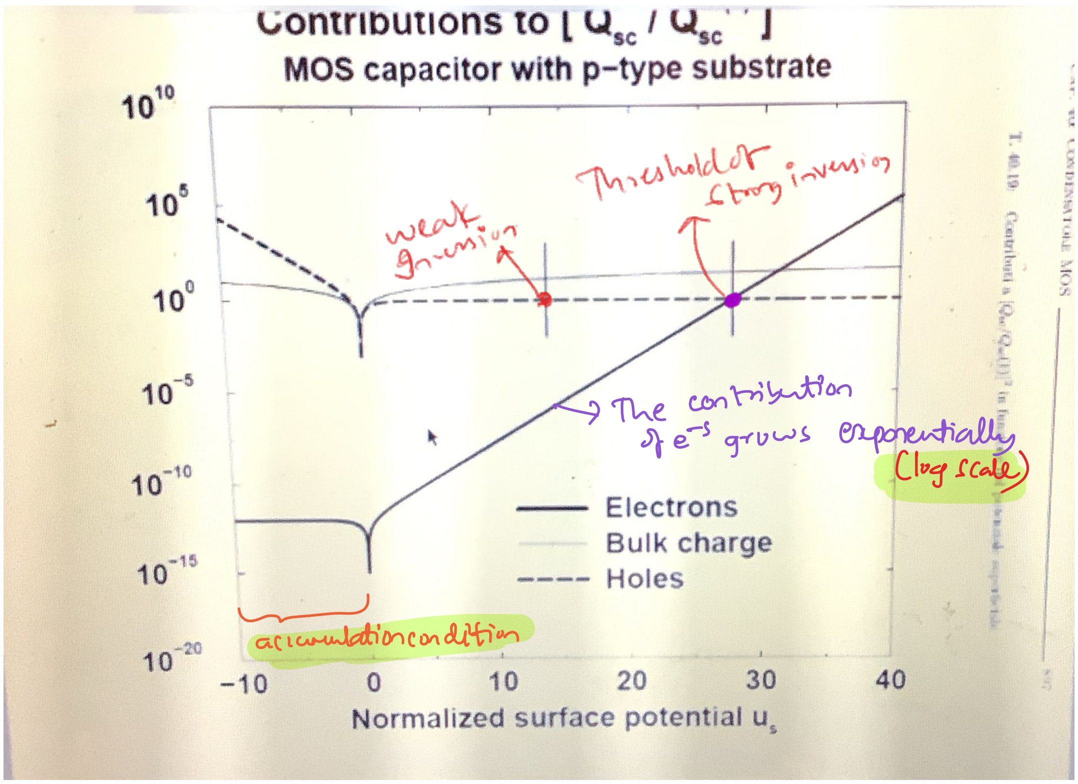
22/05/25

Lecture-14

20/10/20

* **Contributions to $\left[Q_{sc}/Q_{sc}^{(1)}\right]^2$**

MOS capacitor with p-type substrate



. This is Graph with Normalised Surface Potential (u_s) on the x-axis

Revanth Reddy Pannala
EBIT, Unibo
రేవంత్ రెడ్డి పన్నాల

Capacitance of the MOS Structure

p-type substrate, quantitative relations

The normalized capacitance reads

$$\boxed{\frac{C}{C_{ox}} = \frac{1}{1 + C_{ox}/C_{sc}}} \qquad C_{sc} = \pm \frac{2\varepsilon_{sc}}{L_A} \frac{dF}{du_s} > 0\,,$$

where the plus (minus) sign holds for $u_s > 0$ ($u_s < 0$), and $C_{scFB} = \sqrt{2}\,\varepsilon_{sc}/L_A$. Using

$$\frac{dF^2}{du_s} = 2F \frac{dF}{du_s}\,,$$

$$\frac{dF^2}{du_s} = \exp(-2u_F)\,[\exp(u_s) - 1] + 1 - \exp(-u_s) = A(u_s; u_F)$$

yields, with $r = \varepsilon_{sc} t_{ox}/(\varepsilon_{ox} L_A)$,

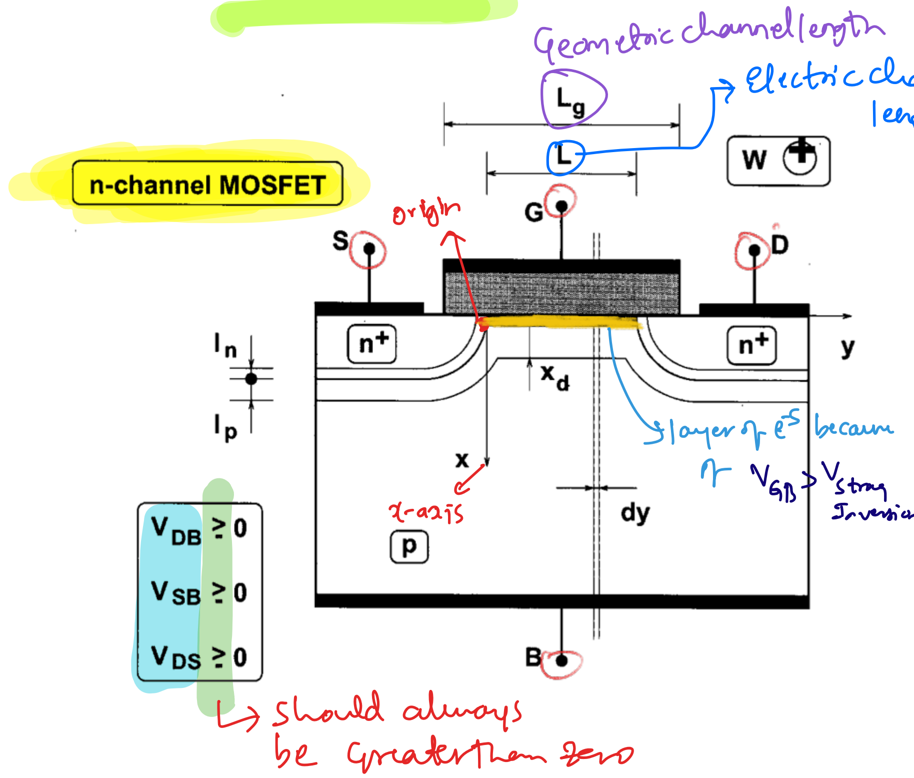
$$C_{sc} = \pm \frac{\varepsilon_{sc}}{L_A} \frac{A}{F} > 0\,, \qquad \frac{C_{ox}}{C_{sc}} = \pm \frac{\varepsilon_{ox} L_A}{\varepsilon_{sc} t_{ox}} \frac{F}{A} = \pm \frac{F}{rA}$$

The relation $C(V_G')$ is found by eliminating u_s from

$$u_G' = u_s \pm 2r\,F \qquad \frac{C}{C_{ox}} = \frac{1}{1 \pm F/(rA)}$$

In particular $C(V_G' = 0) = C_{ox}/[1 + 1/(\sqrt{2}\,r)]$

MOSFET



T. 32.1: Sezione schematica del transistore MOS a canale n.

→ MOS Transistor is the most important device in the IC technology

• The current flowing from 'D' to 'S' depends on the no. of e^{-}s in the Inverted layer.

$$\boxed{\text{no. of } e^{-}\text{s (current)} \propto \text{Gate voltage (control port)}}$$

* → We want to calculate the current flowing from D to S

MOSFET, n-channel — I

electron current density

No current in 'z' direction

Hole current density

But

$$\begin{cases} \boldsymbol{J}_n = J_{nx}\,\boldsymbol{i} + J_{ny}\,\boldsymbol{j} \\ \boldsymbol{J}_p = J_{px}\,\boldsymbol{i} + J_{py}\,\boldsymbol{j} \\ J_{nx} = J_{px} = 0 \end{cases} \qquad \text{Hp:} \begin{cases} \partial/\partial z = 0 \\ \partial/\partial t = 0 \\ V_{GS} \ge V_T \end{cases}$$

steady state condition

at each point we have Strong Inversion condition i.e channel is well formed

for a well formed channel

$$|J_{ny}| \gg |J_{py}| \implies \boldsymbol{J} = \boldsymbol{J}_n + \boldsymbol{J}_p \simeq \boldsymbol{J}_n = J_{ny}(x,y)\,\boldsymbol{j}$$

$$\boxed{\operatorname{div} \boldsymbol{J} = 0} \implies \operatorname{div} \boldsymbol{J}_n = 0\,, \quad U = 0$$

$$\implies I_A - I_B = \iint_A \boldsymbol{J}_n \bullet \boldsymbol{\nu}\,\mathrm{d}x\,\mathrm{d}z - \iint_B \boldsymbol{J}_n \bullet \boldsymbol{\nu}\,\mathrm{d}x\,\mathrm{d}z = 0$$

width of the channel

$$I = \text{const} = \int_{z=0}^{W} \int_{x=0}^{\infty} \boldsymbol{J}_n \bullet \boldsymbol{j}\,\mathrm{d}x\,\mathrm{d}z = W \int_0^{\infty} J_{ny}\,\mathrm{d}x$$

Only this component of the current survives. (Unipolar Device)

Flux of J_n

$$\begin{cases} \boldsymbol{J}_n = -q\mu_n\, n \operatorname{grad} \varphi_n \\ J_{nx} = -q\mu_n\, n\, \partial\varphi_n/\partial x = 0 \\ J_{ny} = -q\mu_n\, n\, \partial\varphi_n/\partial y \end{cases} \implies \begin{cases} \partial\varphi_n/\partial x = 0 \\ \varphi_n = \varphi_n(y) \\ \partial\varphi_n/\partial y = \mathrm{d}\varphi_n/\mathrm{d}y \end{cases}$$

Quasi Fermi potential

$$I = W \frac{\mathrm{d}\varphi_n}{\mathrm{d}y} \int_0^{\infty} -q\mu_n\, n\,\mathrm{d}x\,, \qquad \begin{cases} n = n(x,y) \\ \mu_n = \mu_n(x,y) \\ \infty \leftarrow x_d \end{cases}$$

Recombination Rate is zero!

Simpler expression of the current

unit vector of y-axis

i.e J_n is Solinoidal

The flux J_n does not depend on the position.

∴ We can calculate the current of the channel by simply calculating the flux of the current density at any position 'y' in the channel.

& →

$$I = w \frac{d\phi}{dy} \int_0^{\infty} -q\mu_n n\, dx$$

we can restrict the upper limit of the Integral to x_d

MOSFET, n-channel — II

Inversion charge per unit Area

Average Mobility

- $Q_i(y) = \int_0^{x_d} -q\,n\,\mathrm{d}x < 0$, $\mu_e(y) = \frac{\int_0^{x_d} -q\mu_n\,n\,\mathrm{d}x}{\int_0^{x_d} -q\,n\,\mathrm{d}x} > 0$
- $I = W\,\frac{\mathrm{d}\varphi_n}{\mathrm{d}y}\,\mu_e(y)\,Q_i(y) = \text{const} \implies \varphi_n(y) \Leftrightarrow y(\varphi_n)$

ϕ_n is a Monotonic function of 'y'

$$\Rightarrow \int_0^L I\,\mathrm{d}y = LI = W\int_{\varphi_n(0)}^{\varphi_n(L)} \mu_e(\varphi_n)\,Q_i(\varphi_n)\,\mathrm{d}\varphi_n$$

$$\frac{\mathrm{d}\mu_e}{\mathrm{d}y} \simeq 0 \implies I = \frac{W}{L}\,\mu_e\int_{\varphi_n(0)}^{\varphi_n(L)} Q_i(\varphi_n)\,\mathrm{d}\varphi_n$$

Mobility degradation is almost zero!

Def: $\varphi_s(y) = \varphi(x=0,y)$, Hp: $\varphi_n(\varphi_s) \Leftrightarrow \varphi_s(\varphi_n)$

The surface potential & it's two dimensional

$$I = \frac{W}{L}\,\mu_e\int_{\varphi_s(0)}^{\varphi_s(L)} Q_i(\varphi_s)\,\frac{\mathrm{d}\varphi_n}{\mathrm{d}\varphi_s}\,\mathrm{d}\varphi_s$$

To solve This we introduce an Approximation called Gradual Channel Approximation

ASCE $\Rightarrow$ Abrupt Space charge Edge

MOSFET, n-channel — III

Gradual-channel approximation (GCA)

- $\begin{cases} \text{I. Parallel-plate capacitor } \forall y \\ \text{II. Full depletion + ASCE} \\ \text{III. Ohmic transport (strong inversion } \forall y) \end{cases}$

Inversion charge

expression from MOS capacitor

- $\begin{cases} \text{I+II. } Q_i = -C_{\text{ox}} \left[(V'_{GB} - \varphi_s) - \gamma\sqrt{\varphi_s} \right] & \forall y \\ \text{III. } \varphi_s = \varphi_n + \varphi_F & \forall y \end{cases}$

constant

- III.: $\dfrac{\mathrm{d}\varphi_n}{\mathrm{d}y} = \dfrac{\mathrm{d}\varphi_s}{\mathrm{d}y} \implies J_{ny} = -q\mu_n n \dfrac{\mathrm{d}\varphi_s}{\mathrm{d}y} = q\mu_n n \mathcal{E}_{sy}$

- $\varphi_s = (\varphi_n - \varphi_F) + 2\varphi_F \implies \begin{cases} \varphi_s(0) = V_{SB} + 2\varphi_F \\ \varphi_s(L) = V_{DB} + 2\varphi_F \end{cases}$

- $$I_D = -I = \beta \int_{V_{SB}+2\varphi_F}^{V_{DB}+2\varphi_F} \left[(V'_{GB} - \varphi_s) - \gamma\sqrt{\varphi_s} \right] \mathrm{d}\varphi_s$$

$\beta = \dfrac{W}{L}\mu_e C_{\text{ox}}$, $\quad V_{DS} = V_{DB} - V_{SB} > 0 \Rightarrow I_D > 0$

In This expression for Drain Current, it depends on Three independent voltages V_{DB}, V_{SB}, V'_{GB} & would be NonLinear w.r.to V_{DB} & V_{SB}.

→ Next step is to calculate The Differential conductances for This Device. i.e $\dfrac{\partial I_D}{\partial V_{GB}}$, $\dfrac{\partial I_D}{\partial V_{DB}}$, $\dfrac{\partial I_D}{\partial V_{SB}}$

MOSFET, n-channel — IV

Gradual-channel approximation (GCA)

Drain conductance

$$g_D = g_o = \left(\frac{\partial I_D}{\partial V_{DB}}\right)_{V_{SB},V_{GB}} = \left(\frac{\partial I_D}{\partial V_{DS}}\right)_{V_{BS},V_{GS}}$$

Constants

$$\boxed{g_D = \beta\left[(V'_{GB} - V_{DB} - 2\varphi_F) - \gamma\sqrt{V_{DB} + 2\varphi_F}\right] =}$$

$$= \beta\left[(V'_{GB} - \varphi_s(L)) - \gamma\sqrt{\varphi_s(L)}\right] = \frac{W}{L}\mu_e\left[-Q_i(L)\right]$$

Saturation Surface potential

Def: $\varphi_s^{\mathrm{sat}} = \varphi_s(L) \ni Q_i(L) = 0$, $\quad \begin{cases} V_{DB}^{\mathrm{sat}} = \varphi_s^{\mathrm{sat}} - 2\varphi_F \\ V_{DS}^{\mathrm{sat}} = V_{DB}^{\mathrm{sat}} - V_{SB} \end{cases}$

$$g_D(V_{DS} = 0) = \beta\left[(V'_{GB} - V_{SB} - 2\varphi_F) - \gamma\sqrt{V_{SB} + 2\varphi_F}\right] =$$

$$= \beta\left[(V_{GS} - V_{FB} - 2\varphi_F) - \gamma\sqrt{2\varphi_F - V_{BS}}\right] =$$

$$= \beta\,(V_{GS} - V_T)\,, \qquad V_T = V_{FB} + 2\varphi_F + \gamma\sqrt{2\varphi_F - V_{BS}}$$

Threshold voltage

This has effect on V_T

GCA: $\begin{cases} V_{GS} \geq V_T & \begin{cases} 0 \leq V_{DS} \leq V_{DS}^{\mathrm{sat}} & \text{linear region} \\ V_{DS}^{\mathrm{sat}} < V_{DS} & \text{saturation region} \end{cases} \\ V_{GS} < V_T & \text{off state} \end{cases}$

Not completely OFF, we have SubThreshold current

• V_{BS} can be made constant (as) Source & Bulk are shorted.

Revanth Reddy Pannala
EBIT, Unibo
రేవంత్ రెడ్డి పన్నల

MOSFET, n-channel — V

Gradual-channel approximation — Linear region

$$I_D = \beta \int_{V_{SB}+2\varphi_F}^{V_{DB}+2\varphi_F} \left[(V'_{GB} - \varphi_s) - \gamma\sqrt{\varphi_s}\right] \mathrm{d}\varphi_s$$

- $$\int_{V_{SB}+2\varphi_F}^{V_{DB}+2\varphi_F} V'_{GB}\,\mathrm{d}\varphi_s = V'_{GB}\,V_{DS}$$

- $$\int_{V_{SB}+2\varphi_F}^{V_{DB}+2\varphi_F} \varphi_s\,\mathrm{d}\varphi_s = \frac{1}{2}\left[(V_{DB}+2\varphi_F)^2 - (V_{SB}+2\varphi_F)^2\right] =$$

$$= \frac{1}{2}\left[(V_{DS}+V_{SB})^2 - V_{SB}^2\right] + 2\varphi_F V_{DS} =$$

$$= \frac{1}{2}V_{DS}^2 + (V_{SB}+2\varphi_F)\,V_{DS}$$

$$V'_{GB}\,V_{DS} - \frac{1}{2}V_{DS}^2 - (V_{SB}+2\varphi_F)\,V_{DS} =$$

$$= (V_{GS} - V_{FB} - 2\varphi_F)\,V_{DS} - \frac{1}{2}V_{DS}^2$$

linear & parabolic dependence on V_{DS}

- $$\int_{V_{SB}+2\varphi_F}^{V_{DB}+2\varphi_F} \sqrt{\varphi_s}\,\mathrm{d}\varphi_s = \frac{2}{3}\left[(V_{DB}+2\varphi_F)^{3/2} - (V_{SB}+2\varphi_F)^{3/2}\right]$$

MOSFET, *n*-channel — VI

Gradual-channel approximation — Linear region

elementary
standard eqⁿ for I_D

$$I_D = I'_D - I''_D$$

$$\boxed{I'_D = \beta \left[(V_{GS} - V_{FB} - 2\varphi_F)\, V_{DS} - \frac{1}{2} V_{DS}^2 \right]}$$

Linear parabolic dependence on V_{DS}

$$I''_D = \beta \frac{2}{3} \gamma \left[(V_{DS} + 2\varphi_F - V_{BS})^{3/2} - (2\varphi_F - V_{BS})^{3/2} \right]$$

for small 'γ' I_D'' can be ignored

$$g_m = \left(\frac{\partial I_D}{\partial V_{GB}} \right)_{V_{SB}, V_{DB}} = \left(\frac{\partial I_D}{\partial V_{GS}} \right)_{V_{DS}, V_{BS}} = \beta V_{DS}$$

$$g_B = \left(\frac{\partial I_D}{\partial V_{BS}} \right)_{V_{DS}, V_{GS}}$$

$$I''_D \ll I'_D \quad \Rightarrow \quad \begin{cases} I_D \simeq \beta \left[(V_{GS} - V_{FB} - 2\varphi_F)\, V_{DS} - \frac{1}{2} V_{DS}^2 \right. \\ g_D \simeq \beta\, (V_{GS} - V_{FB} - 2\varphi_F - V_{DS}) \\ V_{DS}^{sat} \simeq V_{GS} - V_{FB} - 2\varphi_F \\ V_T \simeq V_{FB} + 2\varphi_F \\ g_B \simeq 0 \end{cases}$$

Revanth Reddy Pannala
EBIT, Unibo
రేవంత్ రెడ్డి పన్నాల

Gradual-channel approximation — Saturation region

$$V_{GS} > V_T\,, \qquad V_{DS}^{\text{sat}} < V_{DS}$$

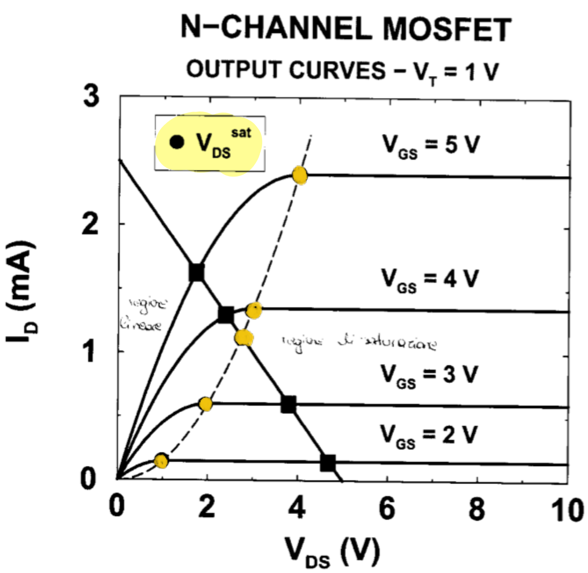
$$I_D \simeq \beta \left[\left(V_{DS}^{\text{sat}} \right)^2 - \frac{1}{2} \left(V_{DS}^{\text{sat}} \right)^2 \right] =$$

$$= \frac{1}{2} \beta \left(V_{GS} - V_{FB} - 2\varphi_F \right)^2 \simeq \frac{1}{2} \beta \left(V_{GS} - V_T \right)^2$$

$$\begin{cases} g_D \simeq 0 \\ g_m = \beta \left(V_{GS} - V_{FB} - 2\varphi_F \right) \simeq \beta \left(V_{GS} - V_T \right) \\ g_B \simeq 0 \end{cases}$$

Gradual-channel approximation — Off state

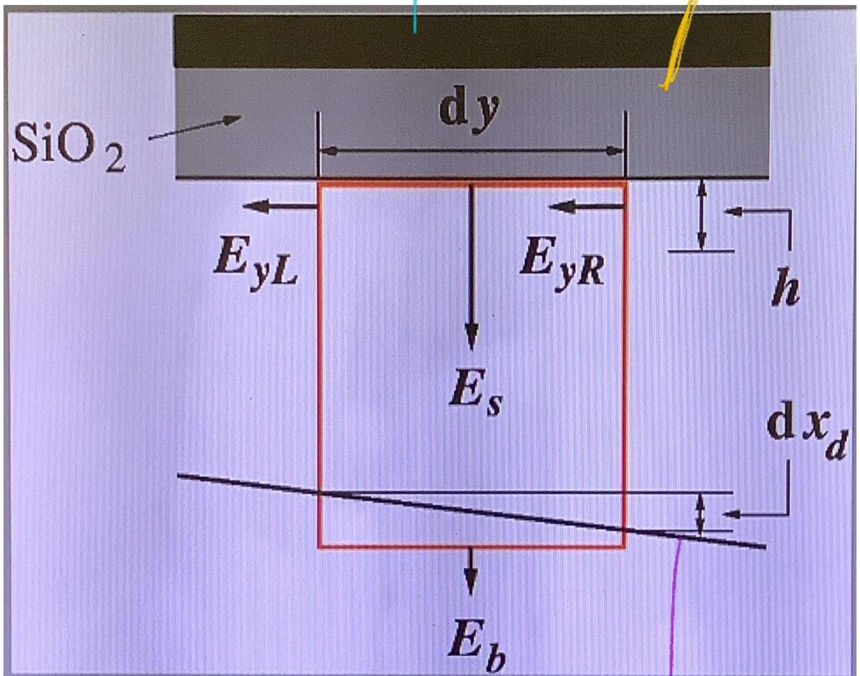
$$V_{GS} < V_T\,, \qquad I_D \simeq 0$$



T. 32.10: Caratteristiche di uscita del transistore MOS a canale n.

Gate

Gate oxide



edge of The Depleted Region

- E_s : Field Normal to the surface (interface b/w insulator & Semiconductor)

  $E_b \simeq 0$

- Interestingly it's Not Horizontal Anymore due to the application of a Drain to Source voltage V_{DS} we also have lateral component of the Electric field

→ E_y is The Horizontal field That is oriented from Right (Drain) to Left (Source)

E_{yL} , E_{yR} if There two components are equal to each other They would compensate exactly. Because one of Them is oriented inside The Cylinder

& The other is oriented on the external side of the cylinder.

$\therefore$ In this case there is no contribution to the charge from the Electric displacement in the 'y' direction.

The Right boundary is large by $d \pm d$

- For approximation we ignore the $d \pm d$ component.

- $E_{YR} \simeq E_{YL}$ (in the linear Region of operation)

$$E_S >> E_{YR} \simeq E_{YL}$$

$$V_D < V_{DSAT}$$

After these simplifications we are back to the case of the MOS capacitor. The only difference is that surface potential is different at the interface b/w oxide layer and the semiconductor (which we have already accounted for)

* → The above proves the Parallel Plate capacitor Approximation. & the Full depletion + ASCE follow the parallel plate Approximation.

→ Now Proving Ohmic Transport (strong Inversion $\forall y$)

We have to demonstrate

$$\boxed{\phi_s = \phi_n + \phi_F} \qquad \forall y$$

This is equivalent to stating the Horizontal variation in the Electric field (E) from left to right over the infinitesimal length dy is negligible.

we know $E = \dfrac{d\phi}{dy}$

$$\boxed{\Rightarrow \frac{dE}{dy} = \frac{d^2\phi}{dy^2} = \text{very small}}$$

Variation of Electric field

We shall exploit this to demonstrate Ohmic Transport.

Majority carrier in the Bulk

Hypothesis ⇒ Hp: $\begin{cases} \partial/\partial z = 0 \\ N = -N_A = \text{const} \\ \varphi(\infty, y) = 0 \\ \varphi'(\infty, y) = 0 \end{cases}$ Def: $\begin{cases} p_{p0} = p(\infty, y) \\ n_{p0} = n(\infty, y) \\ u = q\varphi/(k_B T_L) \\ u_{n,p} = q\varphi_{n,p}/(k_B T_L) \\ L_A = \sqrt{2\varepsilon_{sc} k_B T_L/(q^2 p_{p0})} \end{cases}$

Minority carriers in the Bulk

Normalised Electric potential

Since we are Not in Equillibrium we we Normalised Quasi fermi potentials u_n, u_p

The expression of e^- & e^- concentration in the Non equillibrium condition at we also assume That we are in Non-degenerate condition. So we write the exponentials in Normalised form

$$\begin{cases} n = n_i \exp(u - u_n) = n_i \exp(u - u_F + u_F - u_n) \\ p = n_i \exp(u_p - u) = n_i \exp(u_p - u_F + u_F - u) \end{cases}$$

whence, letting $\xi_n \doteq \varphi_n - \varphi_F$, $\xi_p \doteq \varphi_p - \varphi_F$ and $\chi_n \doteq q\xi_n/(k_B T_L)$, $\chi_p \doteq q\xi_p/(k_B T_L)$, $\chi_n(\infty) = \chi_p(\infty) = 0$, it is

At Equillibrium both go to Zero

Normalised quantities corresponding to ξ_n, ξ_p

$$\varrho = q\,[p_{p0} \exp(\chi_p - u) - n_{p0} \exp(u - \chi_n) + N]\,.$$

$$\varrho(\infty) = 0 \Rightarrow N = n_{p0} - p_{p0} \Rightarrow \varrho = -q p_{p0}\, A(u, \chi_n, \chi_p)$$

$$A = (n_{p0}/p_{p0})\,[\exp(u - \chi_n) - 1] + 1 - \exp(\chi_p - u)$$

$$n_{p0}/p_{p0} = \exp(-2u_F)\,, \qquad u_F > 0\,.$$

$$-\operatorname{div}(\varepsilon_{sc} \operatorname{grad} \varphi) = \varrho \quad \Longrightarrow \quad \boxed{\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = \frac{2}{L_A^2} A\,.}$$

Charge density

→ poisson Eqn

- ϕ_n & ϕ_n i.e ξ_n & ξ_p donot depend on the 'x' co-ordinate They depend only on 'y' at the interface b/w oxide layer & the Bulk

We have to solve it 2D

- Now we introduce The simplication, when we have a well formed channel $E_s >> E_y$ & $E_{y1} \simeq E_{y2}$ which says $\dfrac{\partial^2 u}{\partial y^2} = 0$ which we proved above

- So we have only derivative w.r.to 'x' to solve for. (only for a fully formed channel)

→ So we can neglect the Hole terms from the charge density eqn because of strong inversion

Neglect   very large

$$\varrho = q\,[p_{p0}\exp(\chi_p - u) - n_{p0}\exp(u - \chi_n) + N]\,.$$

$$\varrho(\infty) = 0 \Rightarrow N = n_{p0} - p_{p0} \Rightarrow \varrho = -q p_{p0}\,A(u, \chi_n, \chi_p)$$

$$A = (n_{p0}/p_{p0})\,[\exp(u - \chi_n) - 1] + 1 - \exp(\chi_p - u)$$

$$n_{p0}/p_{p0} = \exp(-2u_F)\,, \qquad u_F > 0\,.$$

$$-\operatorname{div}(\varepsilon_{sc}\operatorname{grad}\varphi) = \varrho \qquad \Longrightarrow \qquad \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = \frac{2}{L_A^2}A\,.$$

$$\therefore \quad A = \left(n_{p0}/p_{p0}\right)\left[\exp(u - \chi_n) - 1\right] + 1 - \exp(\chi_p - u)$$

$= \exp(-2u_F)$ very large   ignored

Poisson's Eq. in n-Channel MOSFETs — II

- If the accumulation condition is not considered, the contribution of holes to A can be neglected:

$$A \simeq \exp(u - \chi_n - 2u_F) + 1 > 0\,,$$

- with $u = u(x, y)$, $\chi_n = \chi_n(y)$. If in addition the applied biases are such that $|\partial\mathcal{E}_x/\partial x| \gg |\partial\mathcal{E}_y/\partial y|$, then

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \simeq \frac{\mathrm{d}^2 u}{\mathrm{d}x^2}\,.$$

- The dependence of A on y can then be treated parametrically in

$$\frac{\mathrm{d}^2 u}{\mathrm{d}x^2} \simeq \frac{2}{L_A^2}A\,.$$

In conclusion, remembering that $u_s \geq 0$ because accumulation is excluded, the same procedure as for the MOS capacitor yields

$$u'u'' = \frac{1}{2}\frac{\mathrm{d}}{\mathrm{d}x}(u')^2 = \frac{2}{L_A^2}A(u)\,u'$$

$$\int_0^{(u_s')^2}\mathrm{d}(u')^2 = \frac{4}{L_A^2}\int_0^{u_s}A(u)\,\mathrm{d}u > 0\,, \qquad u_s = u_s(y)\,.$$

Poisson's Eq. in n-Channel MOSFETs — III

$$\left(\frac{q\mathcal{E}_s}{k_B T_L}\right)^2 = \frac{4}{L_A^2} F^2(u_s; \chi_n, u_F),$$

$$F^2 = \exp(-\chi_n - 2u_F)\,[\exp(u_s) - 1] + u_s,$$

$$Q_{\rm sc} = -\varepsilon_{\rm sc}\mathcal{E}_s = -\frac{2\varepsilon_{\rm sc} k_B T_L}{q L_A} F,$$

we have Two expressions for Q_{sc}

$$Q_{\rm sc} \begin{cases} < 0 & u_s > 0 \\ = 0 & u_s = 0 \quad \text{(flat band)} \end{cases}$$

Combining with $Q_{\rm sc} = -C_{\rm ox}\,(V'_{GB} - \varphi_s)$ yields the relation $\chi_n = \chi_n(u_s)$, with $u'_{GB} \doteq qV'_{GB}/(k_B T_L)$:

surface potential

$$C_{\rm ox}\,(u'_{GB} - u_s) = \frac{2\varepsilon_{\rm sc}}{L_A}\sqrt{\exp(-\chi_n - 2u_F)\,[\exp(u_s) - 1] + u_s}$$

The threshold condition is then $u_{sT} = 2u_F + \chi_n$, which generalizes the equilibrium case $u_{sT} = 2u_F$. Due to the exponential dependence one may also assume that in strong inversion $u_s \simeq u_{sT}$. In conclusion, from $\chi_n = u_n - u_F$ it follows

Normalised Fermi potential of e^-s

$$u_s \simeq u_F + u_n, \qquad \varphi_s \simeq \varphi_n + \varphi_F = \xi_n + 2\varphi_F, \qquad 0 \le y \le L.$$

This proves that after reaching the Threshold condition the surface potential varies little if we try to increase further the Gate voltage

Revanth Reddy Pannala
EBIT, Unibo
రేవంత్ రెడ్డి పన్నాల