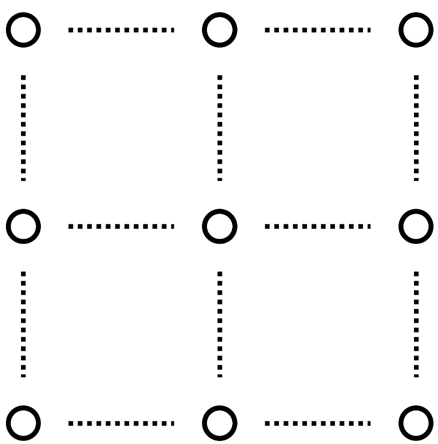
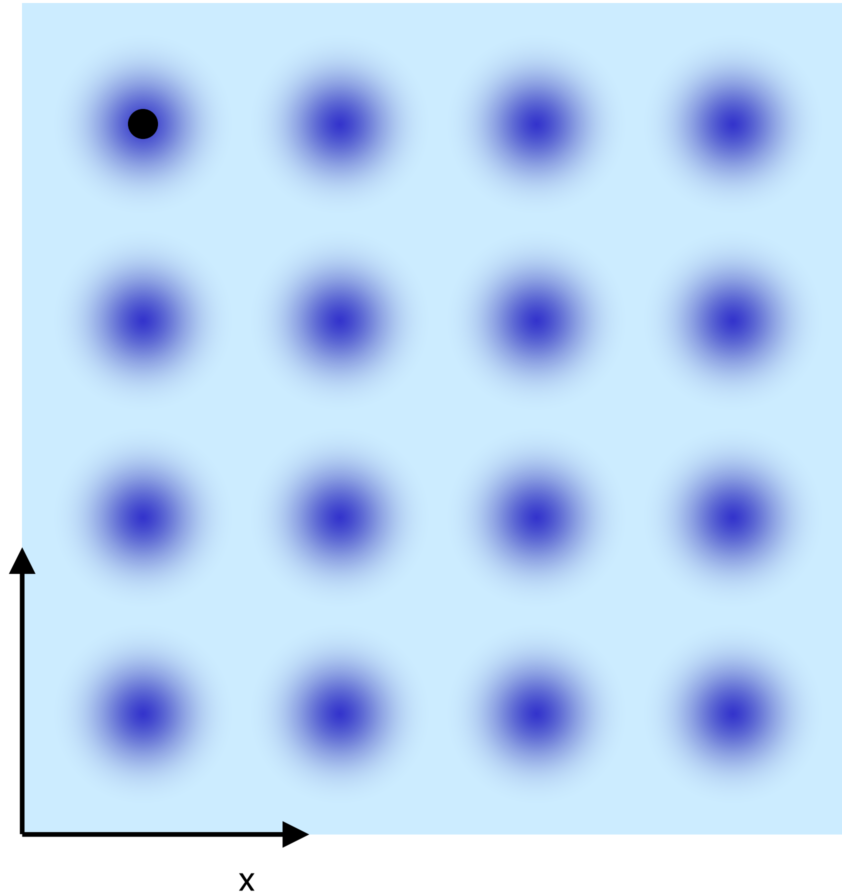
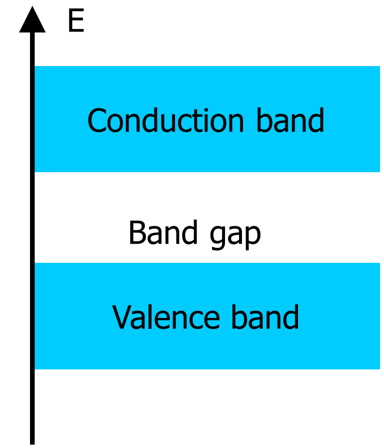
Advanced MOSFET Modelling

MOS Transistor

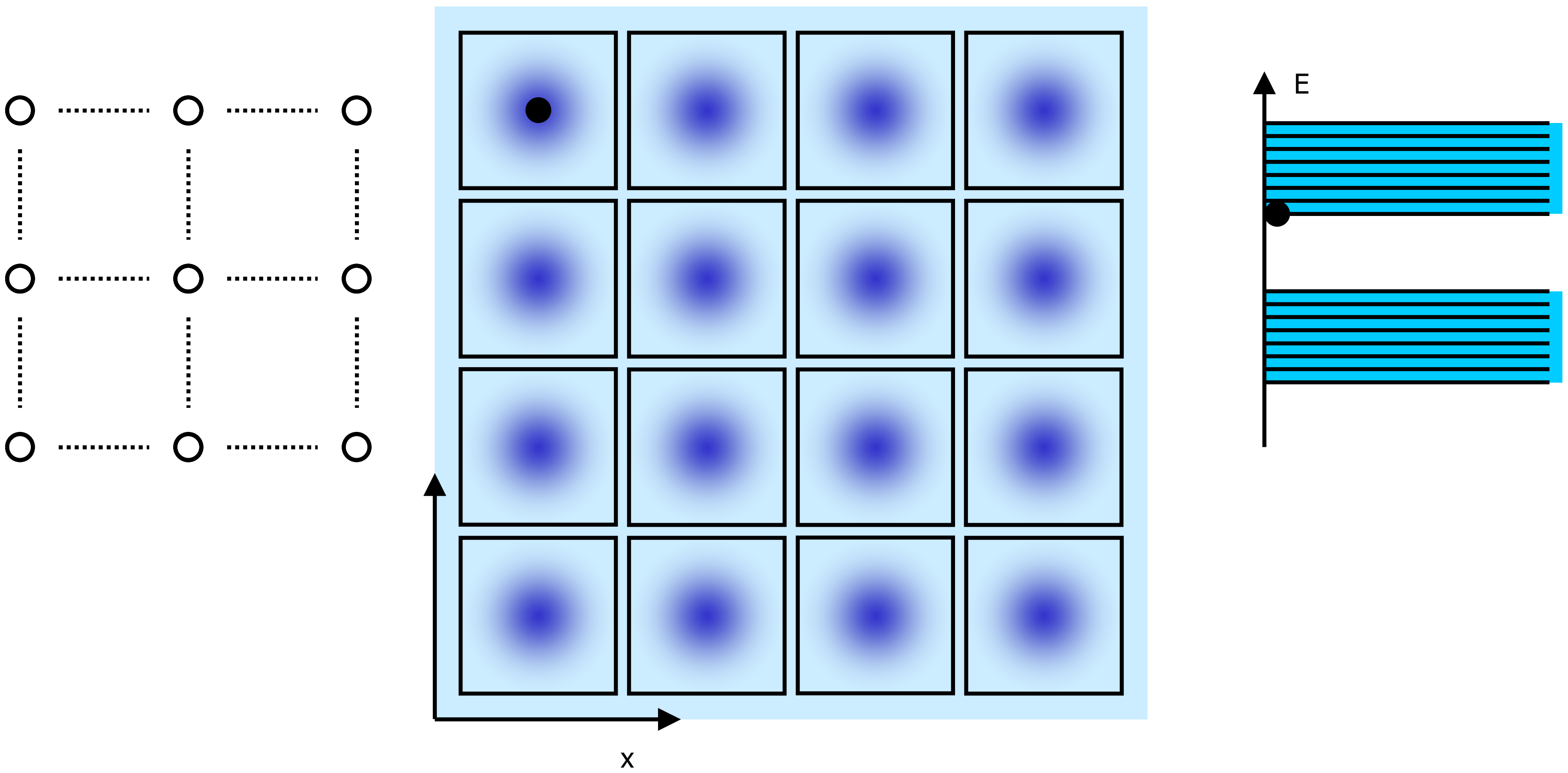
Text is in separated file!!!!



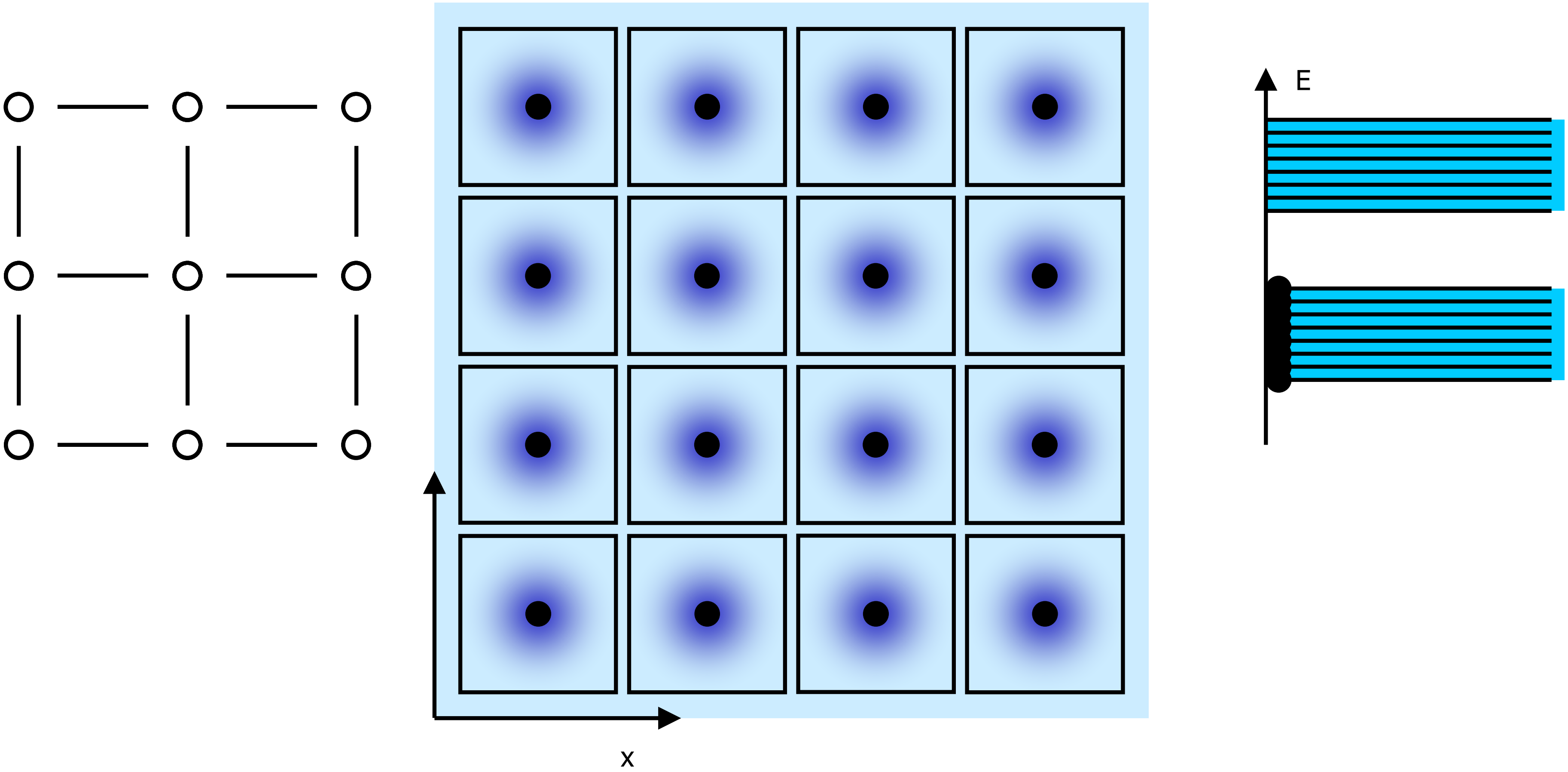




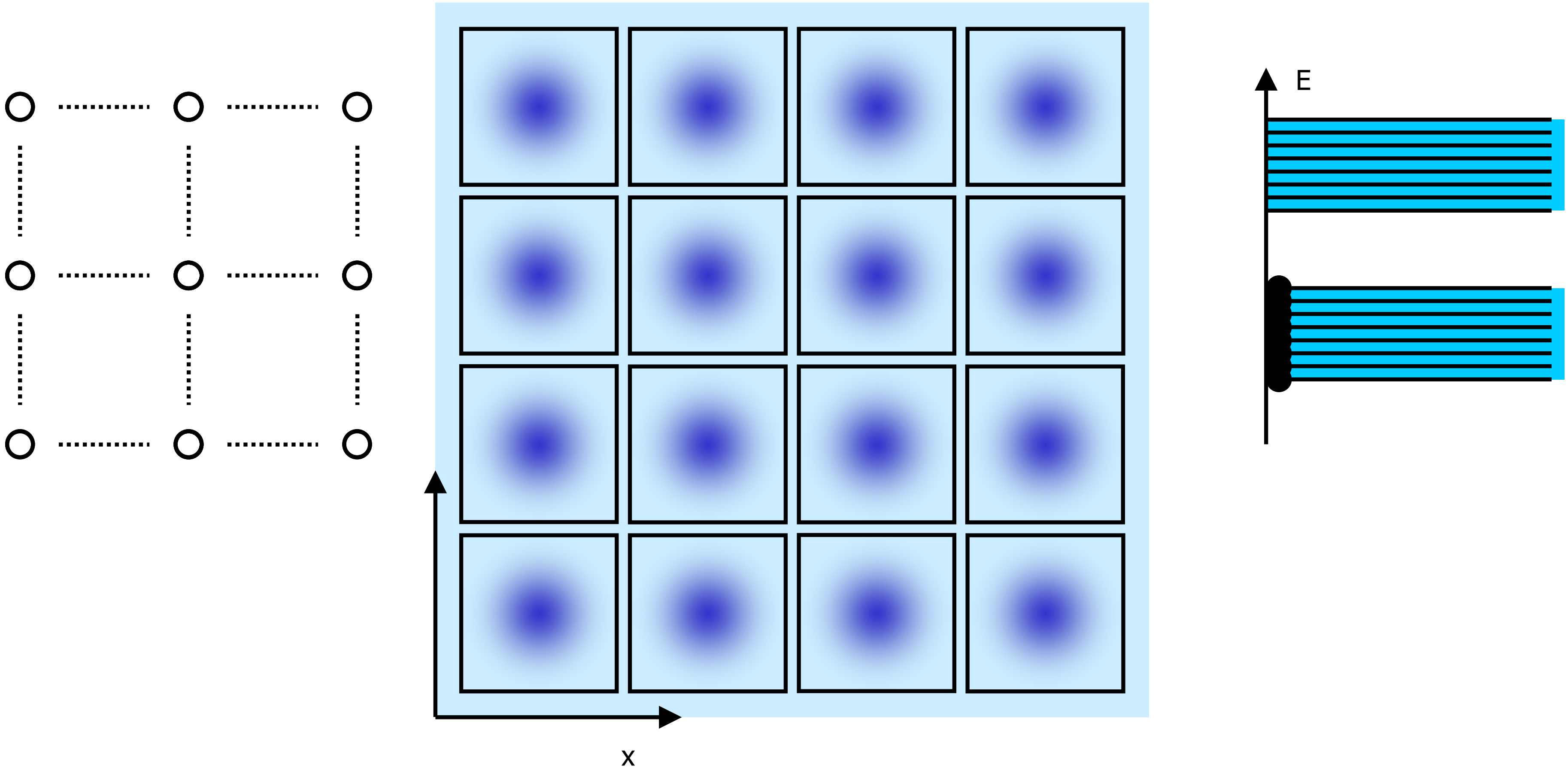
MOS Transistor



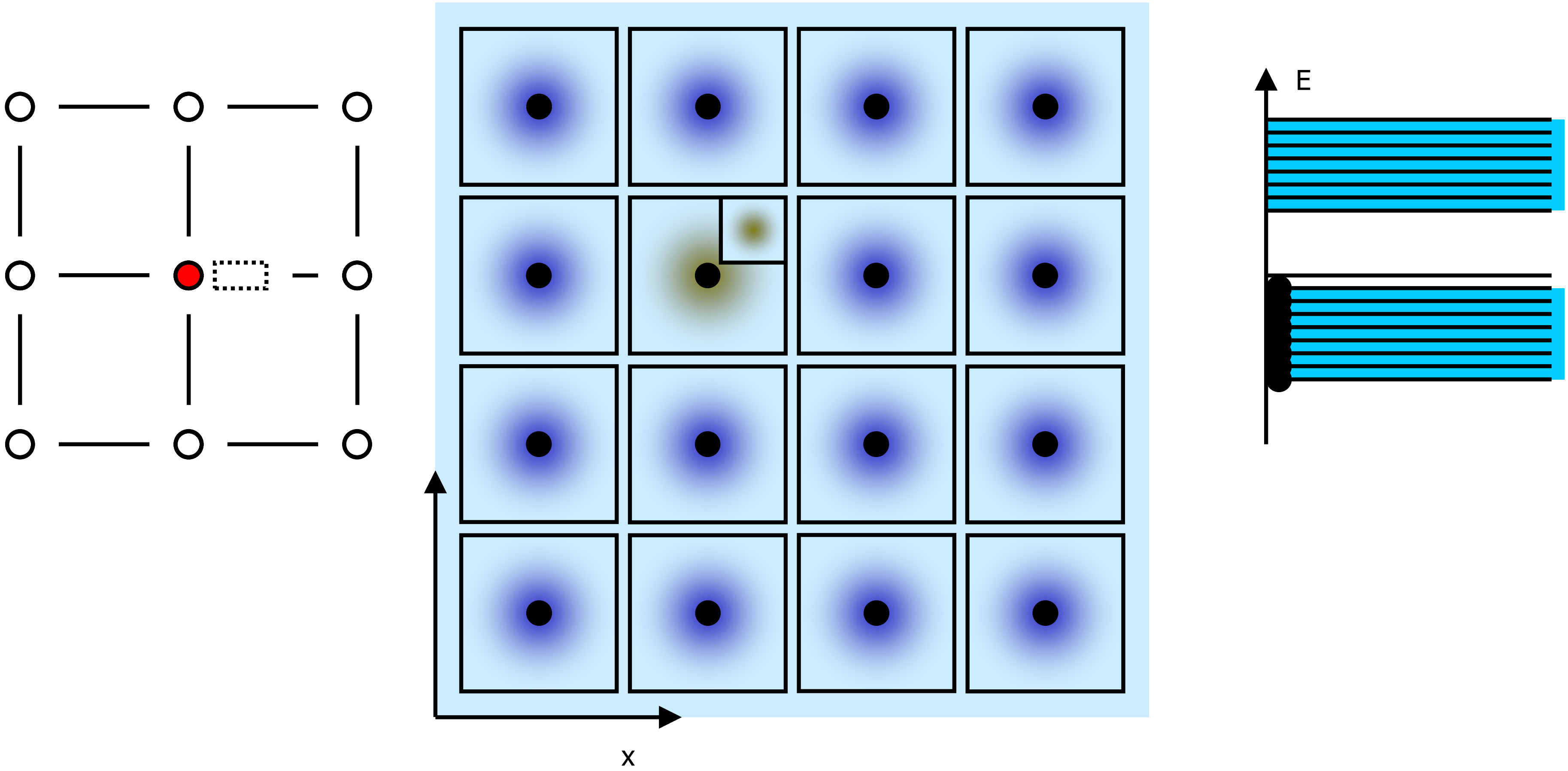
MOS Transistor



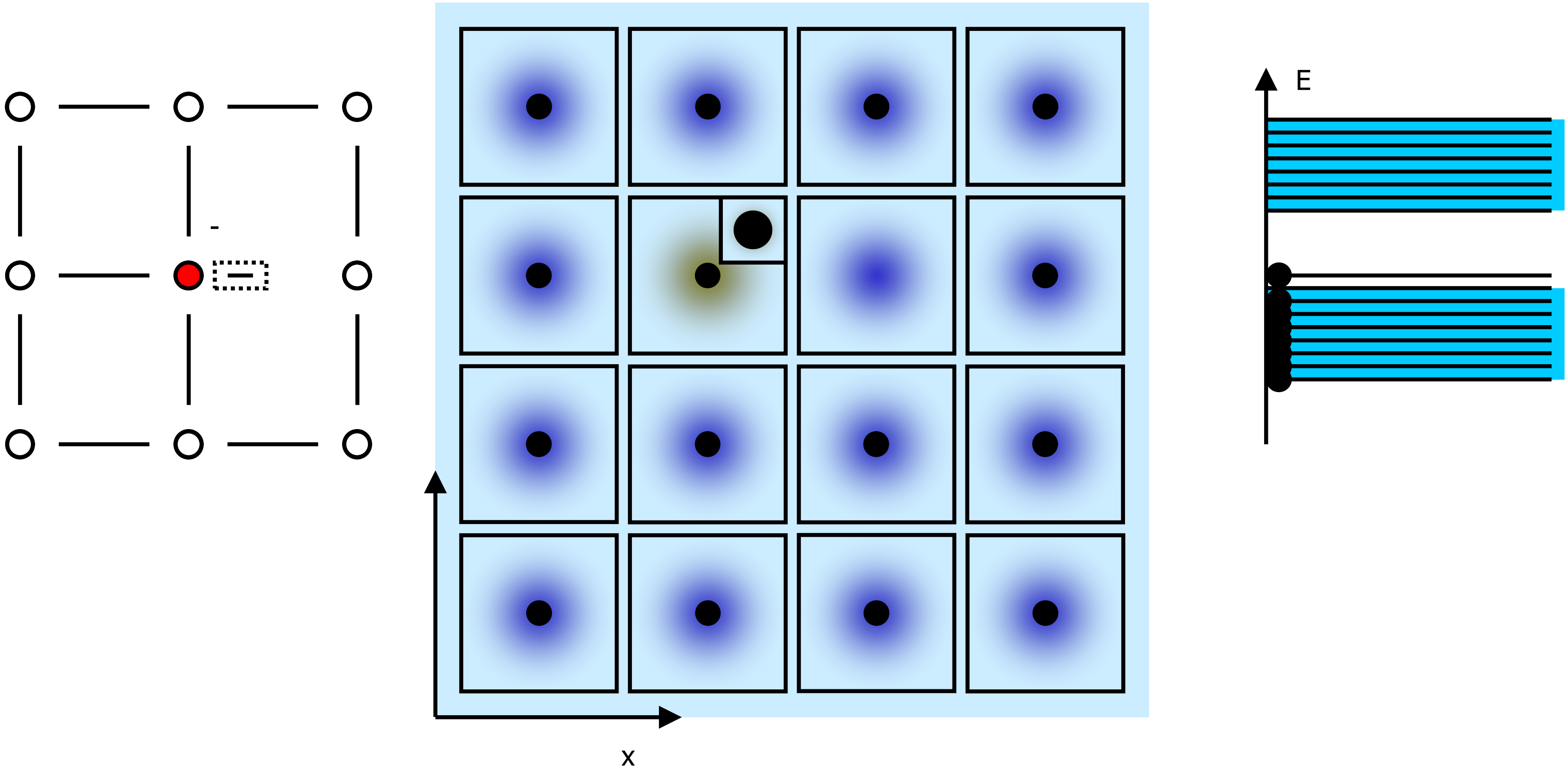
MOS Transistor



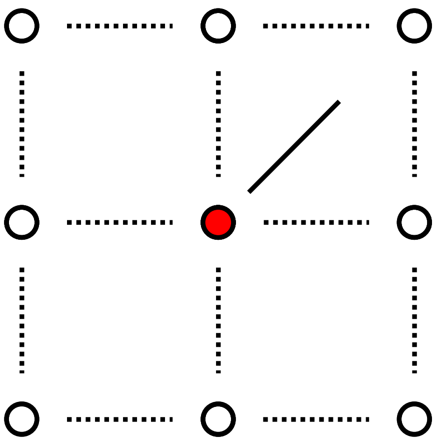
MOS Transistor

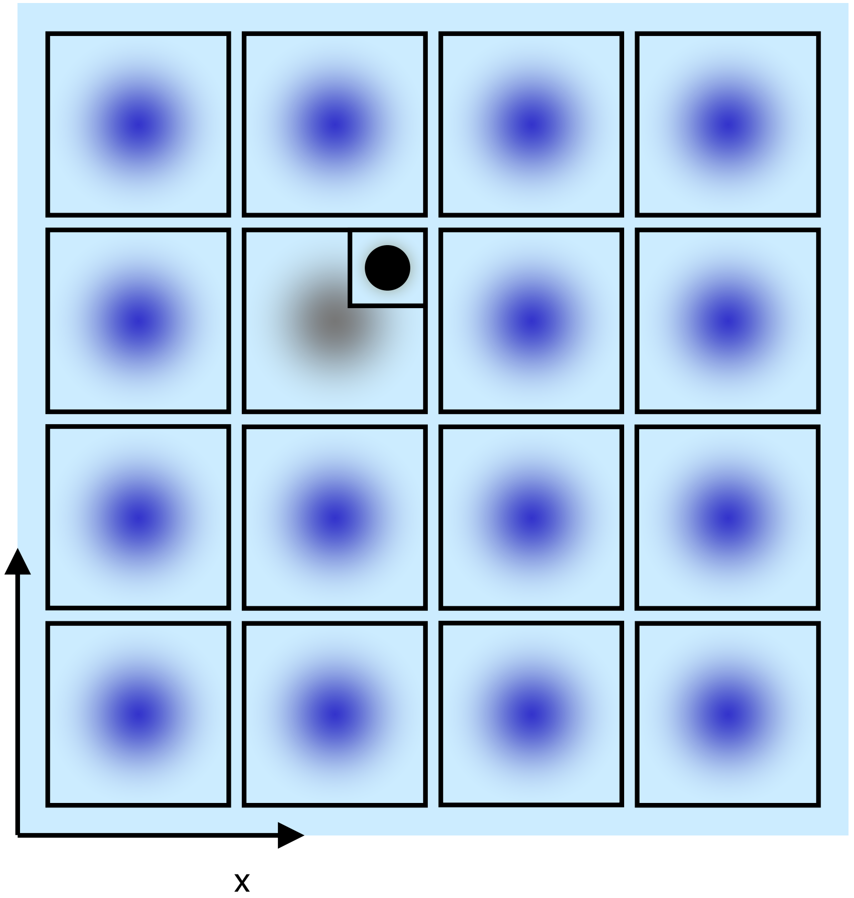


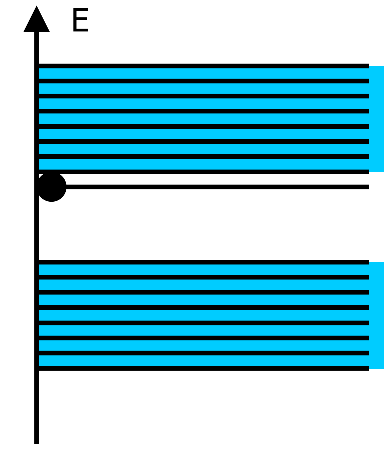
MOS Transistor



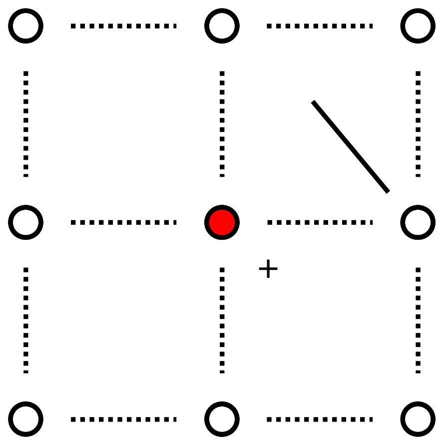
MOS Transistor

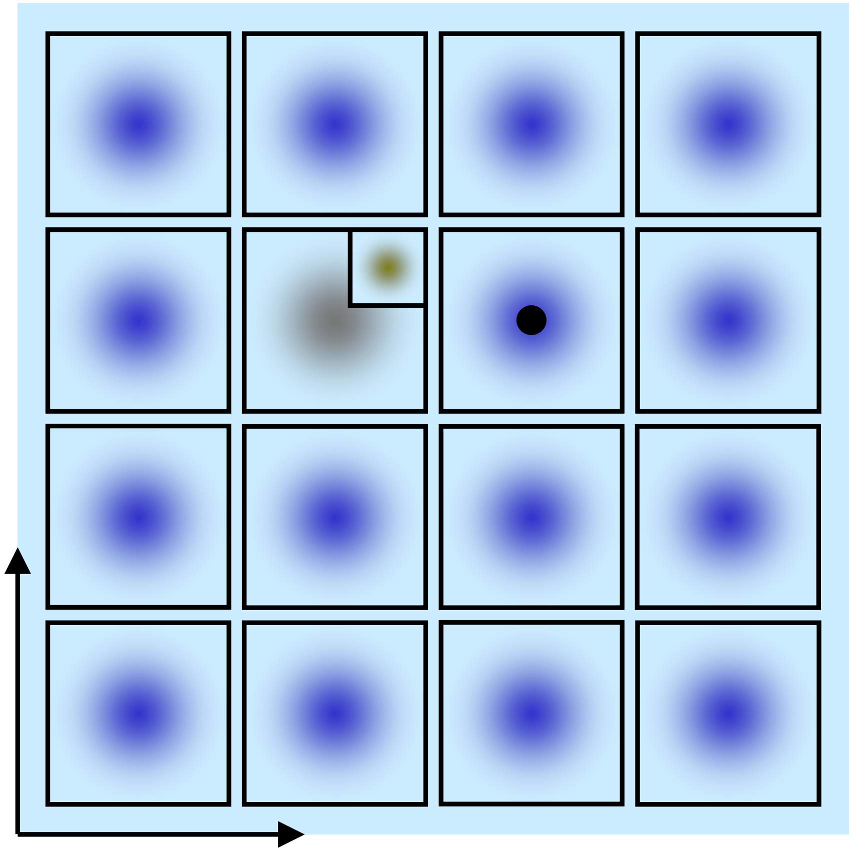


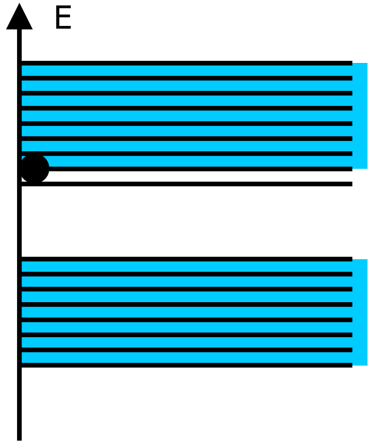




MOS Transistor





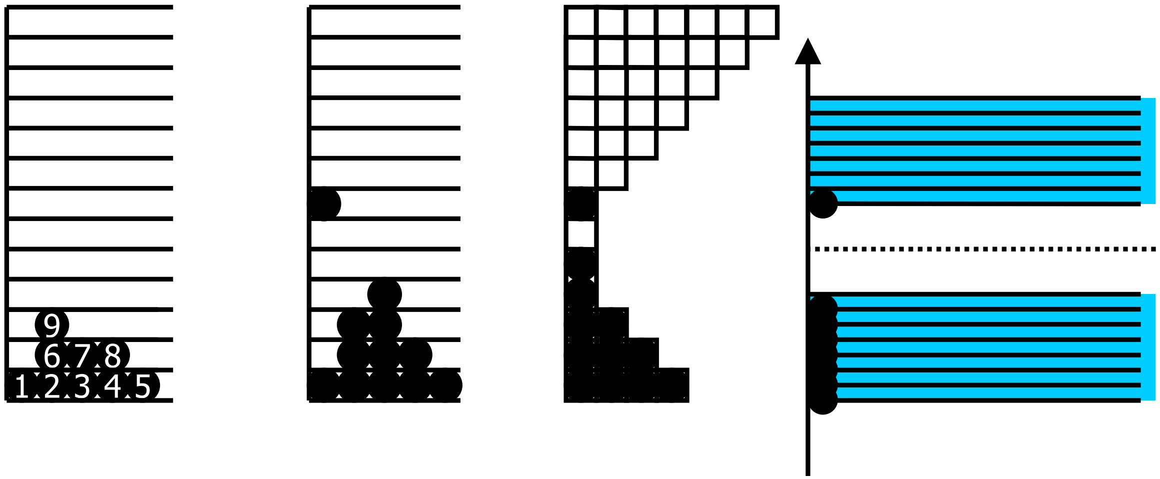


MOS Transistor

$$n = n_0 e^{-\frac{E}{kT}}$$

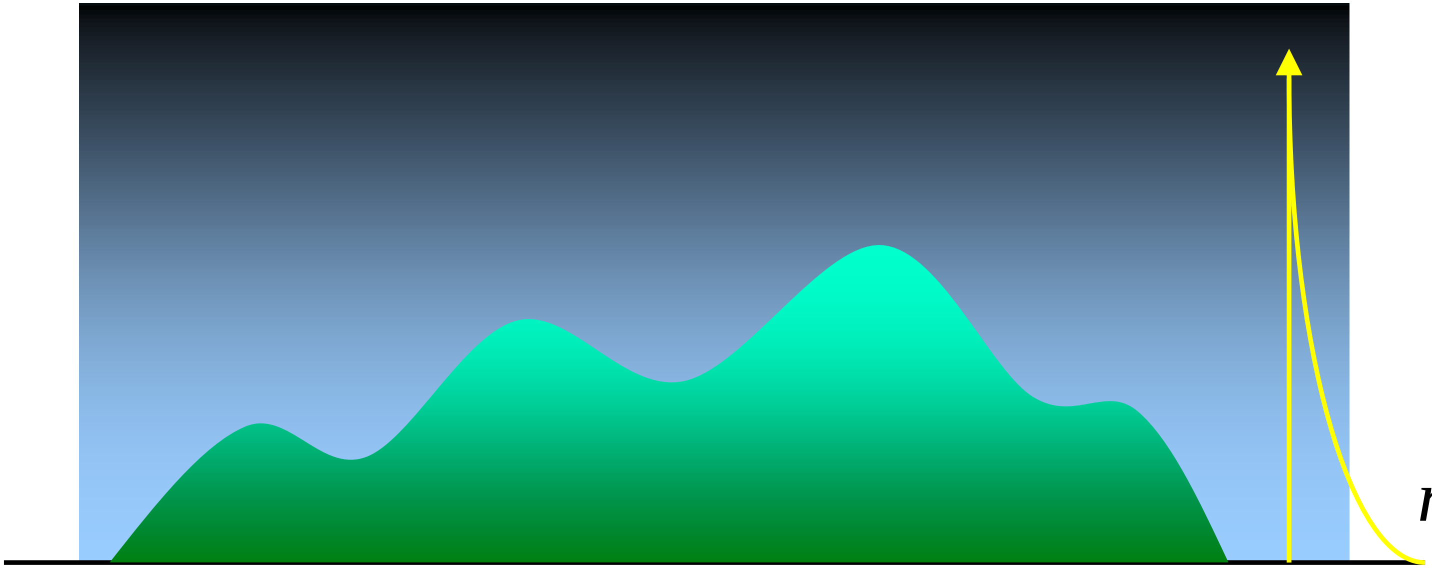
$$n = \frac{1}{e^{\frac{E-\mu}{kT}} - 1}$$

$$n = \frac{1}{e^{\frac{E-E_f}{kT}} + 1}$$



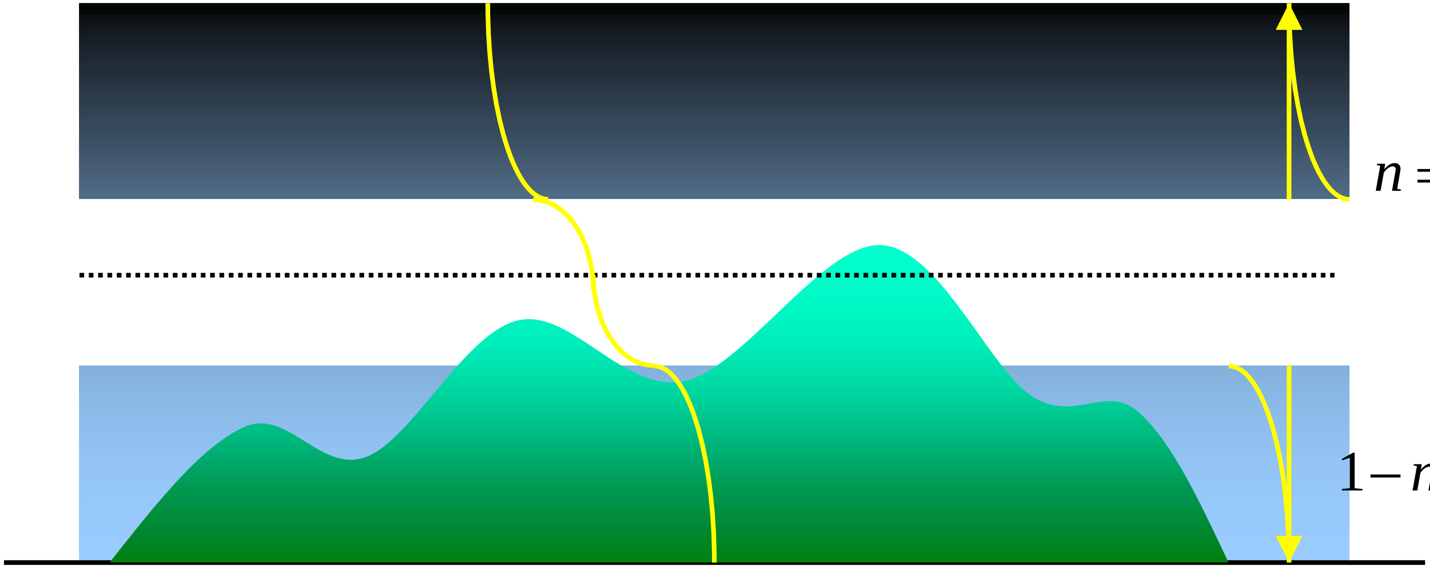
Maxwell-Boltzmann Distribution

$$n = n_0 e^{-\frac{E}{kT}}$$



$$n = n_0 e^{-\frac{mgh}{kT}}$$

Maxwell-Boltzmann Distribution

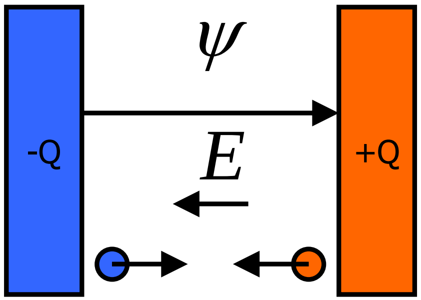


$$n = e^{-\frac{E-E_f}{kT}} = n_0 e^{-\frac{E_e}{kT}}$$

$$1-n = e^{-\frac{E_f-E}{kT}} = p_0 e^{\frac{-E_h}{kT}}$$

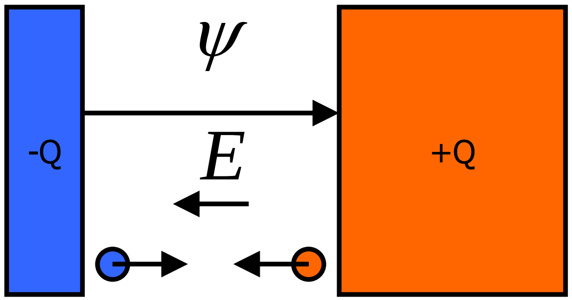
$$n = \frac{1}{e^{\frac{E-E_f}{kT}}+1}$$

Maxwell-Boltzmann Distribution

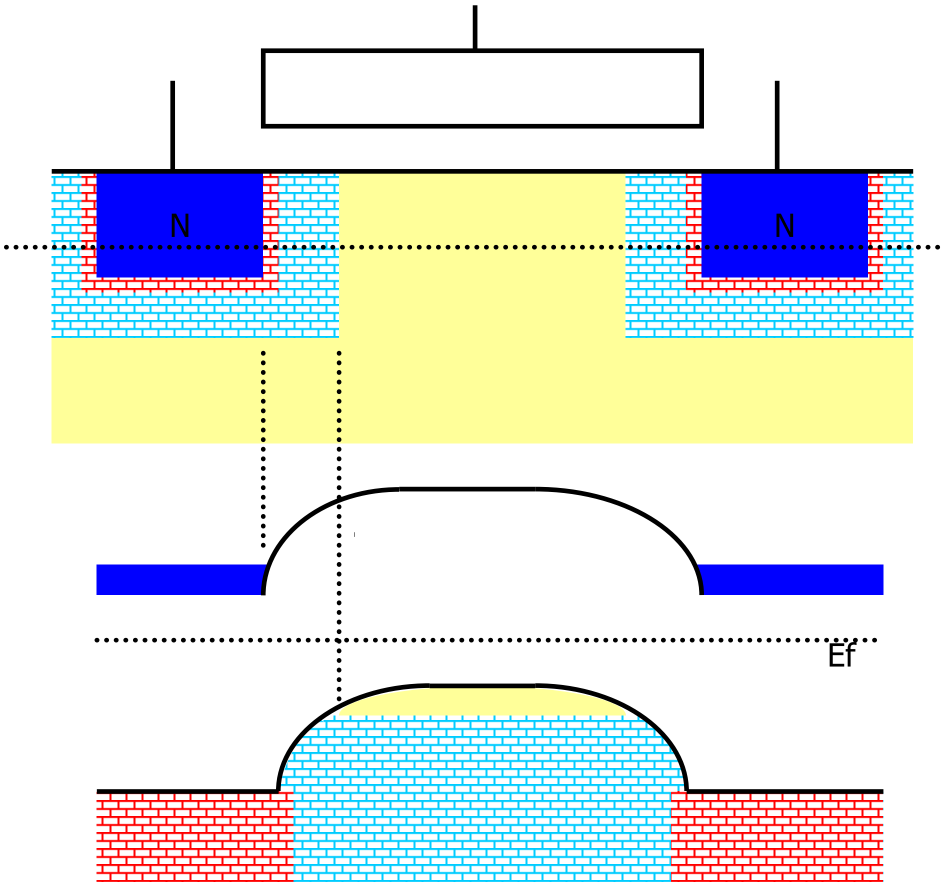


$$C = Q / \psi$$

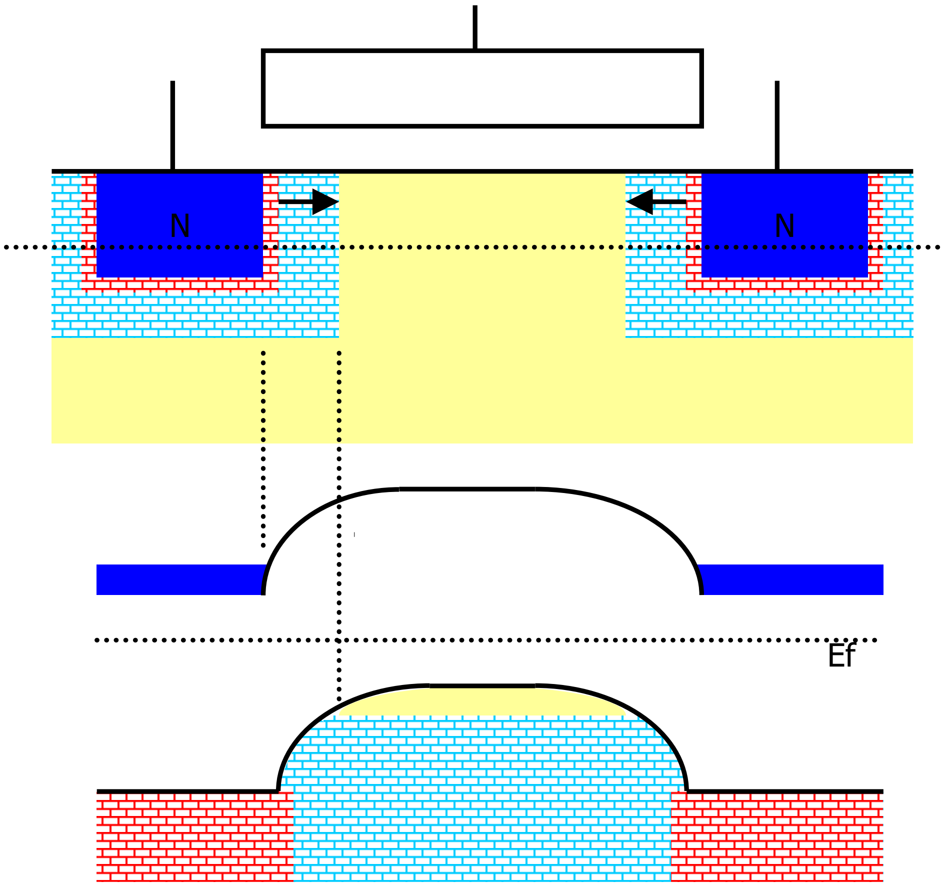
$$C = A\varepsilon_o \varepsilon_r / t$$



MOS Transistor

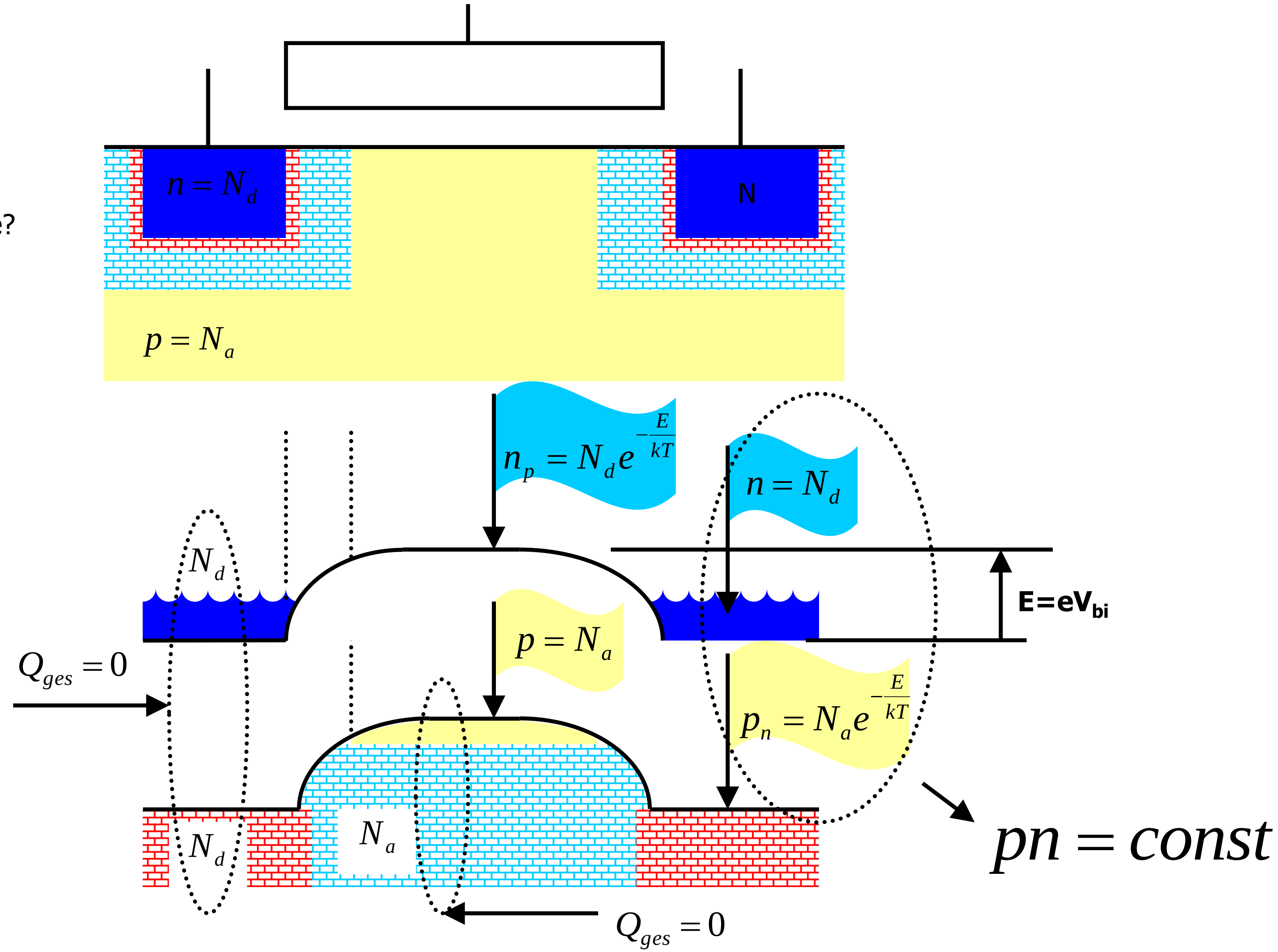


MOS Transistor



MOS Transistor – Carrier Density

Warum Sperrzone?



Intrinsic Semiconductor

TDG

$$pn = const$$

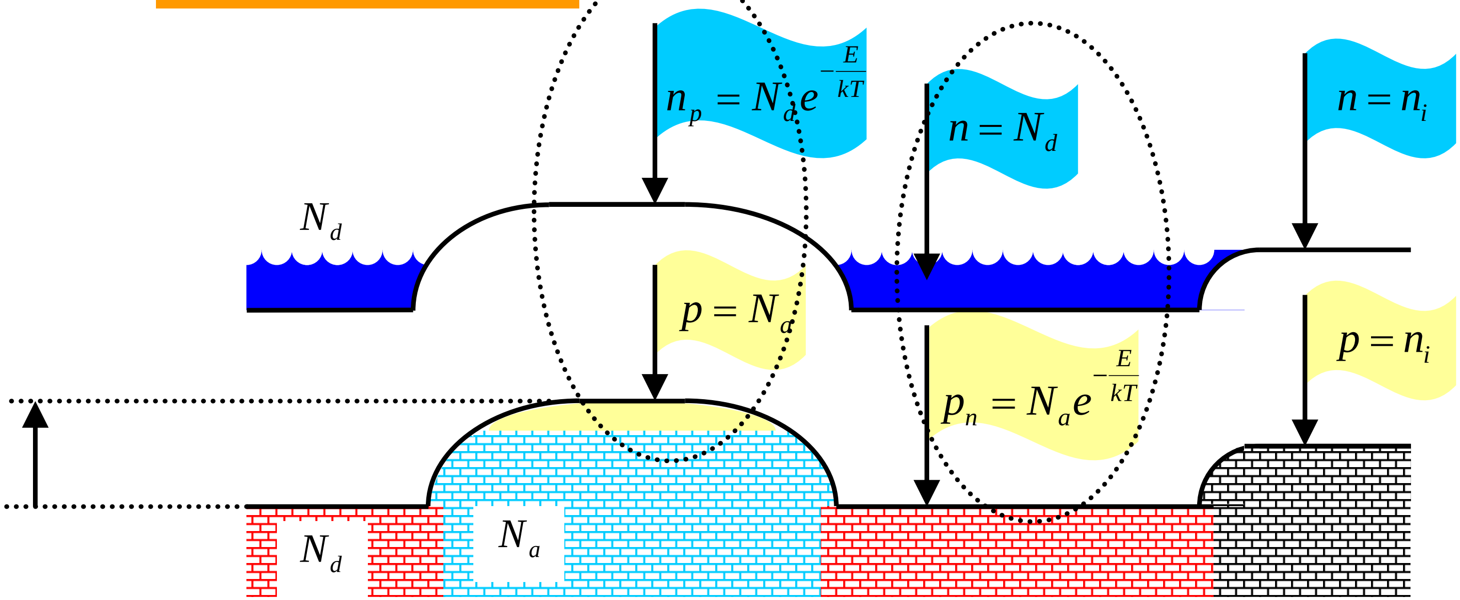
$$pn = n_i^2$$

$$n_i = 1.45 \times 10^{10} cm^{-3}$$

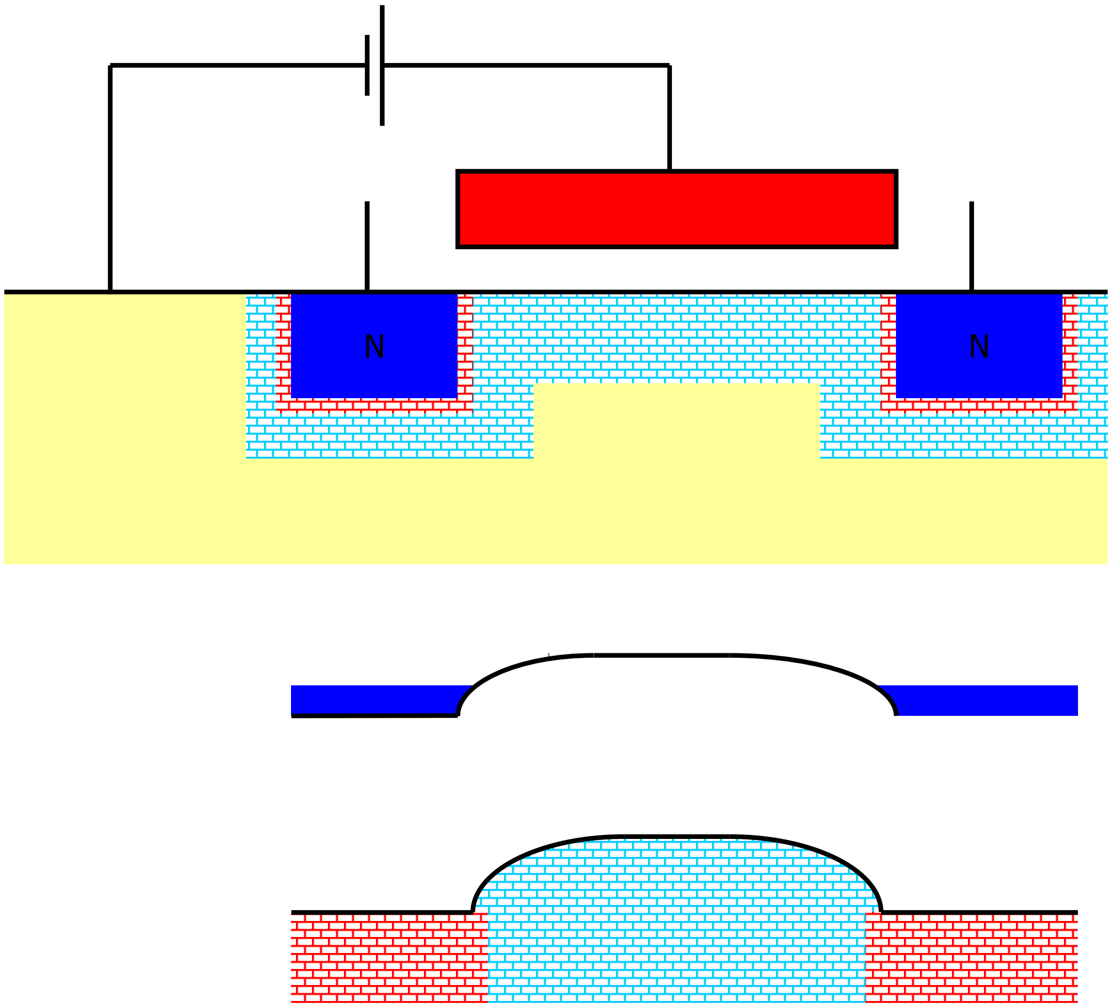
$$n_{atoms} \approx 10^{22} cm^{-3}$$

$$N_a, N_d \approx 10^{16} cm^{-3}$$

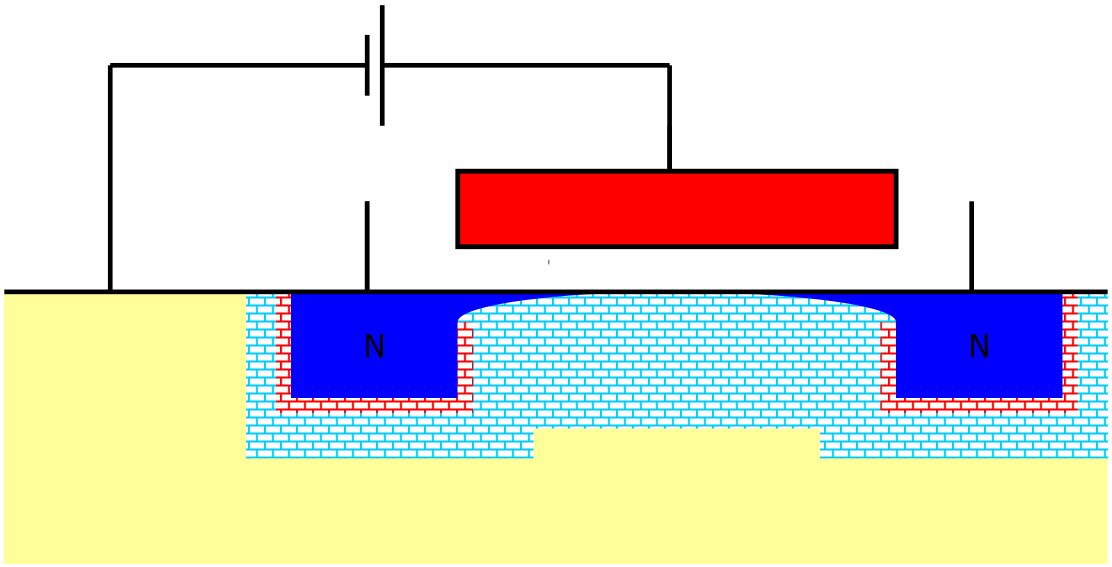
$$n_{p0} = \frac{n_i^2}{N_a} \quad p_{n0} = \frac{n_i^2}{N_d}$$

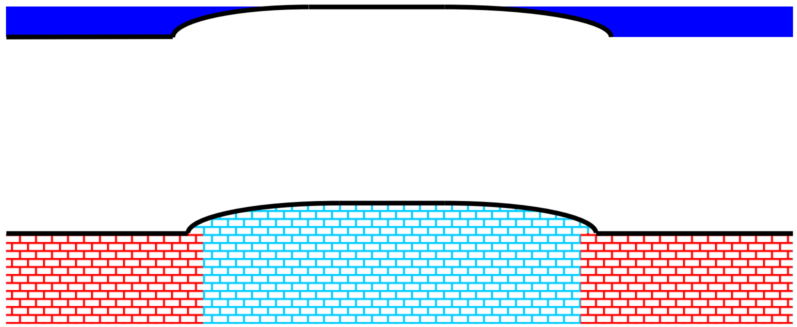


Gate Voltage

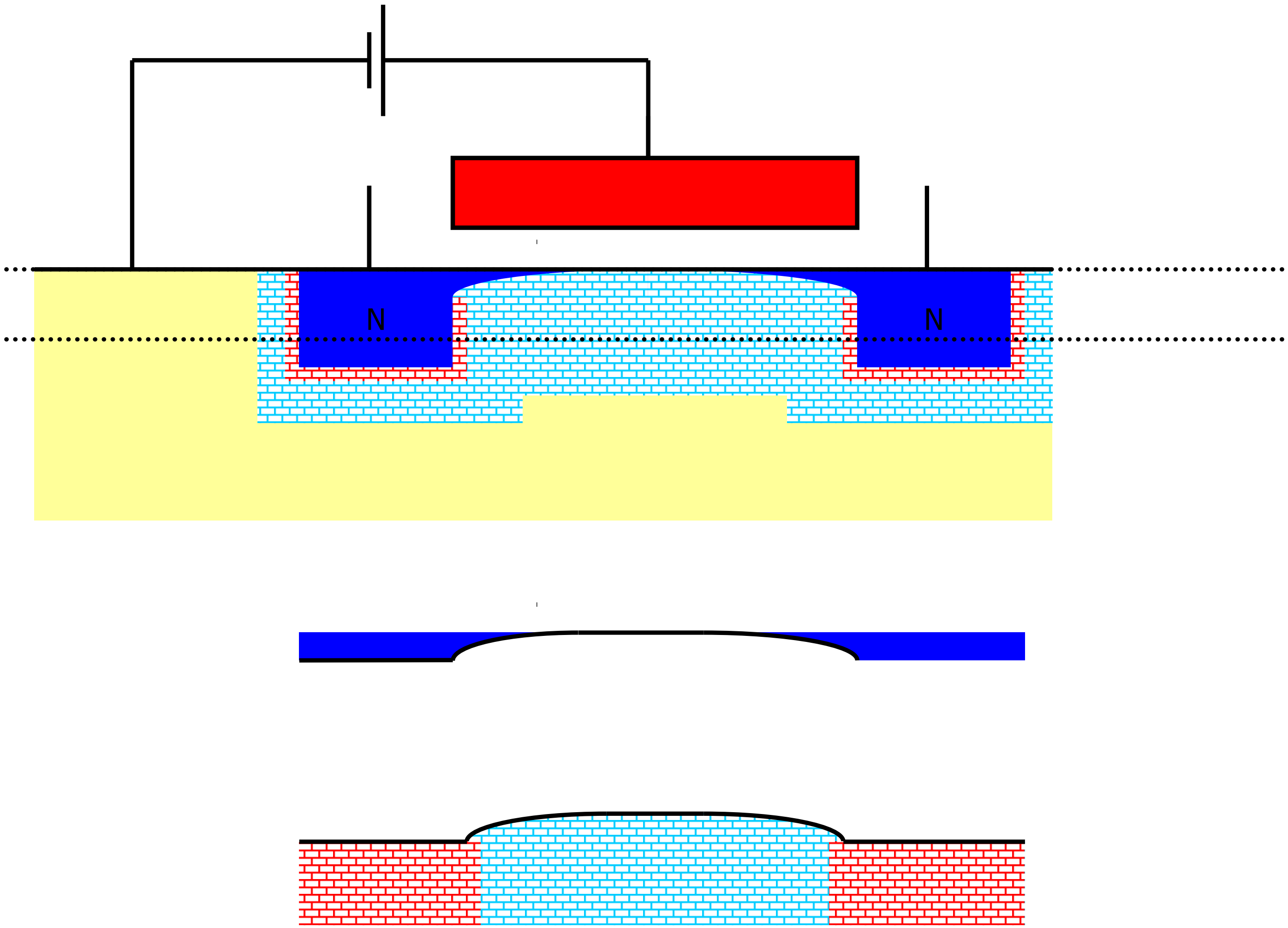


Gate Voltage - Channel

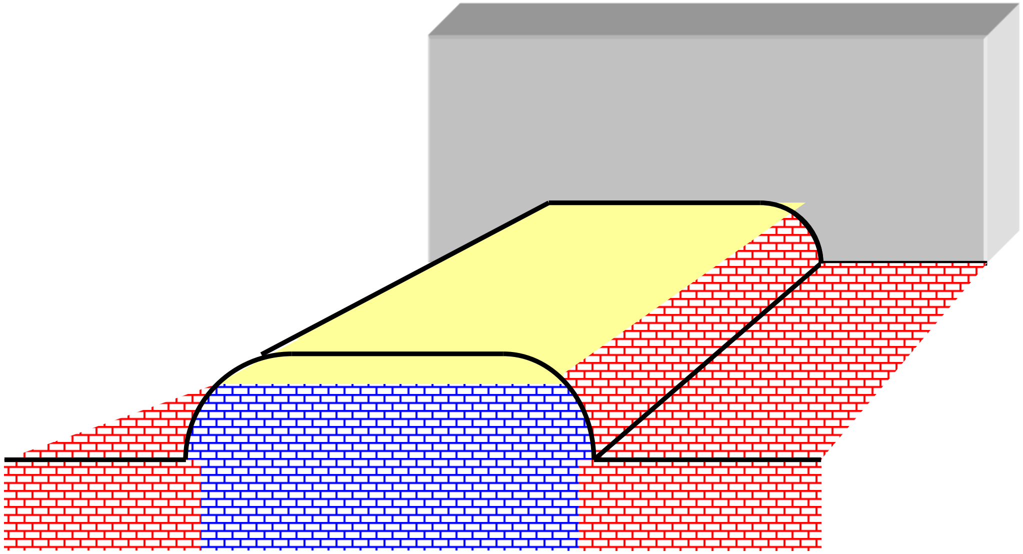


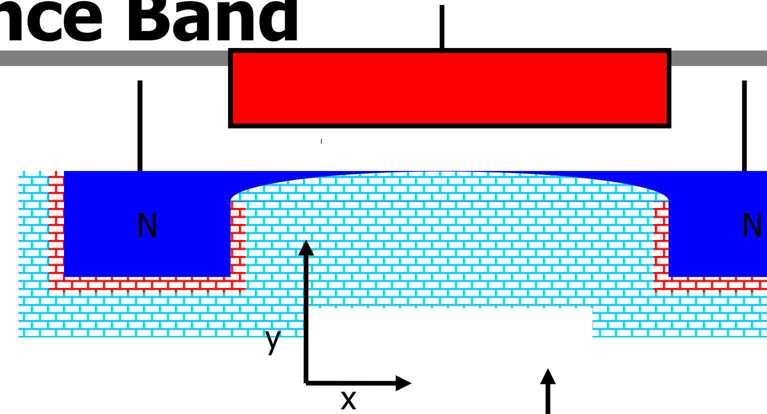


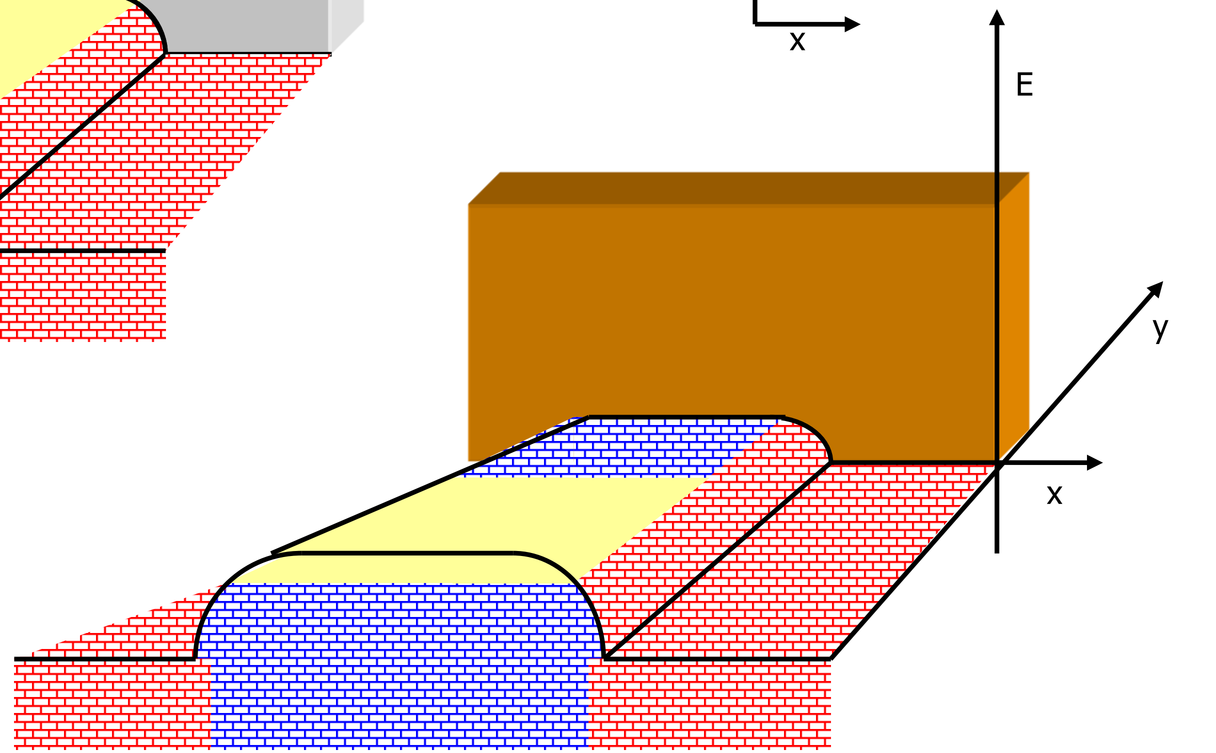
Gate Voltage



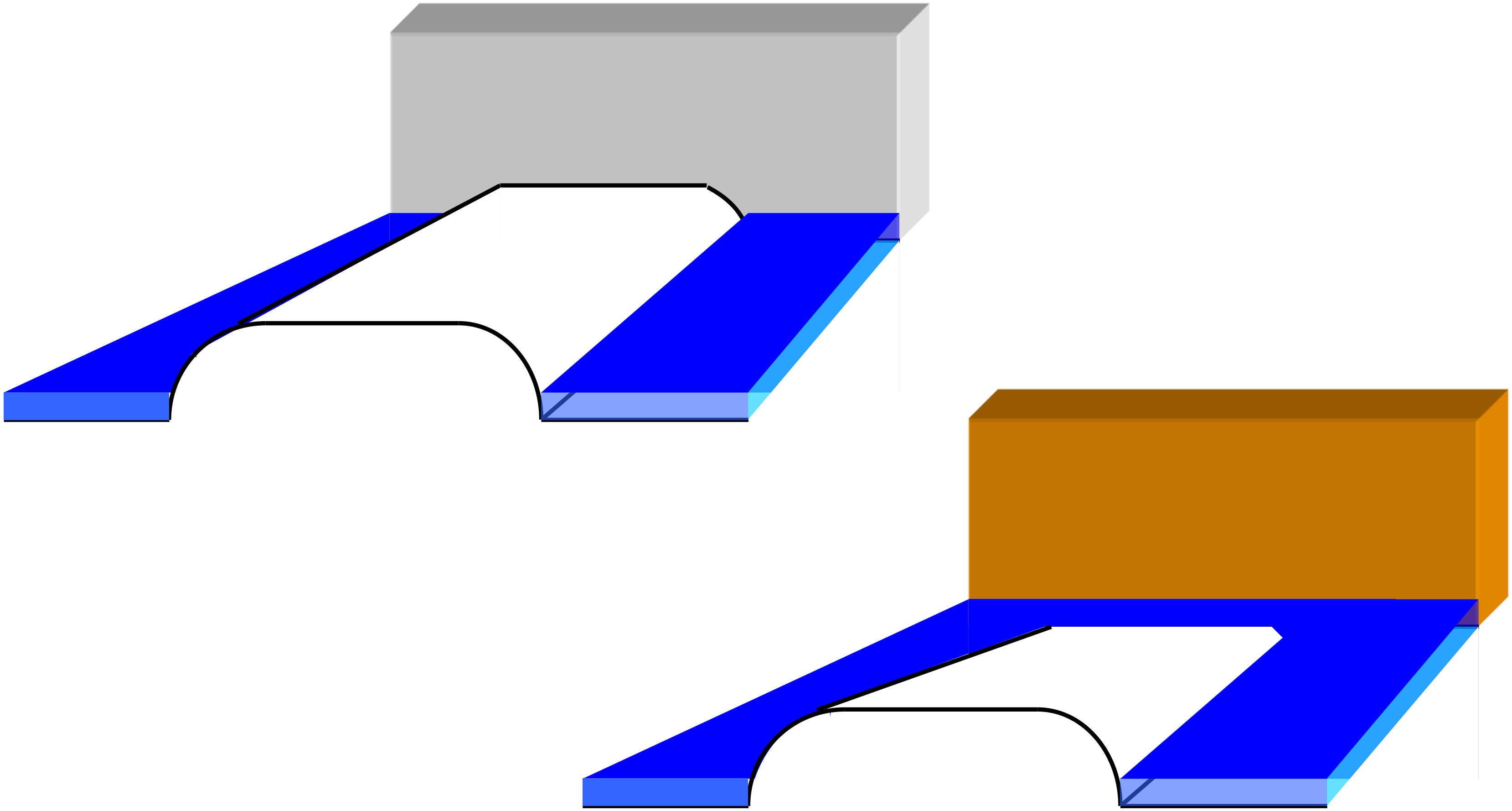
Gate Voltage – Valence Band



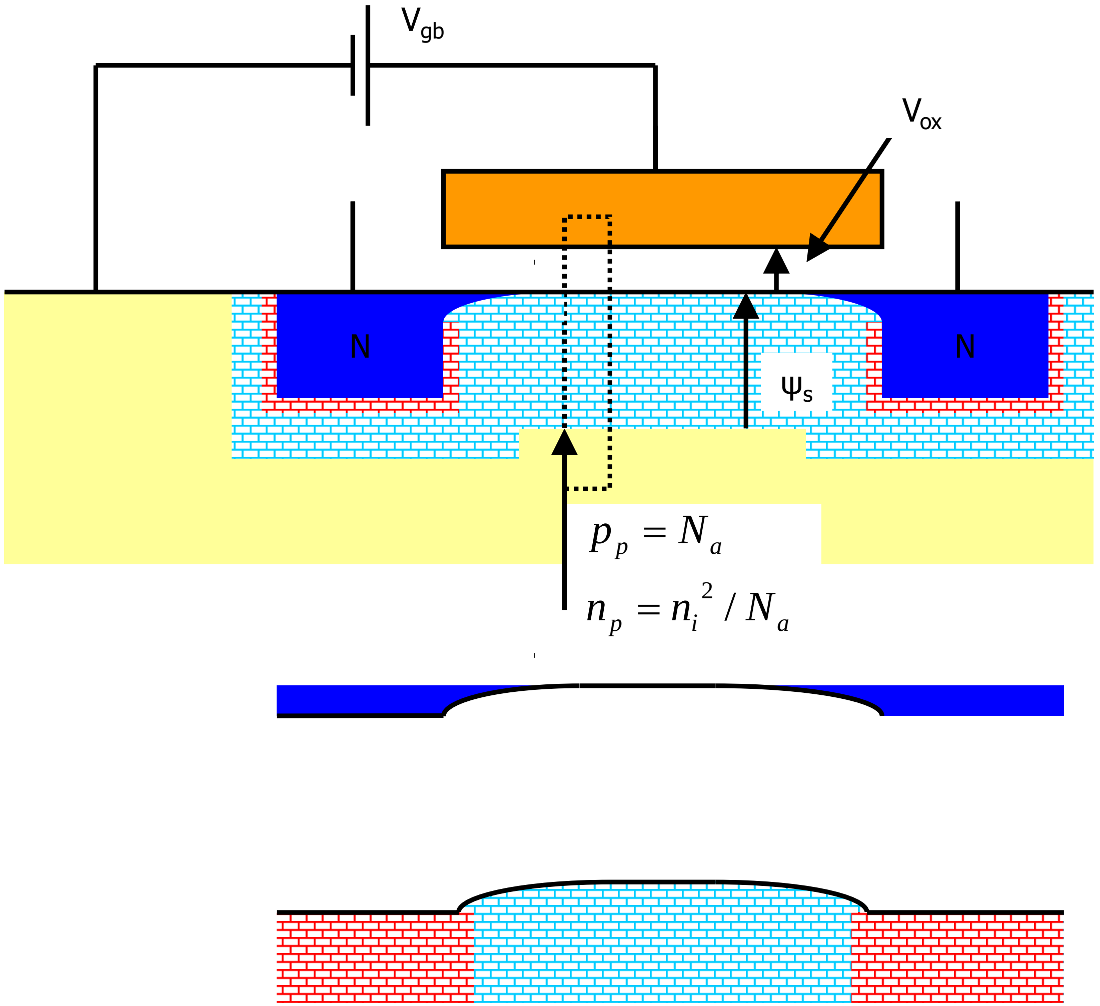




Gate Voltage – Conduction Band

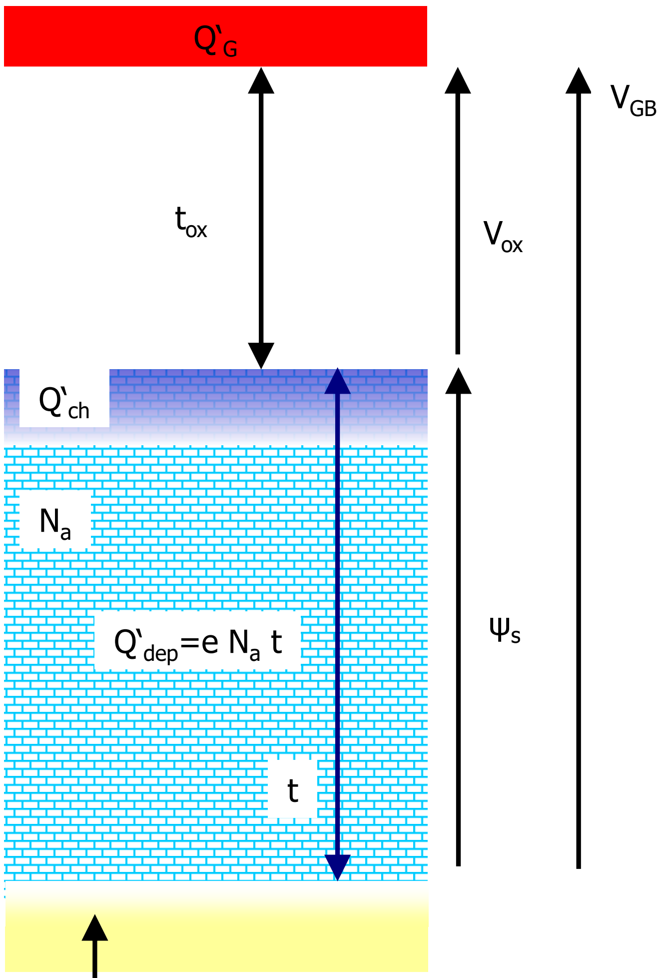


Gate Voltage – Electron Density in Channel



Electron Density in Channel

Warum so steil?



$$p_p = N_a$$

$$n_p = n_i^2 / N_a$$

$$Q'_{ch}(V_{GB}) = ?$$

$$V_{GB} = \psi_s + V_{ox}$$

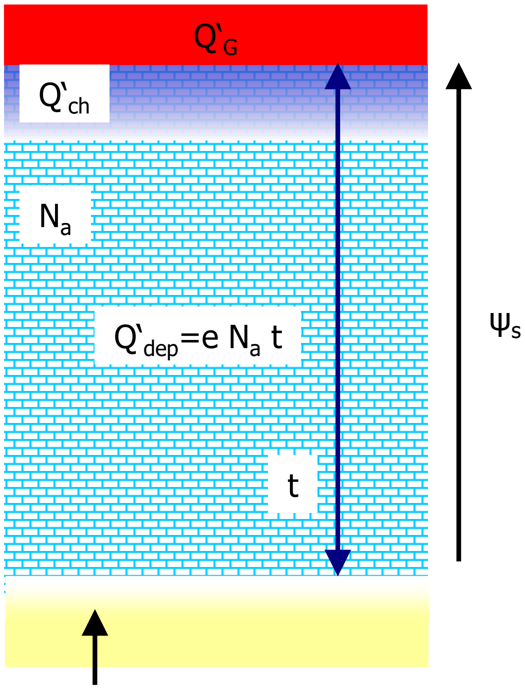
$$Q'_G = Q'_{ch} + Q'_{dep}$$

$$V_{ox} = \frac{Q'_G}{C'_{ox}} = \frac{Q'_{ch} + Q'_{dep}}{C'_{ox}} \quad C'_{ox} = \frac{\varepsilon_{SiO_2}\varepsilon_o}{t_{ox}}$$

$$Q'_{ch}(\psi_s) = ?$$

$$Q'_{dep}(\psi_s) = ?$$

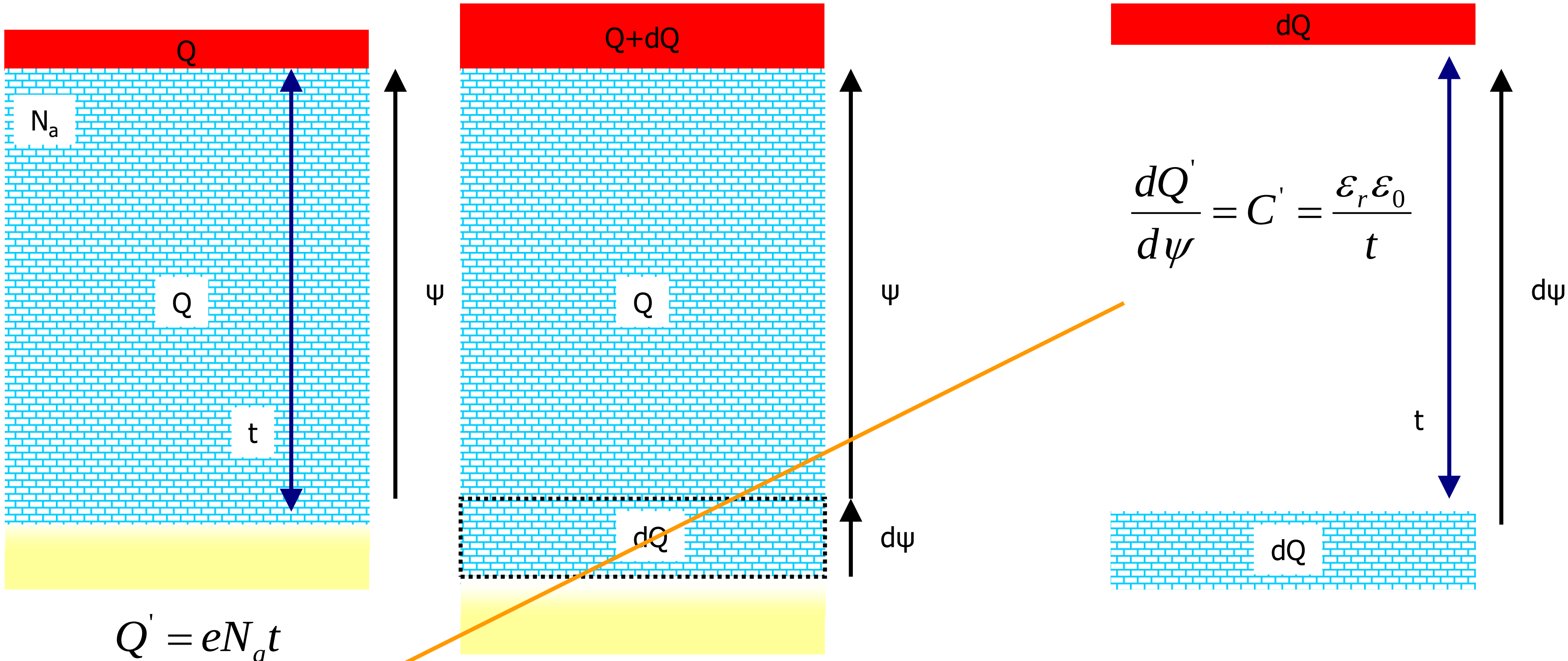
Gate Voltage – Electron Density in Channel



$$p_p = N_a$$

$$n_p = n_i^2 / N_a$$

Charge in depleted Region



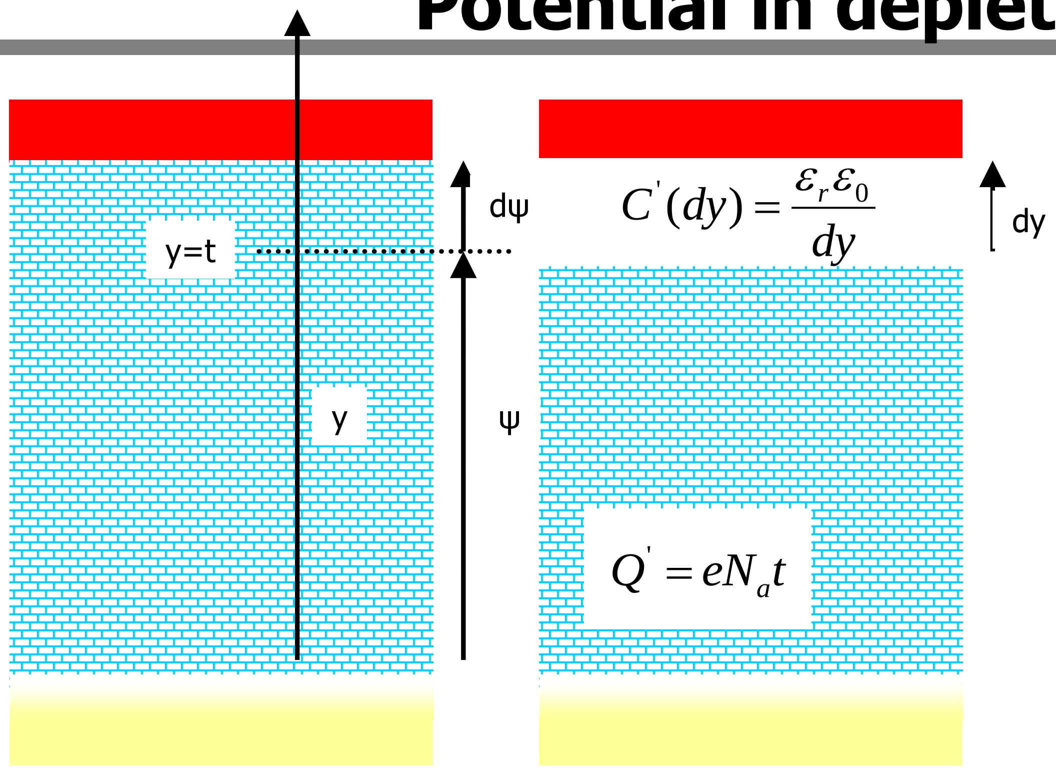
$$\frac{dQ'}{d\psi} = C' = \frac{\varepsilon_r \varepsilon_0}{t}$$

$$Q' = eN_a t$$

$$\frac{dQ'}{d\psi} = \frac{\varepsilon_r \varepsilon_0 e N_a}{Q'} \qquad Q' dQ' = \varepsilon_r \varepsilon_0 e N_a d\psi \qquad \int \qquad \frac{1}{2} Q'^2 = \varepsilon_r \varepsilon_0 e N_a \psi$$

$$Q' = \sqrt{2\varepsilon_r \varepsilon_0 e N_a \psi} \qquad t = \sqrt{\frac{2\varepsilon_r \varepsilon_0 \psi}{e N_a}} \qquad C' = \sqrt{\frac{\varepsilon_r \varepsilon_0 e N_a}{2\psi}}$$

Potential in depleted Region

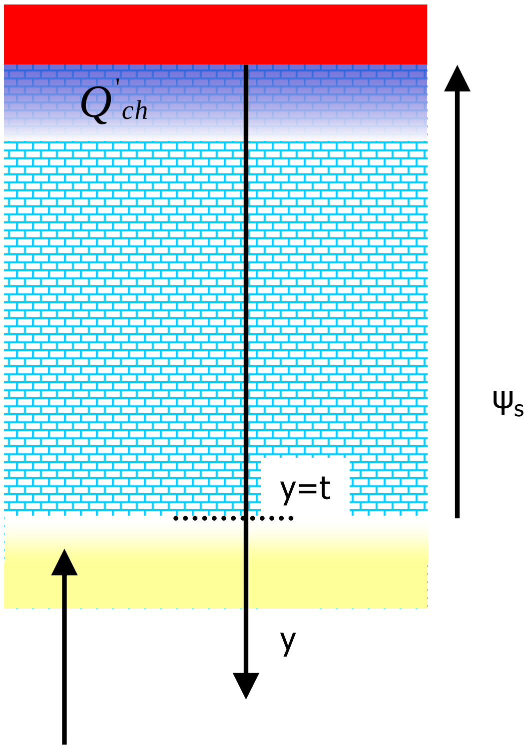


dQ beeinflusst nicht

$$d\psi = \frac{Q'}{C'(dy)} = \frac{eN_a t}{\frac{\varepsilon_r \varepsilon_0}{dy}} = \frac{eN_a dy}{\frac{\varepsilon_r \varepsilon_0}{t}} = \frac{eN_a dy}{C'}$$

$$C' = \sqrt{\frac{\varepsilon_r \varepsilon_0 e N_a}{2\psi}}$$

Charge in Channel



$$p_p = N_a$$

$$n_p = n_i^2 / N_a \equiv n_{p0}$$

$$\frac{d\psi}{dy} = -\frac{eN_a}{C'}$$

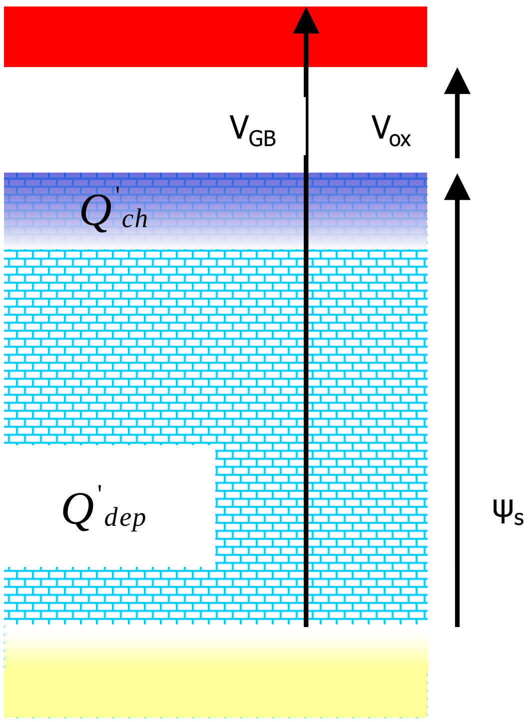
$$n_p = e n_{p0} e^{\frac{\psi(y)}{U_T}} \qquad \psi(y) = \psi_s + \frac{d\psi}{dy} y$$

$$n_p = e n_{p0} e^{\frac{\psi_s}{U_T}} e^{-\frac{eN_a y}{C' U_T}} \qquad Q'_{ch} = \int_0^t e n_{p0} e^{\frac{\psi_s}{U_T}} e^{-\frac{eN_a y}{C' U_T}} dy$$

$$Q'_{ch} = \frac{C' U_T}{eN_a} e n_{p0} e^{\frac{\psi_s}{U_T}}$$

$$C' = \sqrt{\frac{\varepsilon_r \varepsilon_0 e N_a}{2\psi_s}}$$

Charge in Channel

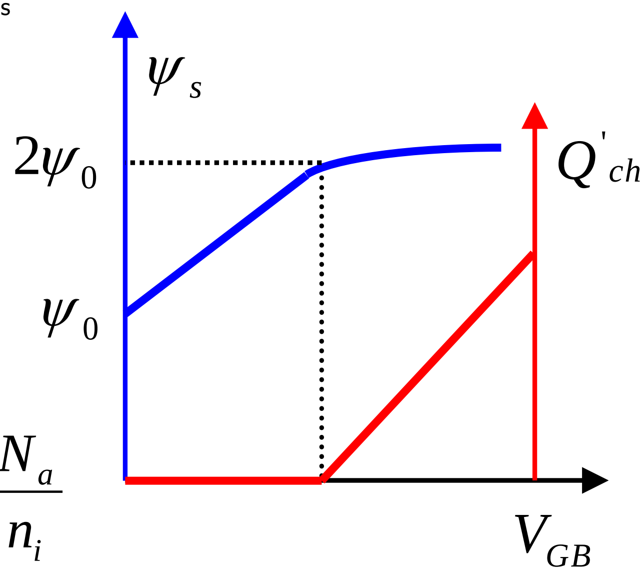


$$Q'_{ch} = C'(\psi_s) U_T \frac{n_i^2}{N_a^2} e^{\frac{\psi_s}{U_T}}$$

$$Q'_{dep} = \sqrt{2\varepsilon_r \varepsilon_0 e N_a \psi_s}$$

$$V_{GB} = \psi_s + V_{ox} = \psi_s + \frac{Q'_{ch}(\psi_s) + Q'_{dep}(\psi_s)}{C'_{ox}} \qquad (+V_{fb})$$

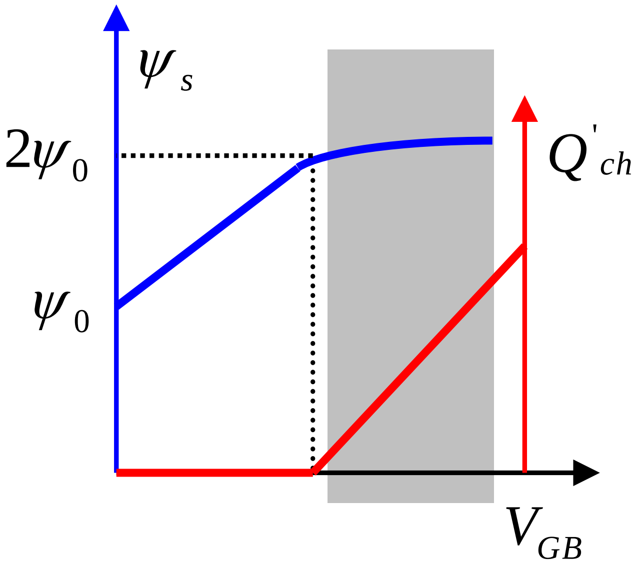
$$(-1)$$



$$\psi_0 \equiv U_T \ln \frac{N_a}{n_i}$$

$$\psi_0 \equiv U_T \ln \frac{N_a}{n_i} = 0.42V$$

strong Inversion



$$\psi_0 \equiv U_T \ln \frac{N_a}{n_i}$$

$$Q'_{ch} = C'(\psi_s) U_T \frac{n_i^2}{N_a^2} e^{\frac{\psi_s}{U_T}}$$

$$Q'_{dep} = \sqrt{2\varepsilon_r \varepsilon_0 e N_a \psi_s}$$

$$\psi_s \approx 2\psi_0 = 2U_T \ln \frac{N_a}{n_i}$$

$$V_{GB} = \psi_s + \frac{Q'_{ch}(\psi_s) + Q'_{dep}(\psi_s)}{C'_{ox}}$$

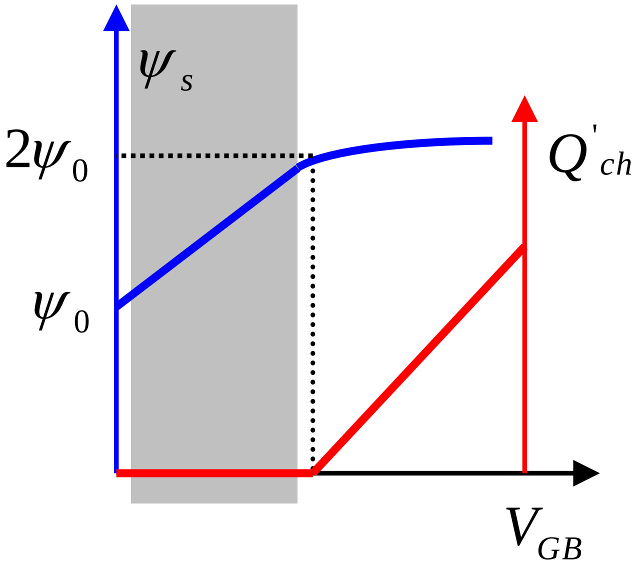
$$2\psi_0 + 6U_T$$

$$V_{GB} = 2\psi_0 + \frac{Q'_{ch} + Q'_{dep}(2\psi_0)}{C'_{ox}}$$

$$V_{TH} = V_{GB}(2\psi_0) = 2\psi_0 + \frac{Q'_{dep}(2\psi_0)}{C'_{ox}}$$

$$Q'_{ch} = C'_{ox}\left(V_{GB} - V_{TH}\right)$$

Weak Inversion



$$Q'_{ch} << Q'_{dep}$$

$$V_{GB} = \psi_s + \frac{Q'_{ch}(\psi_s) + Q'_{dep}(\psi_s)}{C'_{ox}}$$

$$V_{GB}(\psi_s) = \psi_s + \frac{Q'_{dep}(\psi_s)}{C'_{ox}}$$

$$C' = \frac{dQ_{dep}}{d\psi_s}$$

$$V_{GB} = V_{GB}(2\psi_0) + \left.\frac{dV_{GB}}{d\psi_s}\right|_{2\psi_0}(2\psi_0 - \psi_s)$$

$$\psi_0 \equiv U_T \ln\frac{N_a}{n_i}$$

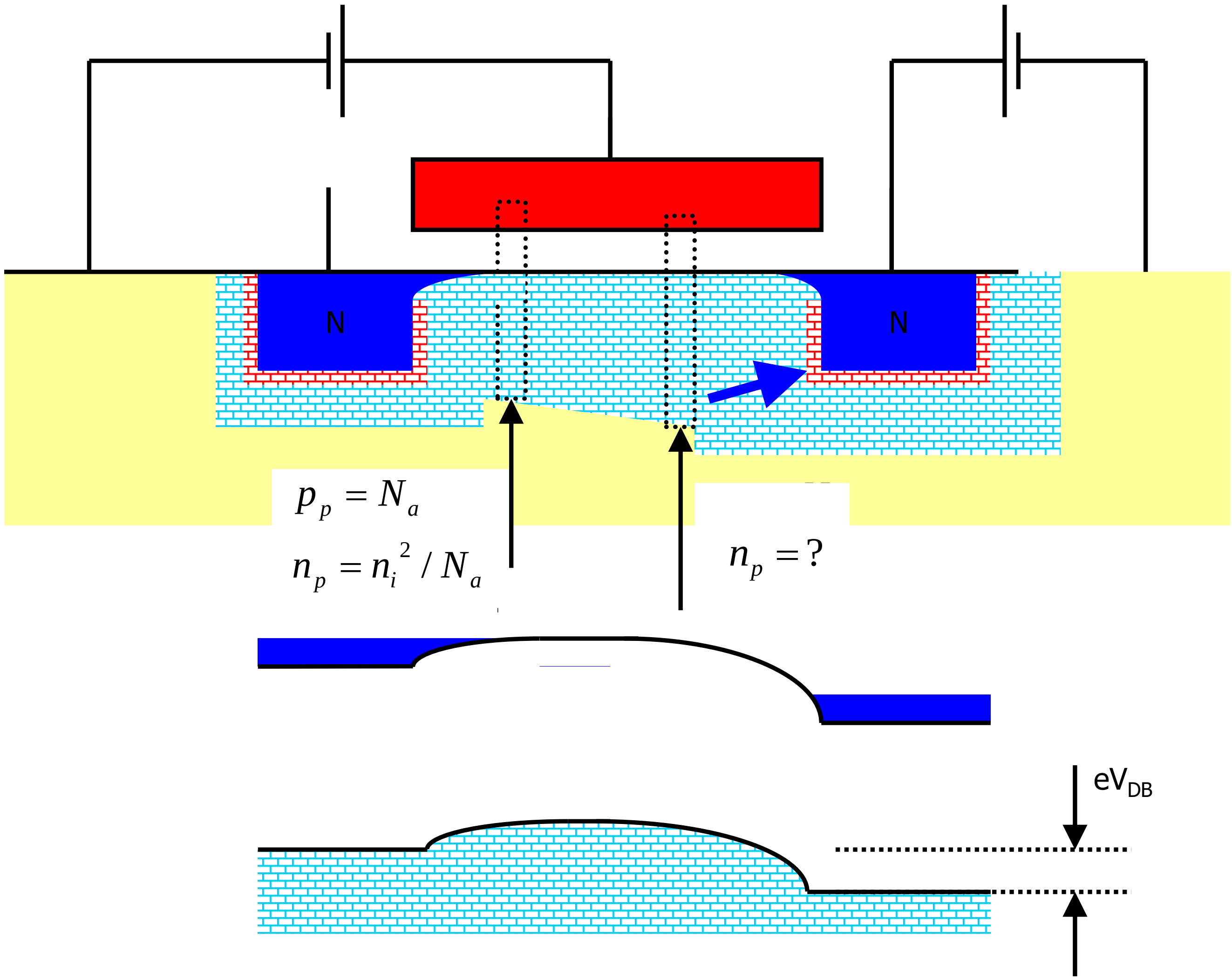
$$Q'_{ch} = C'(\psi_s) U_T \frac{n_i^2}{N_a^2} e^{\frac{\psi_s}{U_T}}$$

$$Q'_{dep} = \sqrt{2\varepsilon_r\varepsilon_0 e N_a \psi_s}$$

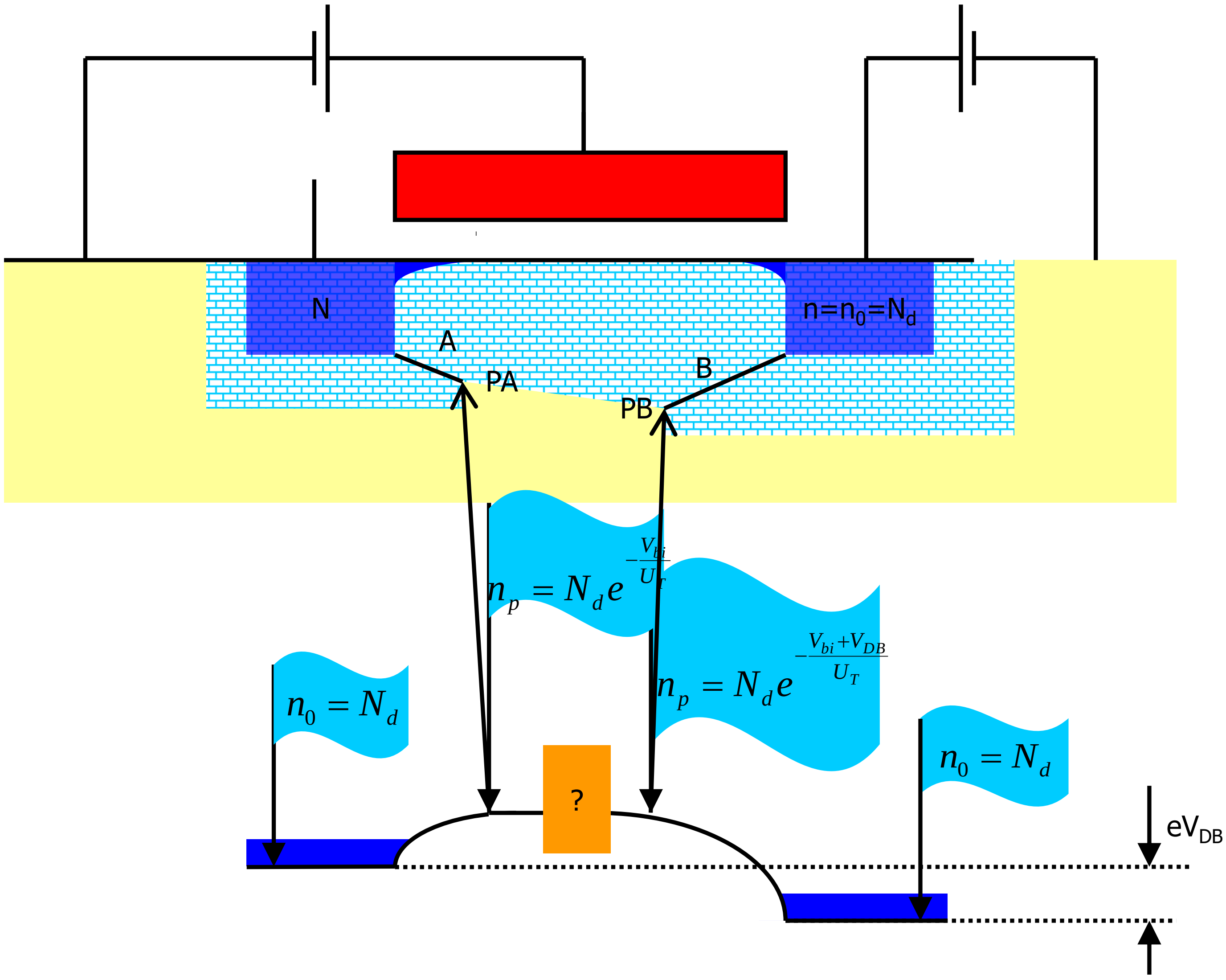
$$\psi_s = 2\psi_0 + \frac{V_{GB} - V_{TH}}{n} \qquad 1 + \frac{C'(2\psi_0)}{C'_{ox}} \equiv n$$

$$Q'_{ch} \approx (n-1) C'_{ox} U_T e^{\frac{V_{GB} - V_{TH}}{n U_T}}$$

Drain Bias

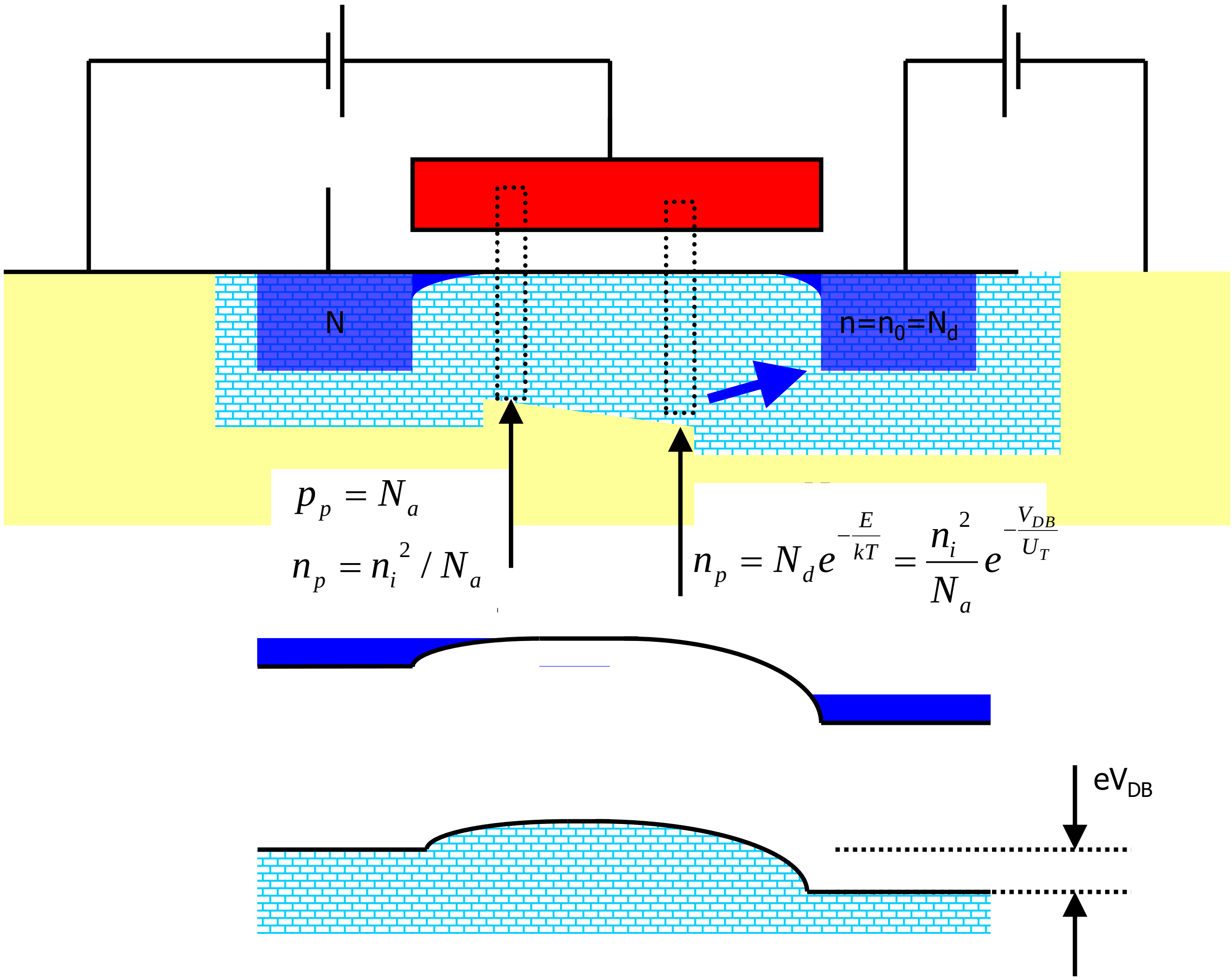


Drain Bias



N
$n=n_0=N_d$
A
PA
B
PB
$n_p = N_d e^{-\frac{V_{bi}}{U_T}}$
$n_p = N_d e^{-\frac{V_{bi}+V_{DB}}{U_T}}$
$n_0 = N_d$
$n_0 = N_d$
?
eV_{DB}

Drain Bias


N
n=n0=Nd
$p_p = N_a$
$n_p = n_i^2 / N_a$
$n_p = N_d e^{-\frac{E}{kT}} = \frac{n_i^2}{N_a} e^{-\frac{V_{DB}}{U_T}}$
eVDB

Drain Bias

$$\psi_0 \equiv U_T \ln \frac{N_a}{n_i}$$

$$V_{TH} = V_{GB}(2\psi_0) = 2\psi_0 + \frac{Q'_{dep}(2\psi_0)}{C'_{ox}}$$

$$Q'_{ch} = C'_{ox}\left(V_{GB} - V_{TH}\right)$$

$$Q'_{ch} \approx (n-1)C'_{ox}U_T e^{\frac{V_{GB}-V_{TH}}{nU_T}}$$

$$\frac{n_i^{\,2}}{N_a} \rightarrow \frac{n_i^{\,2}}{N_a} e^{-\frac{V_{DG}}{U_T}}$$

$$2\psi_0 \rightarrow 2\psi_0 + V_{DB}$$

$$V_{TH} \rightarrow V_{TH} + nV_{DB}$$

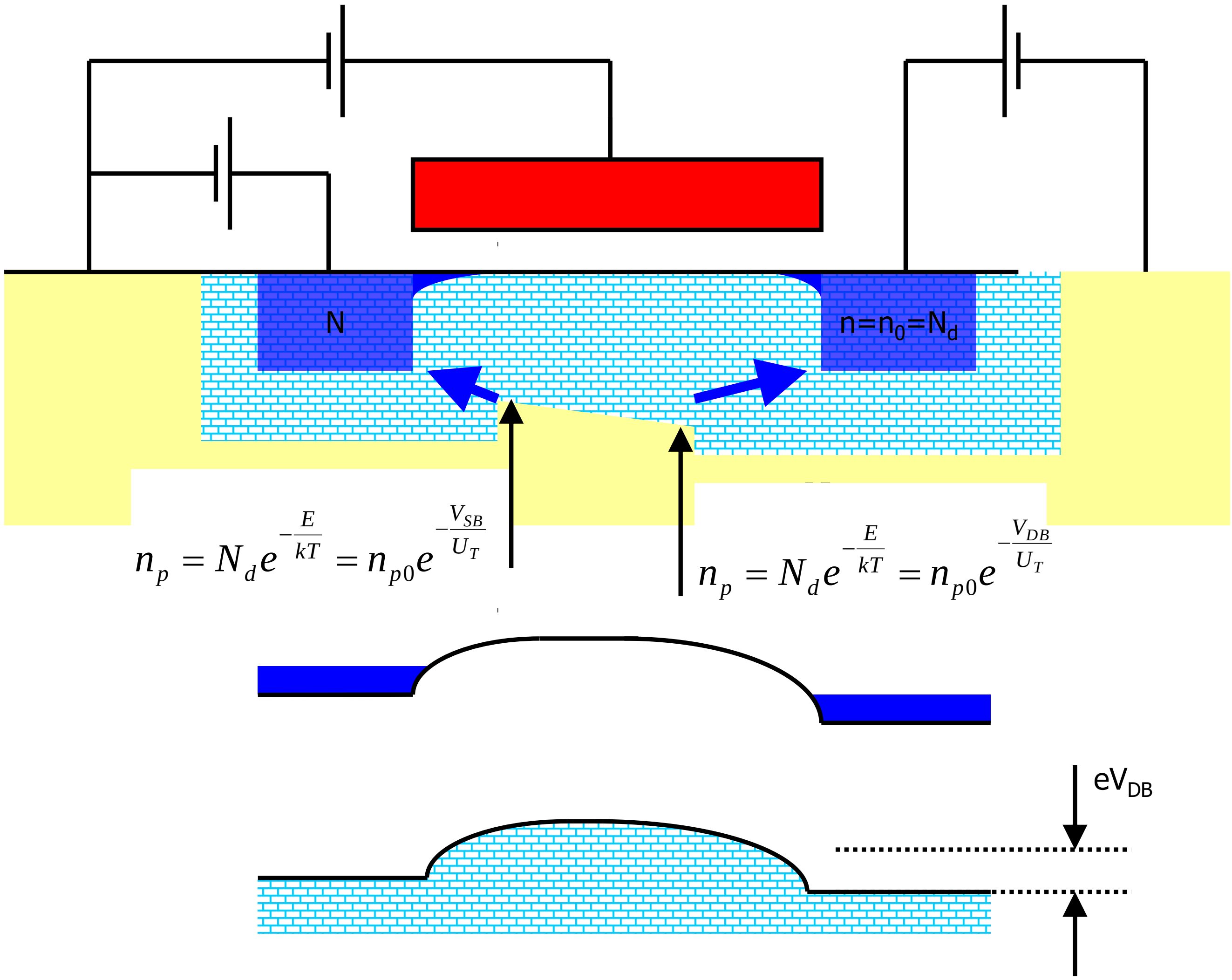
$$Q'_{ch} \approx C'_{ox}\left(V_{GB} - V_{TH} - nV_{DB}\right)$$

$$Q'_{ch} \approx (n-1)C'_{ox}U_T e^{\frac{V_{GB}-V_{TH}}{nU_T}} e^{-\frac{V_{DB}}{U_T}}$$

$$V_{TH} = V_{GB}(2\psi_0) = 2\psi_0 + \frac{\sqrt{2\varepsilon_r\varepsilon_0 e N_a 2\psi_0}}{C'_{ox}}$$

$$1 + \frac{C'(2\psi_0)}{C'_{ox}} \equiv n$$

Drain and Source Bias



$$n_p = N_d e^{-\frac{E}{kT}} = n_{p0} e^{-\frac{V_{SB}}{U_T}}$$

$$n_p = N_d e^{-\frac{E}{kT}} = n_{p0} e^{-\frac{V_{DB}}{U_T}}$$

Charge in Channel

$$Q'_{ch} \approx C'_{ox}\left(V_{GS} - V_{TH} - nV_x\right)$$

$$Q'_{ch} \approx (n-1)C'_{ox}U_T e^{\frac{V_{GS}-V_{TH}}{nU_T}} e^{-\frac{V_x}{U_T}}$$

$$V_x \in (0, V_{DS})$$

$$V_{TH} = 2\psi_0 + \frac{\sqrt{2\varepsilon_r\varepsilon_0 e N_a\left(2\psi_0 + V_{SB}\right)}}{C'_{ox}}$$

$$1 + \frac{C'(2\psi_0 + V_{SB})}{C'_{ox}} \equiv n$$

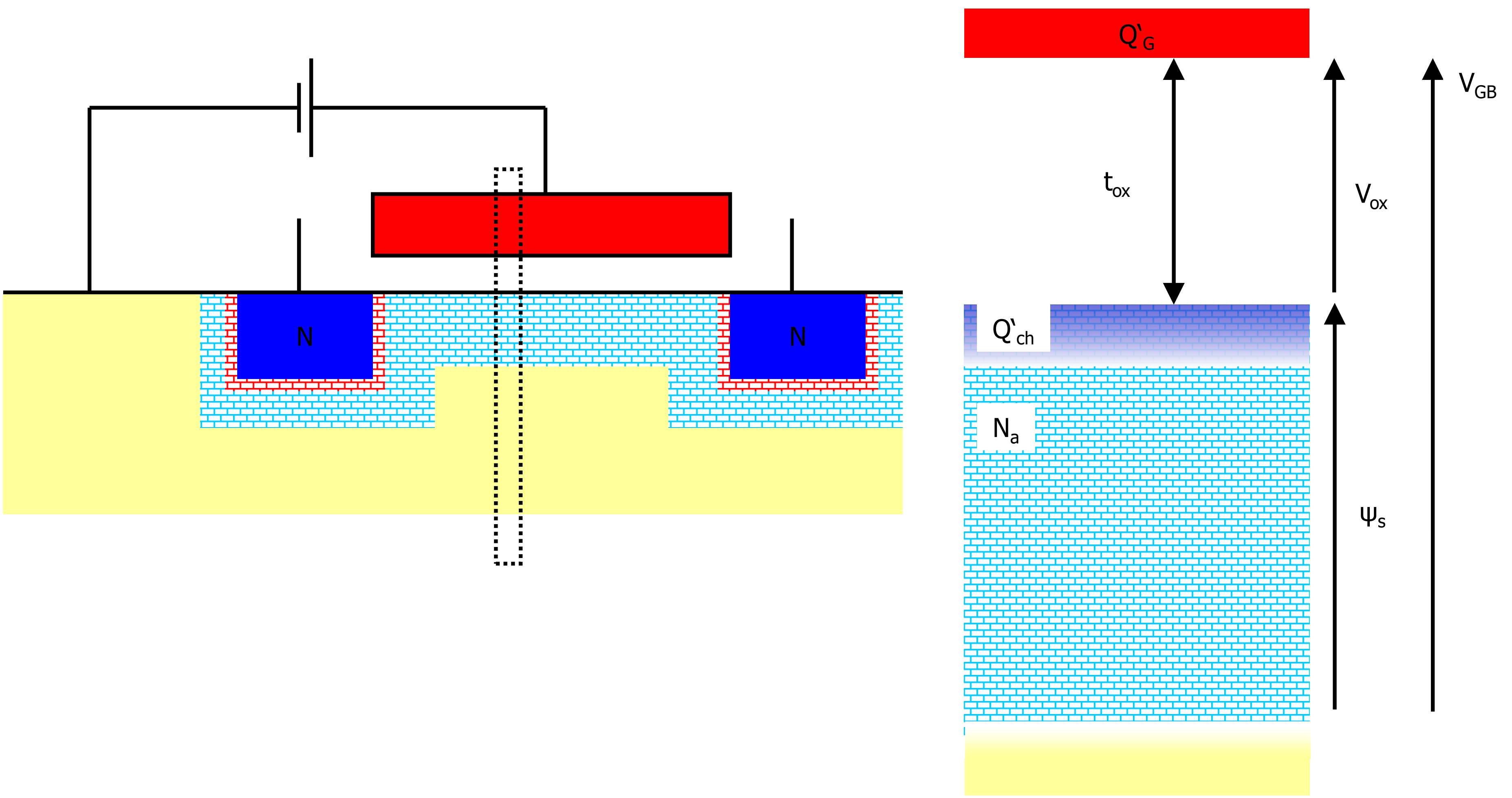
$$Q'_{ch} \approx C'_{ox}\left(V_{GB} - V_{TH0} - nV_x\right)$$

$$Q'_{ch} \approx (n-1)C'_{ox}U_T e^{\frac{V_{GB}-V_{TH0}}{nU_T}} e^{-\frac{V_x}{U_T}}$$

$$V_x \in (V_{SB}, V_{DB})$$

$$V_{TH0} = 2\psi_0 + \frac{\sqrt{2\varepsilon_r\varepsilon_0 e N_a\left(2\psi_0\right)}}{C'_{ox}}$$

Gate Bias



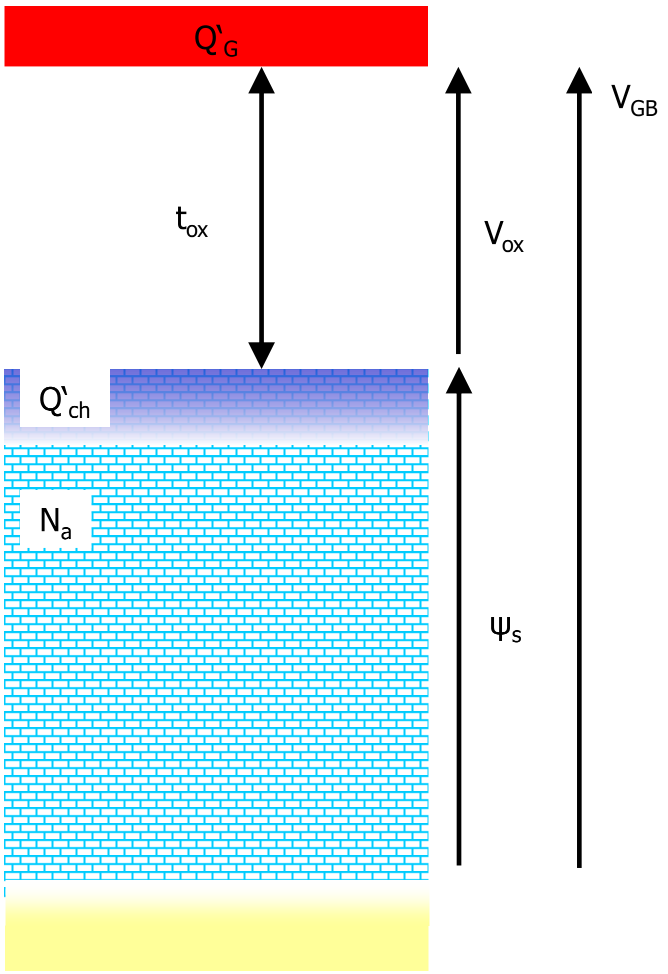
Gate Bias

$$V_{TH} = V_{GB}(2\psi_0) = 2\psi_0 + \frac{\sqrt{2\varepsilon_r\varepsilon_0 e N_a 2\psi_0}}{C'_{ox}}$$

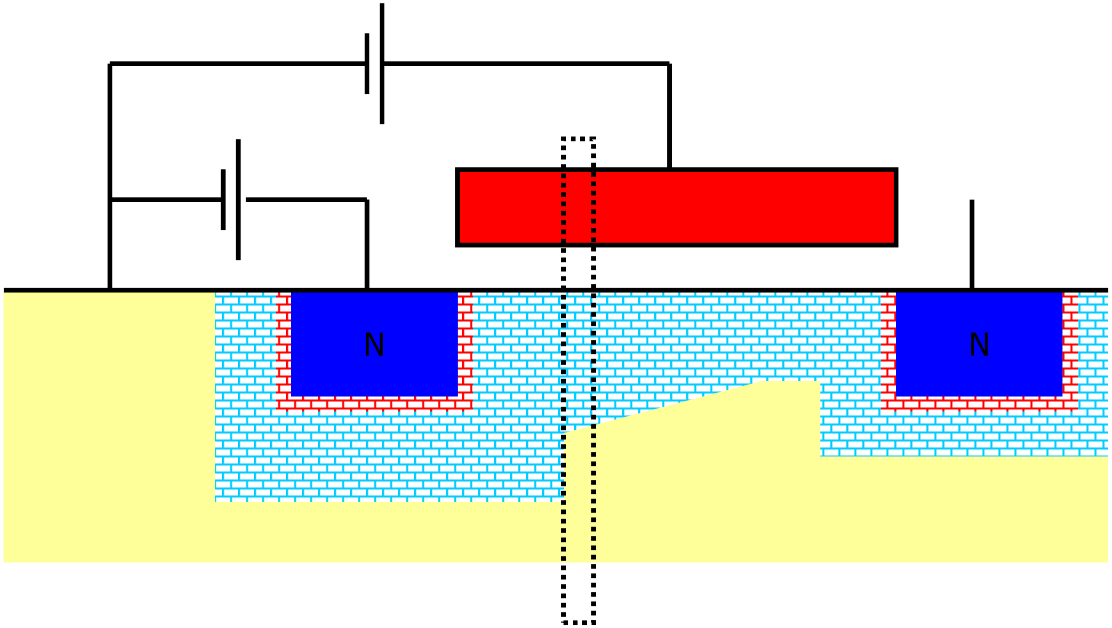
$$Q'_{ch} = C'_{ox}\left(V_{GB} - V_{TH}\right)$$

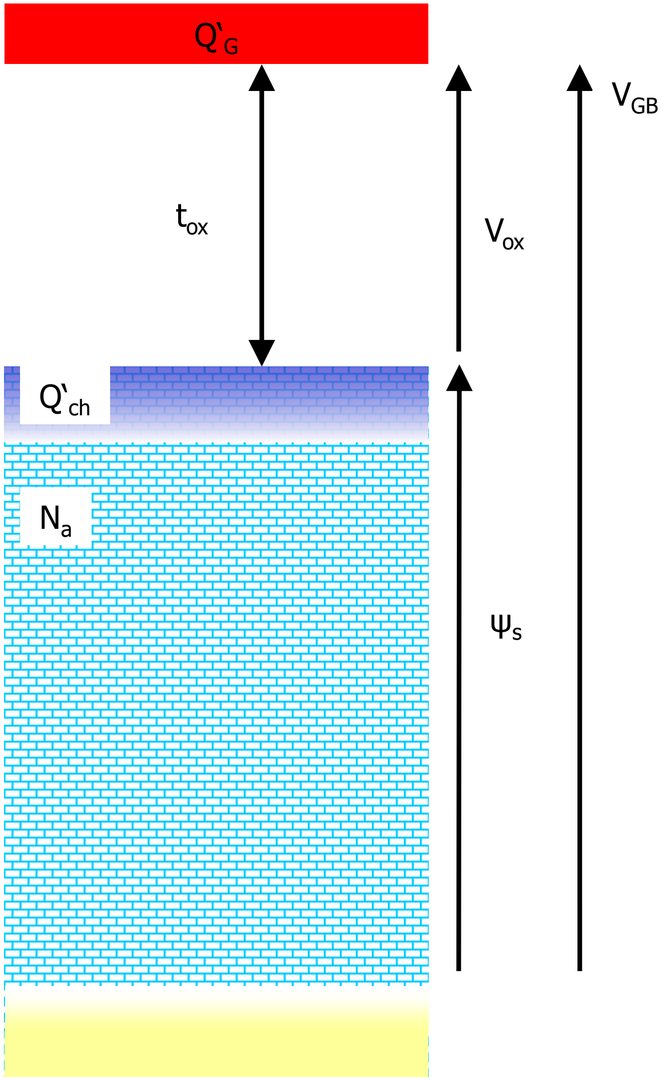
$$Q'_{ch} \approx (n-1)C'_{ox}U_T e^{\frac{V_{GB}-V_{TH}}{nU_T}}$$

$$1 + \frac{C'(2\psi_0)}{C'_{ox}} \equiv n$$



Source Bias





$$\psi_s = 2\psi_0$$

$$\psi_s = 2\psi_0 + V_{SB}$$

Source Bias

$$V_{TH} = 2\psi_0 + \frac{\sqrt{2\varepsilon_r\varepsilon_0 e N_a (2\psi_0 + V_{SB})}}{C'_{ox}}$$

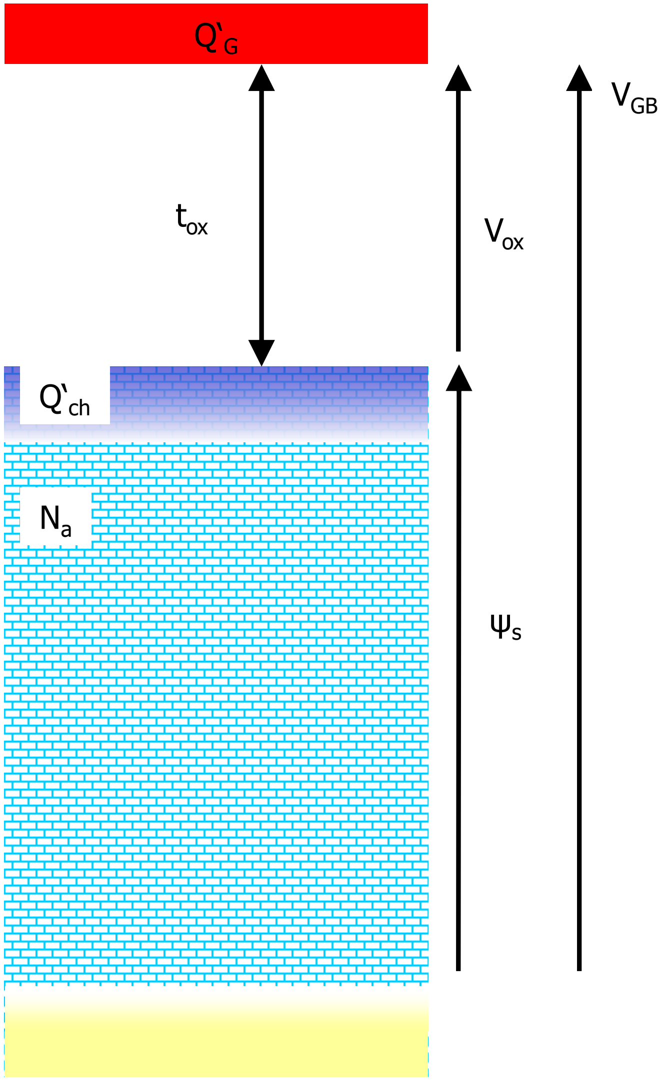
$$Q'_{ch} = C'_{ox}(V_{GS} - V_{TH})$$

$$Q'_{ch} \approx (n-1)C'_{ox}U_T e^{\frac{V_{GS}-V_{TH}}{nU_T}}$$

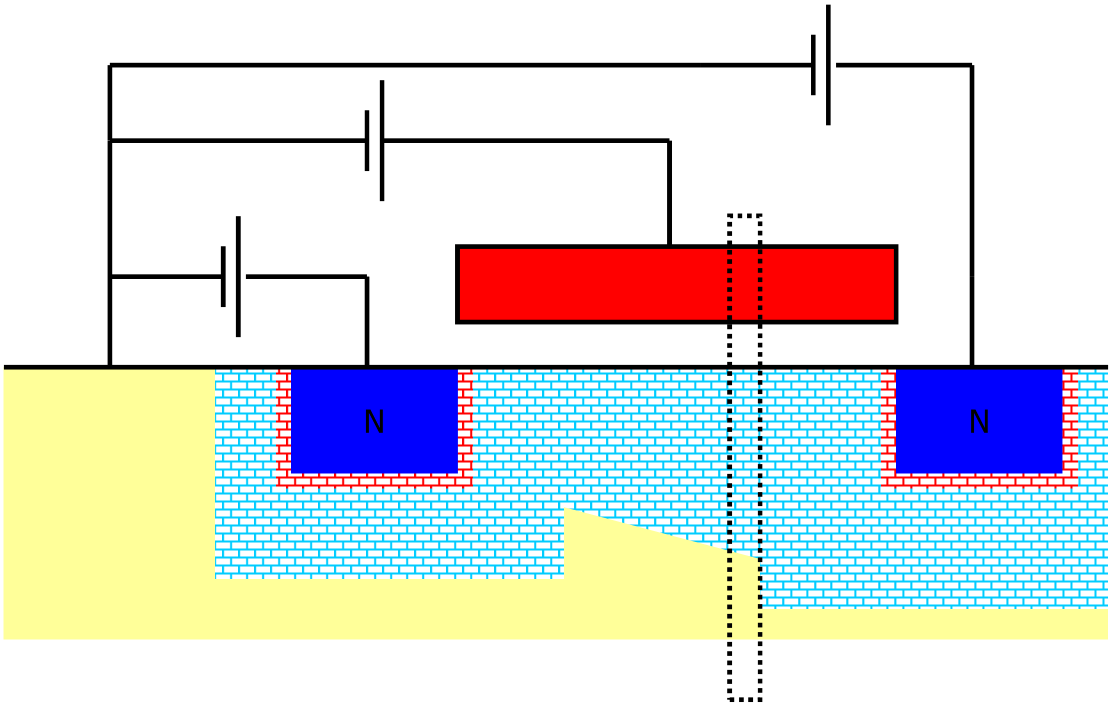
$$1 + \frac{C'(2\psi_0 + V_{SB})}{C'_{ox}} \equiv n$$

$$V_{TH0} = 2\psi_0 + \frac{\sqrt{2\varepsilon_r\varepsilon_0 e N_a 2\psi_0}}{C'_{ox}}$$

$$Q'_{ch} = C'_{ox}(V_{GB} - V_{TH0} - nV_{SB})$$



Drain Bias



Drain Bias

$$V_{TH} = 2\psi_0 + \frac{\sqrt{2\varepsilon_r\varepsilon_0 e N_a (2\psi_0 + V_{SB})}}{C'_{ox}}$$

$$Q'_{ch} = C'_{ox}(V_{GS} - V_{TH} - nV_x)$$

$$Q'_{ch} \approx (n-1)C'_{ox}U_T e^{\frac{V_{GS}-V_{TH}}{nU_T}} e^{-\frac{V_x}{U_T}}$$

$$1 + \frac{C'(2\psi_0 + V_{SB})}{C'_{ox}} \equiv n$$

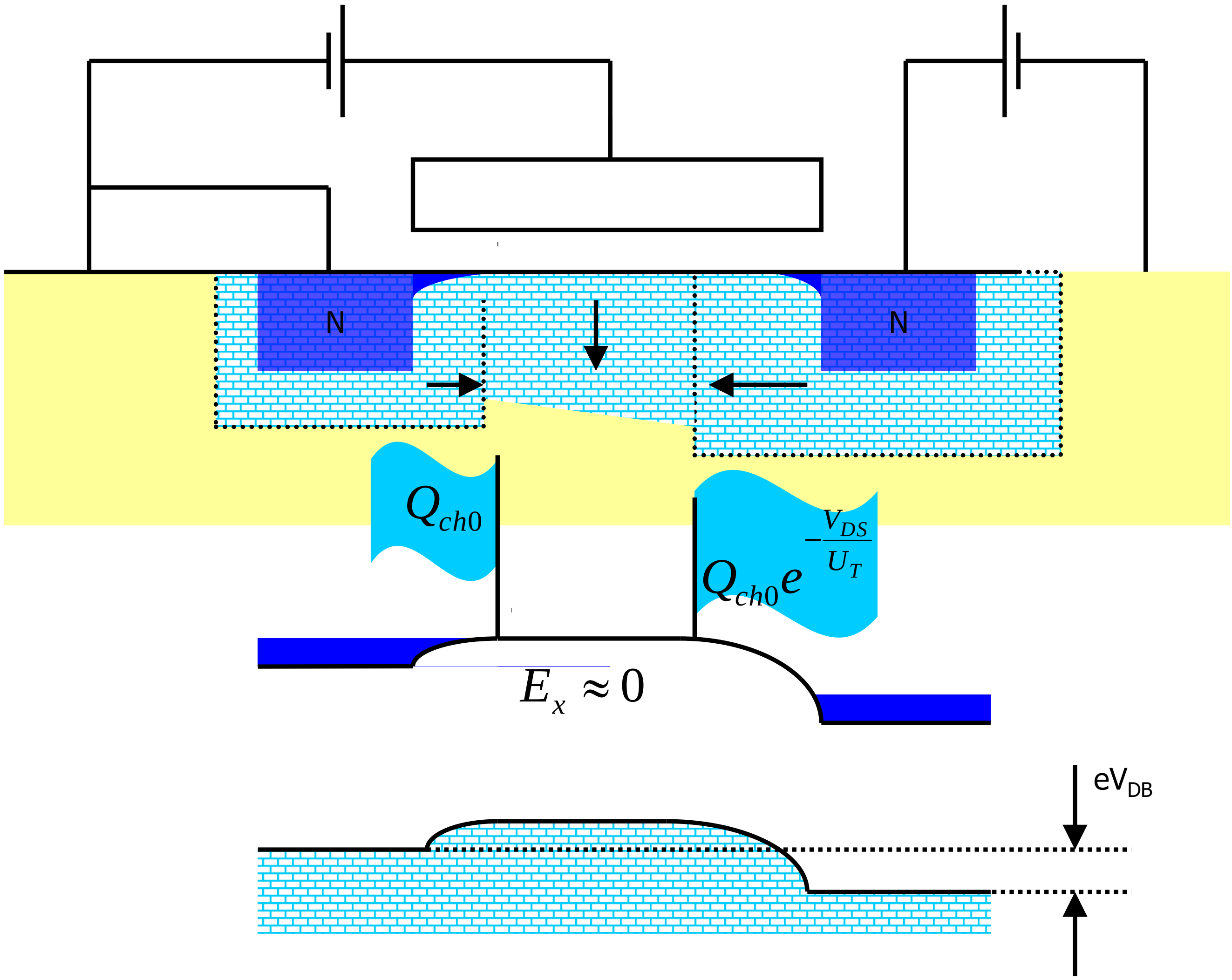
$$V_{TH0} = 2\psi_0 + \frac{\sqrt{2\varepsilon_r\varepsilon_0 e N_a 2\psi_0}}{C'_{ox}}$$

$$Q'_{ch} = C'_{ox}(V_{GB} - V_{TH0} - nV_x)$$

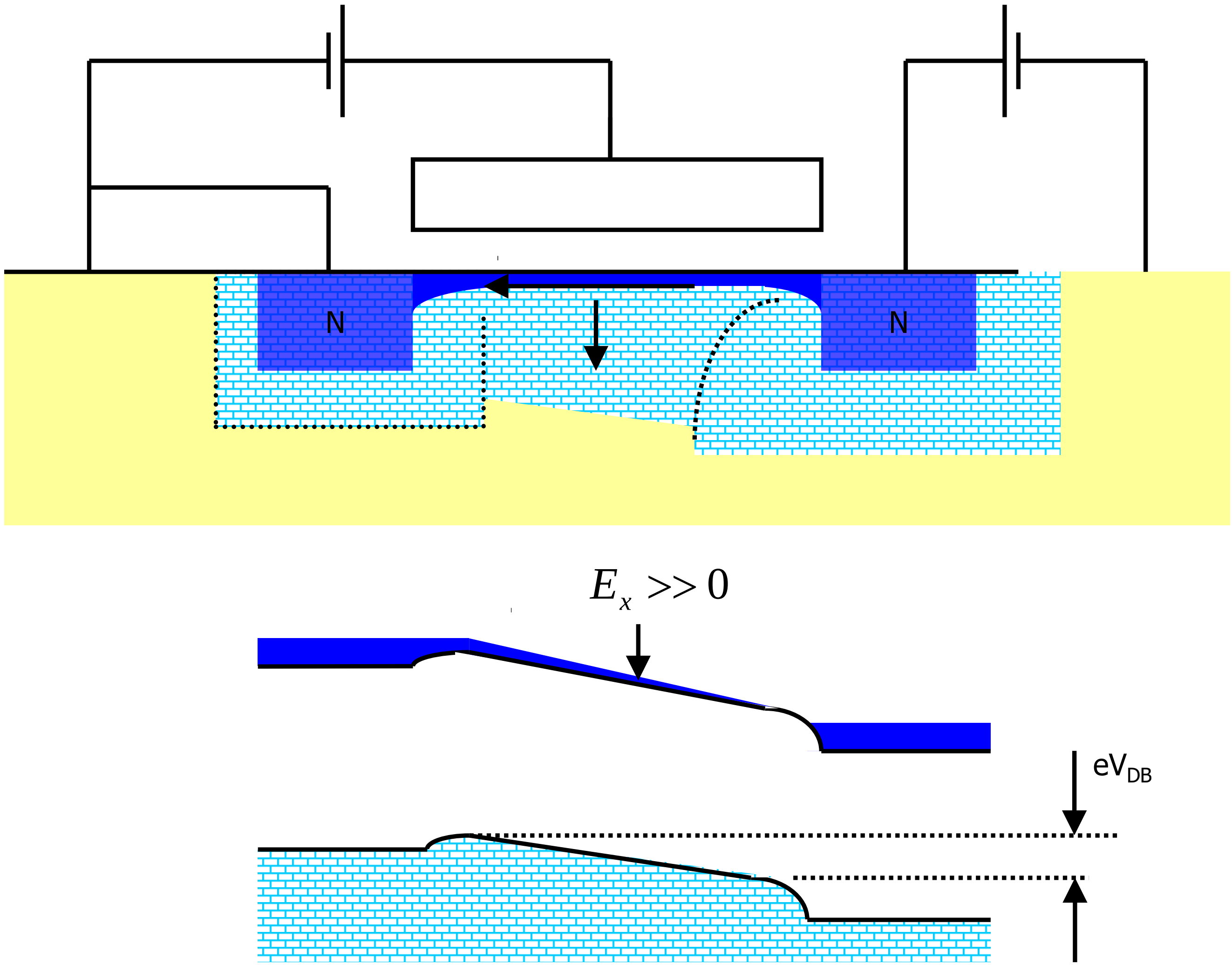
$$Q'_{ch} \approx (n-1)C'_{ox}U_T e^{\frac{V_{GB}-V_{TH0}}{nU_T}} e^{-\frac{V_x}{U_T}}$$

$$V_x \in (V_{SB}, V_{DB})$$

Weak Inversion



Strong Inversion



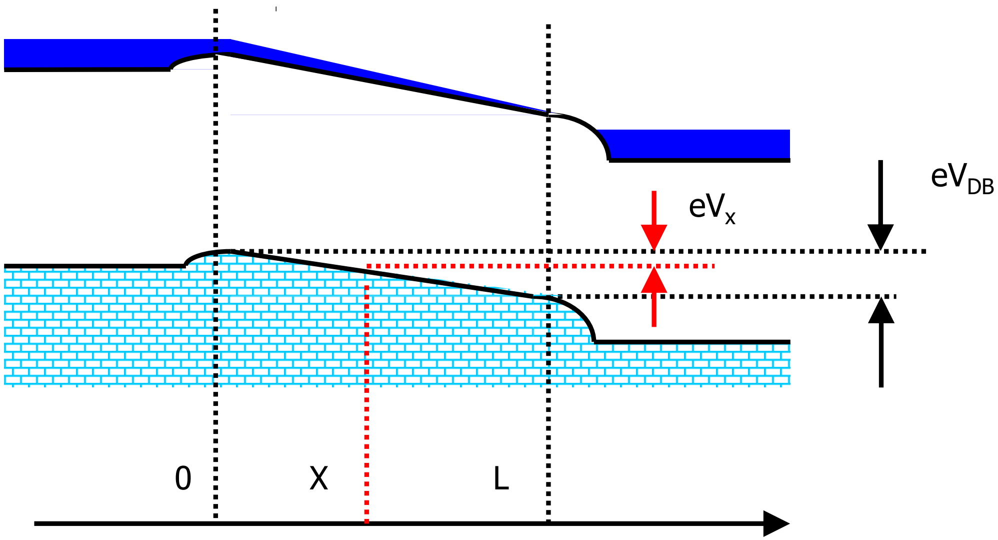
Strong Inversion - Drain Current

$$I(x) = W\mu Q'_{ch}\frac{dV_x}{dx} = const(x)$$

$$\int I dx = \int W\mu Q'_{ch}\frac{dV_x}{dx}dx$$

$$\int_0^L I dx = \int_0^{V_{DS}} W\mu Q'_{ch} dV_x$$

$$IL = \int_0^{V_{DS}} W\mu Q'_{ch} dV_x$$



$$I = \mu\frac{W}{L}\int_0^{V_{DS}} Q'_{ch} dV_x \leftarrow Q'_{ch} \approx C'_{ox}(V_{GS} - V_{TH} - nV_x)$$

Weak Inversion - Drain Current

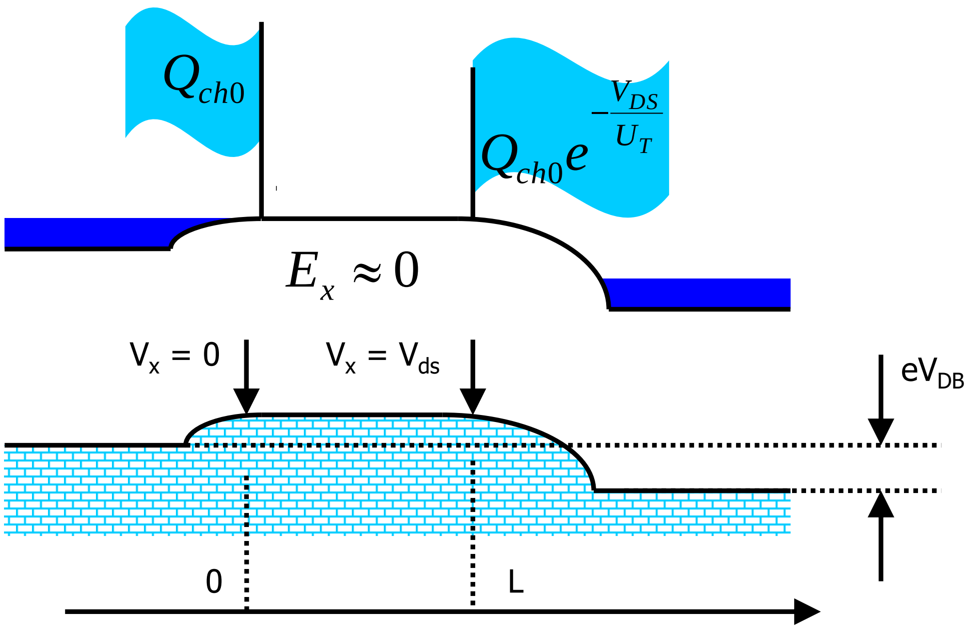
$$I(x) = -WD\frac{dQ'_{ch}}{dx} = const(x)$$

$$\int I(x)dx = -\int WD\frac{dQ'_{ch}}{dx}dx$$

$$\int_0^L Idx = -\int_0^{V_{DS}} WD\frac{dQ'_{ch}}{dV_x}dV_x$$

$$Q'_{ch} \approx (n-1)C'_{ox}U_T e^{\frac{V_{GS}-V_{TH}}{nU_T}} e^{-\frac{V_x}{U_T}}$$

$$LI = \int_0^{V_{DS}} W\frac{D}{U_T}Q'_{ch}dV_x$$



$$I = \mu\frac{W}{L}\int_0^{V_{DS}} Q'_{ch}dV_x$$

Strong- and Weak Inversion

$$I = \mu \frac{W}{L} \int_0^{V_{DS}} Q'_{ch} dV_x$$

$$Q'_{ch} \approx (n-1) C'_{ox} U_T e^{\frac{V_{GS}-V_{TH}}{nU_T}} e^{-\frac{V_x}{U_T}}$$

$$I = \mu C'_{ox} \frac{W}{L} (n-1) U_T{}^2 e^{\frac{V_{GST}}{nU_T}} \left(1 - e^{-\frac{V_{DS}}{U_T}}\right)$$

$$Q'_{ch} \approx C'_{ox} \left(V_{GS} - V_{TH} - nV_x\right)$$

$$I = \mu C'_{ox} \frac{W}{L} \left(V_{GST} V_{DS} - n \frac{V_{DS}{}^2}{2}\right)$$

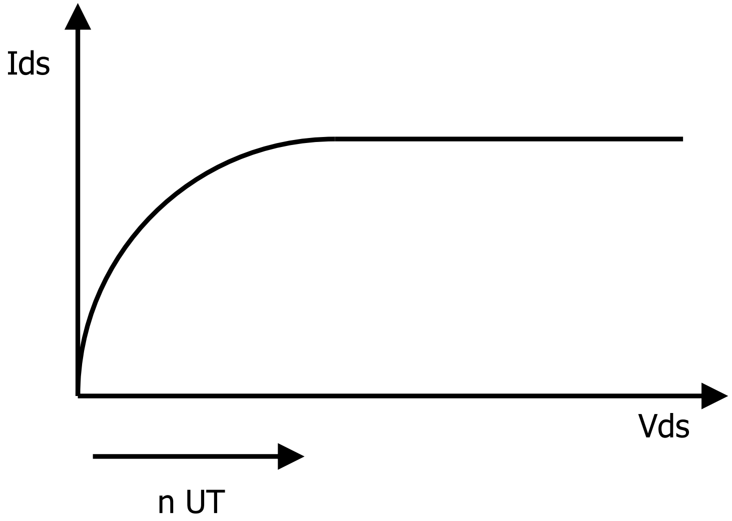
$$I = \mu C'_{ox} \frac{W}{L} \left[\left(V_{GBT} - nV_{SB}\right)^2 - \left(V_{GBT} - nV_{DB}\right)^2\right]$$

$$V_{GST} \equiv V_{GS} - V_T ; \; V_{GBT} \equiv V_{GB} - V_{T0}$$

Weak Inversion

$$Q'_{ch} \approx (n-1)C'_{ox}U_T e^{\frac{V_{GS}-V_{TH}}{nU_T}} e^{-\frac{V_x}{U_T}}$$

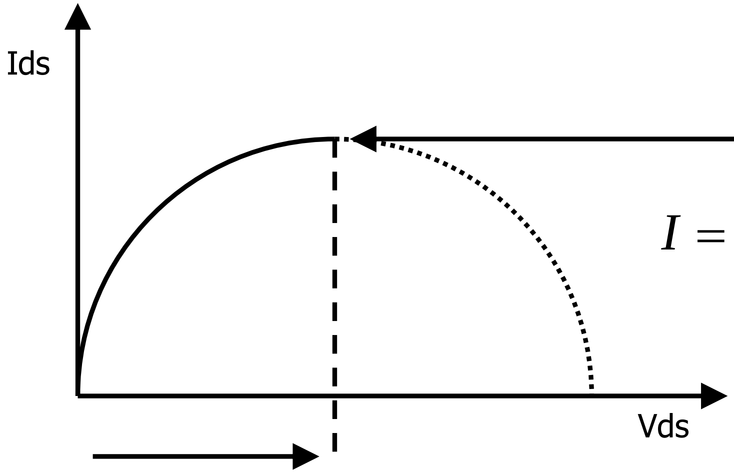
$$I = \mu C'_{ox}\frac{W}{L}(n-1)U_T{}^2 e^{\frac{V_{GST}}{nU_T}}\left(1-e^{-\frac{V_{DS}}{U_T}}\right)$$



Strong Inversion

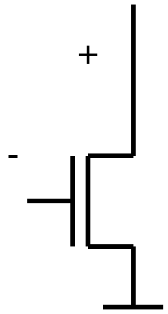
$$Q'_{ch} \approx C'_{ox}\left(V_{GS} - V_{TH} - nV_x\right)$$

$$I = \mu C'_{ox}\frac{W}{L}\left(V_{GST}V_{DS} - n\frac{V_{DS}^{\;2}}{2}\right)$$



$$\frac{V_{GS} - V_{TH}}{n}$$

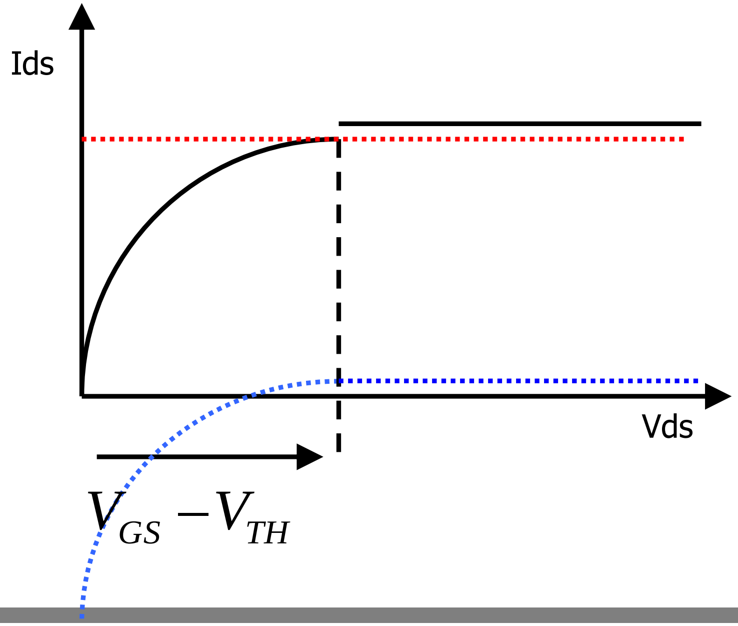
$$I = \mu C'_{ox}\frac{W}{L}\frac{V_{GST}^{\;2}}{2n}$$

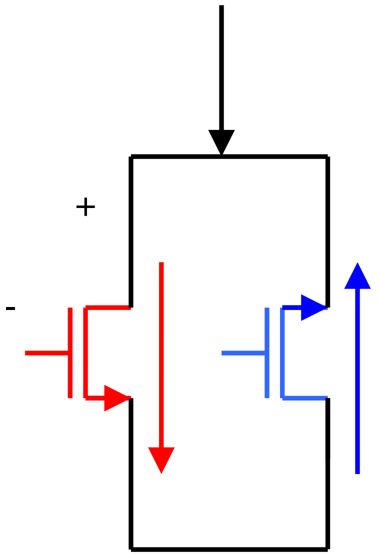


EKV

$$I = \mu C'_{ox} \frac{W}{L}\left[\left(V_{GBT} - nV_{SB}\right)^2 - \left(V_{GBT} - nV_{DB}\right)^2\right]$$

$$V_{GST} \equiv V_{GS} - V_T;\ V_{GBT} \equiv V_{GB} - V_{T0}$$





BSIM - Drain Current

$$I(x) = W\mu Q'_{ch}\frac{dV_x}{dx} = const(x) \qquad Q'_{ch} \approx C'_{ox}\left(V_{GS} - V_{TH} - nV_x\right)$$

$$v = \mu E_x \qquad E_x < E_{sat} \qquad \mu = \frac{\mu_0}{1 + E_x / E_{sat}}$$

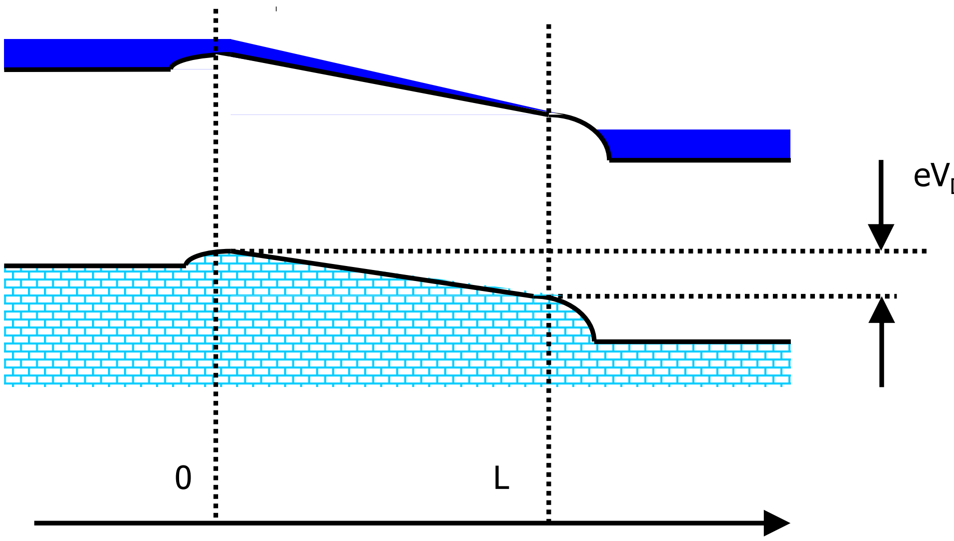
$$E_x > E_{sat} \qquad v = v_{sat} = \frac{\mu_0}{2}E_{sat}$$

$$\int I\left(1 + \frac{1}{E_{sat}}\frac{dV_x}{dx}\right)dx = \int W\mu_0 Q'_{ch}\frac{dV_x}{dx}dx$$

$$I = \frac{\mu_0 C'_{ox} W}{L\left(1 + \frac{V_{DS}}{LE_{sat}}\right)}\left(V_{GST} - n\frac{V_{DS}^{\ 2}}{2}\right)$$

BSIM - Saturation

$$I = \frac{\mu_0 C'_{ox} W}{L\left(1+\frac{V_{DS}}{LE_{sat}}\right)}\left(V_{GST} - n\frac{V_{DS}^2}{2}\right)$$



$$I_{sat} = v_{sat} W Q'_{ch}(L)$$

$$Q'_{ch} \approx C'_{ox}\left(V_{GST} - nV_x\right)$$

$$I_{sat} = \frac{\mu_0}{2} E_{sat} W C'_{ox}\left(V_{GST} - nV_{DSSAT}\right)$$

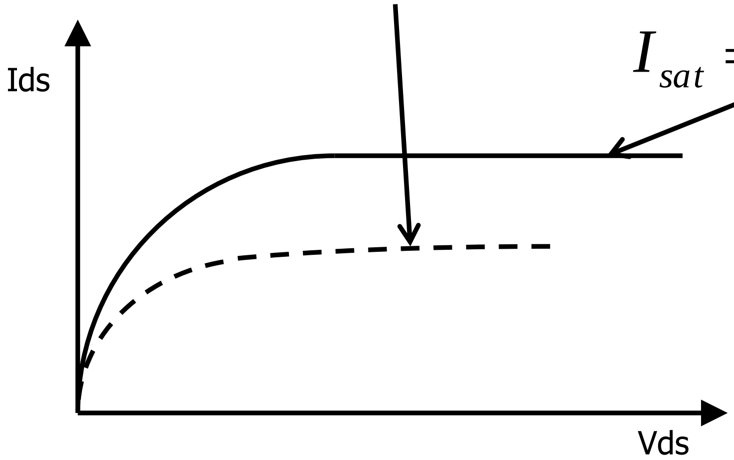
$$\frac{\mu_0 C'_{ox} W}{L\left(1+\frac{V_{DSSAT}}{LE_{sat}}\right)}\left(V_{GST} - n\frac{V_{DSSAT}^2}{2}\right) = \frac{\mu_0}{2} E_{sat} C'_{ox} W\left(V_{GST} - nV_{DSSAT}\right)$$

BSIM - Saturation

$$V_{DSSAT} = \frac{V_{GST}}{n\left(1 + \frac{V_{GST}}{nLE_{sat}}\right)}$$

$$I_{sat} = \frac{\mu_0 C'_{ox} W}{L\left(1 + \frac{V_{GST}}{nLE_{sat}}\right)} \frac{V_{GST}^{\ 2}}{2n}$$

$$I_{sat} = \frac{\mu_0 C'_{ox} W}{L} \frac{V_{GST}^{\ 2}}{2}$$



$$U_T = 26mV$$

$$\varepsilon_{si} = 11\varepsilon_0$$

$$2\psi_0 = 0.85V$$

$$C'_{ox} = 3\,fF/\mu m^2$$

$$\mu_{n0} = 0.067m^2/Vs$$

$$\mu_{p0} = 0.025m^2/Vs$$

$$E_{sn} = 2.4V/\mu m$$

$$E_{sp} = 6.4V/\mu m$$

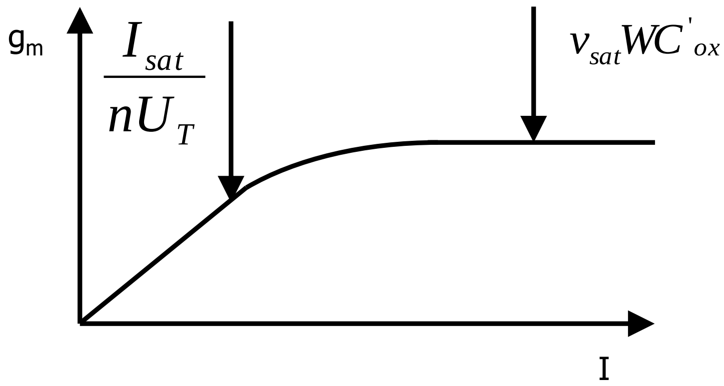
$$V_{TH} = 0.57V$$

$$n = 1.42$$

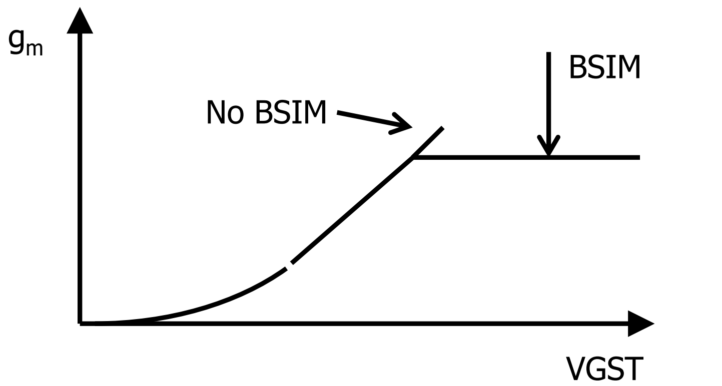
Trans-conductance

$$I_{sat} = \mu C'_{ox}\frac{W}{L}(n-1)U_T^{\,2} e^{\frac{V_{GST}}{nU_T}}$$

$$I_{sat} = \frac{\mu_0 C'_{ox} W}{L\left(1+\frac{V_{GST}}{nLE_{sat}}\right)}\frac{V_{GST}^{\,2}}{2n}$$



$$I_{sat} = \frac{\mu_0 C'_{ox} W}{L}\frac{V_{GST}^{\,2}}{2n}$$



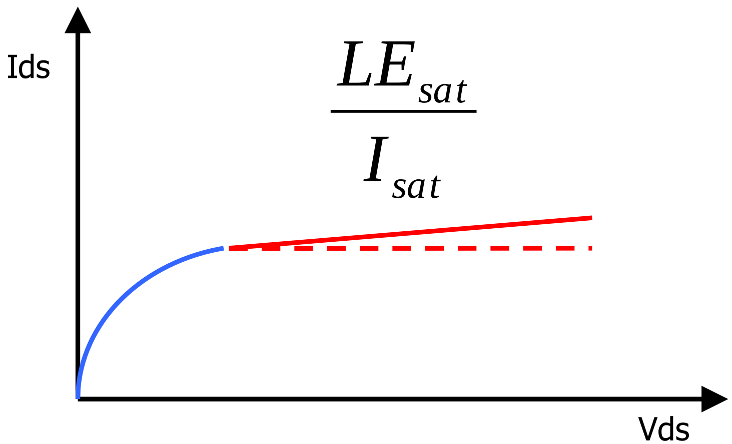
$$I_{sat} = \frac{\mu_0}{2}E_{sat}WC'_{ox}V_{GST} = v_{sat}WC'_{ox}V_{GST}$$

BSIM – Early Effekt

$$I = \frac{\mu_0 C'_{ox} W}{L\left(1+\frac{V_{DS}}{LE_{sat}}\right)}\left(V_{GST} - n\frac{V_{DS}^2}{2}\right)$$

$$I_{sat} = \frac{\mu_0 C'_{ox} W}{L\left(1+\frac{V_{GST}}{nLE_{sat}}\right)}\frac{V_{GST}^2}{2n}$$

$$I = I_{sat} + \left.\frac{\partial I}{\partial V_{DS}}\right|_{V_{DSSAT}}\left(V_{DS} - V_{DSSAT}\right)$$



$$\frac{LE_{sat}}{I_{sat}}$$

$$I = I_{sat}\left(1+\frac{V_{DS} - V_{DSSAT}}{V_A}\right)$$

$$V_A = LE_{sat} + V_{DSSAT}$$