electronics for embedded systems

mos structures
today

- basic structures  (book: ch.2)
  - mos-structures
  - the construction in process

- components in an integrated circuit  (book: ch.3)
  - resistance and capacitance
  - field effects in a mos structure
  - level-controlled switches
  - derivation of the current equation
basic structure of the mos transistor

vertically three layers:
  • metal
    (conductor, now polysilicon)
  • oxyde
    (isolator)
  • semiconductor

horizontally three regions:
  • 2 channel contacts (conductors)
  • in between the ‘channel’ (semiconductor)
cross section of an n-type mos transistor

- **aluminum for longer 'wires'**
- **thick oxide (glass) as isolation layer**

- **channel contacts:**
  - dotted silicon
  - channel forms itself under the thin oxide

- **metal conductor is polysilicon:**
  - this is the 'gate'

- **oxide isolator is a thin layer of glass**
  - siliciumoxide ('thin oxide')

- **semiconductor is silicium substrate**
principle operation of n-type transistors

at low gate voltage the switch is ‘open’ (non-conducting): there is no conducting connection between both channel contacts (the diodes “reverse biased”)
principle operation of n-type transistors

inversion:
free charge carriers form a conducting channel

at higher gate voltages the switch "closes": there is a conducting layer (the channel) under the gate.
integration of transistors

possible parasitic transistor!
prevent by 'channel-stop diffusion'
complementary technology (CMOS)
L-Edit: een inverter-layout
Press mouse to place cross section
substrate
n-well
p-implant
n-implant
ccd-implant
nnp base implant
field oxide
active area etch
gate oxide
polysilicon
not-poly etching
second field oxide
second gate oxide
second polysilicon
not-poly2 etching
first level metal
not-metall1 etching
oxide
via
second level metal
overglass
overglass
pad opening
Press any mouse-button to continue...
layout van de mos-transistor

crossing of a strip conductor material (polysilicion) and semiconductor material under thin oxyde

the layout designer only has to indicate that crossing (possibly with length / width)
Variety of MOS transistors (in a circuit)

Layer modifications (ion implantatie, well) have to be indicated!

Enhancement nmos transistor, both in nmos- and cmos technology

Depletion nmos transistor in nmos technology

PMOS transistor in complementary technology

Green line may never cross the black dashed line
line diagrams

layer indicated by a color code

green: diffusion (thin oxide)
red: polysilicon
blue: metal

intersection of lines of the same color indicates connection.

intersection of lines of different color indicates no interaction, except with green and red (transistor)

for a connection between different layers one has to indicate a contact hole:
line diagram of an inverter 1
field effects in a mos structure

decreasing $v_{gb}$ makes “holes” move to the surface to compensate charge at the gate: “accumulation”

increasing $v_{gb}$ makes “holes” move away from the surface leaving negative charged ionen: “depletion”

$C_{acc} > C_{depl}$

these are “free” carriers (charge can move)

no free “carriers” (no conduction!)
elektrostatics van depletion

in a homogeneous elektrostatic field: \( E(z) = -\frac{d\phi}{dz} \) and \( \frac{dE}{dz} = \frac{\rho}{\varepsilon} \)

\( \phi_g \)

\( \phi_o \)

\( \phi_b \)

\(-D < z < 0 \)

\( \rho = 0 \)

\( E = E_{ox} \)

\( 0 < z < d_{dep} \)

\( \rho = -qN_A \)

\( \frac{dE}{dz} = -\frac{qN_A}{\varepsilon_o \varepsilon_{si}} \)

\( z > d_{dep} \)

\( \rho = 0 \)

\( E = 0 \)

the potential variation over the "depletion region" \( (0 < z < d_{dep}) \)
satisfies the one-dimensional poisson equation:

with constraints

\[ \left( \frac{d\phi}{dz} \right)_o = E_{ox} \]

\[ E(d_{dep}) = - \left( \frac{d\phi}{dz} \right)_{d_{dep}} = 0 \]

\[ \phi(0) = \phi_o \]

\[ \phi(d_{dep}) = \phi_b \]
**depletion depth**

**Poisson equation**
\[
\frac{d^2 \phi}{dz^2} = K_0 - \frac{qN_A}{\varepsilon_0 \varepsilon_{Si}}
\]

**Constraints**
\[
E(d_{dep}) = -\left(\frac{d\phi}{dz}\right)_{d_{dep}} = 0
\]
\[
\phi(0) = \phi_o
\]
\[
\phi(d_{dep}) = \phi_b
\]

\[
\frac{d\phi}{dz} = -E(z) = K_o z + K_1
\]

\[
\phi(z) = \frac{1}{2}K_0 z^2 + K_1 z + K_2
\]

\[
E(d_{dep}) = -K_0 d_{dep} - K_1 = 0
\]

\[
\rightarrow K_1 = -K_0 d_{dep}
\]

\[
E(z) = K_0 (d_{dep} - z)
\]

\[
\phi(z) = \frac{1}{2}K_0 z^2 - K_0 d_{dep} z + K_2
\]

\[
\phi(0) = K_2 = \phi_o
\]

\[
\phi(z) - \phi_b = \frac{1}{2}K_0 z^2 - 2z\sqrt{\frac{K_0}{2}\phi_o - \phi_b} + \phi_o - \phi_b =
\]
\[
= \left(z\sqrt{\frac{K_0}{2} - \phi_o - \phi_b}\right)^2
\]

Remark:
\[\phi_o\] is not explicitly available

\[
d_{dep} = \sqrt{\frac{\phi_o - \phi_b}{K_0}}
\]

\[
\phi(d_{dep}) = \frac{1}{2}K_0 d_{dep}^2 - K_0 d_{dep}^2 + \phi_o = \phi_b
\]
elimination of the surface potential

\[ d_{\text{dep}} = \sqrt{\frac{2(\phi_o - \phi_b)}{K_o}} \], but \( \phi_o \) is a dependent variable

\[ v_{\text{gb}} \] is equal to the sum of the potential differences over the MOS structure

- over oxide: \( E_{ox}D \)
- over depletion region: \( \phi_o - \phi_b \)
- contact potentials
- charges in the oxide

flat-band voltage

Kirchhoff voltage law: boundary condition (Gauss' law):

Poisson solution:

\[ v_{\text{gb}} = E_{ox}D + \phi_o - \phi_b \]

\[ \varepsilon_{ox}E_{ox} = \varepsilon_{Si}E(0) \]

\[ E(0) = K_o d_{\text{dep}} = \sqrt{2K_o(\phi_o - \phi_b)} \]

\[ \gamma = \frac{\varepsilon_{si}D\sqrt{2K_o}}{\varepsilon_{ox}} = \frac{D\sqrt{2\varepsilon_o\varepsilon_{si}qN_A}}{\varepsilon_0\varepsilon_{ox}} \]

\( \gamma \), the "body-factor", is a process constant
inversion (p-type bulk)

- if the surface voltage is "high enough"
  then free electrons are being attracted
- these minority charge carriers are then the majority
- at the surface the semiconductor seems to be "inverted"
- this happens at $\phi_o - \phi_b = V_i$, the "inversion voltage", a process constant

\[
\max\{d_{dep}\} = \frac{2V_i}{K_o}
\]

for $\phi_o - \phi_b > V_i$:
- depletion depth stays constant
- additional charge compensation by free electrons at the surface
- electrons at the surface do not have a big recombination probability

Attention! free electrons come available in a slow generation process

$(\tau \approx 0.1 - 0.01 \text{ sec})$
realisation of de level-controlled switch

required: a level-controlled switch, that is:
\[ v_g > v_t \rightarrow \text{free charge carriers between } s \text{ en } d \rightarrow R_{sd} \text{ is small} \]
\[ v_g < v_t \rightarrow \text{no free charge carriers between } s \text{ en } d \rightarrow R_{sd} \text{ is large} \]

observation: mos-capacitance:
\[ v_g > v_t : \text{inversion} \]
even the number of carriers can be controlled by \( v_g \)!

question:
what do the holes do, certainly in accumulation? \( v_b \) at the lowest potential! \( \rightarrow \)
p-n-junctions always reverse biased!

conclusion: \( v_g \) high enough: good conduction
\[ v_g \] low enough: no conduction

[Lilienfeld, 1935]
mos structure with channel contact

channel contact acts as a reservoir for free electrons
therefore, quick supply of electrons with increase of $v_{gb}$ after inversion

inversion occurs when the surface voltage is $V_i$ higher than $\phi_b$

$$d_{dep} = \sqrt{\frac{2\varepsilon_0 \varepsilon_{si} V_i}{qN_A}}$$

inversion occurs when the surface voltage is $V_i$ higher than $\phi_b$

$$d_{dep} = \sqrt{\frac{2\varepsilon_0 \varepsilon_{si} V_i}{qN_A}}$$

inversion only occurs when $v_{sb}$ is compensated

$$d_{dep} = \sqrt{\frac{2\varepsilon_0 \varepsilon_{si} (V_i + v_{sb})}{qN_A}}$$
threshold voltage

the threshold voltage \( v_t \) is the voltage difference between the gate and the channel contacts (\( v_{gs} \)) at which a conducting channel start to exist!

- in depletion \( (\phi_o - \phi_b < V_i + v_{sb}) \)
  we have:
  \[
v_{gb} = v_{gs} + v_{sb} = \gamma \sqrt{\phi_o - \phi_b + \phi_o - \phi_b + V_{fb}}
  \]

- inversion is reached when \( (\phi_o - \phi_b := V_i + v_{sb}) \)
  \[
v_{gb} = v_{gs} + v_{sb} = \gamma \sqrt{V_i + v_{sb} + V_i + v_{sb} + V_{fb}}
  \]

\[
\begin{align*}
v_t &= \gamma \sqrt{V_i + v_{sb} + V_i + V_{fb}} \\
v_{to} &= v_t(v_{sb} = 0) = \gamma \sqrt{V_i} + V_i + V_{fb}
\end{align*}
\] \[
\left\{ \begin{array}{c}
v_t = v_{to} + \gamma \left( \sqrt{V_i + v_{sb}} - \sqrt{V_i} \right) \\
"\text{"body-effect}"
\end{array} \right\}
\]

if \( v_{gs} > v_t \)
then there is per unit of surface \( -\frac{\varepsilon_o \varepsilon_{ox}}{D} (v_{gs} - v_t) \) of free charge
crossing time in an inverted channel

average \[ \langle v_{gx} \rangle = v_{gs} - \frac{1}{2} v_{ds} \]
channel is inverted if \( v_{gd} > v_t \)
then free charge in the channel
\[ Q = \frac{e_o e_{ox}}{D} W \cdot L \left[ \langle v_{gx} \rangle - v_t \right] \]
speed of an electron: \( u = \mu_n E_x \)
\( \mu_n \) (= "mobility" of electrons at the surface)
suppose \( E_x \) and \( \mu_n \) are constant,
then is the time to cross the channel
\[ \tau = \frac{L}{u} = \frac{L}{\mu_n E_x} = \frac{L}{\mu_n v_{ds}} = \frac{L}{\mu_n v_{ds}} \]
current in an inverted channel, \( v_{gd} > v_t \)

\[
\tau = \frac{L^2}{\mu_n V_{ds}}
\]

\[
Q = \frac{\varepsilon_0 \varepsilon_{ox}}{D} W \cdot L \left[ v_{gx} - v_t \right]
\]

\[
\langle v_{gx} \rangle = v_{gs} - \frac{1}{2} V_{ds}
\]

\[
i_{ds} = \frac{Q}{\tau}
\]

\[
i_{ds} = \frac{\varepsilon_0 \varepsilon_{ox} W \cdot L \left( v_{gx} - v_t \right)}{L^2} = \frac{\varepsilon_0 \varepsilon_{ox} W \cdot L \left( v_{gs} - \frac{1}{2} V_{ds} - v_t \right)}{L^2} = \frac{\varepsilon_0 \varepsilon_{ox} \mu_n W}{L} \left[ \left( v_{gs} - v_t \right) V_{ds} - \frac{1}{2} V_{ds}^2 \right]
\]

\[
\beta = \frac{\varepsilon_0 \varepsilon_{ox} \mu_n}{D} \frac{W}{L} = K \frac{W}{L}
\]

is the current in an inverted channel \( (v_{gd} > v_t) \)

\[
i_{ds} = \beta \left[ (v_{gs} - v_t) V_{ds} - \frac{1}{2} V_{ds}^2 \right] = \frac{1}{2} \beta \left[ (v_{gs} - v_t)^2 - (v_{gd} - v_t)^2 \right]
\]

\[
V_{ds} = V_{gs} - V_{gd}
\]
the transistor in saturation ($v_{gs} > v_t > v_{gd}$)

if $v_{gd} = v_t$:
$$i_{ds} = \frac{1}{2} \beta(v_{gs} - v_t)^2 = \frac{1}{2} \beta v_{ds}^2$$

what happens if $v_{gd} < v_t$? (but $v_{gs} > v_t$)

experiment:
$$\beta((v_{gs} - v_t)v_{ds} - \frac{1}{2}v_{ds}^2)$$

$[v_{gs} = \text{constant}]$

no inversion
in the book:

\[ V_i = -2\Phi F \]