Beyond classical circuit design
lecture 7

Gate internals continued

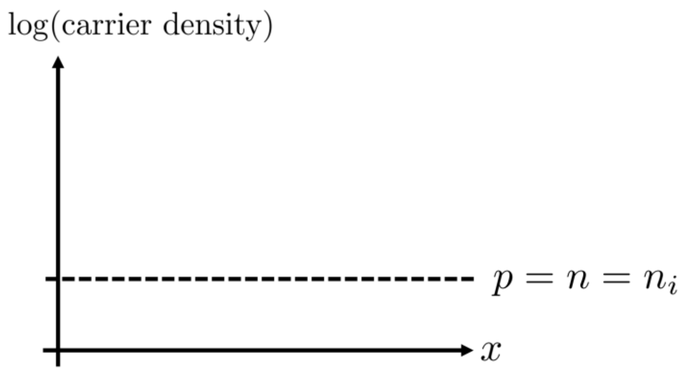
Further Reading

Simon M. Sze, Kwok K. Ng: *Physics of Semiconductor Devices. 3rd edition.* Wiley, 2006.

Jan M. Rabaey, Anantha Chandrakasan, Borivoje Nikolic: *Digital Integrated Circuits. A Design Perspective. 2nd edition.* Prentice Hall, 2003.

Carrier densities

semiconductor at thermal equilibrium



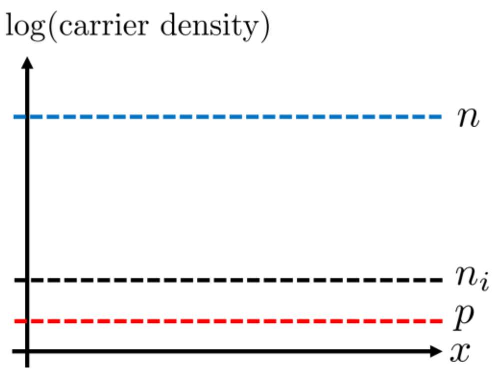
p = density of free h+
n = density of free e-

Carrier densities

adding donor atoms -> n-doped semiconductor

-> free e-

n



mass-action law

$$pn = n_i^2$$

charge neutrality

$$n + N_A^- = p + N_D^+$$

Si: has 4 valence e-
in a crystal, all 4 bond with neighboring Si e-

donor atom: has 5 valence e- ->
one is free when four bond to neighboring Si-atom e-
in this state: atom is uncharged.
if the free e- moves, the donor atom becomes charged with +q.

acceptor atom: has 4 valence e- ->
needs one more to bond with all four Si neighbors
in this state: uncharged.
the missing e- needed to bond to one of the four Si can be
spent from a neighboring Si atom -> the acceptor now has charge –q
and the place where the e- is from has a hole with charge +q

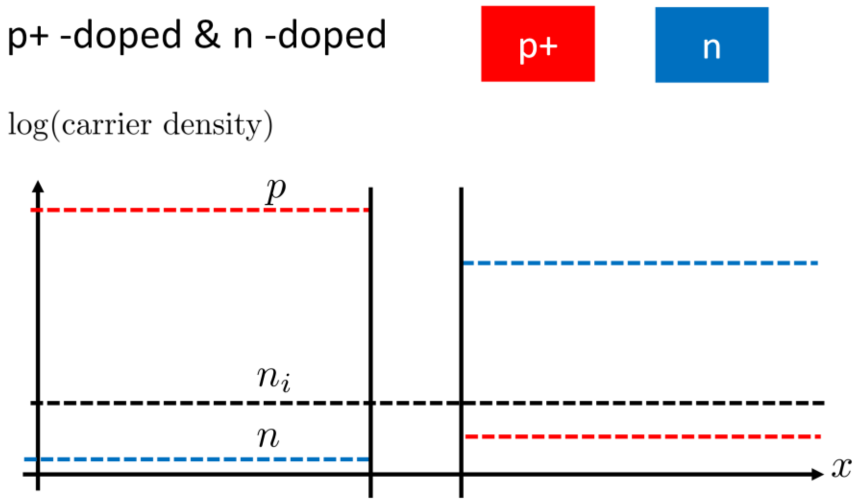
within the crystal: charge neutrality has to hold.

N_A = density of acceptor atoms (both charged or uncharged)
N_D = density of donor atoms (both charged or uncharged)

N_A^- = density of acceptor ions without h+ (-> these are negatively charged)
N_D^+ = density of donor ions without e- (-> these are positively charged)

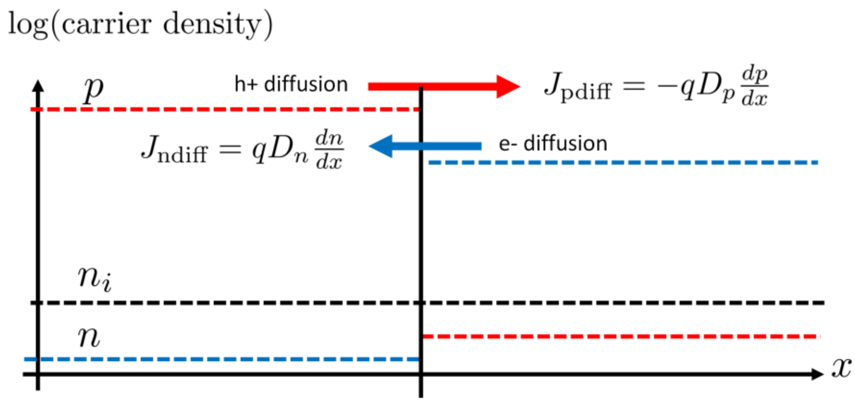
Carrier densities

p+ -doped & n -doped



Diffusion

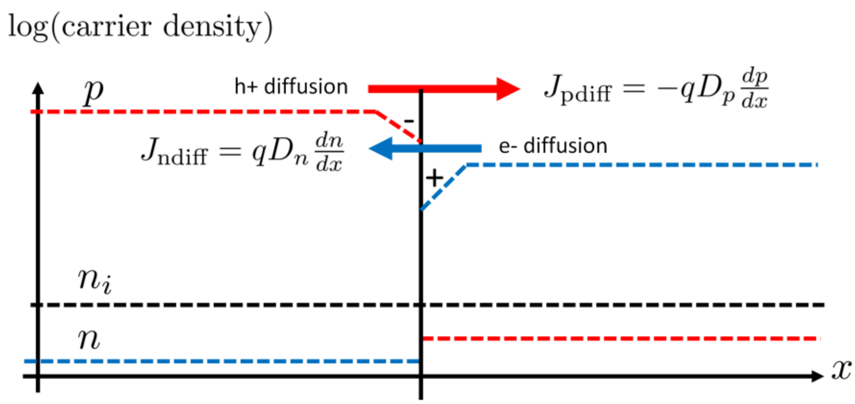
merging p+ -doped & n -doped



diffusion: because of different concentrations -> concentrations try to establish equilibrium in concentrations on both sides -> diffusion current.

Diffusion

merging p+ -doped & n -doped

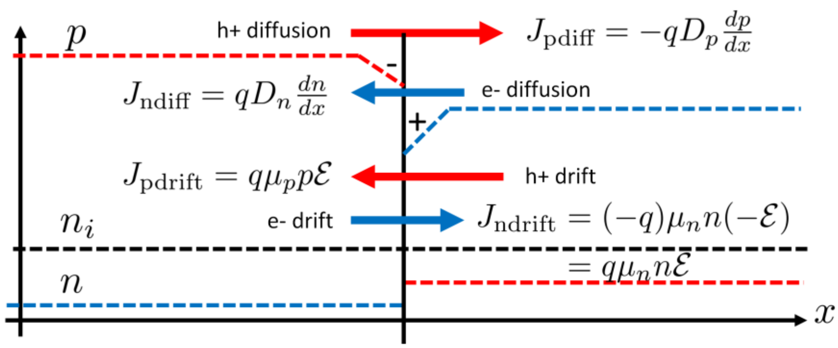


note: the donor and acceptor ions cannot move. They remain, but now are charged since e- is missing or extra (= hole missing)

Drift

merging p+ -doped & n -doped

log(carrier density)



Mind: all currents with respect to “->” direction.
A left arrow means that the current is negative.

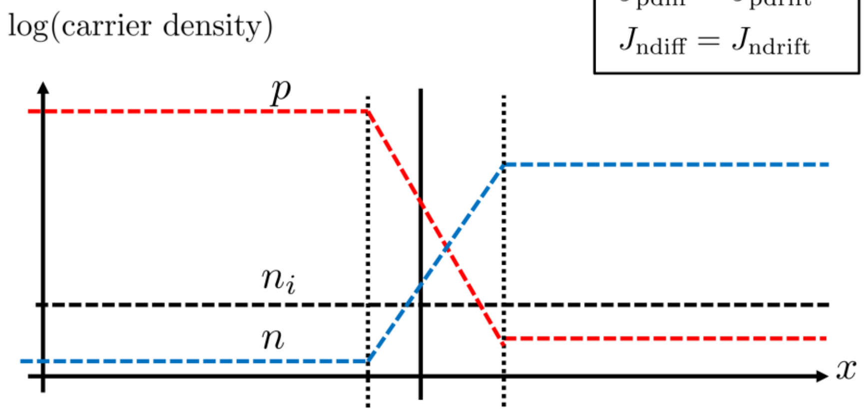
Equilibrium carrier densities

merging p+ -doped & n -doped

equilibrium

$J_{\text{pdiff}} = J_{\text{pdrift}}$

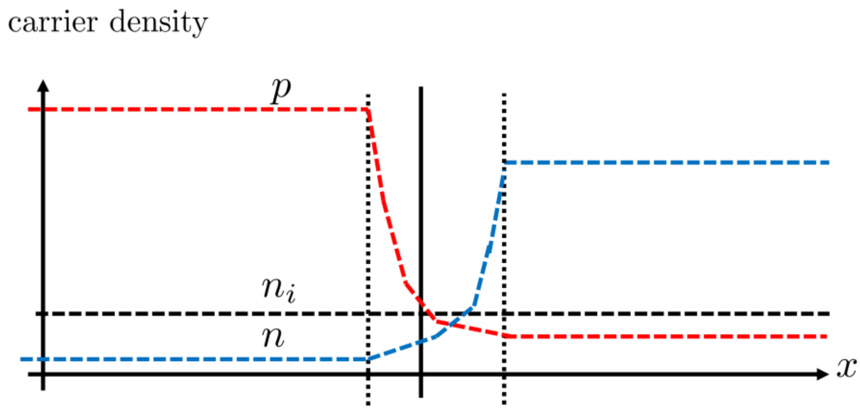
$J_{\text{ndiff}} = J_{\text{ndrift}}$



logarithmic carrier density scale. Mind: this is not a linear concentrations decrease!

Carrier densities

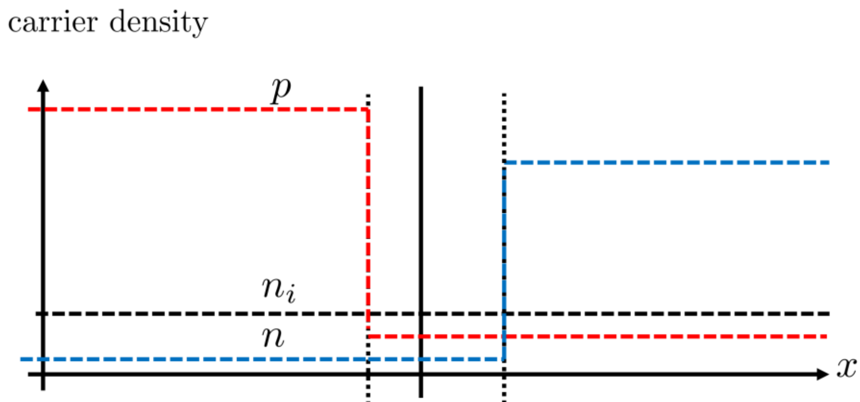
merging p+ -doped & n -doped



it is exponential as seen with linear carrier density scale.

Carrier densities

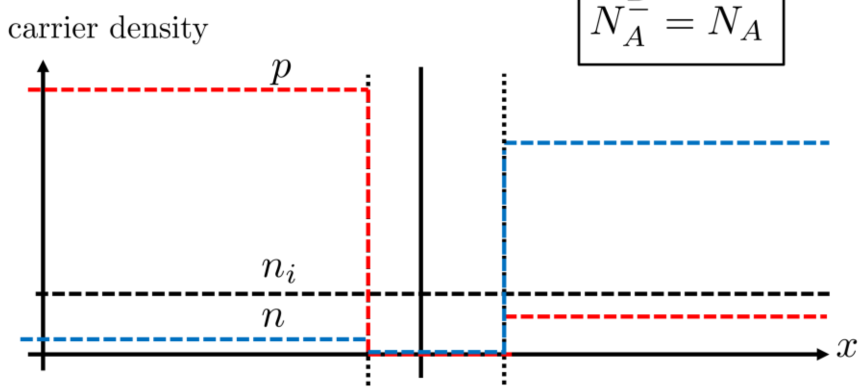
A1. box profile approximation



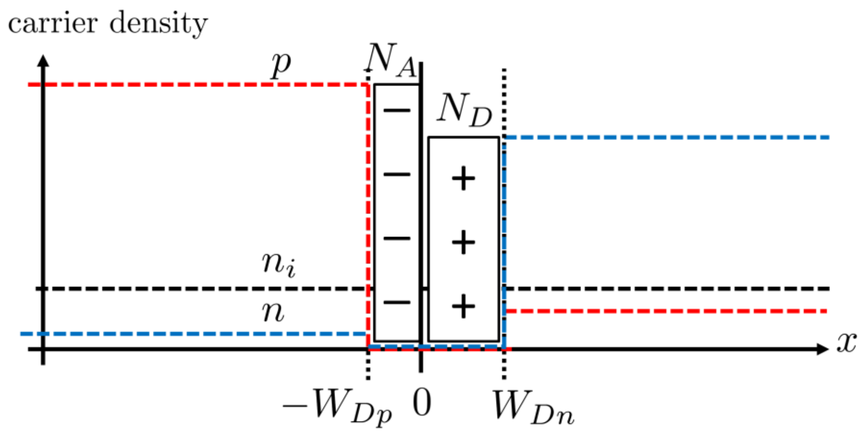
Carrier densities

A2. depletion region: no free carriers $n = p = 0$

A3. all donors/acceptors ionized $N_D^+ = N_D$, $N_A^- = N_A$

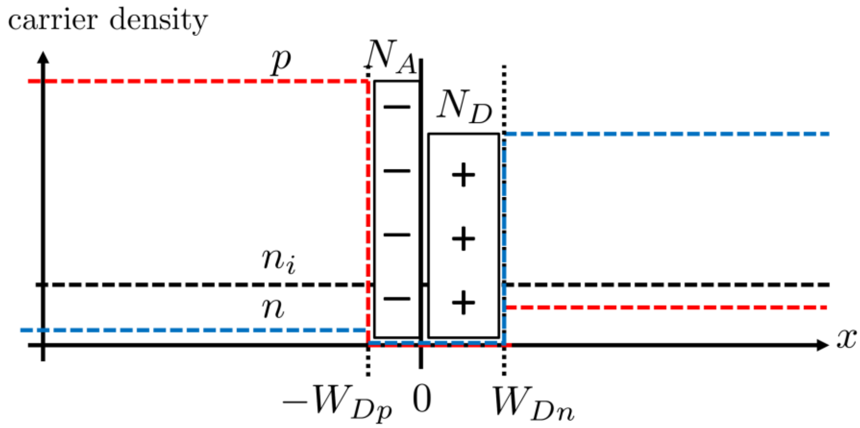


Carrier densities

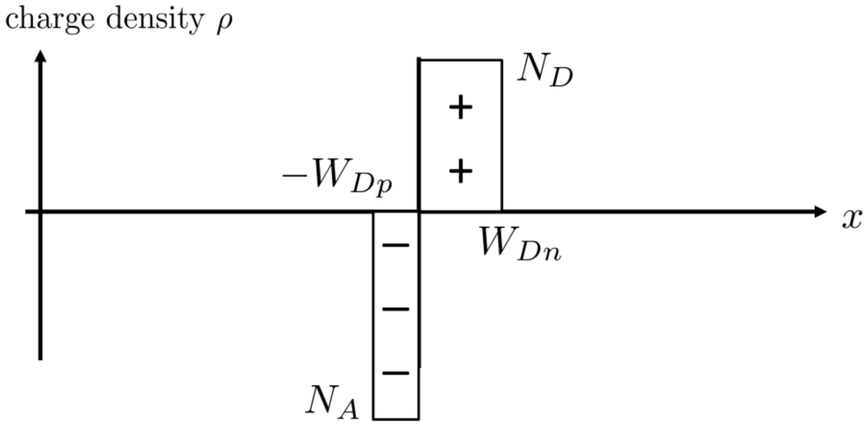


Carrier densities

neutrality $N_D W_{Dn} = N_A W_{Dp}$

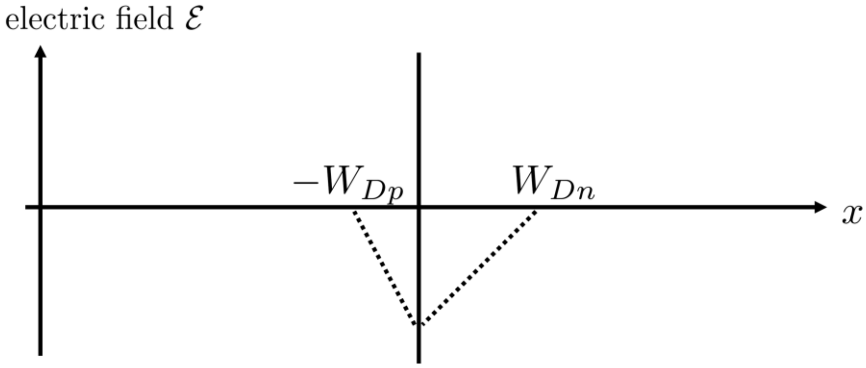


Charge density



from Poisson $\frac{d\mathcal{E}}{dx} = \frac{\rho(x)}{\varepsilon_S}$

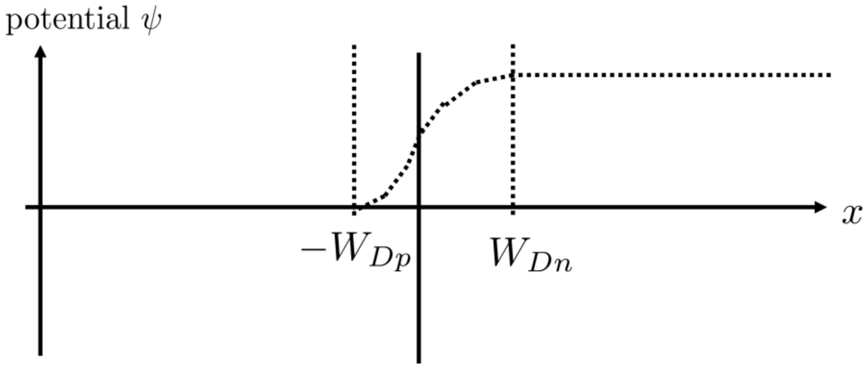
Electric field



from Poisson $\frac{d\mathcal{E}}{dx} = \frac{\rho(x)}{\varepsilon_S}$

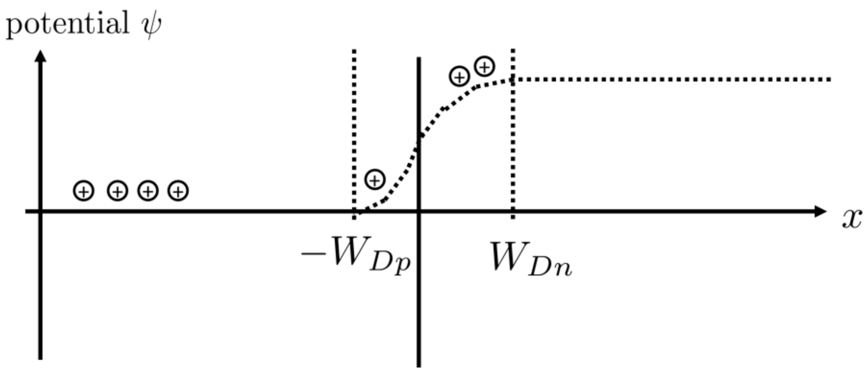
electric field induces a force on carriers. a positive carrier like a h+ is pushed to the left by a negative electric field.

Potential



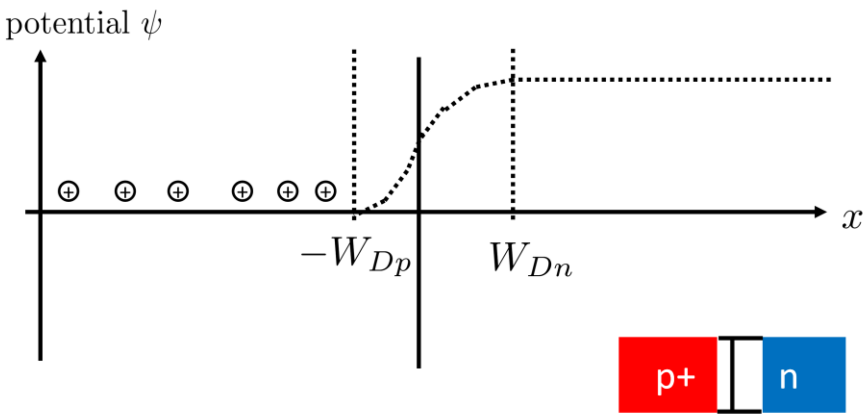
from Poisson $\frac{d\psi}{dx} = -\mathcal{E}(x)$

Potential



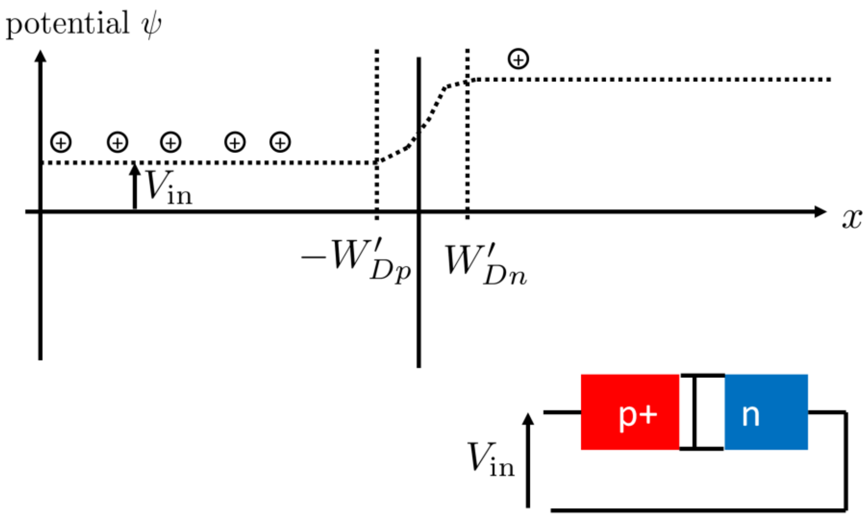
from Poisson $\frac{d\psi}{dx} = -\mathcal{E}(x)$

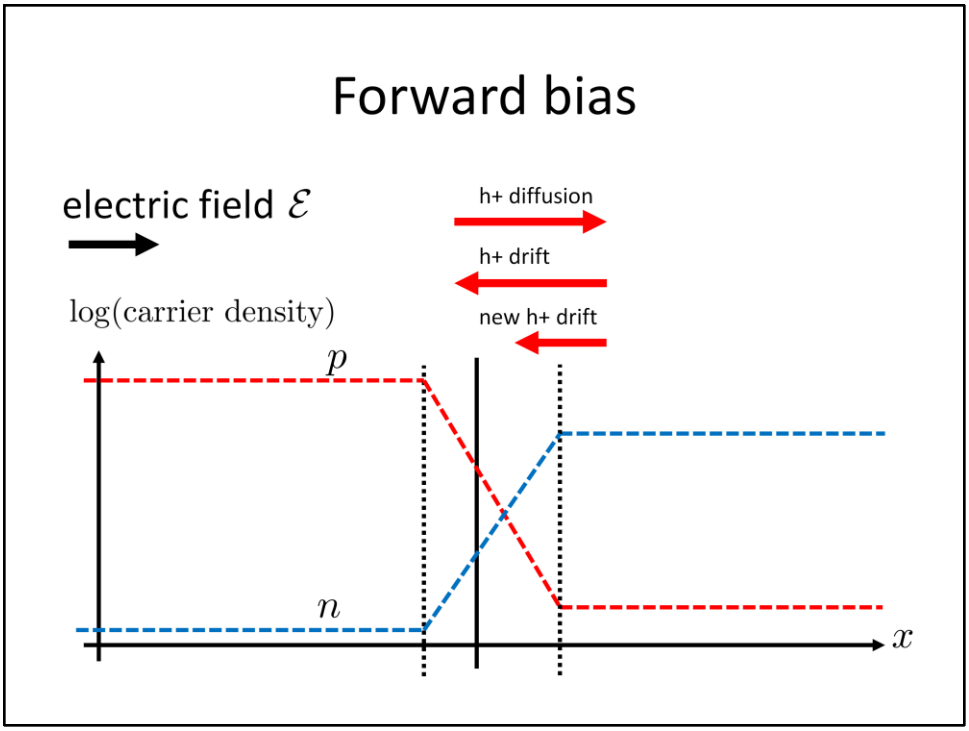
Potential



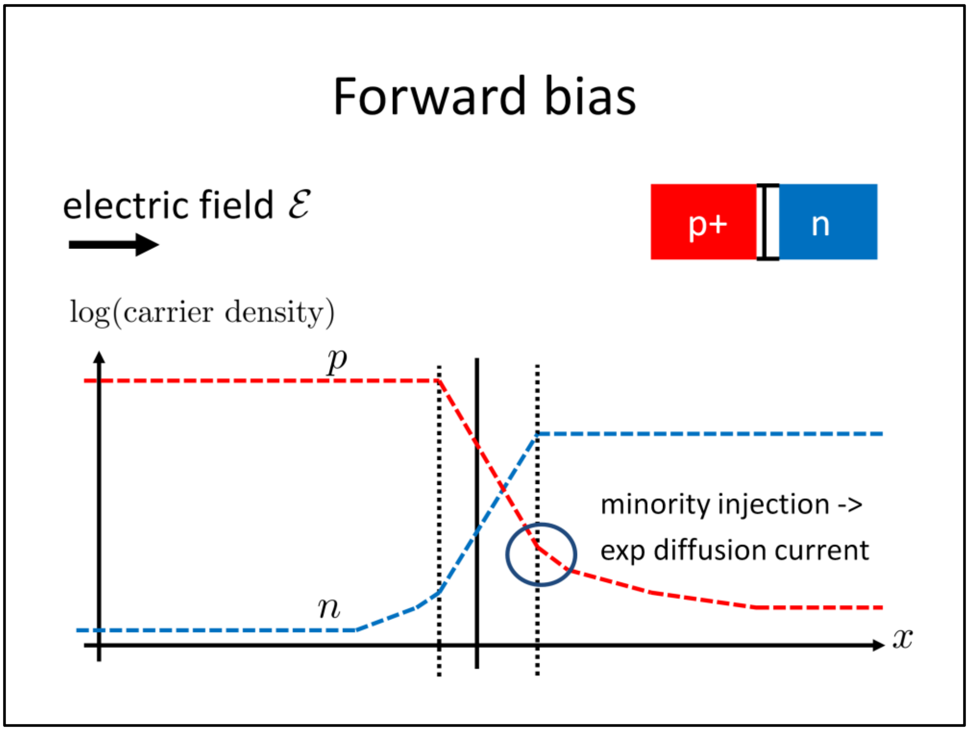
from Poisson $\frac{d\psi}{dx} = -\mathcal{E}(x)$

Decrease barrier





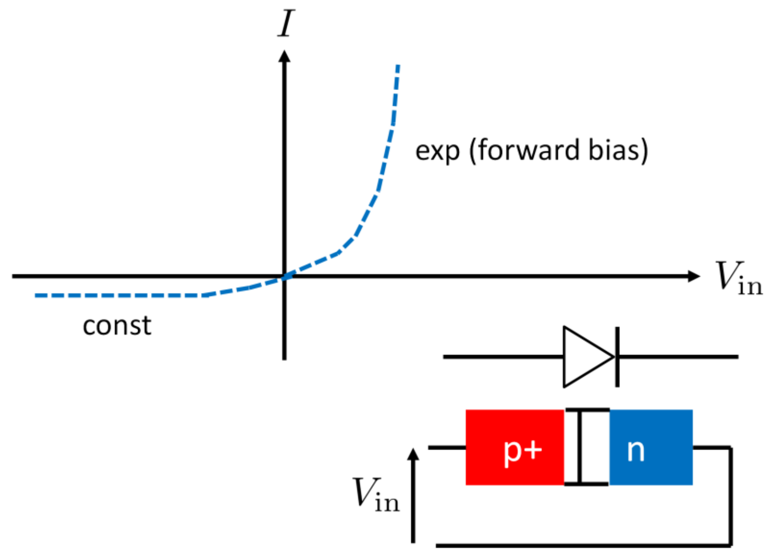
Forward bias
electric field $\mathcal{E}$
h+ diffusion
h+ drift
new h+ drift
log(carrier density)
p
n
x



electric field -> more h+ make it to the other side of the depletion region ("minority injection")

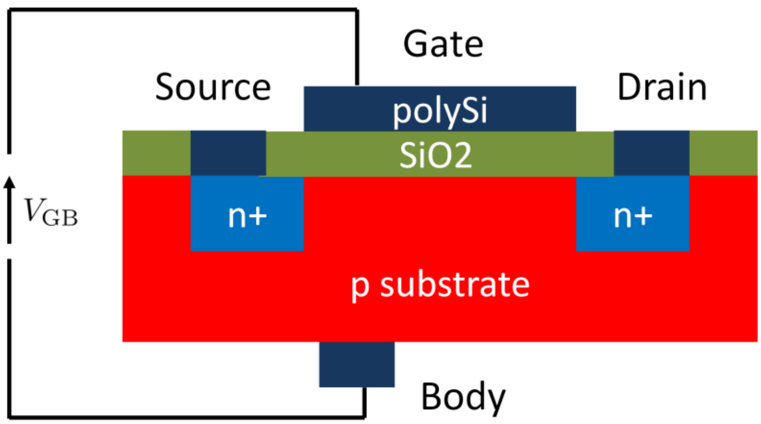
from the amount of minority injection one can calculate the current through the depletion region ->
we obtain the current through the pn junction.

pn-junction current



MOSFET

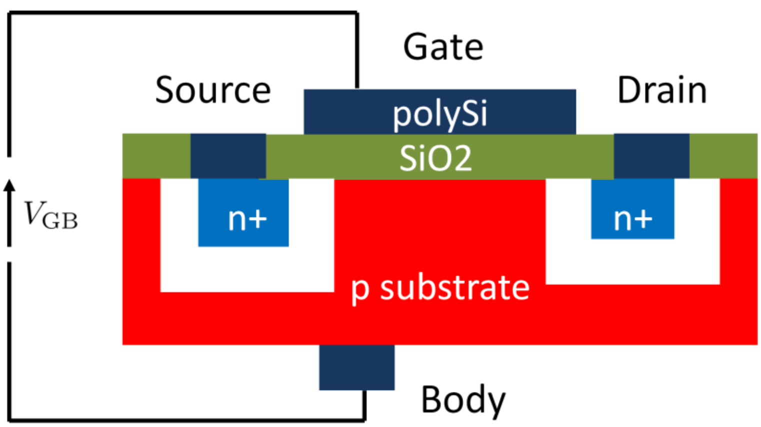
n (channel) MOSFET



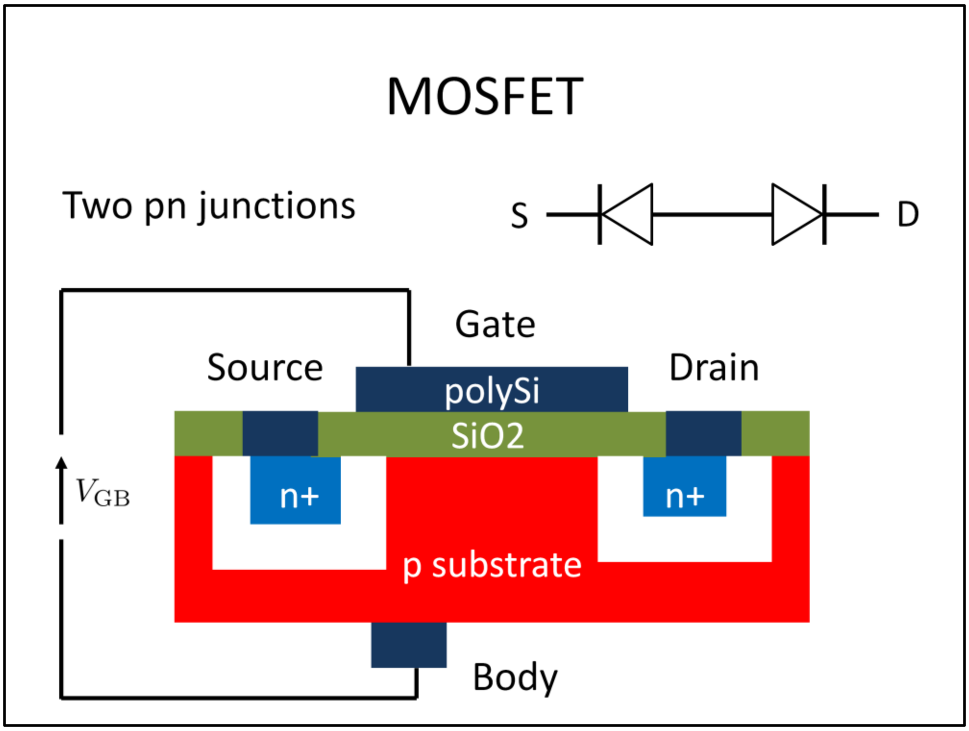
SiO2: dielectric
polySi: contacts

MOSFET

Two pn junctions



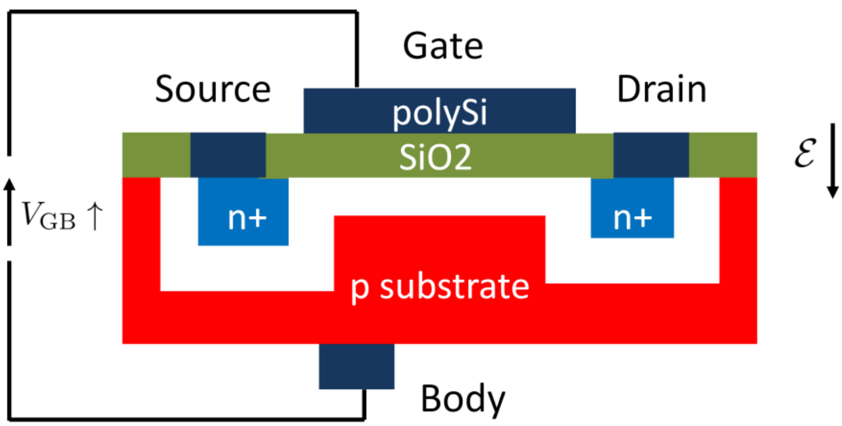
white: depletion region



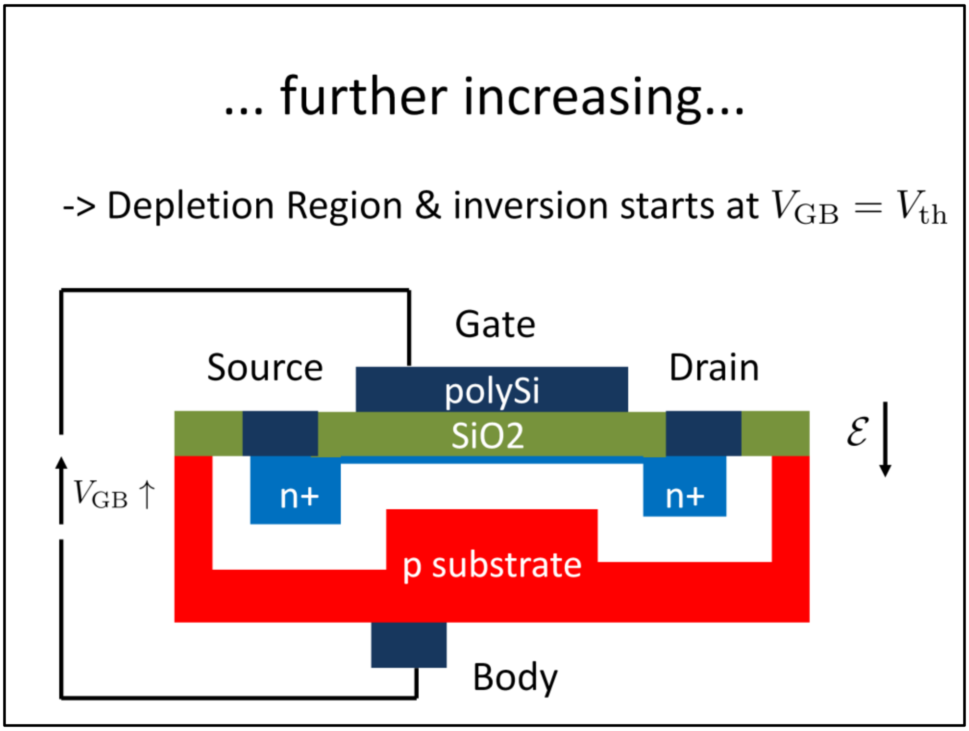
white: depletion region

Increasing VGB...

-> Electric field -> Depletion Region



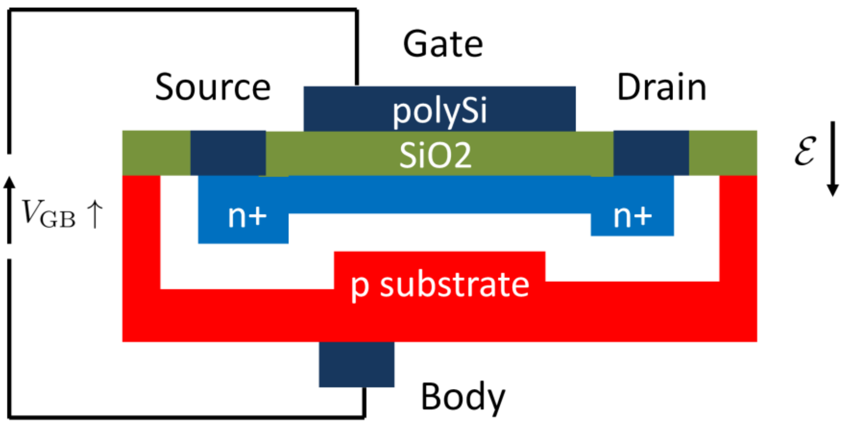
channel forms by inversion



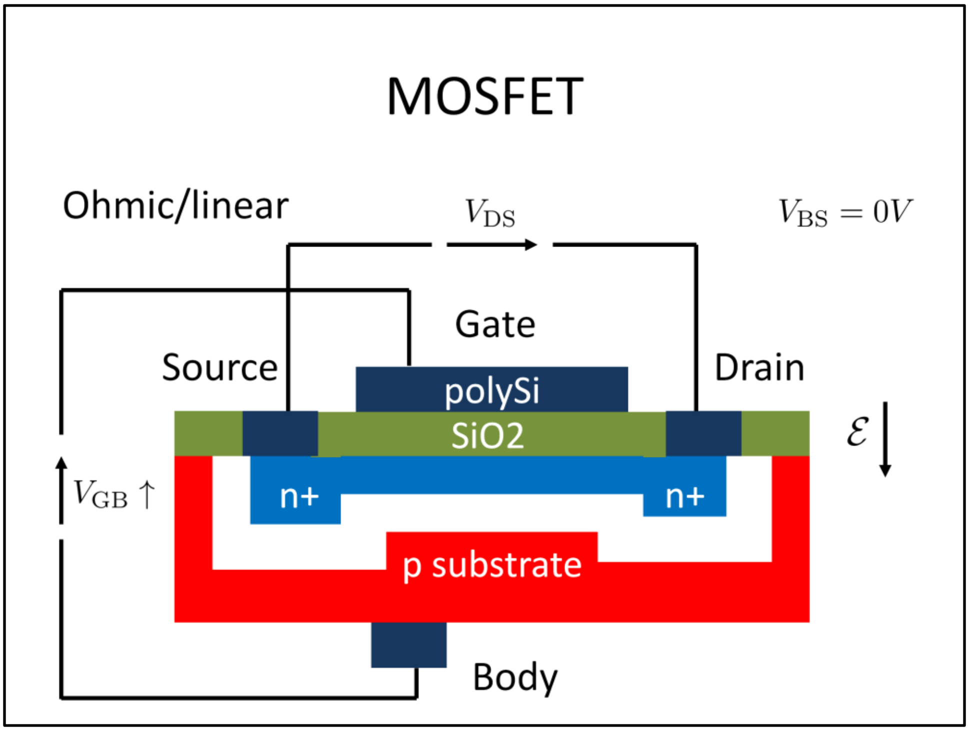
channel forms by inversion

... & further increasing

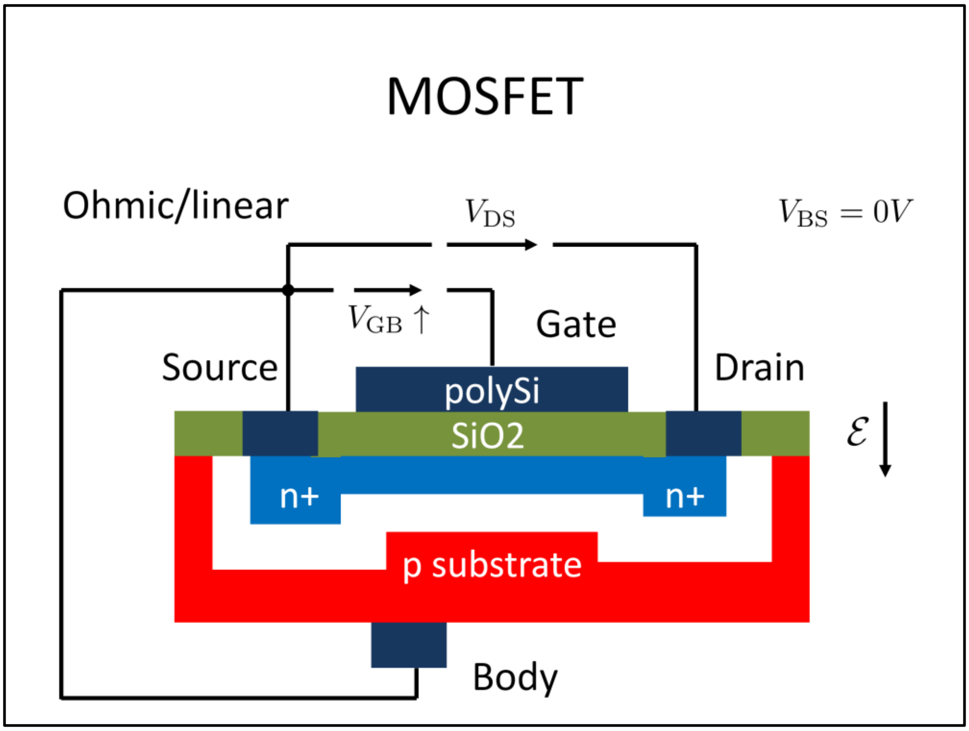
-> Inversion & n-channel forms: $V_{\mathrm{GB}} \geq V_{\mathrm{th}}$



channel forms by inversion

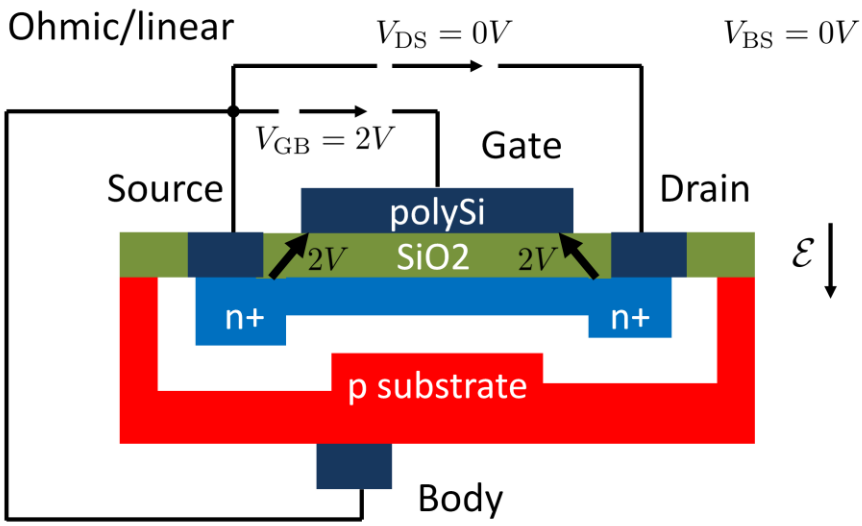


we apply a positive DS Voltage

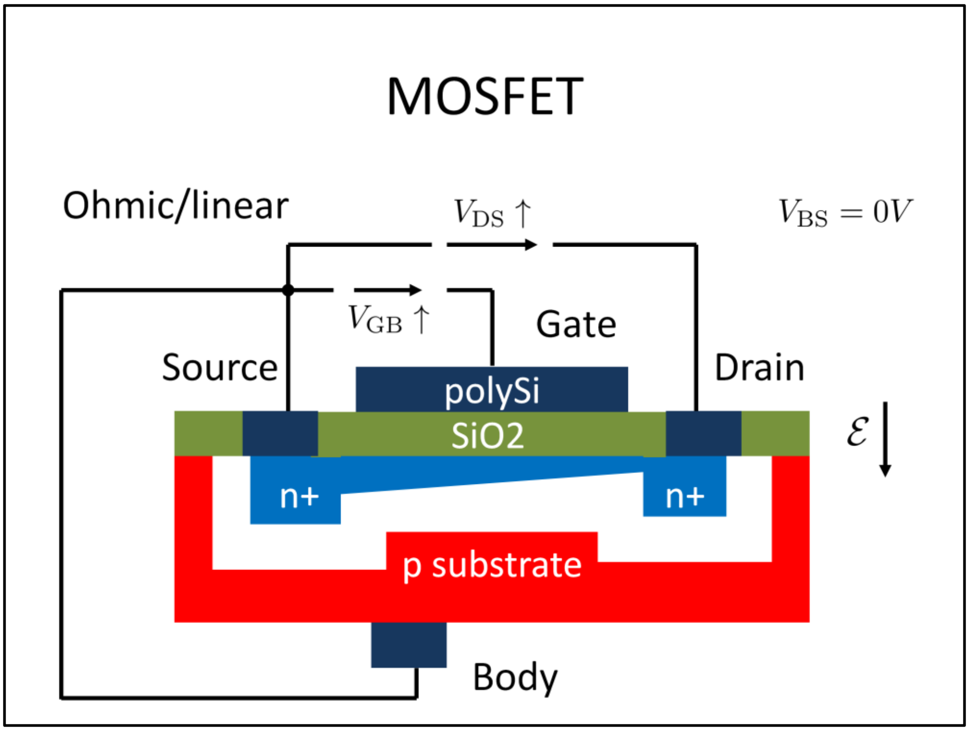


just reordering

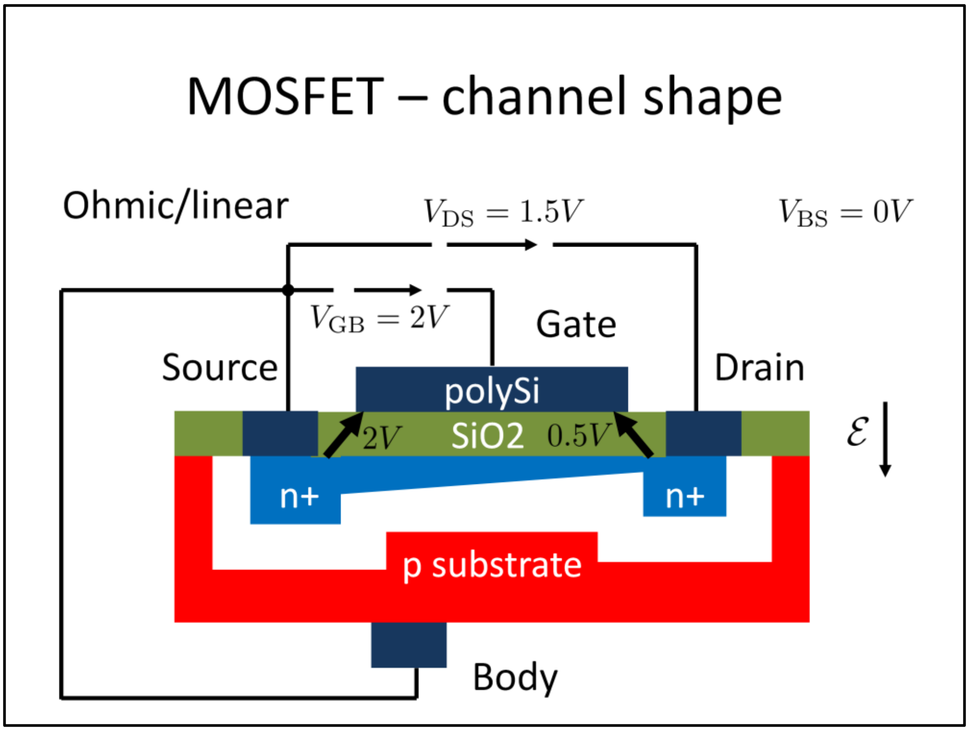
MOSFET – channel potential



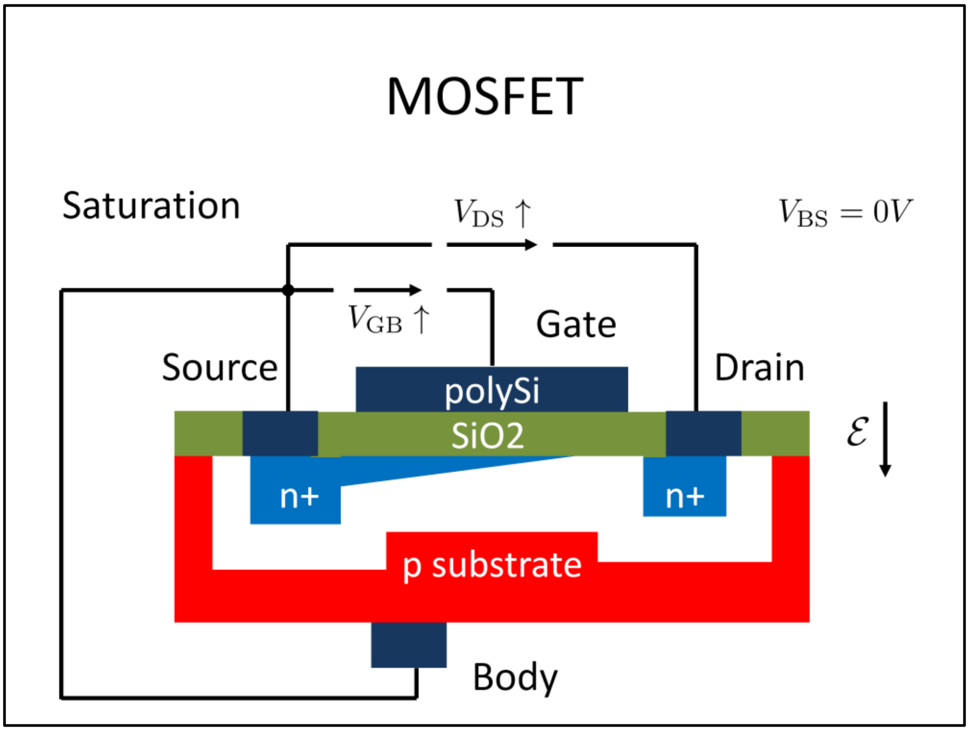
channel begin: 2V from channel point to gate.
channel end: 2V from channel point to gate.



now increase: V_DS
small increases: Linear region: n-channel behaves like an ohmic conductor with an V_DS = R*I_DS behavior.

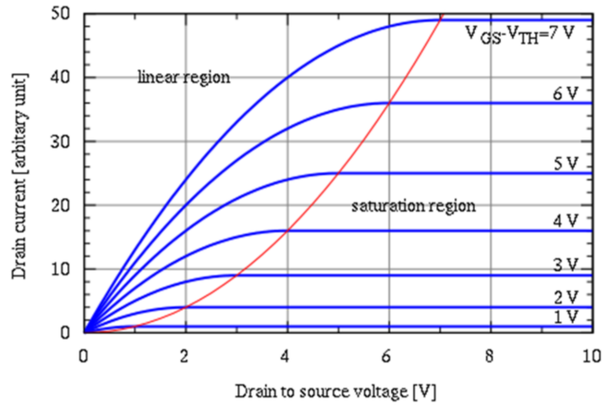


channel cone shape



Saturation region if we further increase V_DS

MOSFET



calculated, from commons.wikimedia.org/wiki/File:IvsV_mosfet.svg#/media/File:IvsV_mosfet.svg

three regions of MOSFET:
cutoff, ohmic, saturation
the drain current i_d is the current that flows from drain to source. It is positive here as we only look at forward bias.