Section 28
MOS Electrostatics & MOScap

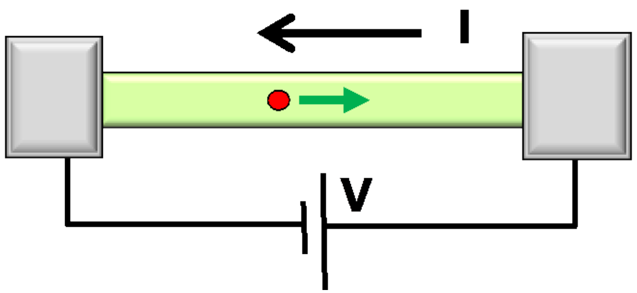
28.4 MOScap Induced charges in depletion and inversion

Gerhard Klimeck
gekco@purdue.edu

PURDUE UNIVERSITY

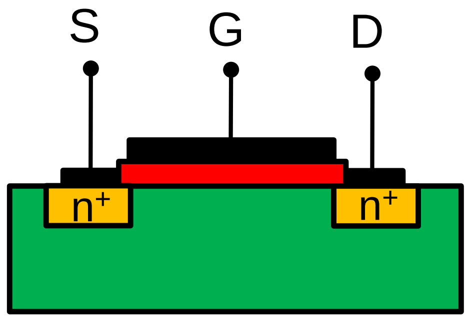
School of Electrical and Computer Engineering

Section 28
MOS Electrostatics & MOScap

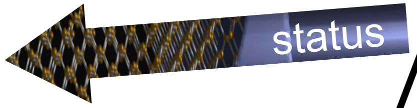


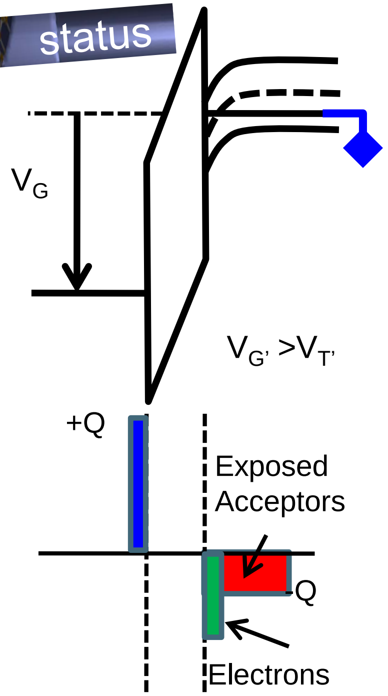
$$I = G \times V$$
$$= q \times n \times v \times A$$

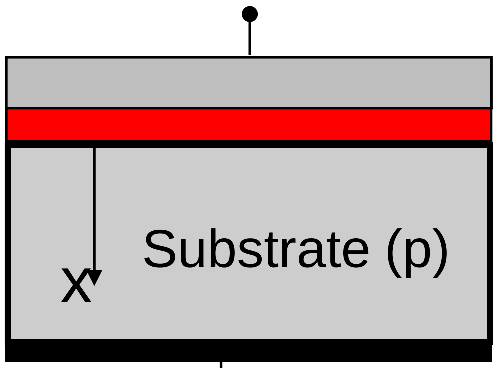
charge density velocity area



- 28.1 Background
- 28.2 Band diagram in equilibrium and with bias => MOScap
- 28.3 Qualitative Q-V characteristics of MOS capacitor
- 28.4 MOScap Induced charges in depletion and inversion
- 28.5 MOScap Exact solution of electrostatic problem







REF: Chapters 15-18 from SDF

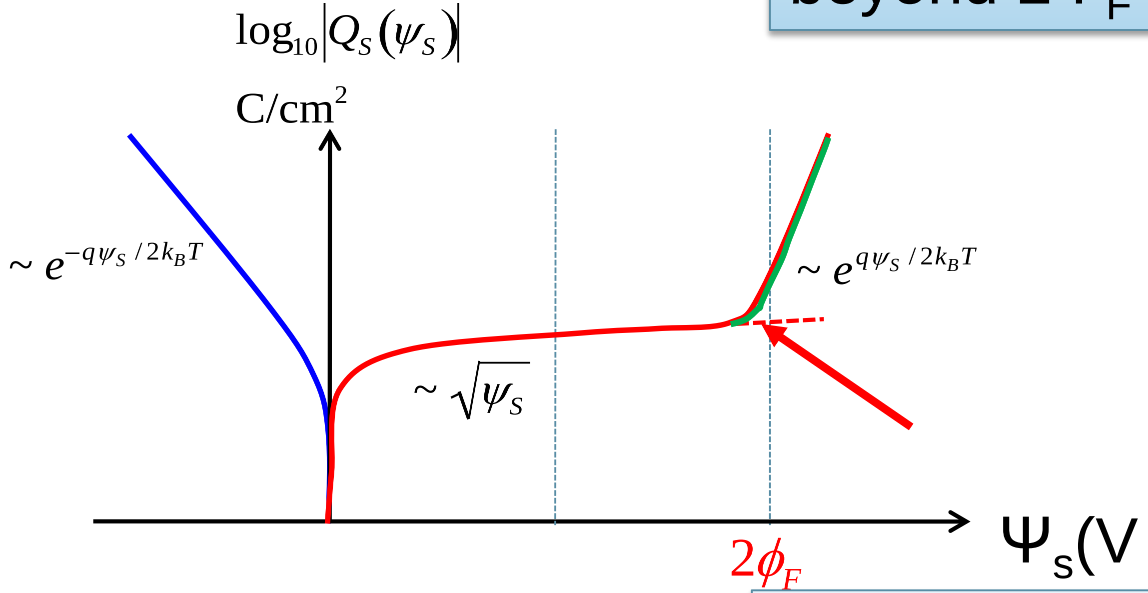
Threshold for Inversion

Ψ_F : distance between Ef and intrinsic Ef

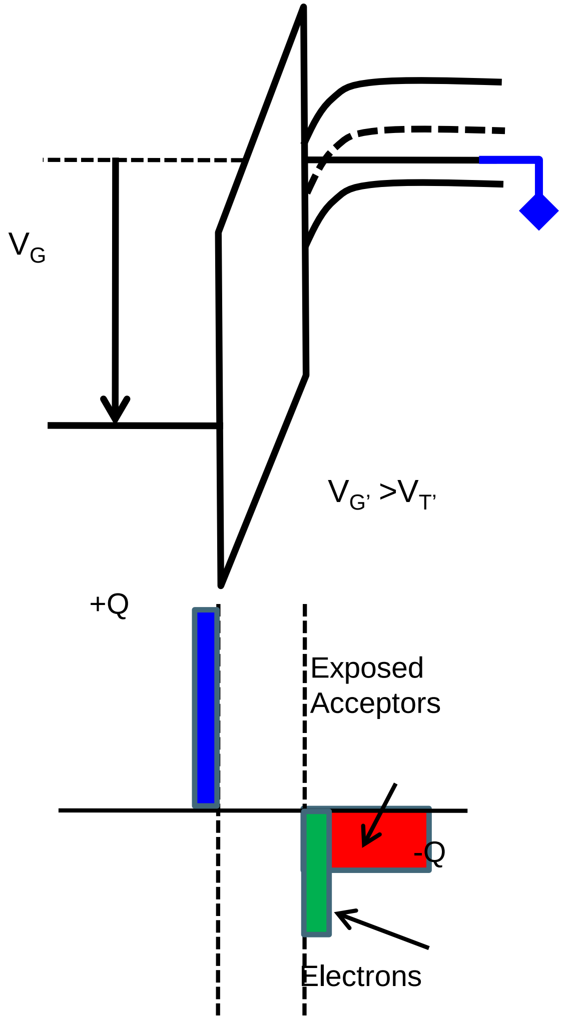
$$V_G = \frac{qN_A x_0}{\kappa_{ox}\varepsilon_0}\sqrt{\frac{2\kappa_{ox}\varepsilon_0}{qN_A}}\sqrt{\psi_s} + \psi_s$$

$$V_{th} = \frac{qN_A x_0}{\kappa_{ox}\varepsilon_0}\sqrt{\frac{2\kappa_{ox}\varepsilon_0}{qN_A}}\sqrt{2\phi_F} + 2\phi_F$$

It very difficult to change Ψs beyond $2\Psi_F$



Threshold voltage



What happens when surface potential is $2\phi_F$?

$$V_{th} = \frac{qN_A x_0}{\kappa_{ox}\varepsilon_0}\sqrt{\frac{2\kappa_{ox}\varepsilon_0}{qN_A}}\sqrt{2\phi_F} + 2\phi_F$$

$$n_{1s} = n_i e^{(E_F - E_{is})\beta}$$

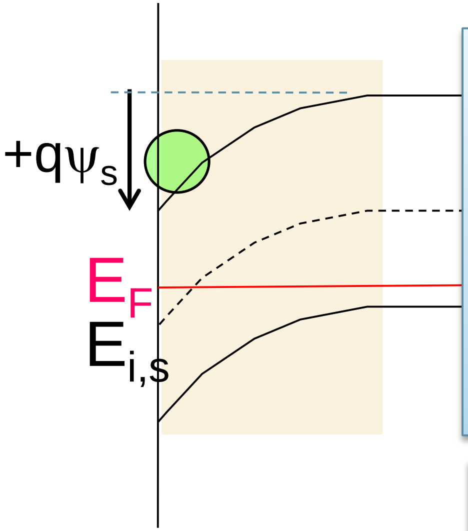
$$= n_i e^{(E_F - E_{i(bulk)})\beta} \times e^{(E_{i(bulk)} - E_{is})\beta}$$

$$= n_i e^{-\phi_F \beta} e^{(E_{i(bulk)} - E_{is})\beta}$$

$$n_{1s} = n_i e^{-\phi_F \beta} e^{2\phi_F \beta}$$

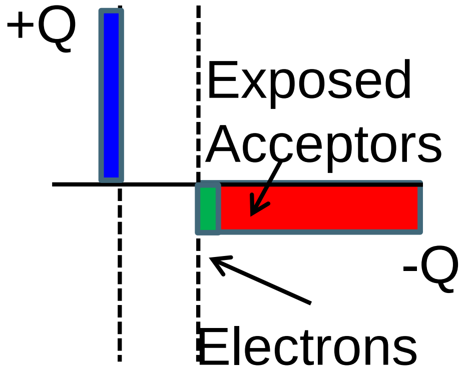
$$= n_i e^{\phi_F \beta} = N_A$$

Electron concentration equals background acceptor concentration



Above threshold:
Can pile up electrons at the interface with exponential changes in potential!

"All" additional potential drop will occur over the oxide!



At threshold:
Total amount of electrons in green are much less than red charge

A little bit about scaling ….

$$V_{th} = \frac{qN_A x_0}{\kappa_{ox}\varepsilon_0}\sqrt{\frac{2\kappa_{ox}\varepsilon_0}{qN_A}}\sqrt{2\phi_F} + 2\phi_F$$

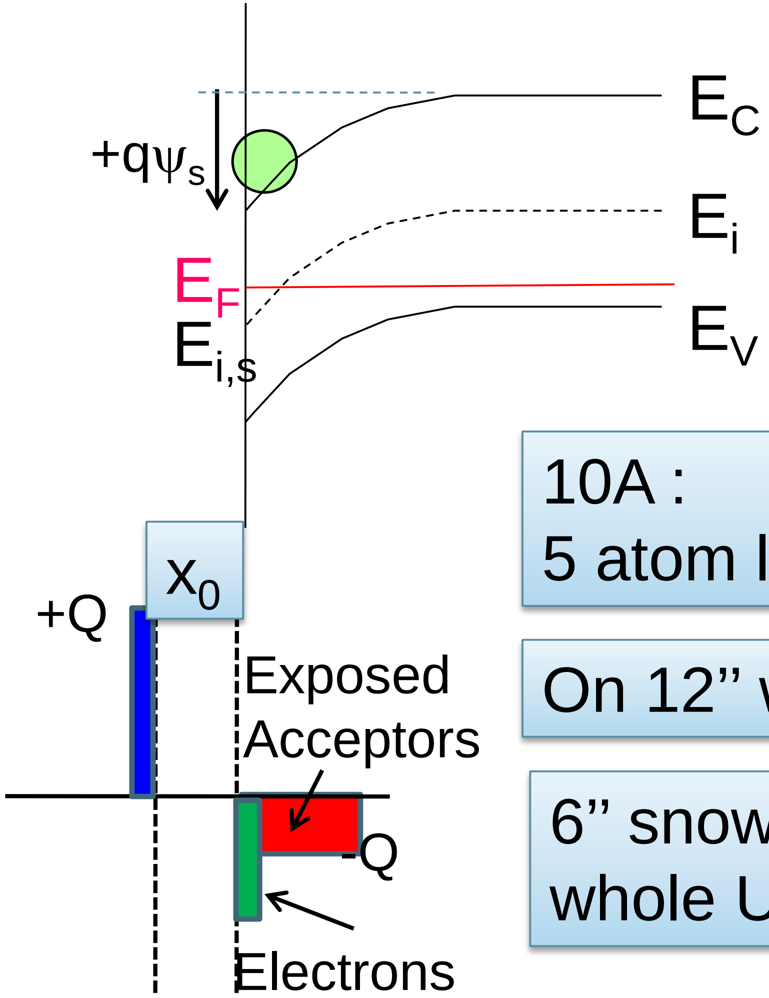
Need to operate MOSFET above V_{th} to have charge in a channel

Power consumption as square of V_{th}

Reduce V_{th} by …

Reducing oxide thickness (from 1000 A in 1970s to 10 A now)

Increase dielectric constant (SiO_2 historically, HfO_2 today)



10A :
5 atom layer

On 12” wafer

6” snow on the whole US, FLAT

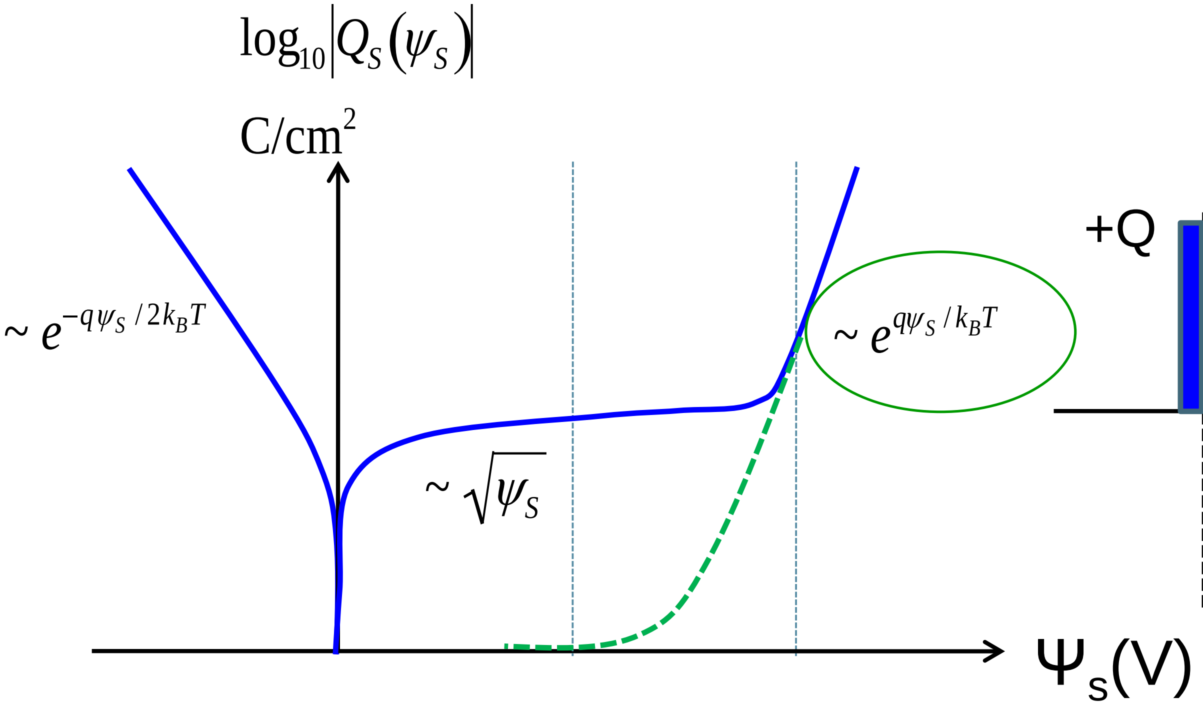
Thin oxide will cause large leakage current

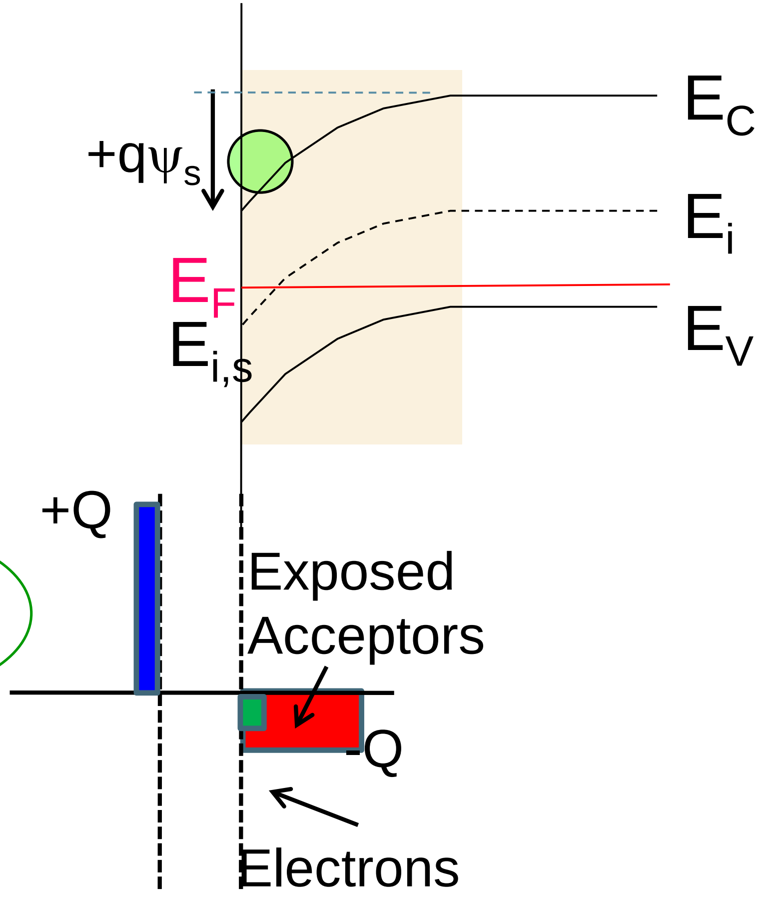
Induced charges below threshold

$$n_{1s} = n_i e^{-\phi_F \beta} e^{\left(E_{i(bulk)} - E_{is}\right)\beta}$$

$$\equiv B e^{q\psi_s \beta}$$

$$V_G = \frac{qN_A x_0}{\kappa_{ox}\varepsilon_0}\sqrt{\frac{2\kappa_{ox}\varepsilon_0}{qN_A}}\sqrt{\psi_s} + \psi_s$$





Integrated charges above Threshold

$$\frac{Q_i}{q} = \int_0^\infty n(x)\,dx = \int_0^\infty \frac{n_i^2}{N_B} e^{q\psi(x)\beta}\,dx$$

$$= \frac{n_i^2}{N_B}\int_0^\infty e^{q\psi(x)\beta}\frac{1}{\frac{d\psi}{dx}}d\psi$$

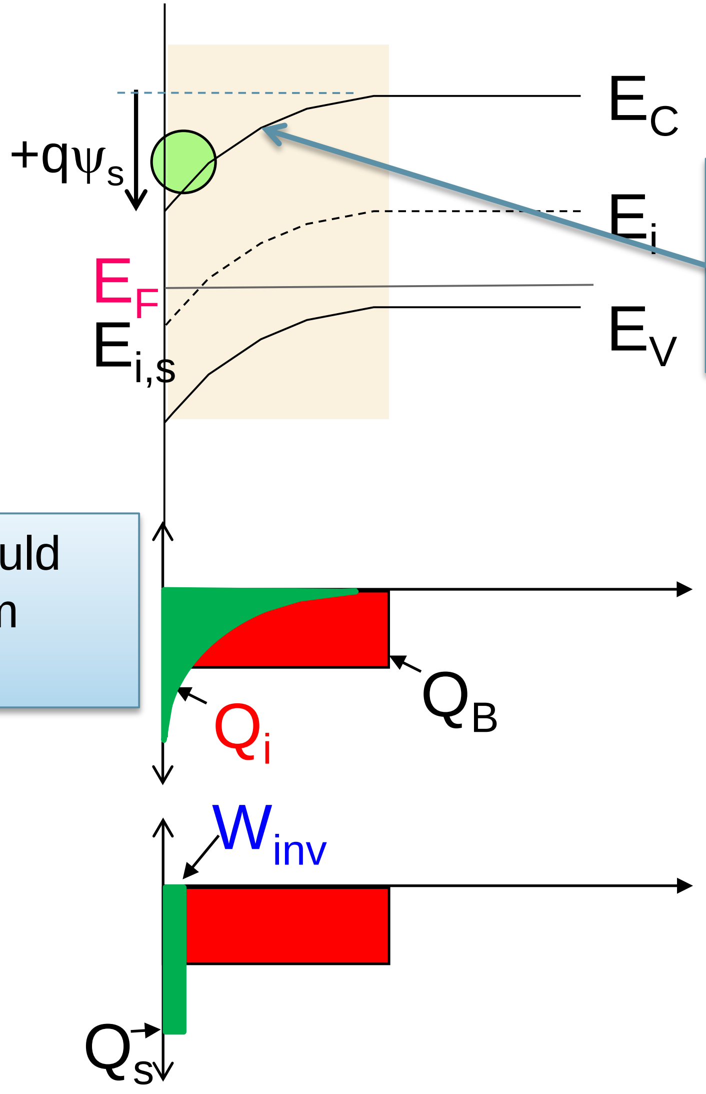
$$= \frac{n_i^2}{N_B}\int_0^\infty e^{q\psi(x)\beta}\frac{1}{\mathcal{E}(x)}d\psi$$

Now we should integrate from ψ(0) to ψ(∞)

$$\approx \frac{1}{\langle\mathcal{E}(x)\rangle}\frac{n_i^2}{N_B}\int_0^\infty e^{q\psi(x)\beta}d\psi$$

voltage

$$= \frac{\left(\frac{k_B T}{q}\right)}{\langle\mathcal{E}(x)\rangle}\times\frac{n_i^2}{N_B}e^{q\psi_s\beta} \equiv W_{inv}\times n_s$$

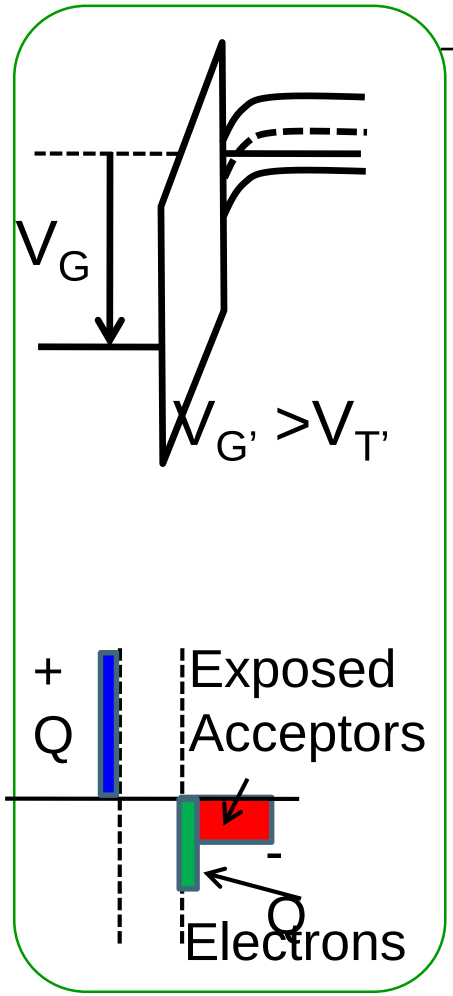


Like a triangular potential→ constant E field

Charges above Threshold

Assume there is no charge in the oxide

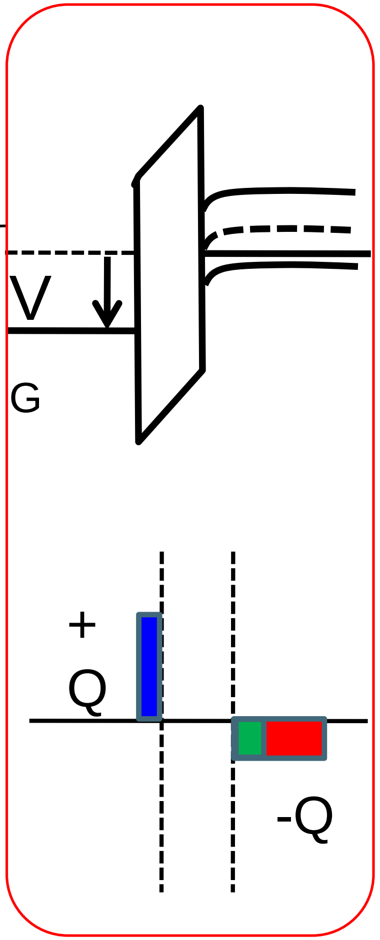
Field in a plate capacitor: total charge / dielectric constant



$$V_G = \psi_s + \mathcal{E}_{ox} x_o = \psi_s - \left[\frac{Q_i(\psi_s) + Q_F}{\kappa_{ox}\varepsilon_0} \right] x_o$$

$$V_{th} = 2\phi_F + \mathcal{E}_{ox} x_o = 2\phi_F - \left(\frac{Q_i(2\phi_F) + Q_F}{\kappa_{ox}\varepsilon_0} \right) x_o$$

$$V_G - V_{th} = (\psi_s - 2\phi_F) + \frac{Q_i(\psi_s) - Q_i(2\phi_F)}{\kappa_{ox}\varepsilon_0} x_o$$



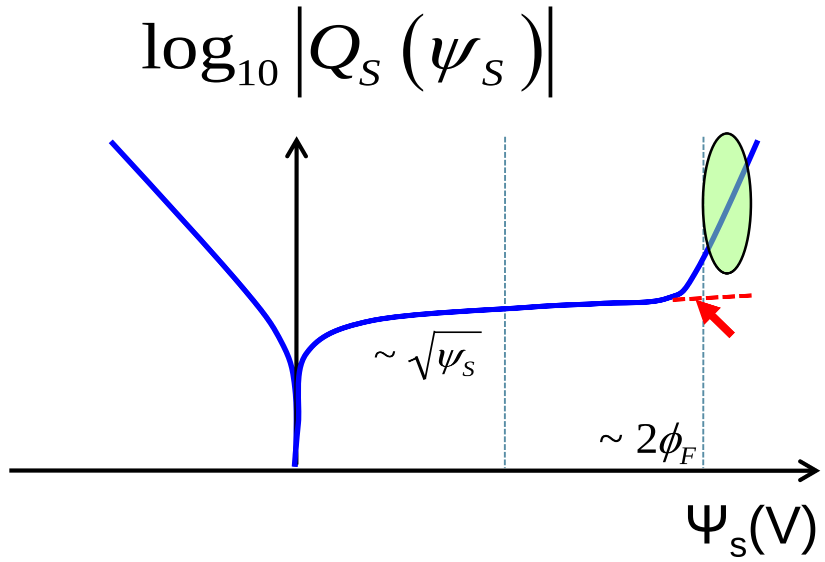
This term is small, ψ_s is pinched

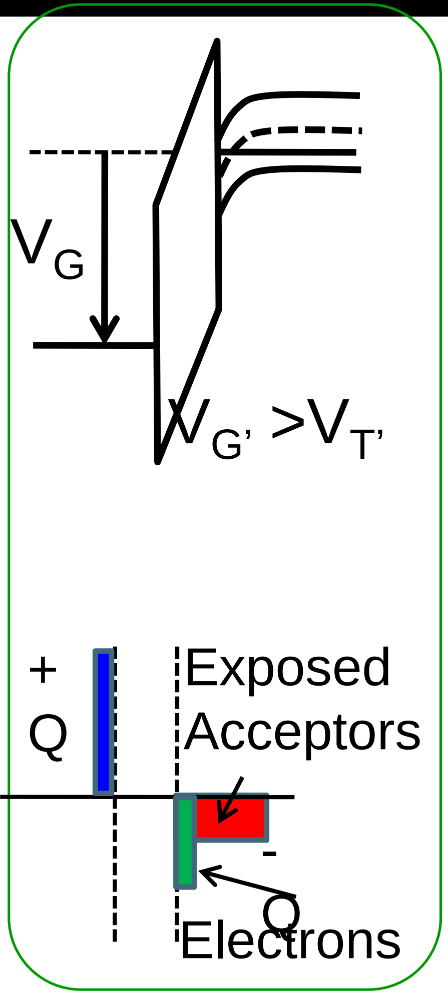
The blue region is thin, But the height increase exponentially

$$Q_i = C_{ox}(V_G - V_{th})$$

Charge has exponential behavior on Psi_S But LINEARLY with gate voltage!

Linear Charge Build-up Above Threshold?





- Small changes ψ_s in changes Q_i a lot ..
- Change in Q_i changes E_{ox}, because $E_{ox}=Q_i/\kappa_0 e_0$
- V_{ox} is large because $V_{ox}=E_{ox}\,x_{0,}$ i.e. most of the drop above $2\psi_F$ goes to V_{ox}.
- Acts like a parallel plate capacitor, hence the inversion equation.

Tunneling Current

Thermionic current

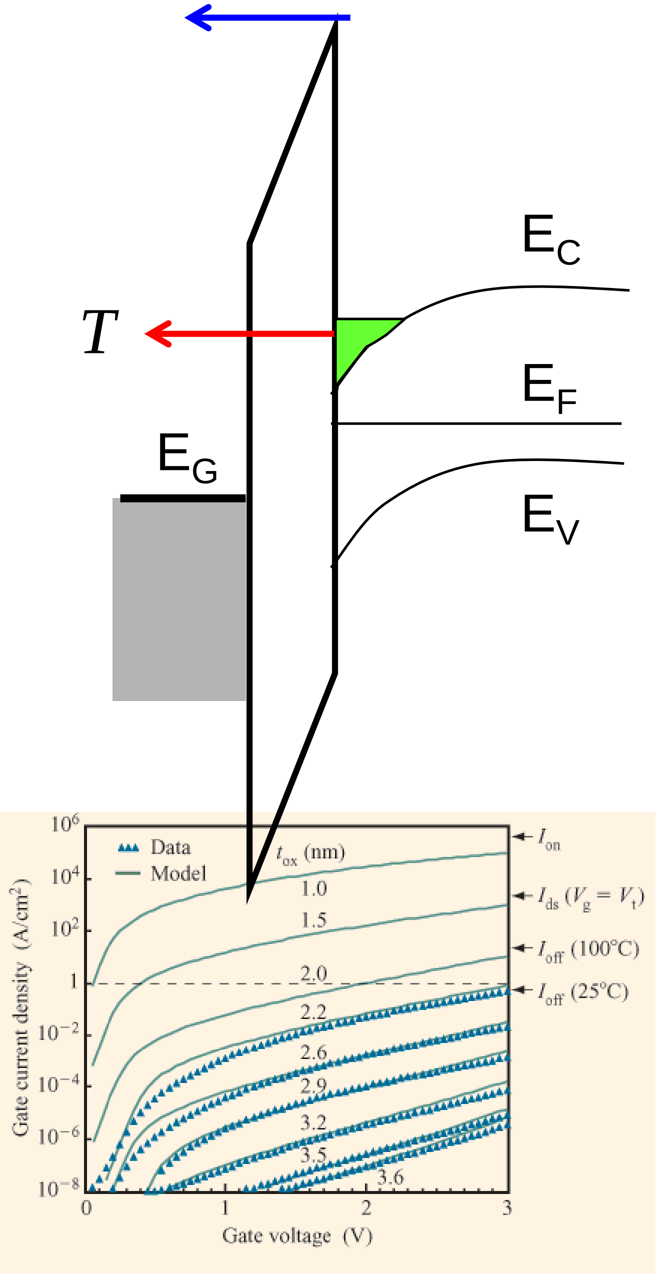
$$J_T = J_{s\to g} - J_{g\to s}$$
$$= \left[Q_i(V_G) e^{-\Delta E_C \beta} - q n_m e^{-\Delta E_C \beta} e^{-qV_{ox}\beta} \right] \upsilon_{th}$$
$$= \left[Q_i(V_G) - q n_m e^{-qV_{ox}\beta} \right] \upsilon_{th} T \qquad T \equiv e^{-\Delta E_C \beta}$$

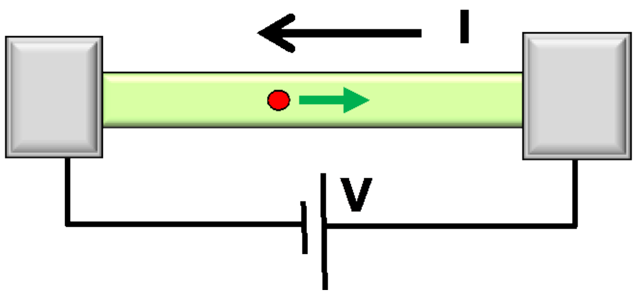
Negligible!!!

$$J_T = \left[Q_i(V_G) - q n_m e^{-qV_G\beta} \right] \upsilon_{th} \langle T(E) \rangle$$

Oxide can not be too thin because of the tunneling current

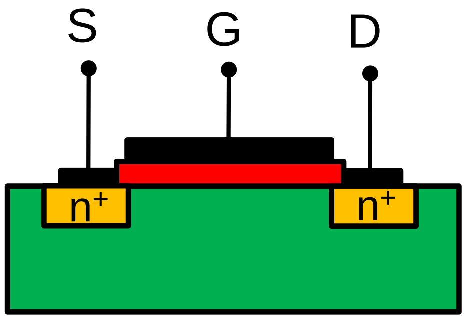
Starts to look like base current in a BJT





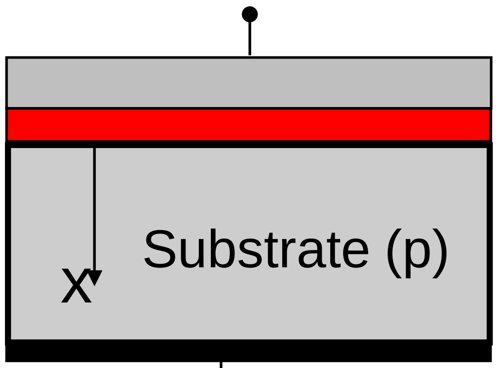
$$I = G \times V$$
$$= q \times n \times v \times A$$

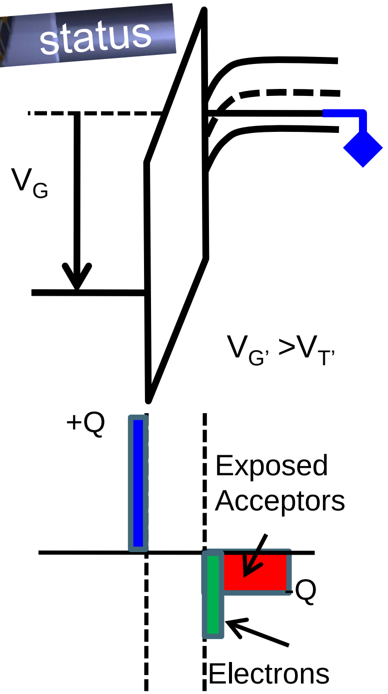
charge density velocity area



- 1 28.1 Background
- 2 28.2 Band diagram in equilibrium and with bias => MOScap
- 3 28.3 Qualitative Q-V characteristics of MOS capacitor
- 4 28.4 MOScap Induced charges in depletion and inversion
- 5 28.5 MOScap Exact solution of the electrostatic problem

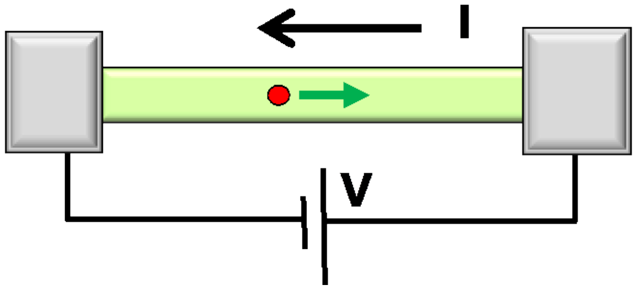
status





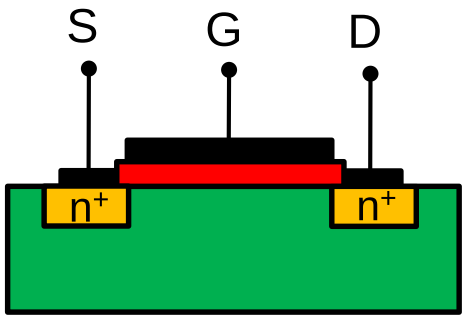
REF: Chapters 15-18 from SDF

Section 28
MOS Electrostatics & MOScap

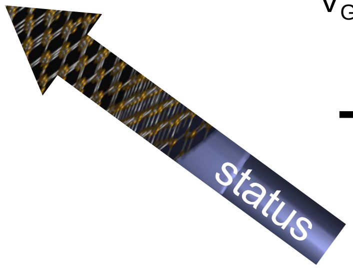


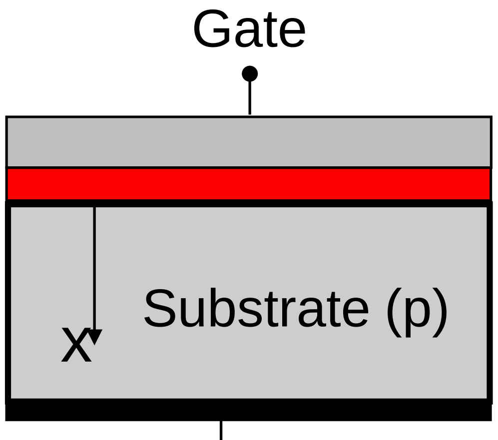
$$I = G \times V$$
$$= q \times n \times v \times A$$

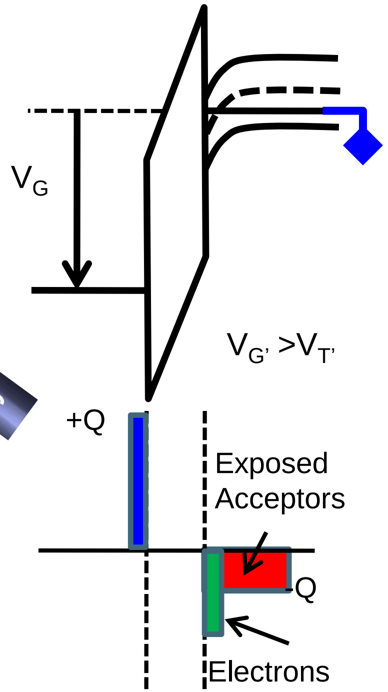
charge density velocity area



- 28.1 Background
- 28.2 Band diagram in equilibrium and with bias => MOScap
- 28.3 Qualitative Q-V characteristics of MOS capacitor
- 28.4 MOScap Induced charges in depletion and inversion
- 28.5 MOScap Exact solution of the electrostatic problem







REF: Chapters 15-18 from SDF