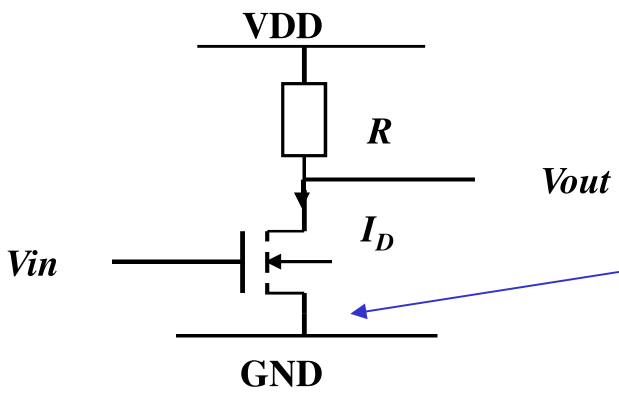
Chapter 4

Basics of analog MOS IC

- Inverter Circuit
- Differential Amplifier
- Current Mirror

A common source circuit



Constant Source-Potential

Input Vin low

⇨ NMOS off

⇨ Output Vout = V_{DD} = High

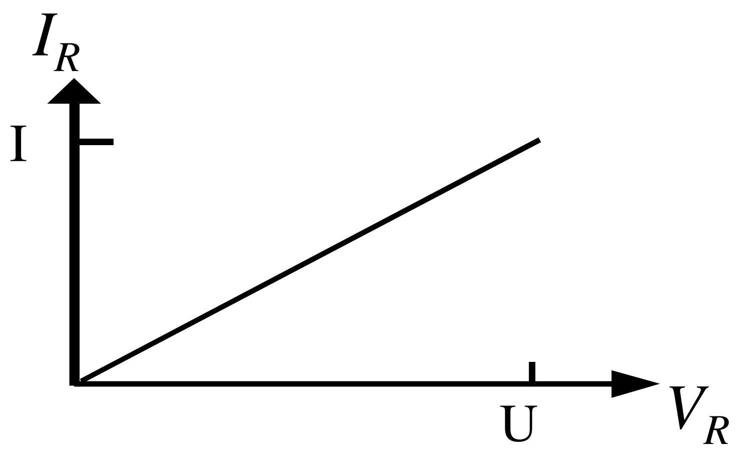
Input Vin high

⇨ drain current is flowing

⇨ Output Vout = $V_{DD} - I_D * R$ = Low

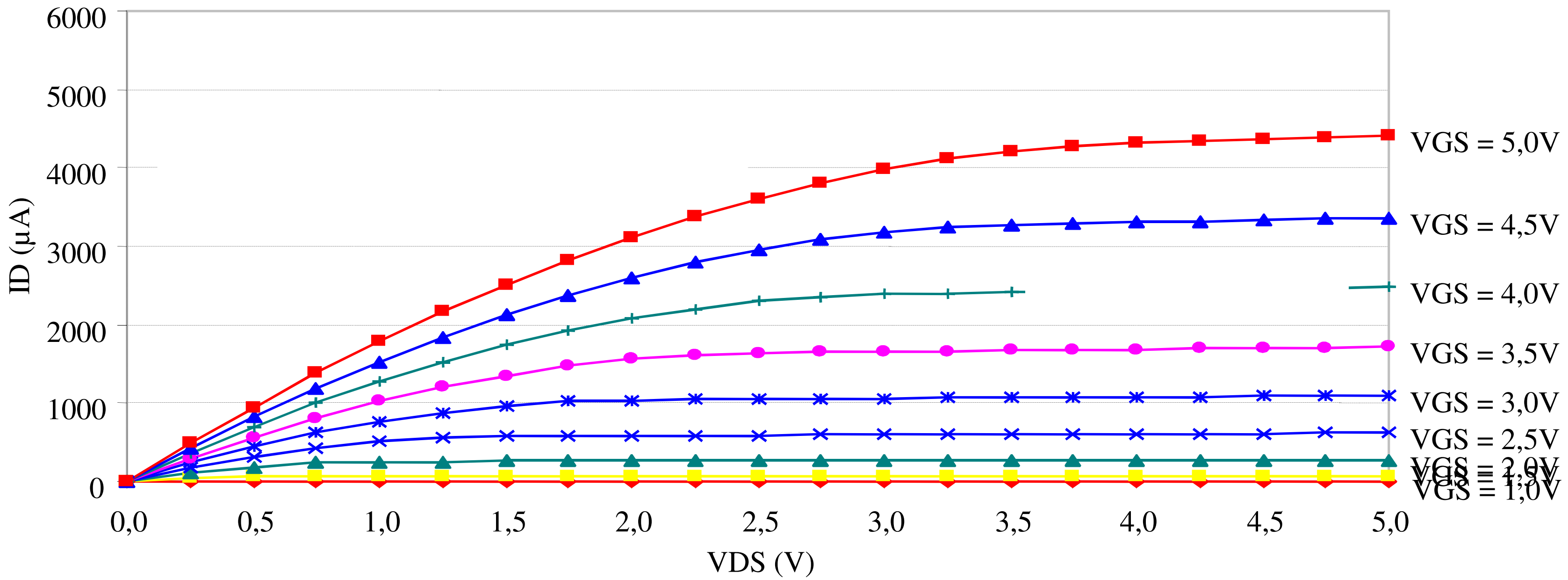
It is an inverter circuit.

Characteristic curves of resistor and MOSFET

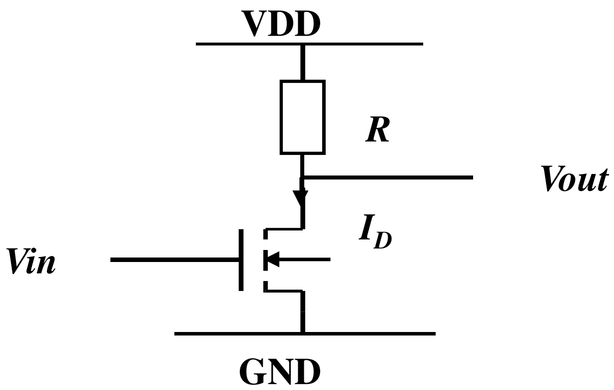


$I_R = I_D$

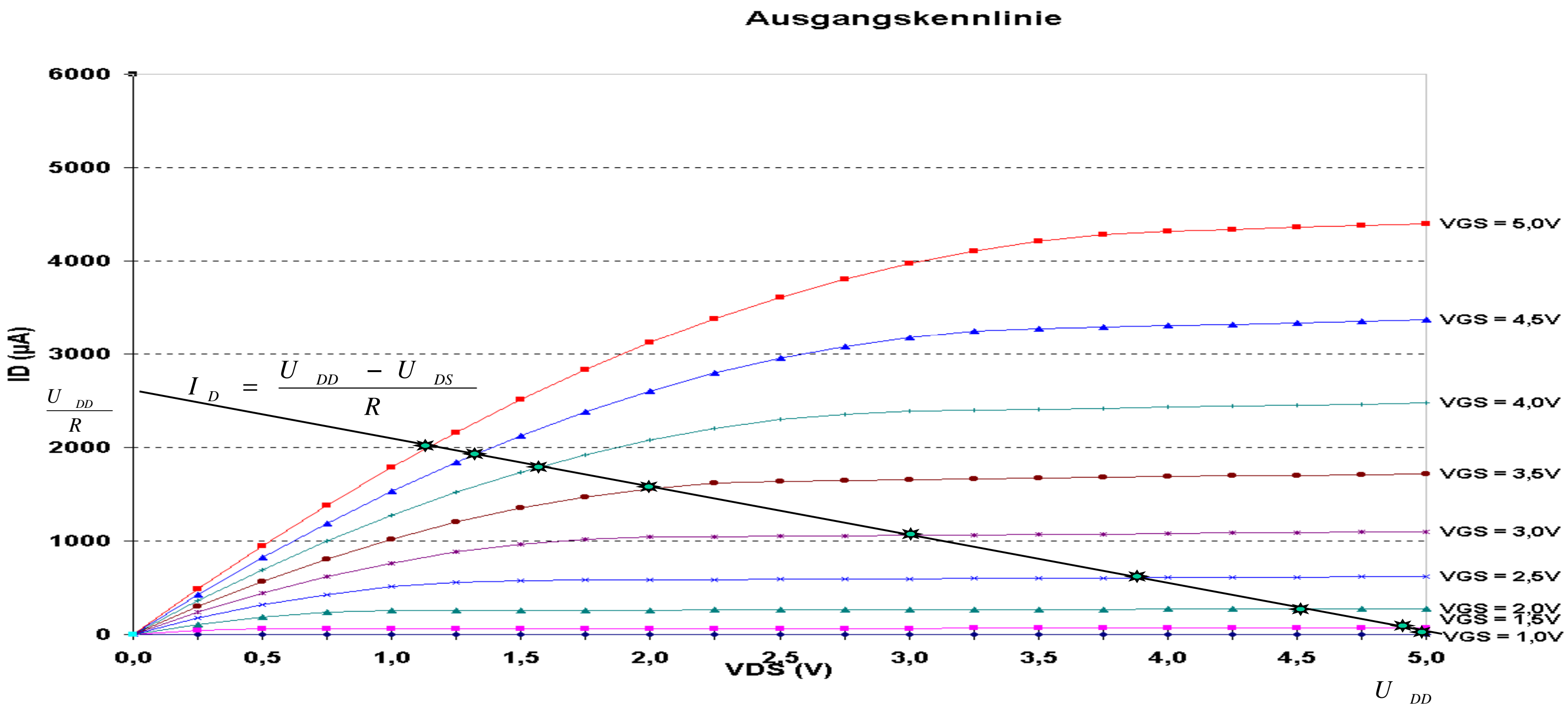
$V_R = V_{DD} - V_{DS}$



Determination of the inverter characteristic

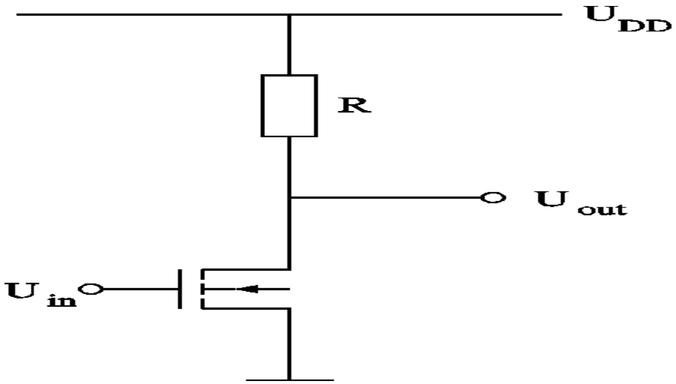


$$I_R = I_D = \frac{V_{DD} - V_{DS}}{R}$$

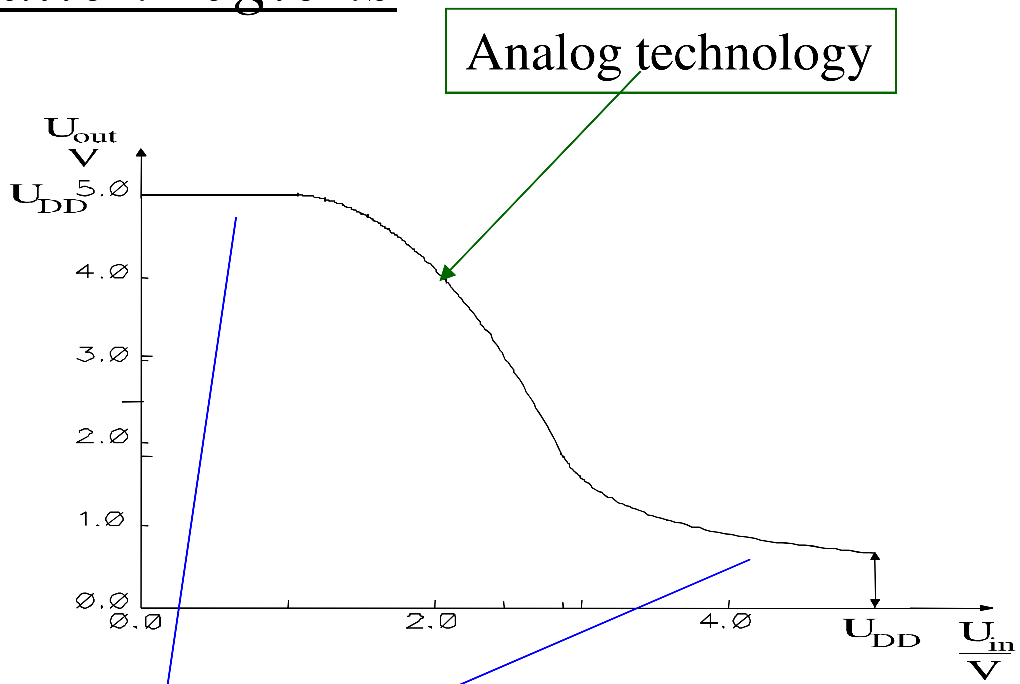


<u>Inverter transfer characteristic</u>

<u>and operation regions</u>



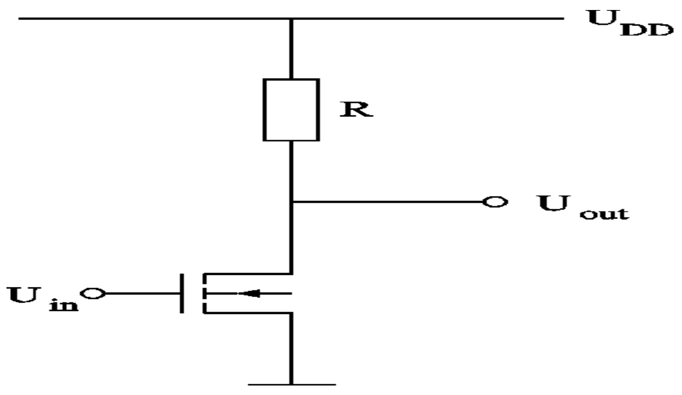
Inverter



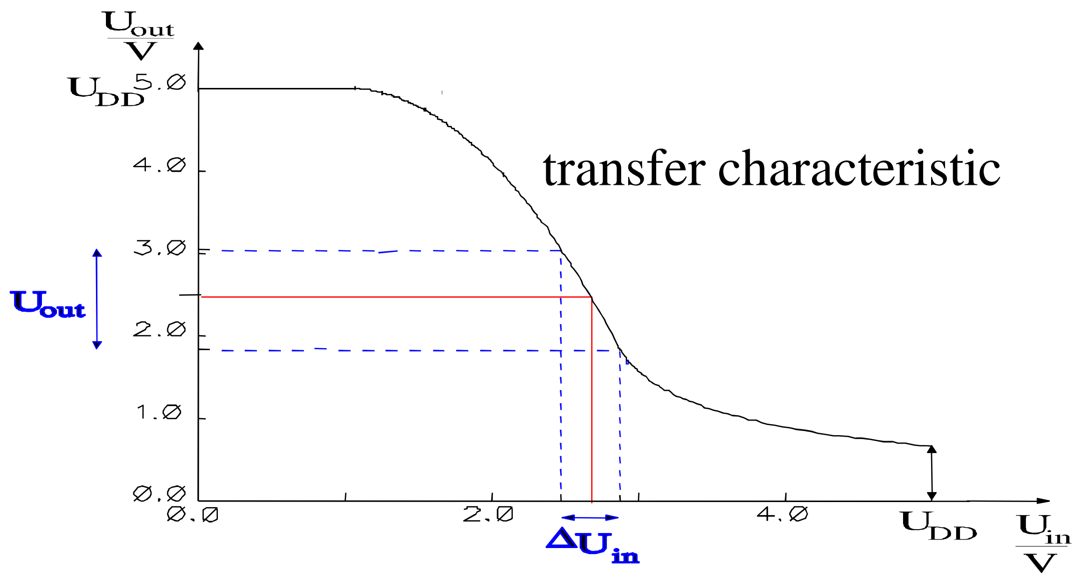
Inverter characteristic

Digital technology

Inverter Transfer Characteristic



Inverter



Large signal <> Small signal

Calculation of Operation Point

Given;

$$V_{DD} = 5V$$

$$V_T = 1V$$

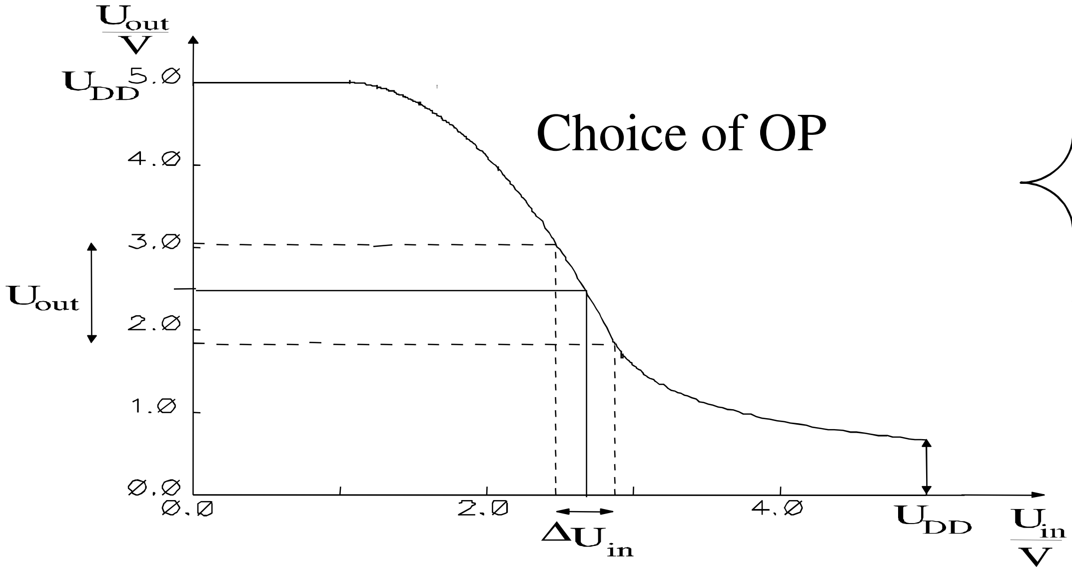
From ciurcuit

$$U_{in} = U_{GS}$$

$$U_{out} = U_{DS} = U_{DD} - I_D \cdot R$$

$$I_D = \frac{\beta}{2} \cdot (U_{GS} - U_T)^2$$

Operation point V_{in}, V_{out}, (I_D, R, W/L)



Choice of OP

$$\left\{ \begin{array}{l} U_{in} = \frac{U_{DD}}{2} = 2.5V \\ U_{out} = \frac{U_{DD}}{2} = 2.5V \\ I_R = 250\mu A \end{array} \right.$$

Dimensioning of R , W/L

$$U_{DD} - U_{Out} = I_R \cdot R$$

$$\Rightarrow \quad R = 10k\Omega$$

$$U_{GSeff} = U_{in} - U_T = 1.5V < U_{DS} = 2.5V$$

$\Rightarrow$ Transistor is in the saturation region

$$I_D = \frac{\beta}{2}(U_{GS} - U_T)^2 = 250\mu A$$

$$I_D = \frac{\beta}{2}\left(U_{GS} - U_T\right)^2 = 250\,\mu A$$

$$t_{ox} = 50\,nm$$

$$\beta_0 = \mu_n \cdot \frac{\varepsilon_{OX}}{t_{OX}} = 93,2\,\mu A/V^2$$

$$\beta = \frac{W}{L} \cdot \beta_0$$

$$\frac{W}{L} = \frac{2 \cdot I_D}{\beta_0 \cdot (U_{GS} - U_T)^2}$$

$$= \frac{2 \cdot 250\,\mu A}{93.2\,\frac{\mu A}{V^2} \cdot (1.5\,V)^2}$$

$$= 2.38$$

$$W/L = 2.38$$

Dimensioning for a 1µm-process

L=1µm W=2.38µm?

No, mask resolution were too fine

L=10µm W=23.8µm?

No, area too large

A reasonable solution:

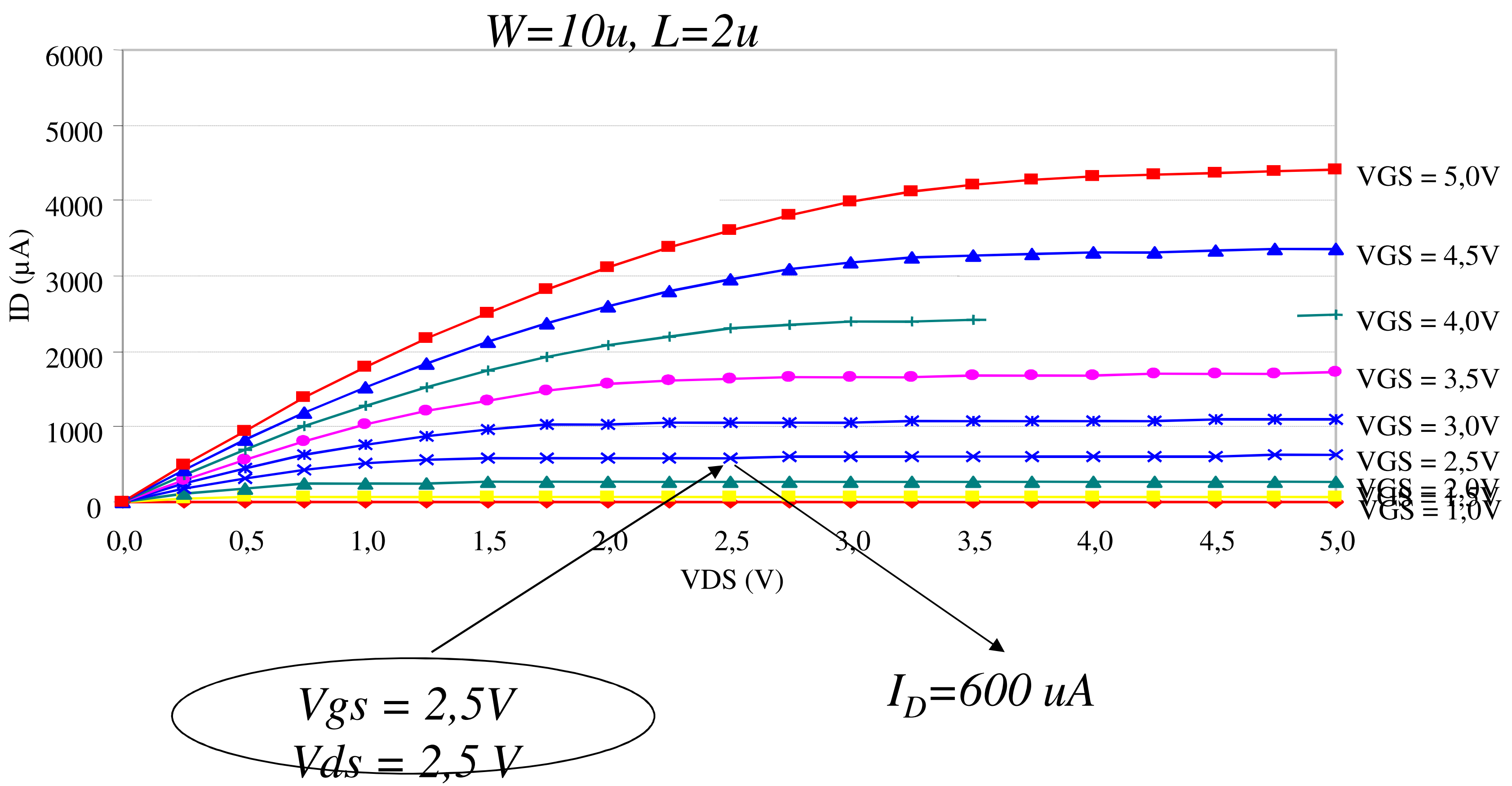
L=1µm W=2.4µm

$$W/L = 2.38$$

Realization with processes

W(µm)	L(µm)	W/L
3,5	1,5	2,33
2,4	1	2,4
1,7	0,7	2,43
1,2	0,5	2,4
0,85	0,35	2,43

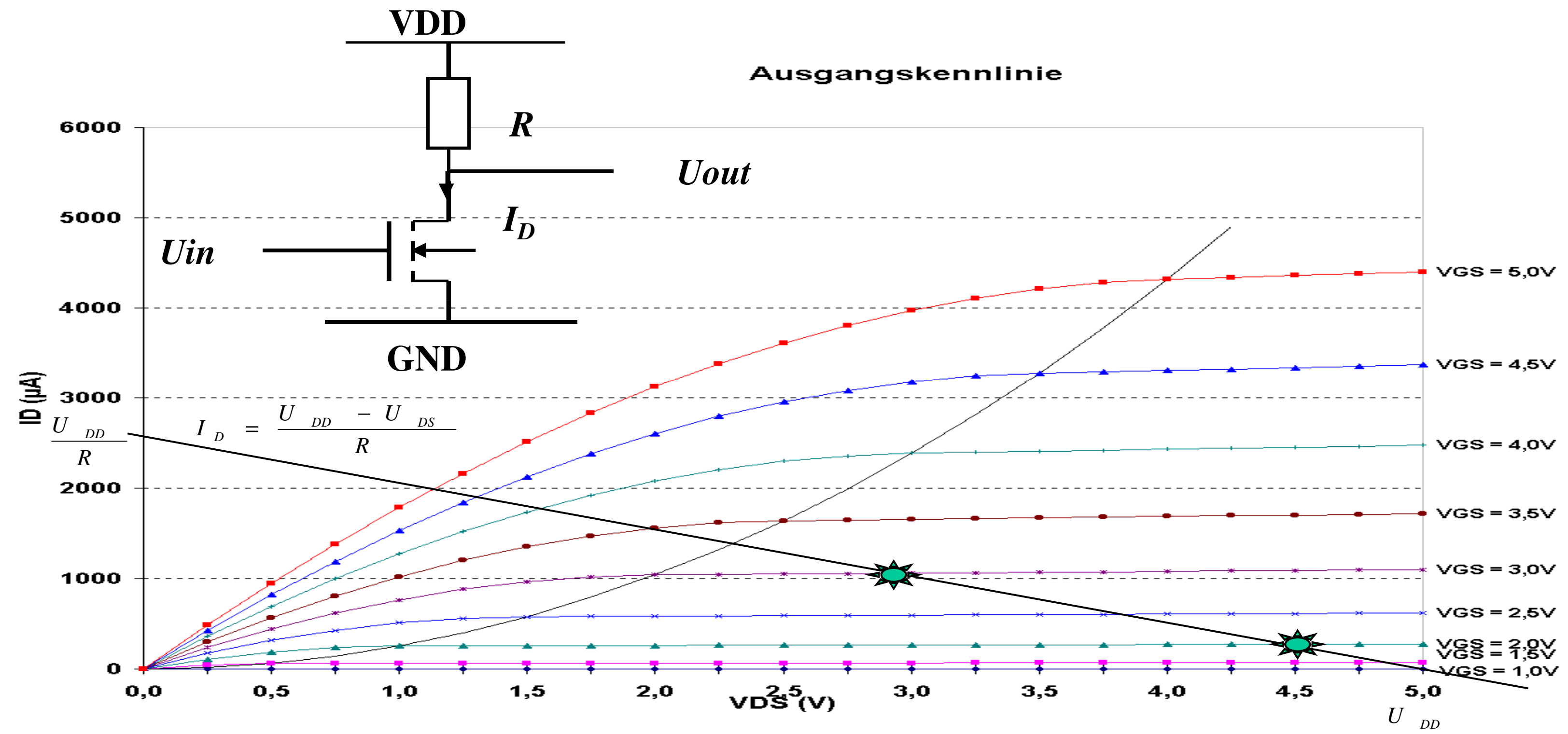
Calculation of operation point using output characteristics



Objective: $I_D = 250\ uA$

$W/L = 250\ uA / 600\ uA * 10um / 2um = 2,1$

Calculation of the gain of an inverter



$$\Delta I_D = G \cdot \Delta U_{in}$$

$$\Delta U_{out} = -R \cdot \Delta I_D$$

$$\Rightarrow \quad \Delta U_{out} = -R \cdot G \cdot \Delta U_{in}$$

$$\Delta U_{in} = \Delta U_{GS}$$

$$\Delta U_{out} = \Delta U_{DS}$$

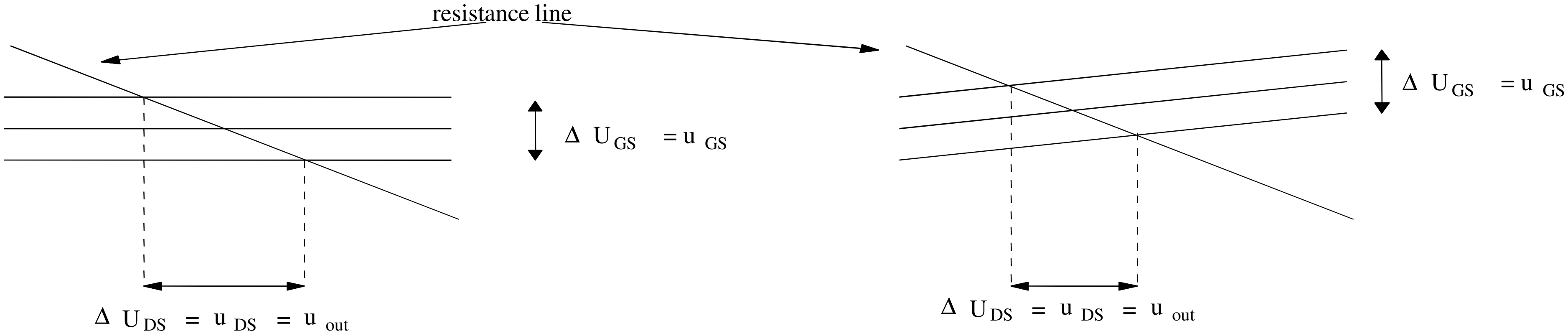
$$G = \frac{\Delta I_D}{\Delta U_{in}} = \frac{\Delta I_D}{\Delta U_{GS}}$$

$$A = \frac{\Delta U_{out}}{\Delta U_{in}} = -g_m \cdot R$$

Transition into differential $\frac{dI_D}{dU_{GS}} = g_m$

g_m is the most important parameter of MOSFET

Small signal behaviour of the MOS transistor



ideal | Non-ideal (exaggerated)

Ideal and non-ideal characteristics

Ideal:

$$I_D = \frac{\beta}{2} \cdot (U_{GS} - U_T)^2$$

$$\frac{dI_D}{dU_{DS}} = 0$$

$$\Rightarrow \quad g_{DS} = 0$$

$$\Rightarrow \quad r_{DS} = \infty$$

Non-ideal:

$$I_D = \frac{\beta}{2} \cdot (U_{GS} - U_T)^2 \cdot (1 + \lambda \cdot U_{DS})$$

$$\frac{1}{r_{DS}} = \frac{dI_D}{dU_{DS}} = \frac{1}{2} \cdot \beta \cdot (U_{GS} - U_T)^2 \cdot \lambda$$

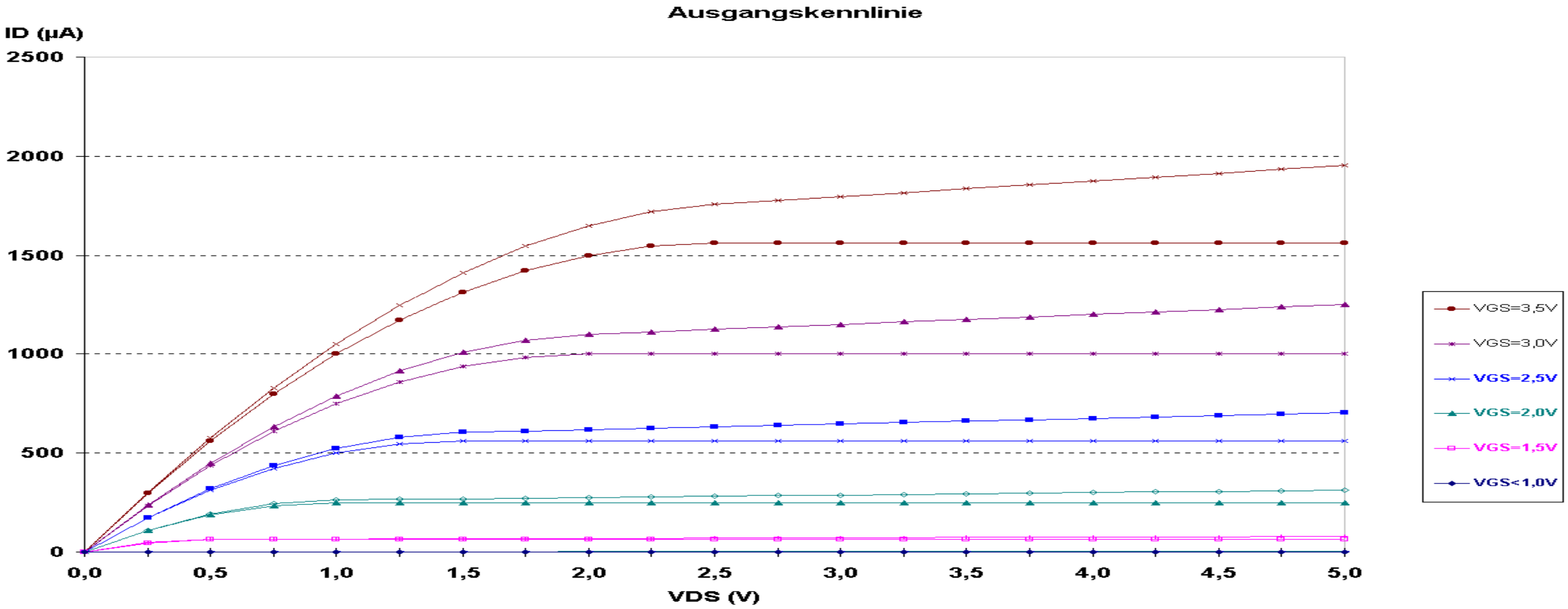
$$= I_D \cdot \frac{\lambda}{1 + \lambda \cdot U_{DS}} \approx I_D \cdot \lambda$$

$$\Rightarrow \quad g_{DS} = I_D \cdot \lambda$$

with $\lambda <<$

$$\lambda \approx 0.01 - 0.05 \ (V^{-1}) \quad @ \quad L = 10 \ \mu m$$

G_{DS} depends on the operation point

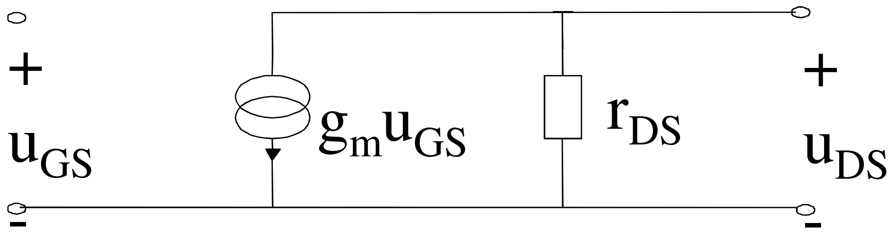


$$g_{DS} = \frac{dI_D}{dV_{DS}} = \lambda \cdot I_D$$

Or more physical

$$g_{DS} = \frac{dI_D}{dV_{DS}} = \frac{k_2 \cdot I_D}{2 \cdot L_O \cdot \sqrt{U_{DS} - U_{DSS}}}$$

Small-signal equivalent circuit



$$g_m = \frac{dI_D}{dU_{GS}} \qquad I_D = \frac{\beta}{2} \cdot (U_{GS} - U_T)^2 \cdot (1 + \lambda \cdot U_{DS})$$

$$g_m = \beta \cdot (U_{GS} - U_T) \qquad I_D = \frac{\beta}{2} \cdot (U_{GS} - U_T)^2$$

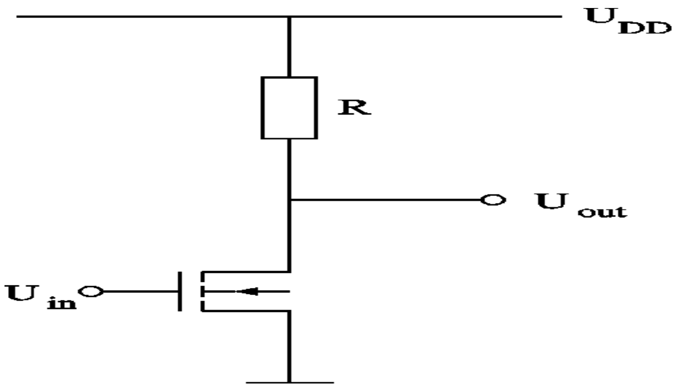
$$= \beta \cdot U_{GSeff}$$

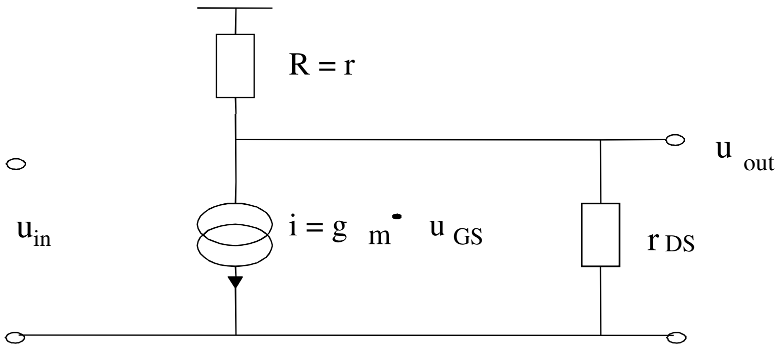
$$= \sqrt{2 \cdot I_D \cdot \beta}$$

with $\beta = \beta_0 \cdot \frac{W}{L} = \mu \cdot \frac{\varepsilon_{OX}}{t_{OX}} \cdot \frac{W}{L}$

$$g_{DS} = \frac{dI_D}{dU_{DS}} \qquad g_{DS} = I_D \cdot \lambda = \frac{1}{r_{DS}}$$

Small signal equivalent circuit of the inverter





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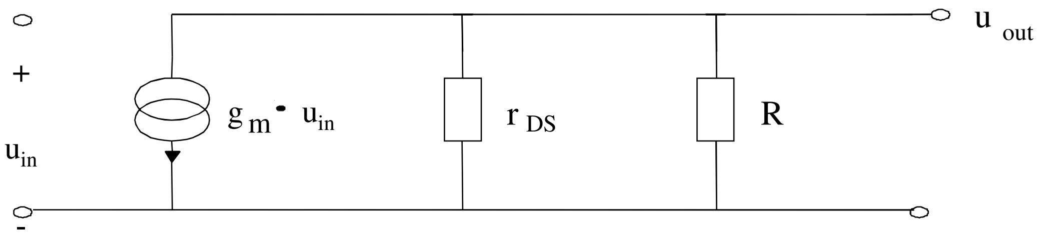


$$A = \frac{\Delta U_{out}}{\Delta U_{in}} = \frac{u_{out}}{u_{in}} = \frac{-g_m \cdot u_{in} \cdot R'}{u_{in}} = -g_m \cdot R'$$

$$g_m = \beta \cdot (U_{GS} - U_T) = \sqrt{2 \cdot I_D \cdot \beta} \qquad R' = (R \| r_{DS})$$

$$A = -g_m \cdot (R \| r_{DS})$$

Example of dimensioning

Given by process:

$$\beta_0 = \mu \cdot \frac{\varepsilon_{OX}}{t_{OX}} = \mu \cdot C'_{OX} = 93,2\ \mu A / V^2 \qquad U_{To} = 1V$$

$$\lambda = 0.02\ \frac{1}{V}$$

Chosen:

$$\frac{W}{L} = \frac{50\ \mu m}{5\ \mu m}$$

Operation point should be:

$$U_{GS} = 2V \qquad U_{DS} = 5V$$

This results in:

$$I_D = \frac{\beta}{2} \cdot (U_{GS} - U_T)^2 \cdot (1 + \lambda \cdot U_{DS}) \Rightarrow I_D \approx 510\ \mu A$$

$$g_m = \beta \cdot (U_{GS} - U_T) \cdot (1 + \lambda \cdot U_{DS}) \Rightarrow g_m \approx 1000\ \mu S$$

$$g_{DS} = I_D \cdot \lambda / (1 + \lambda \cdot U_{DS}) \Rightarrow g_{DS} = 9,3\ \mu S$$

$$r_{DS} = 110\ k\Omega$$

Gain of an inverter with resistive load:

$$R = 10\,k\Omega \qquad r_{DS} \| R = 9{,}2\,k\Omega$$

$$A = -g_m \cdot (r_{DS} \| R)$$

$$= -1000\,\mu S \cdot 9{,}2\,k\Omega$$

$$= -9{,}2$$

If the amplifier is „open“ (R=∞), the result is:

$$A = -g_m \cdot r_{DS} = -1000\,\mu S \cdot 110\,k\Omega = -110$$

Internal gain of a transistor

$$R \gg r_{DS} \quad \Rightarrow \quad A \approx -g_m \cdot r_{DS}$$

$$= -\frac{\sqrt{2 \cdot I_D \cdot \beta}}{\lambda \cdot I_D}$$

$$\boxed{A \propto -\frac{1}{\sqrt{I_D}}}$$

Dependent of operation point

A large-signal parameter which determines the small signal behaviors

Specifica of analog integrated circuit

(*compared to discrete circuit*)

- Limited isolation / limited interconnectivity due to many parasitic pn-transitions

- Large variation/scattering of component parameters (e.g.: Vt: ± 100mV, R: ± 20%)

- Limited choice of components and non-ideal components

- Matching of scattering and isotherme

- Highly developed models

- Large complexe circuit possible

Example of a tolerance calculation

Gain of an inverter

$$A \approx g_m \cdot R \approx \beta \cdot (V_{GS} - V_T) \cdot R$$

$$= \frac{W}{L} \mu_n \cdot \frac{\varepsilon_{OX}}{t_{OX}} \cdot (V_{GS} - V_T) \cdot R$$

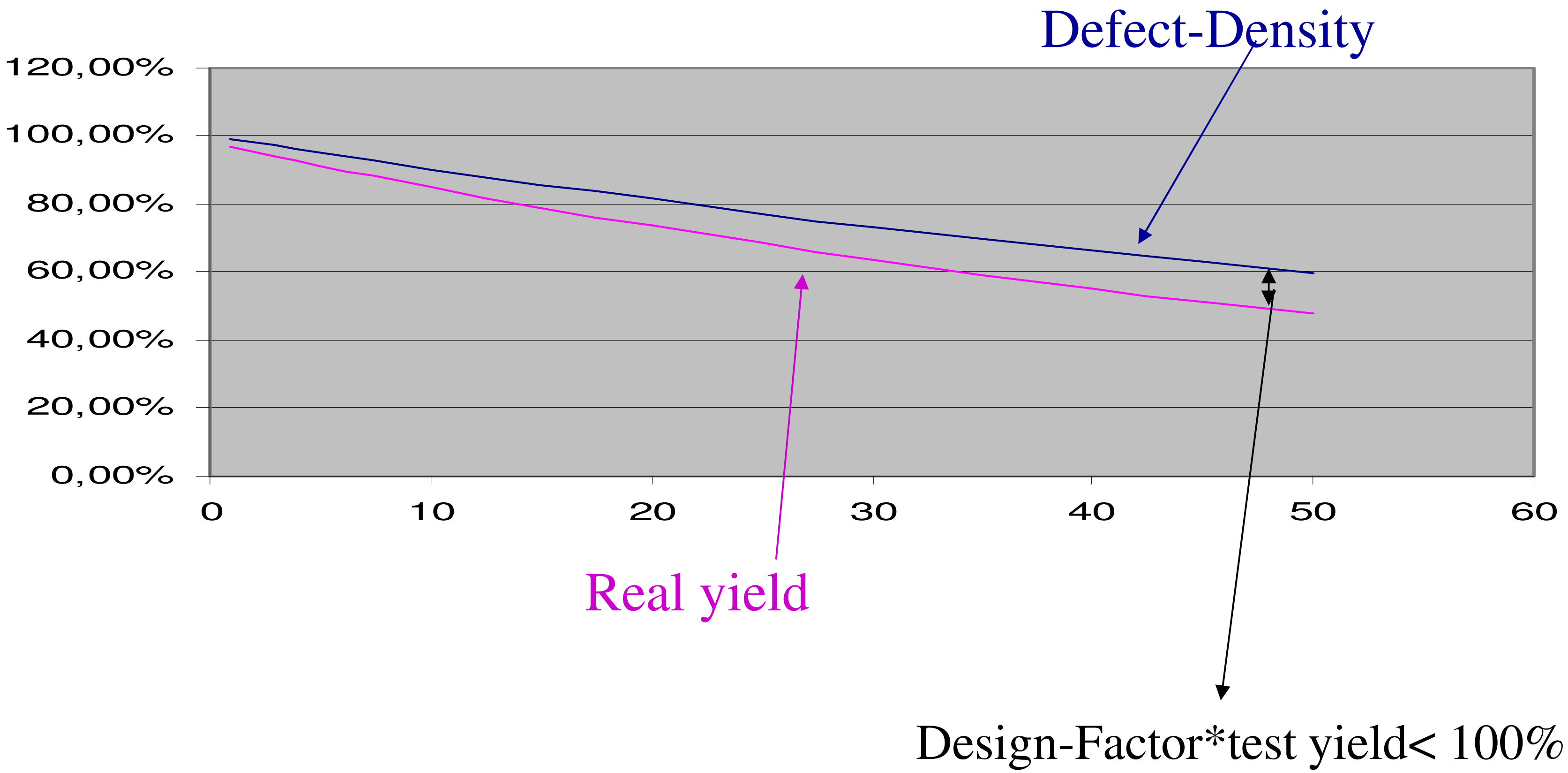
Scattering of processes:

R: ± 15%
Vt: ± 100 mV $\Rightarrow$ ± 10% bei V_{GSE} = 1 V
Tox: ± 10%

Overall Scattering

$$= \sqrt{15\%^2 + 10\%^2 + 10\%^2} > \pm 20\%$$

Yield in dependance on chip area



Yield decreases exponentially with chip area

Real yield is reduced by the design-factor and the test yield.

Method for robust design

(insensitive for sattering and allowing so high design-factor)

1. Usage of matching devices for example :

- Divider (resistor, capacity, MOS)
- Current mirror/ current source

2. Usage of larger structures and symmetric layout for critical functions

2. Bandgap voltage reference

3. Regelung instead Steuerung

4. Difference amplifier