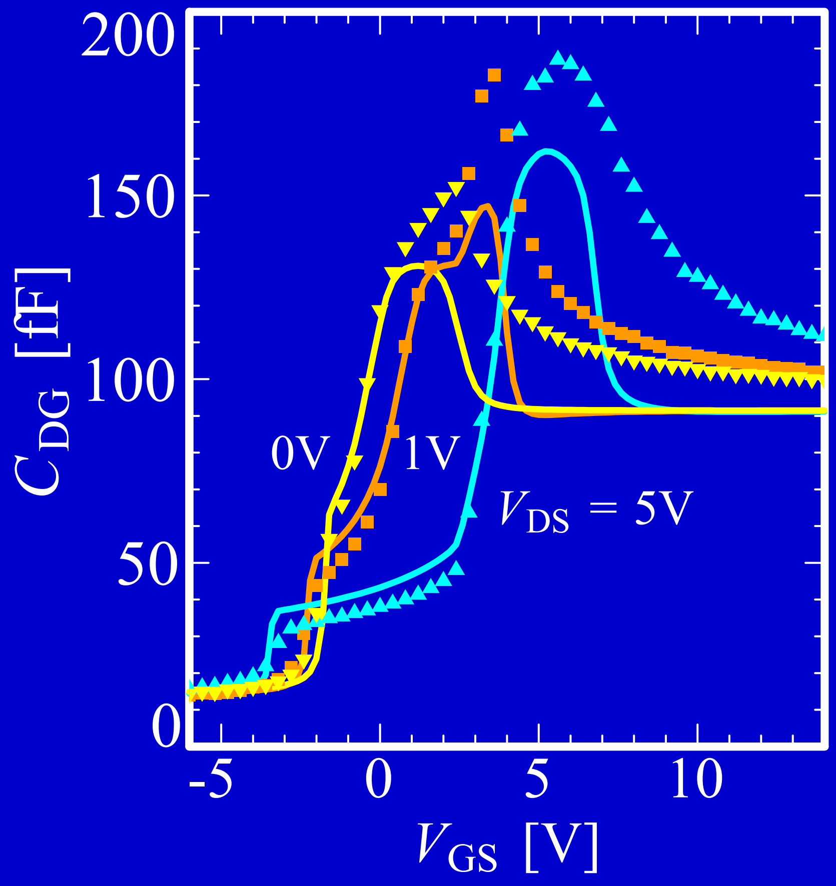
MOS Model 20: experimental data

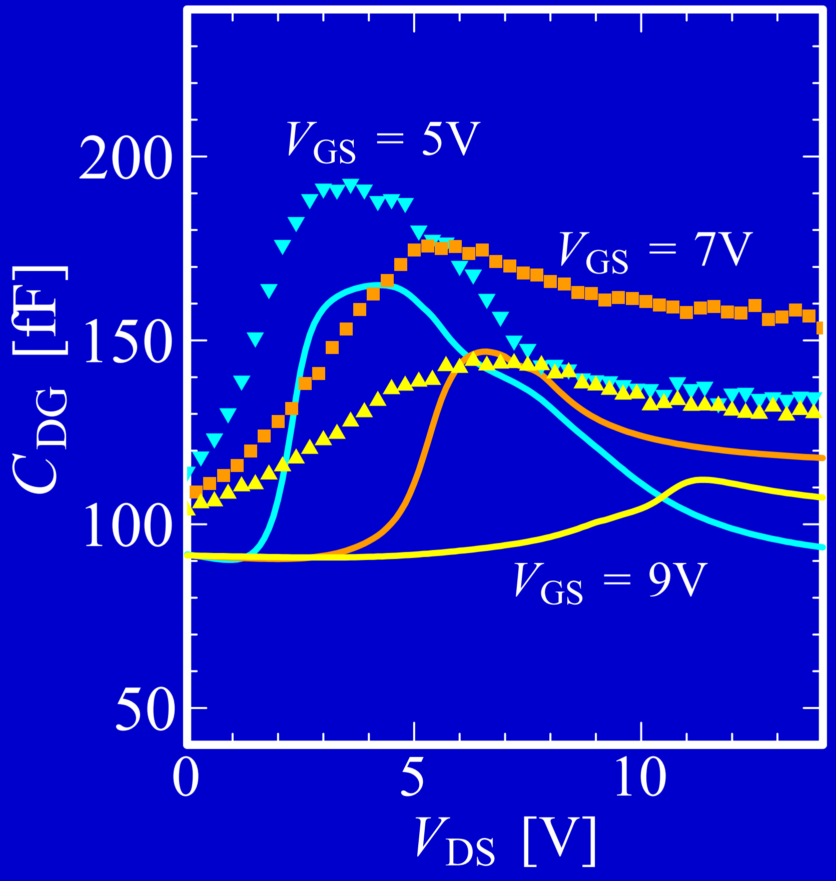
14V SOI-LDMOS: T_{ox}= 60 nm, W = 50 μm, L = 5 μm, T = 25 ºC



MOS Model 20: experimental data

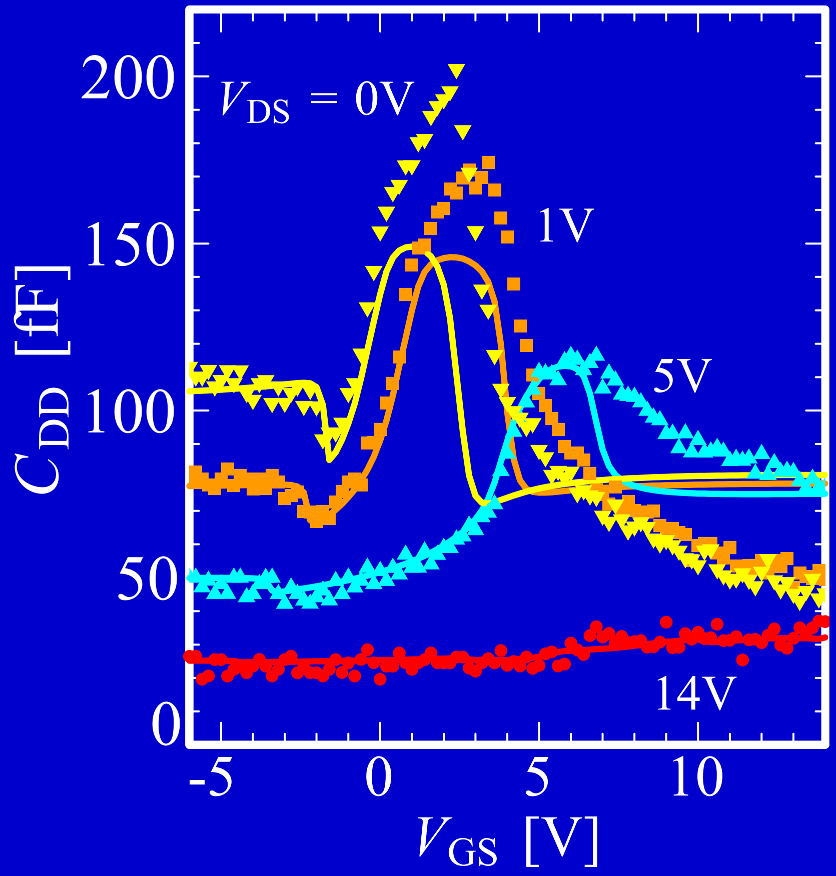
14V SOI-LDMOS: T_{ox}= 60 nm, W = 50 μm, L = 5 μm, T = 25 °C





MOS Model 20: experimental data

14V SOI-LDMOS: T_{ox}= 60 nm, W = 50 μm, L = 5 μm, T = 25 °C



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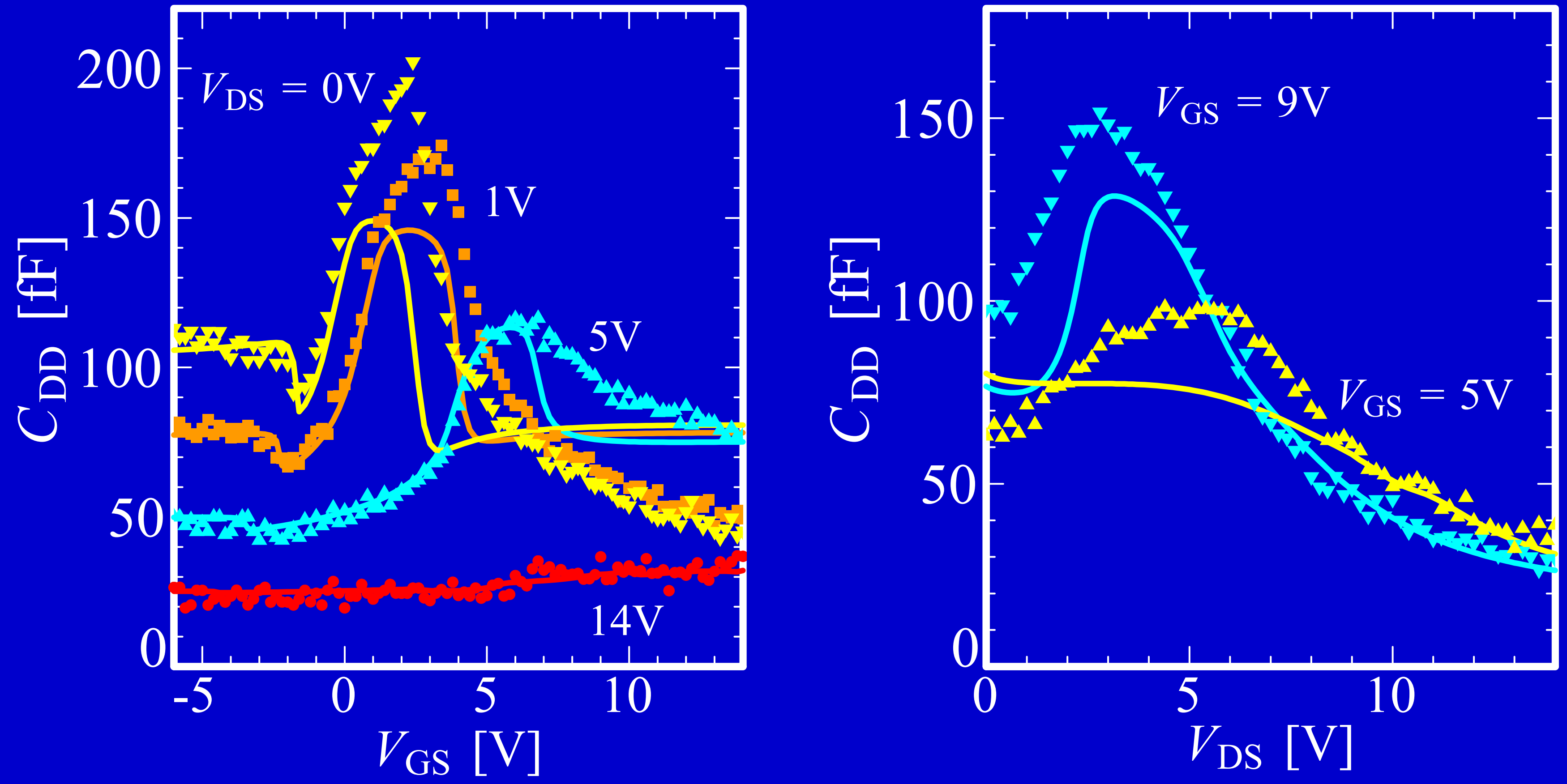

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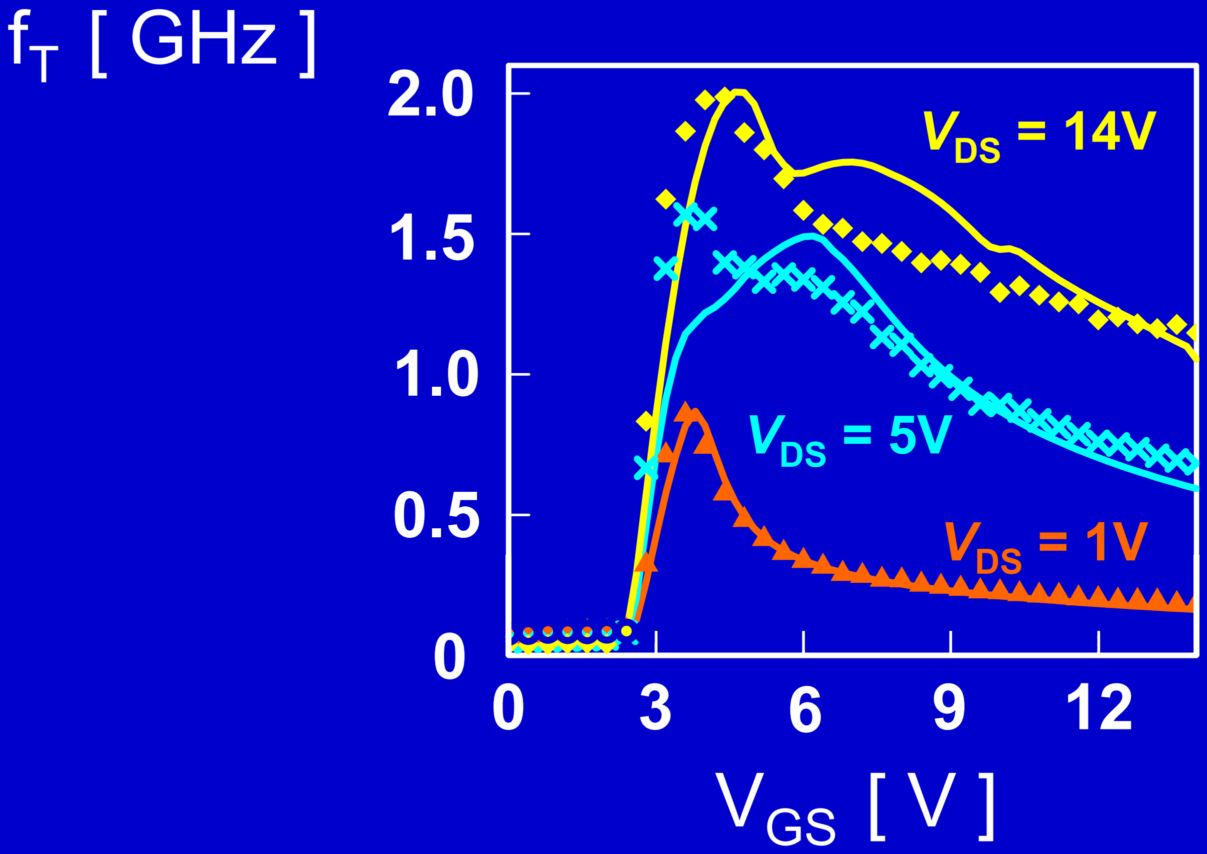
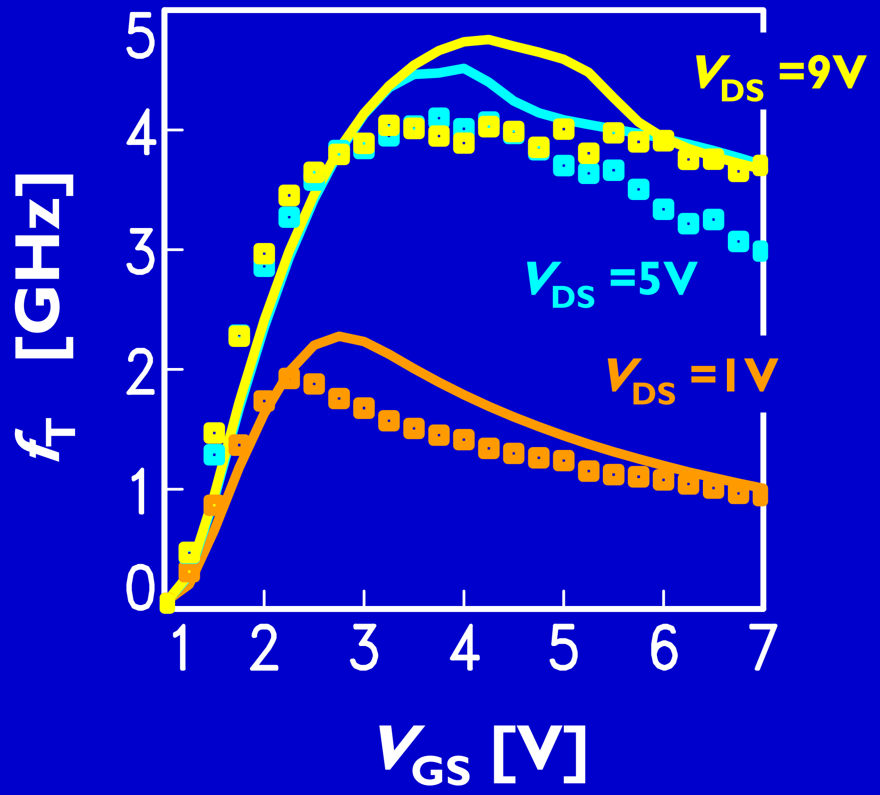


MOS Model 20: experimental data

12V SOI-LDMOS: T_{ox}= 30 nm, T = 25 °C



outline

- introduction
- MOS Model 20
  - basic model
  - ➡ additional model features
    - parameters
    - self-heating and temperature scaling
    - geometry scaling
    - bulk current
    - noise
- summary

MOS Model 20: parameters

- 24 DC parameters

parameters of electrical model

no.	parameter	meaning
0	LEVEL	2002
1	TREF	reference temperature
2	VFB	flatband voltage of channel at reference temp.
3	STVFB	temperature scaling coefficient
4	VFBD	flatband voltage of drift region at ref. temp.
5	STVFBD	temperature scaling coefficient
6	KO	body factor of channel region
7	KOD	body factor of drift region
8	PHIB	surface potential at onset of strong inversion in channel region at reference temperature
9	STPHIB	temperature scaling coefficient
10	PHIBD	surface potential at onset of strong inversion in drift region at reference temperature
11	STPHIBD	temperature scaling coefficient

parameters of electrical model

no.	parameter	meaning
12	BET	gain factor of channel region at reference temp.
13	ETABET	temperature scaling exponent
14	BETACC	accumulation gain factor in drift region at reference temp.
15	ETABETACC	temperature scaling exponent
16	RD	on-resistance of drift region at reference temp.
17	ETARD	temperature scaling exponent
18	LAMD	quotient of depletion layer thickness at V_{SB}>0, to effective thickness of drift region at V_{SB}=0
19	THE1	channel mobility reduction coefficient due to vertical field caused by strong inversion
20	THE1ACC	drift region mobility reduction coefficient due to vertical field caused by accumulation

parameters of electrical model

no.	parameter	meaning
21	THE2	channel mobility reduction coefficient due to vertical field caused by depletion
22	THE3	channel mobility reduction coefficient due to horizontal field
23	ETATHE3	temperature scaling exponent
24	MEXP	transition from linear to saturation regime
25	THE3D	drift region: channel mobility reduction coefficient due to horizontal field
26	ETATHE3D	drift region: temperature scaling exponent
27	MEXPD	drift region: trans. from linear to sat. regime
28	ALP	factor for channel length modulation
29	VP	char. voltage of channel length modulation

parameters of electrical model

no.	parameter	meaning
30	SDIBL	factor for drain-induced barrier-lowering
31	MSDIBL	exponent for DIBL dependence on back bias
32	MO	parameter for subthreshold slope
33	SSF	factor for static feedback
34	A1	factor of weak-avalanche current at ref. temp.
35	STA1	temperature scaling coefficient for A1
36	A2	exponent of weak avalanche current
37	A3	factor of drain-source voltage above which weak avalanche occurs
38	COX	oxide capcitance for intrinsic channel region
39	COXD	oxide capacitance for intrinsic drift region
40	CGDO	gate-drain overlap capacitance
41	CGSO	gate-source overlap capacitance

parameters of electrical model

no.	parameter	meaning
42	NT	coefficient of thermal noise at ref. temperature
43	NFA	first coefficient of flicker noise
44	NFB	second coefficient of flicker noise
45	NFC	third coefficient of flicker noise
46	TOX	thickness of oxide above channel region
47	DTA	temperature offset to ambient temperature
48	MULT	number of devices in parallel

MOS Model 20: parameters

- 24 DC parameters
- temperature scaling
  - 6 parameters

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- 24 DC parameters
- temperature scaling
  - 6 parameters
- width scaling
  - 7 parameters

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  - basic model
  - additional model features
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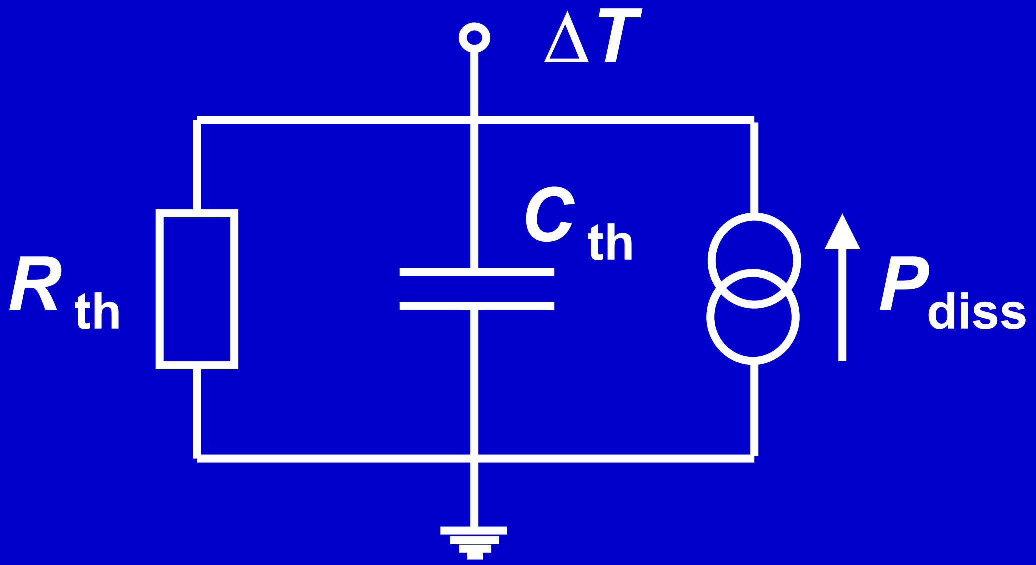
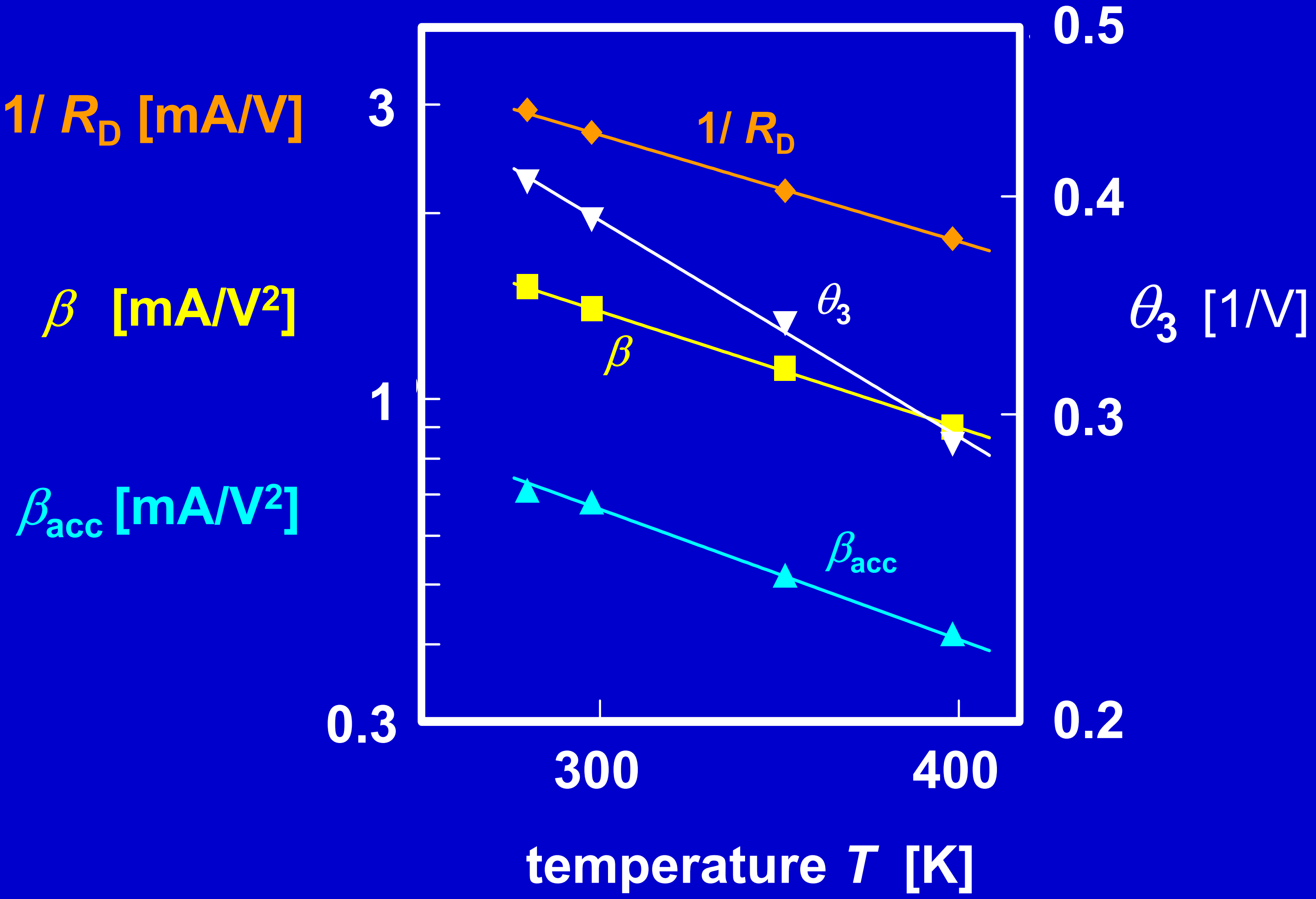
MOS Model 20: self-heating

- self-heating network inside model:



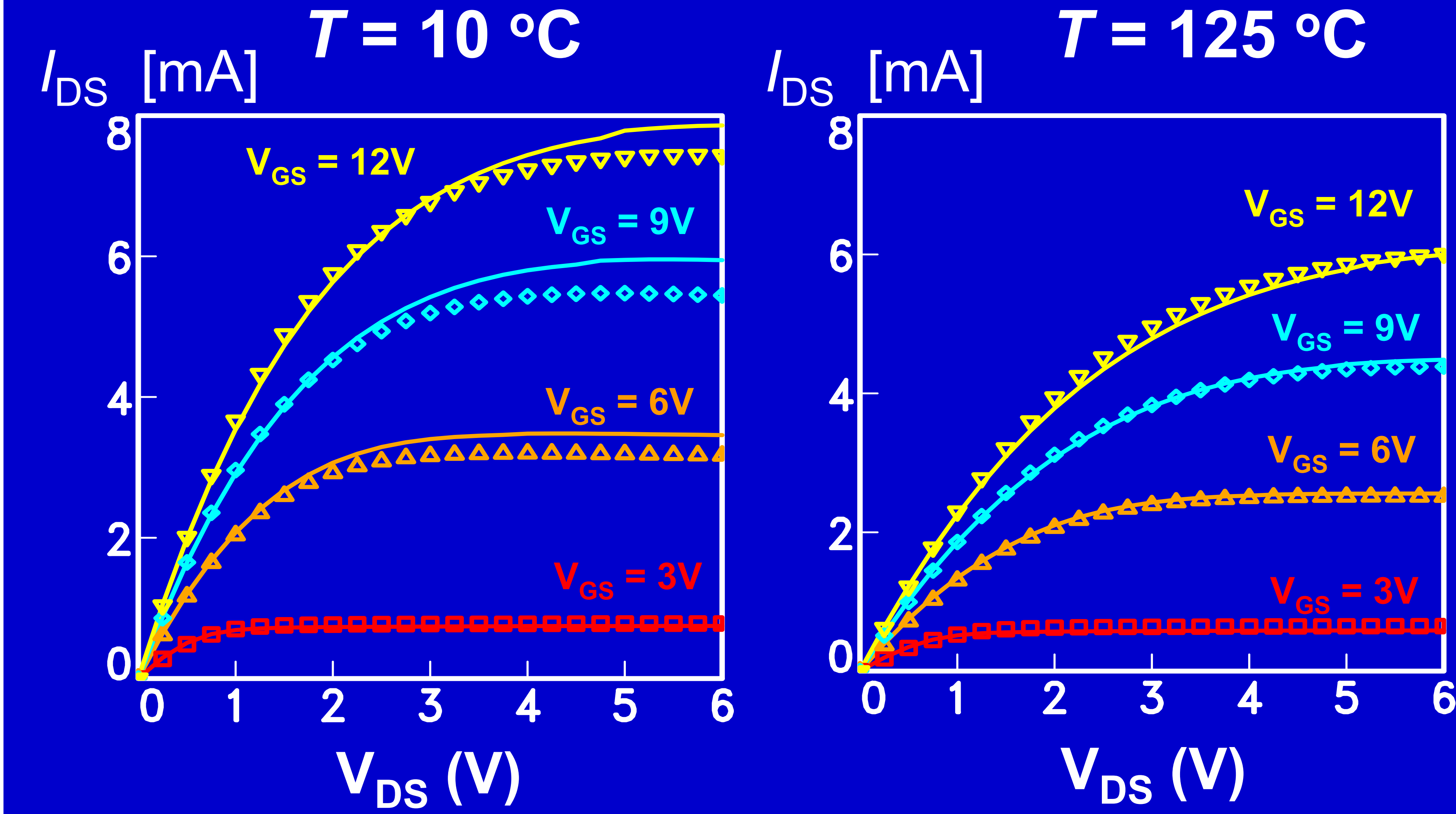
- temperature-dependent model parameters
- derivatives w.r.t. temperature (ac and transient)

MOS Model 20: temperature scaling



MOS Model 20: temperature scaling

12V SOI-LDMOS: T_{ox} = 38 nm, W = 17 μm, L = 1.6 μm



outline

- introduction
- MOS Model 20
  - basic model
  - additional model features
    - parameters
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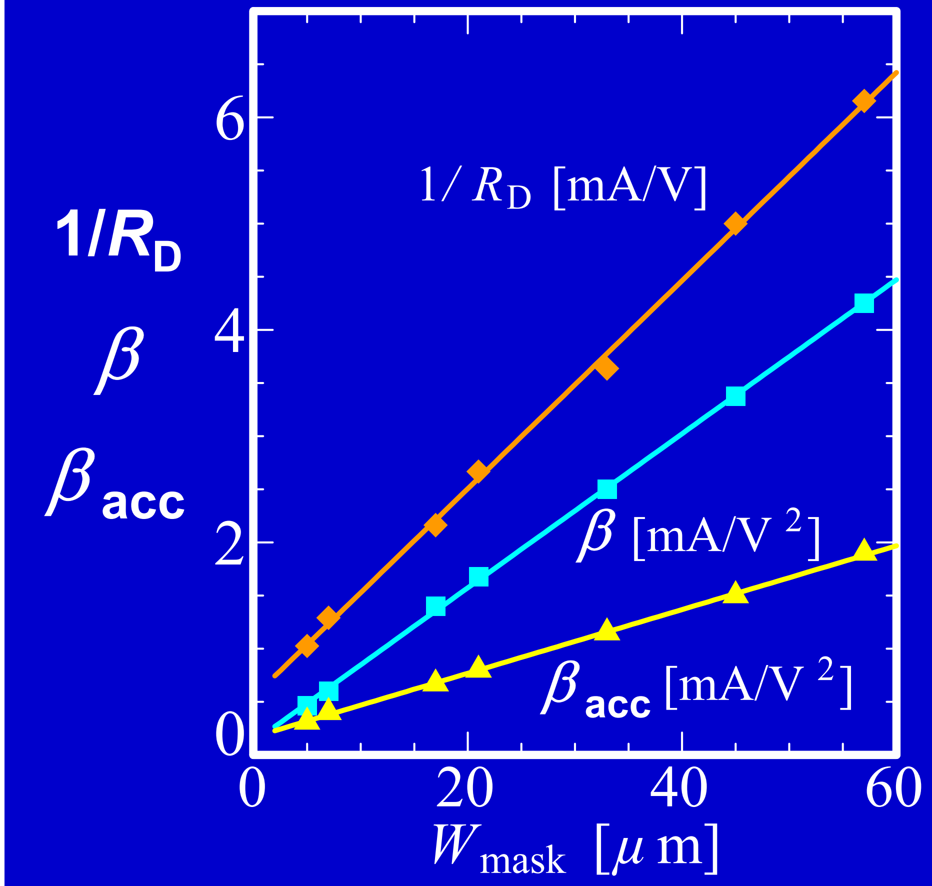
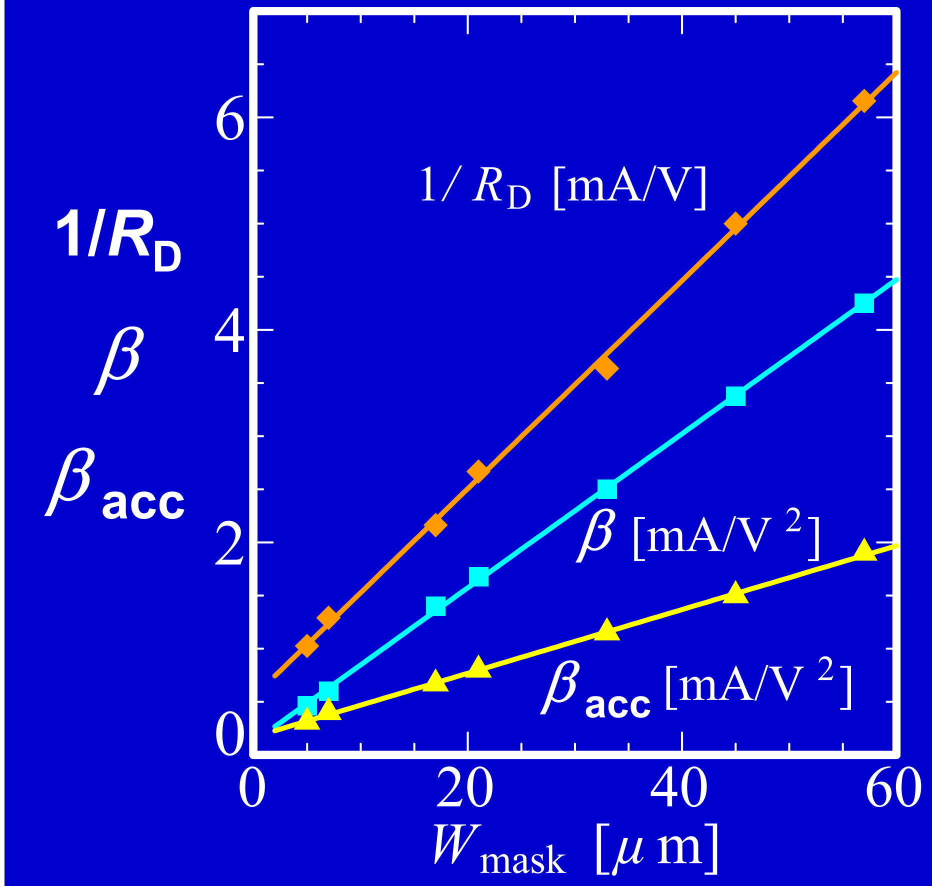
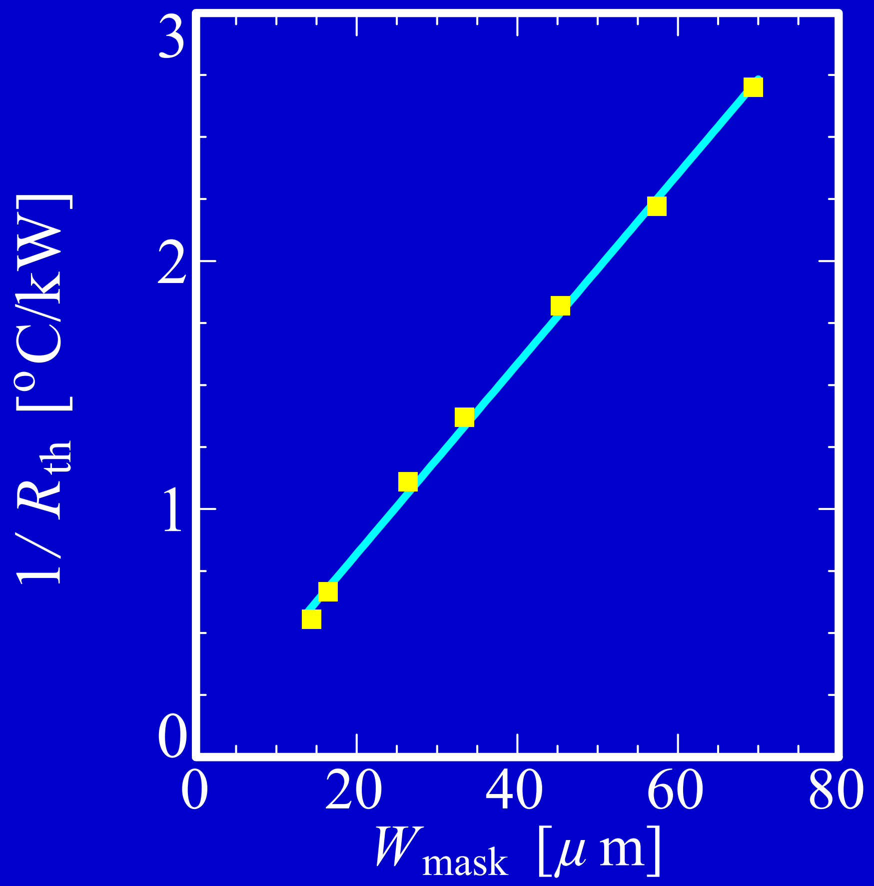
MOS Model 20: width scaling



MOS Model 20: width scaling



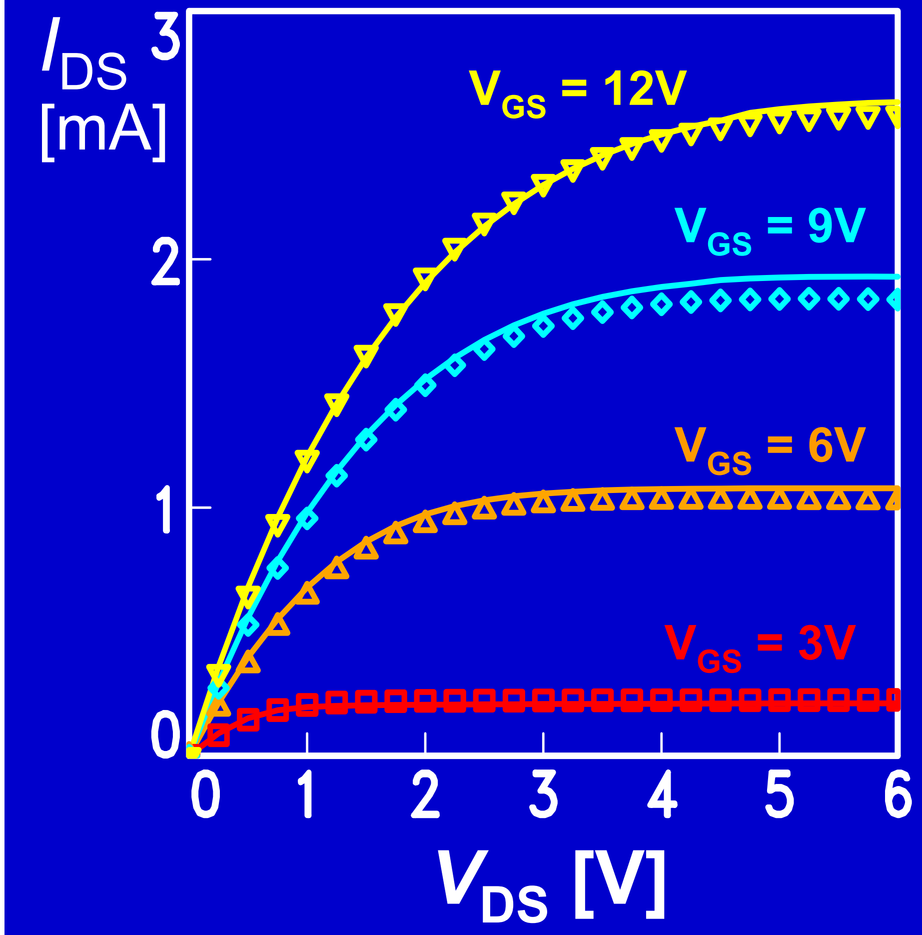
thermal resistance



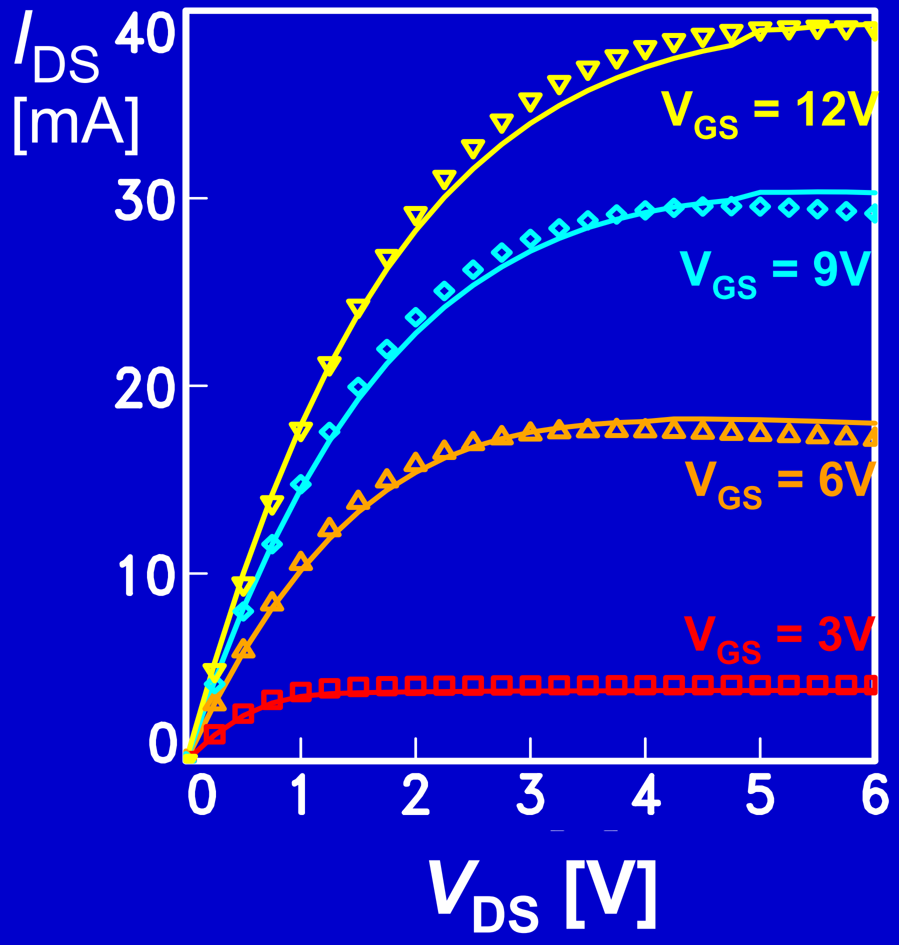
MOS Model 20: width scaling

12V SOI-LDMOS: T_{ox} = 38 nm, L = 1.6 μm, T = 25 °C

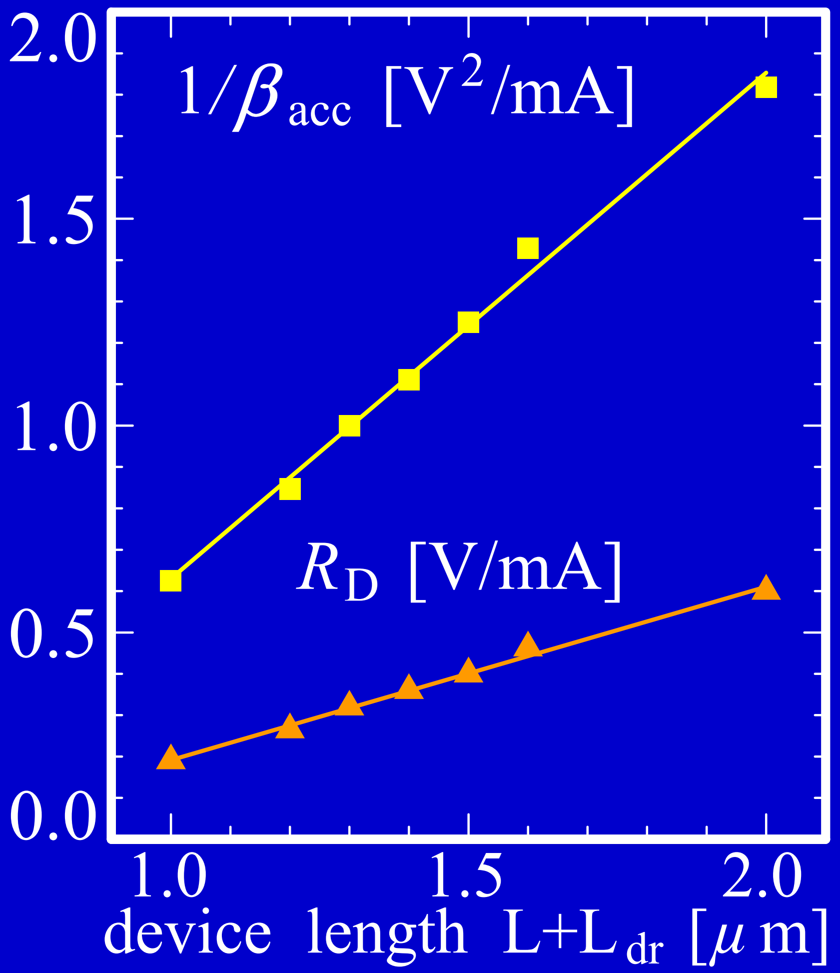
W = 5 μm



W = 114 μm

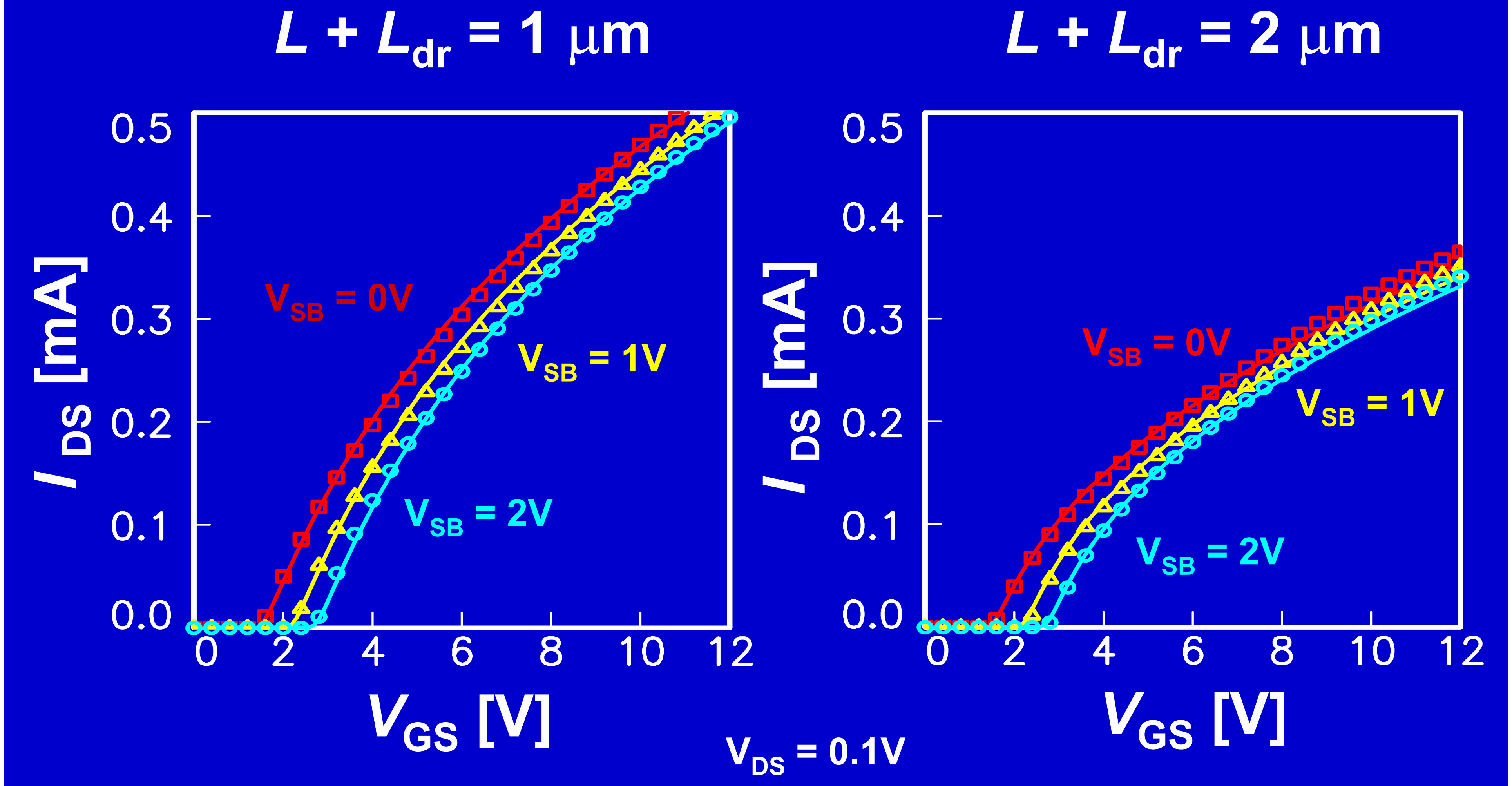


MOS Model 20: length scaling drift region



MOS Model 20: length scaling drift region

12V SOI-LDMOS: T_{ox} = 38 nm, W = 17 μm, T = 25 °C



outline

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  - basic model
  - additional model features
    - parameters
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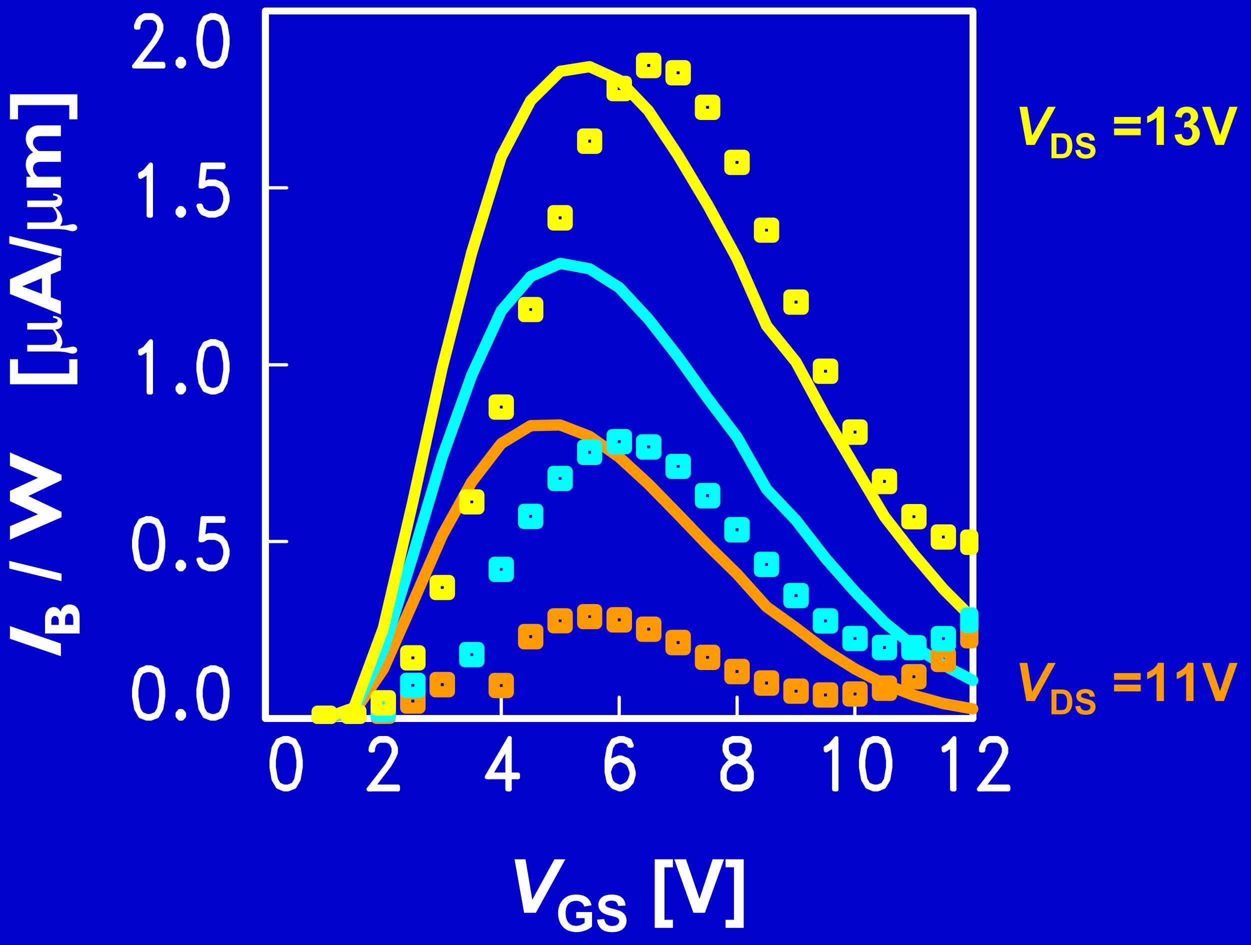
MOS Model 20: bulk current



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- introduction
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  - basic model
  - additional model features
    - parameters
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    - geometry scaling
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MOS Model 20: noise

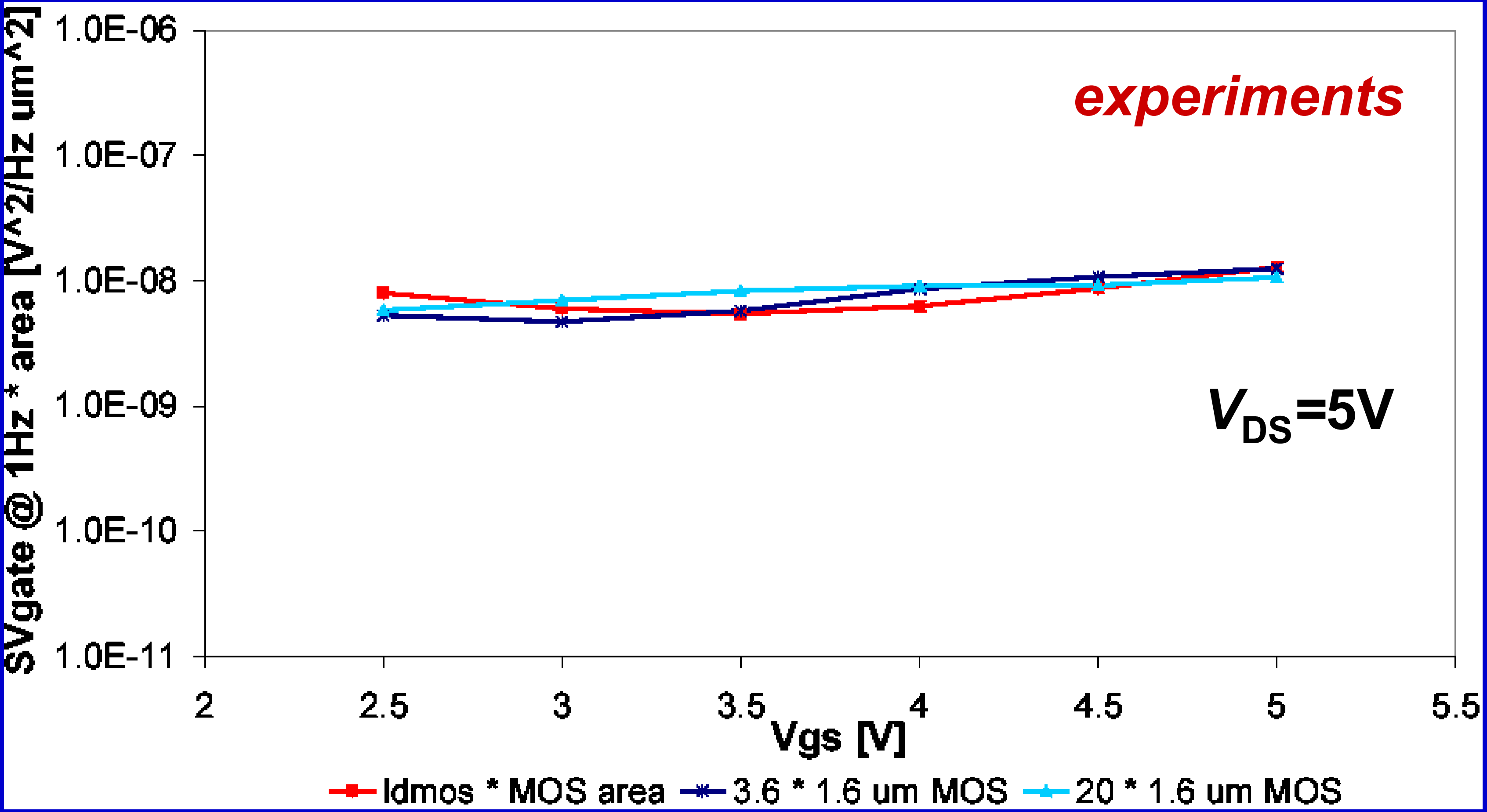
included: noise from the channel region

- 1/f noise
- thermal noise
- induced gate noise
- correlation

as in MOS Model 11

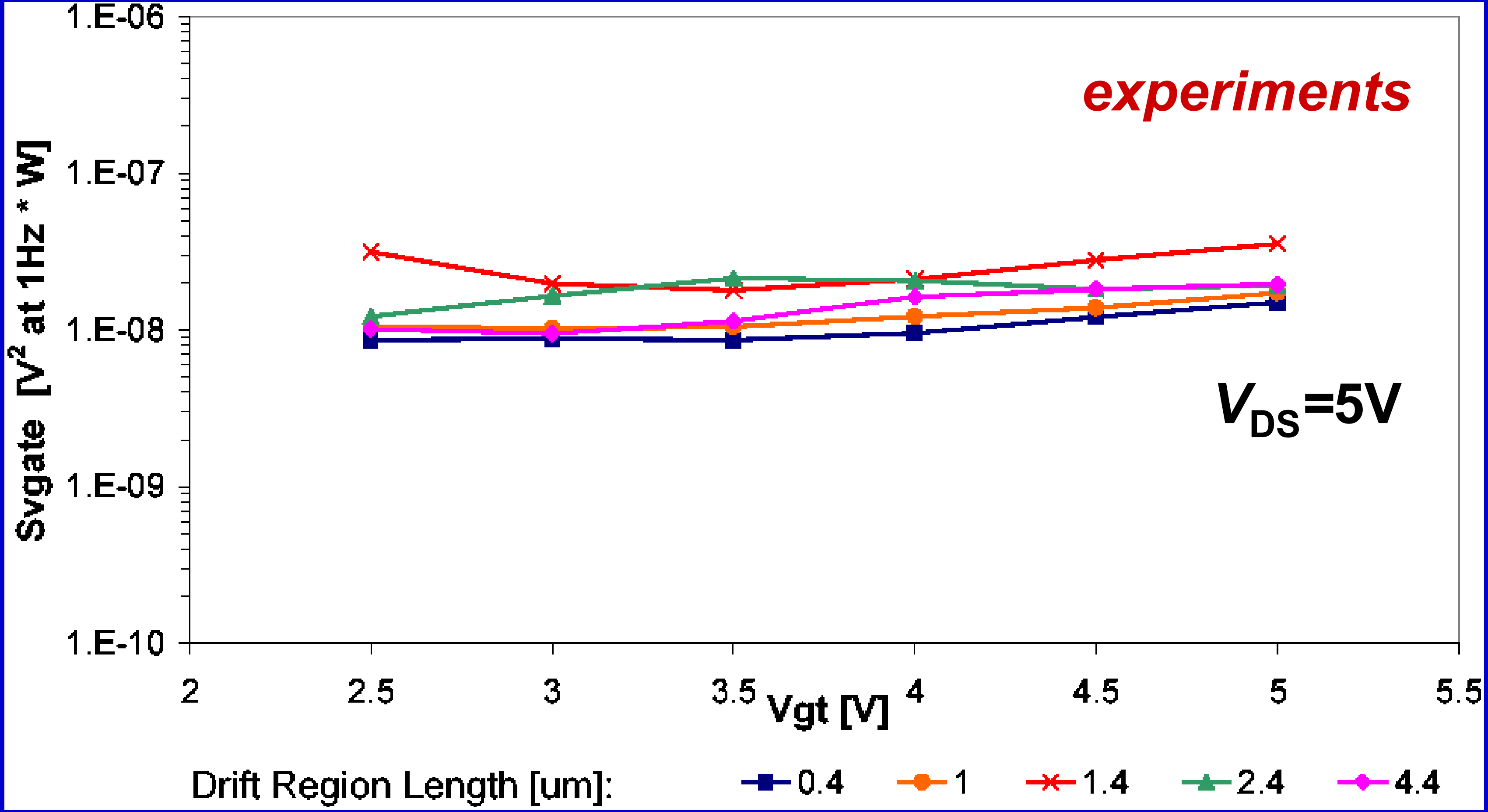
MOS Model 20: noise

1/f noise: comparison LDMOS - CMOS



MOS Model 20: noise

1/f noise: dependence on drift region



MOS Model 20: noise

included: noise from the channel region

- 1/f noise
- thermal noise
- induced gate noise
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as in MOS Model 11

supported by experiments

outline

- introduction
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  - basic model
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  - ➡ circuit behaviour
  - “must have” list
  - concluding remarks

MOS Model 20: circuit behaviour

- **MM20 tested for wide variety of HV-MOS**
  (LDMOS, EDMOS, 12-300 V)
- **MM20 tested in many different circuits**
- **excellent convergence behaviour**
- **simulation times equal to subcircuit models**

MOS Model 20: “must have” list

1a accurate DC/AC **OK**
derivatives of terminal currents and node charges **OK**
charge conservative **OK**
voltage-drop across source- and drain **drain OK**

1b drift region resistance, incl. velocity saturation **OK**

1c drift region capacitance **OK**

1d parasitic effects **via sub-circuit**

1e 1/f, thermal, gate-induced noise **OK**

MOS Model 20: "must have" list

2 V_{supply} up to 200V **OK, till ~100V**
T = – 50 till 200 °C **OK**

3 self-heating and temperature-dependence parameters **OK**

4 quasi-saturation, and g_m fall-off **OK**

5 C_{GD} drop **OK**

6 source-drain resistances, and junctions **via sub-circuit**

7 substrate current **OK**

MOS Model 20: “must have” list

8 geometry scaling, with one parameter set **OK**
drift region length as parameter **can be added**

9 reverse working ($V_{DS} < 0$) **OK**

10 both p-type and n-type **OK**

11 breakdown behaviour **X**

12 good convergence in circuit simulation **OK**

outline

- introduction
- MOS Model 20
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  - additional model features
- summary
  - circuit behaviour
  - “must have” list

➡ concluding remarks

MOS Model 20: concluding remarks

- MOS Model 20 gives good description of
  - currents
  - capacitances

  of LDMOS devices (verified up to 100V)
- good convergence behaviour
- most items on CMC list included

MOS Model 20: concluding remarks

- on website

http://www.semiconductors.philips.com/Philips_Models

documentation and source code available

    - C-code
    - interfaces directly to e.g. Spectre, ADS, …

- supporting institution:
  - Eindhoven University of Technology
  - A.C.T. Aarts: a.c.t.aarts@tue.nl

MOS Model 20: literature

- A. Aarts, N. D’Halleweyn, R. v. Langevelde,
  “A surface-potential-based high-voltage compact LDMOS transistor model”,
  IEEE Trans. Electron Devices, Vol. 52, No. 5, 2005
- A.C.T. Aarts and W.J. Kloosterman
  “Compact modeling of high-voltage LDMOS Devices including quasi-saturation”,
  IEEE Trans. Electron Devices, Vol. 53, No. 4, 2006

TU/e

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