The Three terminal MOS structure

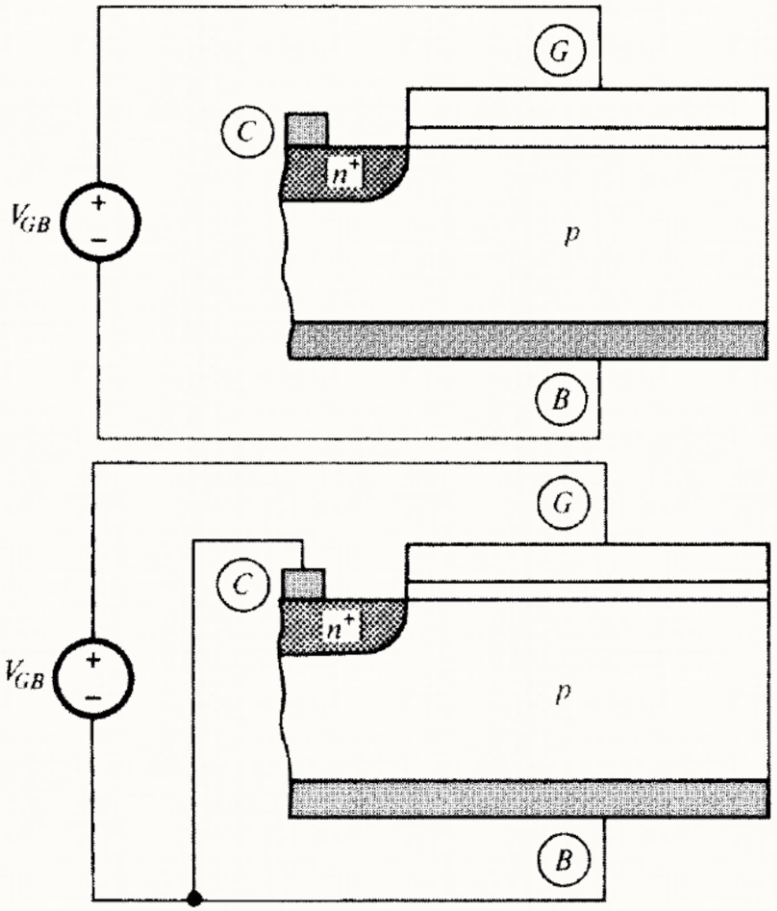
Introduction

- MOS transistor→ two terminal MOS with another two opposite terminal (back to back of inversion layer).
- Theses two new terminal make the current flow if there is a voltage difference between them!
- In this device there are many phenomena happen simultaneously which some of them are due to current and some of them are independent of current flow.
- To investigate these phenomena it is better to study them separately. Therefore we consider three terminal MOS to study the current independent phenomena.
- This structure is formed by contacting the inversion layer of the basic MOS structure at only one end.
- We will study the changes that take place in the charges and the potential distribution of the three-terminal structure, caused by the application of an external voltage between this new terminal and the substrate

Contacting the Inversion Layer

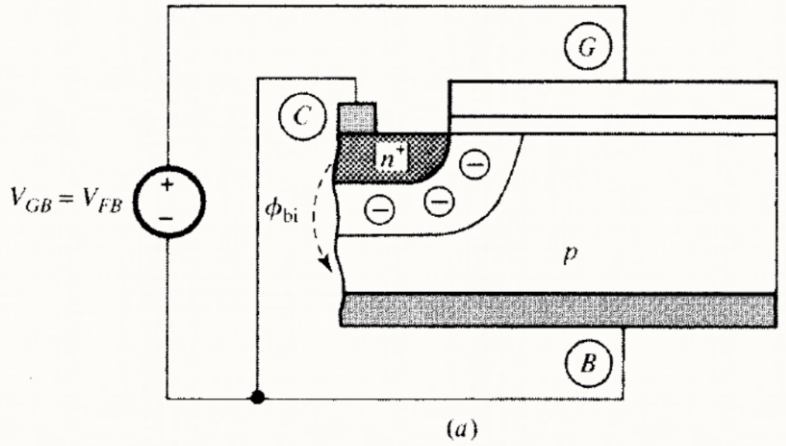
Contacting the Inversion Layer

- Assume that an n^+ region is added to the basic MOS two-terminal structure.
- Study of electron concentration near the surface of p type region can be altered due to voltage applied to contact C.
- If this contact shorted to ground as shown in following figure there is no voltage difference between n^+ region and body!
- For this connection, the **part of the structure away from the n^+ region** is still governed by **the basic equations** we have developed for the two-terminal structure.
- Now we focusing on how the potential, and the corresponding potential energy, vary horizontally at the surface for different cases



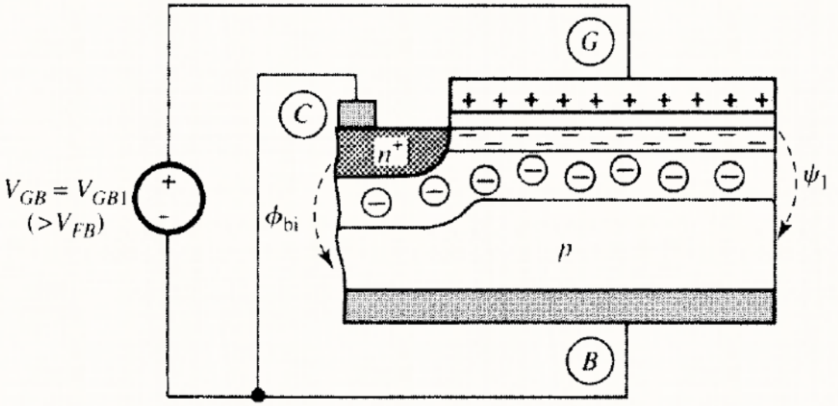
Contacting the Inversion Layer

- *Case 1: $V_{GB}=V_{FB}$ and $V_{CB}=0$*
  - The p body is neutral away from the n^+ region.
  - The depletion region on the p side contains ionized acceptor atoms as it is shown. For simplicity depletion region in n^+ region is ignored. Why?
  - Φ_{bi} is the built-in potential in n^+p junction.
  - This potential increases the allowable energy (by $q\Phi_{bi}$) for electrons in p body exactly at end of depletion region in p body. Therefore electron movement to p body (due to diffusion mechanism) is limited by this phenomenon.
  - Φ_{bi} → Potential barrier as it prevent from movement of electrons.



(a)

- *Case 2: $V_{GB}>V_{FB}$ and $V_{CB}=0$*
  - This barrier can be lowered by applying positive voltage to p body.
  - This applying voltage can be ψ_S, made by increasing V_{GB} **from** V_{FB}.
  - Now the barrier decreases and it become $q(\Phi_{bi}-\psi_1)$.
  - In this case lots of electron (exp dependence) can diffuse to p body from n^+ region.



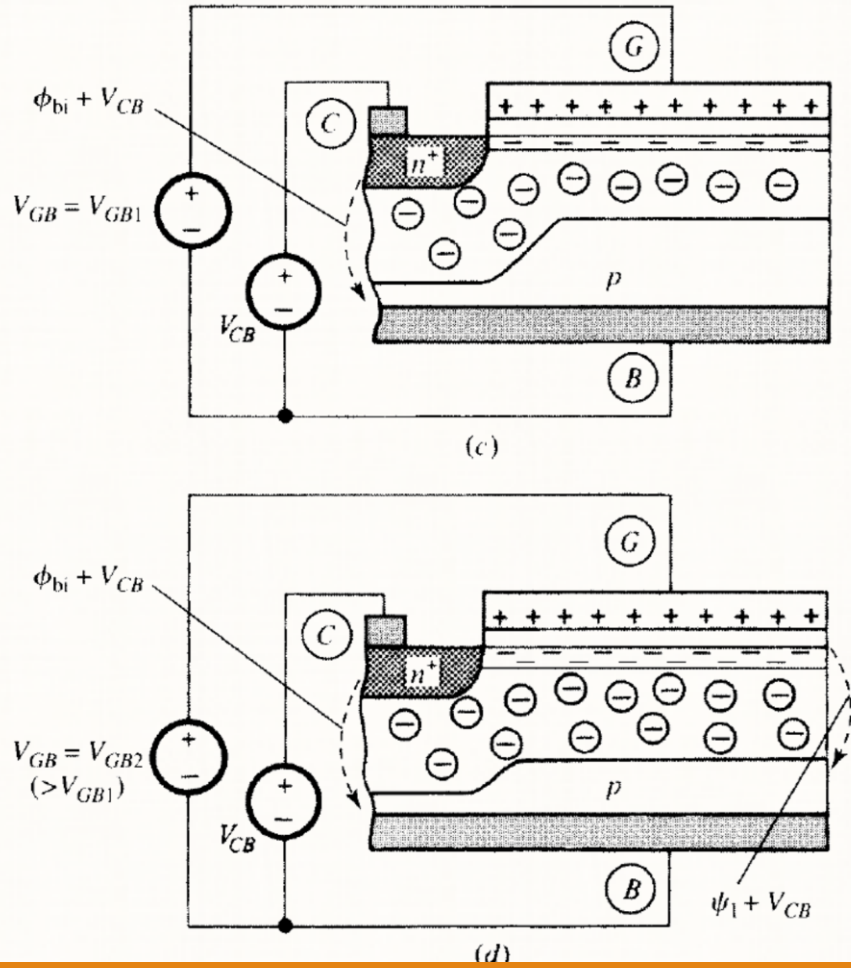
(b)

Contacting the Inversion Layer

- *Case 3: $V_{GB1}>V_{FB}$ and $V_{CB}>0$*
  - The value of V_{CB} will be assumed nonnegative to ensure that the n^+p junction is not forward-biased.
  - Reverse bias rule should be applied to calculate the barrier voltage.
  - The structure is now in *nonequilibrium.*
  - With V_{CB} applied, the total potential vertically across the n^+p junction will increase from Φ_{bi} to $\Phi_{bi}+V_{CB}$.
  - Barrier energy increased as the electron energy lowered by $V_{CB.}$ *Therefore electron movement can again limited (broken line c) by this voltage source.*
  - In this condition inversion layer may vanishes completely.
  - To decrease the barrier and hence increase the inversion layer electron (flow form n^+ region) the VGB should be increased.

- *Case4:$V_{GB2}>V_{GB1}>V_{FB}$ and $V_{CB}>0$*
  - In this case, barrier can be decreased by increasing gate-body voltage. (restoring ψ_1)
  - Electron can flow to inversion layer form n^+ region.
  - By further increasing the VGB, more electron can flow (line d) to inversion layer.
  - Now the barrier height will become:

$$q(\phi_{bi} - V_{CB}) - q(\psi_1 - V_{CB}) = q(\phi_{bi} - \psi_1)$$



Contacting the Inversion Layer

- *Case 4…*
  - We thus see that what determines the "attractiveness" of the surface for the electrons is not how large the surface potential ψ_S, is, but rather how large ψ_s, is in comparison to V_{CB}.
  - As long as that difference is fixed, the electron concentration at the surface is also fixed.
  - Surface concentration of electron:

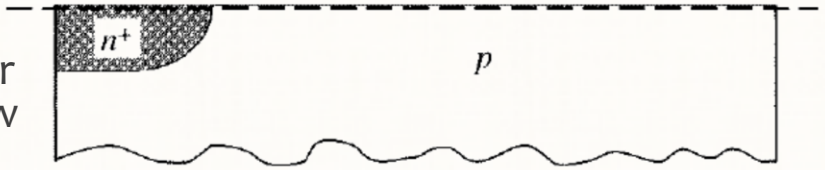
$$n_{surface} = n_0 e^{(\psi_s - V_{CB})/\phi_T}$$

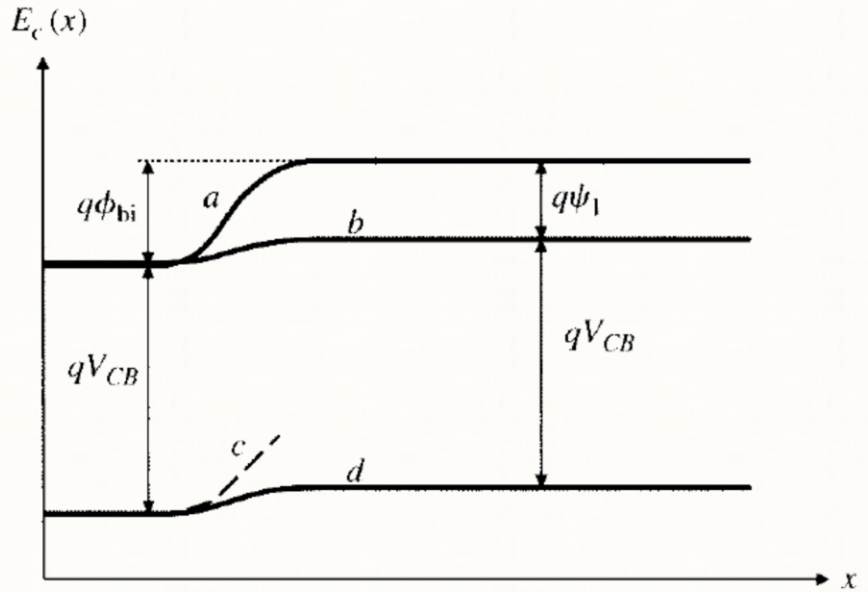
$$n_{surface} = n_i e^{(\psi_s - V_{CB} - \phi_F)/\phi_T}$$

$$n_{surface} = p_0 e^{(\psi_s - V_{CB} - 2\phi_F)/\phi_T}$$

$$n_{surface} = N_A e^{(\psi_s - V_{CB} - 2\phi_F)/\phi_T}$$

  - Comparing with 2 terminal structure results , $2\phi_F \rightarrow V_{CB} + 2\phi_F$
  - Back to figure we can say that for three terminal MOS $n_{surface} = p_{surface}$ when surface potential is equal to $V_{CB} + \phi_F$



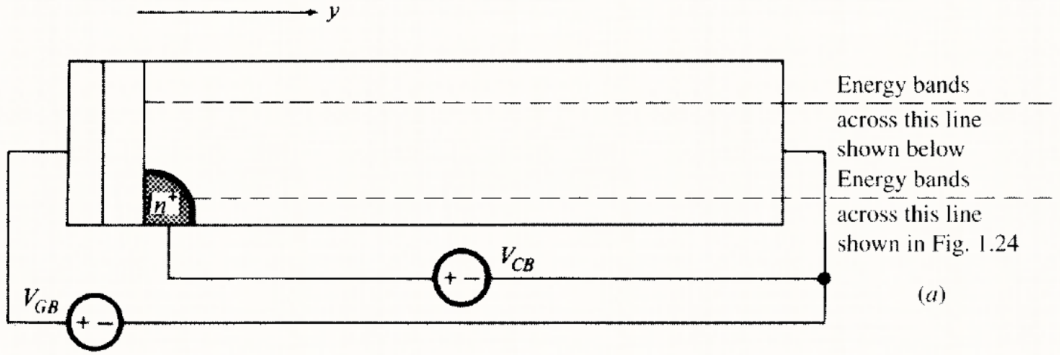


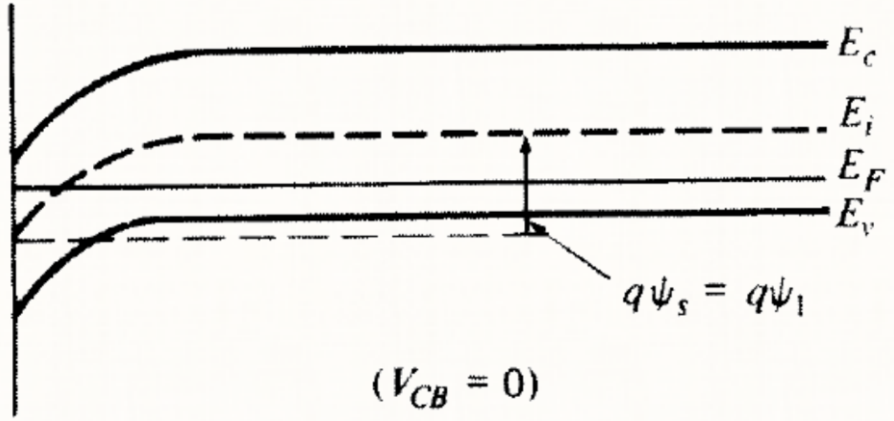
Proof Using Energy bands

- Consider the energy bands in the body in more detail.
- Recall from past studies of zero bias pn junction and reverse pn junction for lower broken line.
- Like as before band bending due to definite value of positive V_{GB}, we will have same situation (below figure).
- Assume further that the gate-body voltage is such that we are in inversion, with the surface potential value being ψ_1.
- The total band bending from the bulk to the surface is $q\psi_1$ as shown.
- Note that the band diagram on the *p* side for this case and the one for the corresponding n^+p. junction are rather similar.
- In fact, if the surface is strongly inverted, it is sometimes helpful to think of the inversion layer as an extension of the n^+ region.
- Like as before, In this case surface electron concentration become:

$$n_{surface} = n_i e^{(E_{fn} - E_{i,Surface})/kT}$$

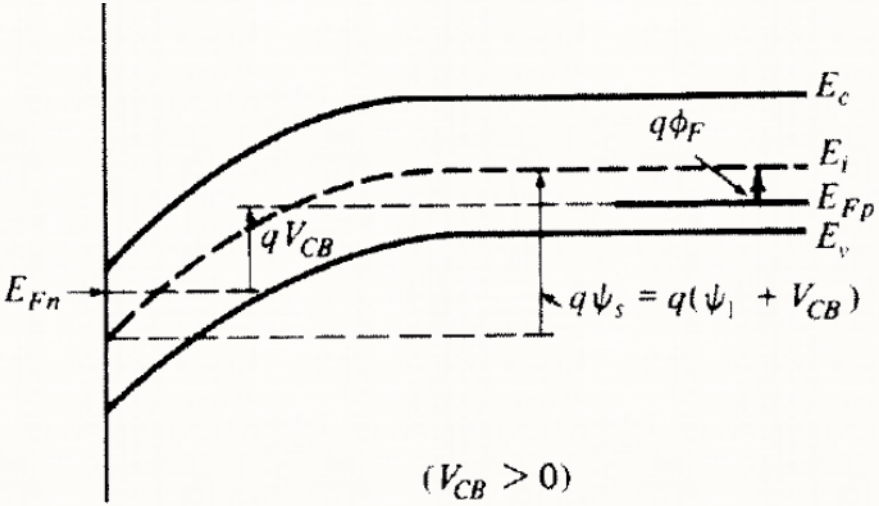
- Where E_{fn} is equal to E_f if V_{CB}=0.





Proof Using Energy bands

- Assume V_{CB}>o → As shown in figure Quasi Fermi level introduced.
  - E_{Fn} in then$^+$ region is lowered in comparison with E_{Fp}, on the p side, by an amount qV_{CB}.
  - Because the n$^+$ region is in contact with the inversion layer, this change is communicated to the inversion layer electrons, and E_{Fn} is lowered there as well by the same amount.
  - Thus, as dictated by previous equation, the surface density will decrease.
  - If we want to restore this density to its previous level, we will have to raise V_{GB} in order to decrease E_i at the surface (with respect to its position deep in the p side) by as much as E_{Fn} has decreased, i.e., by qV_{CB}.
  - This means that, at the surface, we will need an extra band bending of qV_{CB} .



General analysis

- Generally assumed that the quasi-Fermi level is constant as one goes away from the surface and into the bulk. Thus, the previous arguments remain valid for a point at distance y from the surface, where the potential is $\psi\,(y)$:

$$n(y) = n_0 e^{\frac{(\psi\,(y) - V_{CB})}{\phi_T}} = n_0 e^{\frac{\psi\,(y)}{\phi_T}} e^{\frac{-V_{CB}}{\phi_T}}$$

- Unlike electron quasi-Fermi The hole quasi-Fermi level, E_{Fp} remains at its bulk value throughout the semiconductor.
- This is because the holes do not "communicate" with the external source V_{CB}. the n^+ region does not attract holes to it, as it does electrons.
- Thus, we have, just as for the two-terminal structure, so:

$$p(y) = p_0 e^{\frac{-\psi\,(y)}{\phi_T}} \quad (\text{link})$$

- Using these equations in the charge density equation, Poisson's equation becomes:

$$\frac{d^2\psi}{dy^2} = -\frac{q}{\epsilon_s}\left(p_0 e^{\frac{-\psi\,(y)}{\phi_T}} - N_A + N_D - n_0 e^{\frac{\psi\,(y)}{\phi_T}} e^{\frac{-V_{CB}}{\phi_T}}\right)$$

General analysis

- Compare this equation with two terminal MOS It is identical to it, except that n_0 has been replaced by $n_0 e^{\frac{-V_{CB}}{\phi_T}}$, where $-V_{CB}$ is a constant independent of $\psi\,(y)$.
- Thus, proceeding exactly as for the two-terminal structure, we obtain general equations that have the same form as in that section, except that n_0 is replaced by $n_0 e^{\frac{-V_{CB}}{\phi_T}}$.
- Thus, for example, for the total semiconductor charge we get:

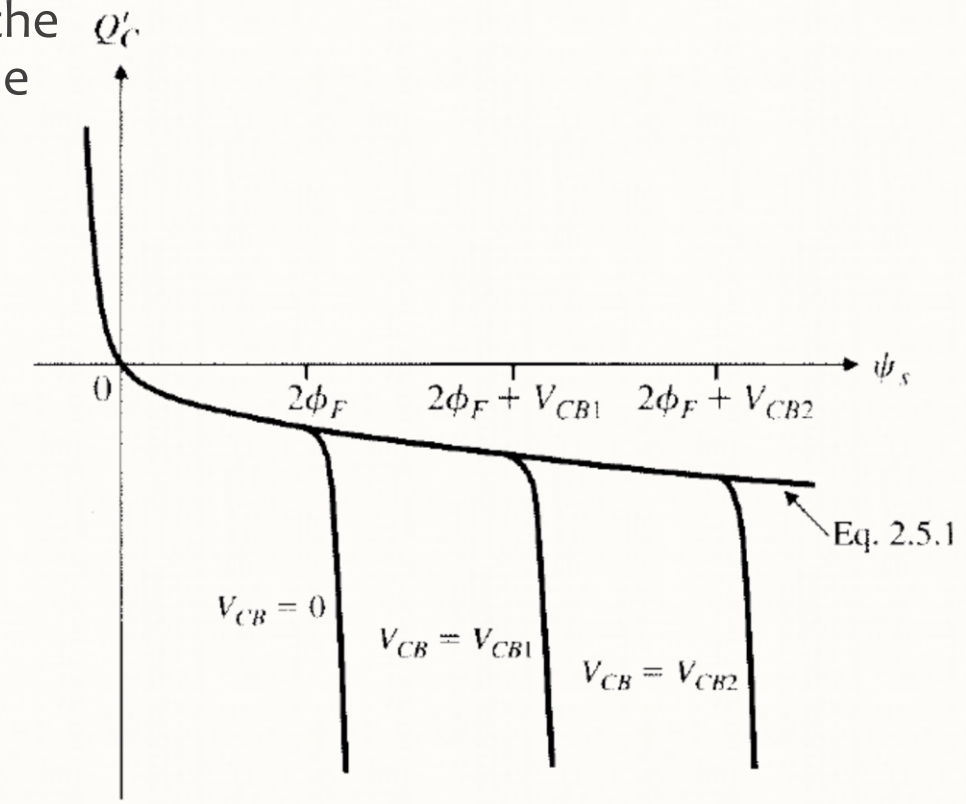
$$Q_C' = -sgn(\psi_s)\sqrt{2q\epsilon_s}\sqrt{p_0\phi_T(e^{-\psi_s/\phi_T}-1)+(N_A-N_D)\psi_s+n_0\boldsymbol{e^{-V_{CB}/\phi_T}}\phi_T(e^{\psi_s/\phi_T}-1)}$$

- and for the case of a p-type substrate we get:

$$Q_C' = -sgn(\psi_s)\sqrt{2q\epsilon_s N_A}\sqrt{\phi_T e^{-\psi_s/\phi_T}+\psi_s-\phi_T+e^{-(2\phi_F+V_{CB})/\phi_T}(\phi_T e^{\psi_s/\phi_T}-\psi_s-\phi_T)}$$

General analysis

- V_{CB} clearly affects the inversion characteristics of the three terminal MOS. It is because only in this regime electron concentration is the main parameter that effects the charge concentration in p-type body.
- The take off voltage increase for positive V_{CB} as shown in figure.
- Now analogy to previous treatment of the two-terminal structure can be proceed here:
  - Potential balance: $V_{GB} = \phi_{MS} + \psi_s + \psi_{ox}$
  - Charge balance: $Q'_G + Q'_C + Q'_o = 0$
  - The gate charge-potential relation: $Q'_G = C'_{ox}\psi_{ox}$
  - *The bulk charge-potential relation*: $Q'_C = Q'_C(\psi_s, V_{CB})$



- If the external voltages (V_{GB} and V_{CB}) and the fabrication process parameters are known, the preceding system can in principle be solved to determine ψ_s, ψ_{ox}, Q'_C and Q'_G.
- In accumulation and depletion, where this density is negligible, this control through V_{CB} is lost, and thus the behavior of the structure becomes the same as that of the two-terminal structure.
- As discussed before for charge and potential balance we should have:

$$Q'_C = -C'_{ox}(V_{GB} - V_{FB} - \psi_s)$$

$$V_{GB} = V_{FB} + \psi_s - \frac{Q'_C}{C'_{ox}}$$

- Finally by substituting equations:

$$V_{GB} = V_{FB} + \psi_s - sgn(\psi_s)\gamma\sqrt{\phi_T e^{-\psi_s/\phi_T} + \psi_s - \phi_T + e^{-(2\phi_F + V_{CB})/\phi_T}(\phi_T e^{\psi_s/\phi_T} - \psi_s - \phi_T)}$$

- This equation is one of the foundations of charge sheet models, but cannot be explicitly solved as discussed before. Highly efficient
- numerical solutions have been proposed, and extremely accurate explicit approximate solutions have been developed, as will be discussed in four terminal MOS discussion.

General analysis

- Small signal capacitance for constant value of V_{CB} :

$$C'_{gb} = \frac{dQ'_G}{dV_{GB}}$$

$$\frac{1}{C'_{gb}} = \frac{1}{C'_{ox}} + \frac{1}{C'_c}$$

- where

$$C'_C = sgn(\psi_s)\sqrt{2q\epsilon_s N_A}\,\frac{1 - \phi_T e^{-\frac{\psi_s}{\phi_T}} + e^{-\frac{2\phi_F + V_{CB}}{\phi_T}}\left(\phi_T e^{\frac{\psi_s}{\phi_T}} - 1\right)}{2\sqrt{\phi_T e^{-\frac{\psi_s}{\phi_T}} + \psi_s + e^{-\frac{2\phi_F + V_{CB}}{\phi_T}}\left(\phi_T e^{\frac{\psi_s}{\phi_T}} - \psi_s - \phi_T\right)}}, \psi_s \neq 0$$

$$C'_C = \sqrt{2q\epsilon_s N_A\left(1 + e^{-\frac{2\phi_F + V_{CB}}{\phi_T}}\right)/\phi_T}, \psi_s = 0$$

- These results are valid in all regions, from accumulation to inversion. As discussed before , we now derive simplified expressions valid in particular regions.

Inversion and Depletion

- As already mentioned, all differences discussed between the three- and two-terminal cases involve the population of electrons, which is drastically affected by V_{CB}. If the electron density is negligible, such differences are irrelevant and the corresponding equations derived before are valid for the three terminal structure as well. This is precisely the case in accumulation and in depletion.
- All results derived for those regions in previous discussion are valid for the three-terminal structure and will not be repeated here. If desired, those results can be derived in a straightforward manner directly from the equations given in the previous section, by neglecting appropriate terms in these regions.

Inversion

- The development of equations in inversion parallels that for the two terminal structure with following changes:
  - $n_0 \rightarrow n_0 e^{\frac{-V_{CB}}{\phi_T}}$
  - $2\phi_F \rightarrow 2\phi_F + V_{CB}$
- Starting with charge density equation in inversion regime:

$$Q'_C = -\sqrt{2q\epsilon_s}\sqrt{(N_A)\psi_s + n_0 e^{-V_{CB}/\phi_T}\phi_T(e^{\psi_s/\phi_T})}$$

- or

$$Q'_C = -\sqrt{2q\epsilon_s N_A}\sqrt{\psi_s + e^{-(2\phi_F+V_{CB})/\phi_T}(\phi_T e^{\psi_s/\phi_T})}$$

- This charge consists of inversion layer and depletion region components:

$$Q_c = Q_I + Q_B$$

- Under the charge sheet approximation for the inversion layer, we have a pure depletion region for which applies:

$$Q'_B = -\sqrt{2q\epsilon_s N_A}\sqrt{\psi_S} = -C'_{ox}\gamma\sqrt{\psi_S}$$

Inversion

- Thus, from the last three equations we obtain:

$$Q_I' = -\sqrt{2q\epsilon_s N_A}\left(\sqrt{\psi_s + \phi_T e^{(\psi_s-(2\phi_F+V_{CB}))/\phi_T}} - \sqrt{\psi_s}\right)$$

- Other equations:

$$Q_I' = -C_{ox}'(V_{GB} - V_{FB} - \psi_s) - Q_B'$$
$$Q_I' = -C_{ox}'\left(V_{GB} - V_{FB} - \psi_s - \gamma\sqrt{\psi_S}\right)$$

- Finally, we can develop a relation between the externally applied gate-body voltage and the surface potential:

$$V_{GB} = V_{FB} + \psi_s - \frac{Q_C'}{C_{ox}'}$$
$$V_{GB} = V_{FB} + \psi_s - \gamma\sqrt{\psi_s + e^{-(2\phi_F+V_{CB})/\phi_T}(\phi_T e^{\psi_s/\phi_T})}$$

- This equation cannot be solved explicitly.
- Numerical solution introduced for this equation for four terminal MOS.

Inversion

- Depletion region and inversion layer capacitances can be defined as:

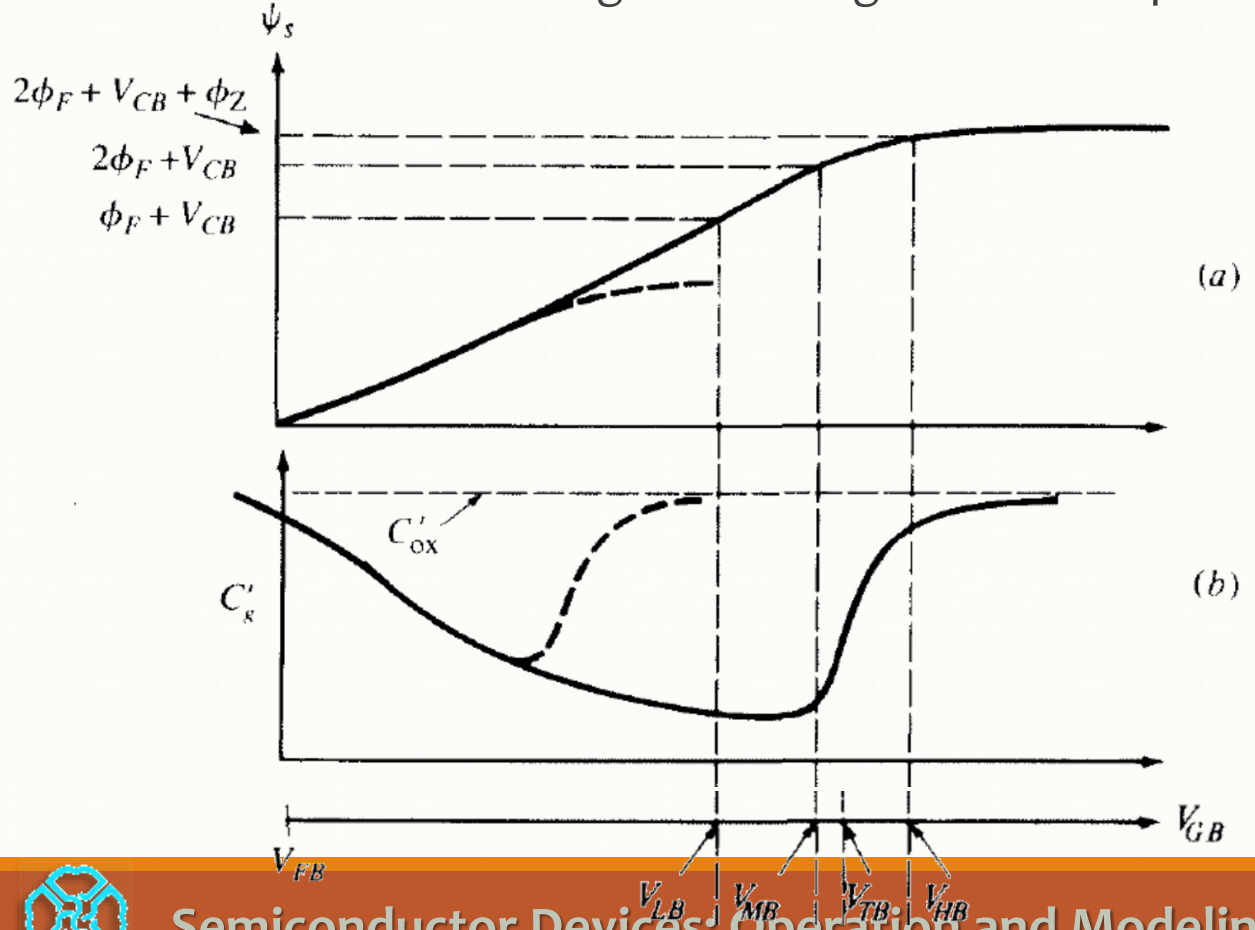
$$C_b' = \sqrt{2q\epsilon_s N_A}\frac{1}{2\sqrt{\psi_s + \phi_T e^{\frac{\psi_s-(2\phi_F+V_{CB})}{\phi_T}}}}$$

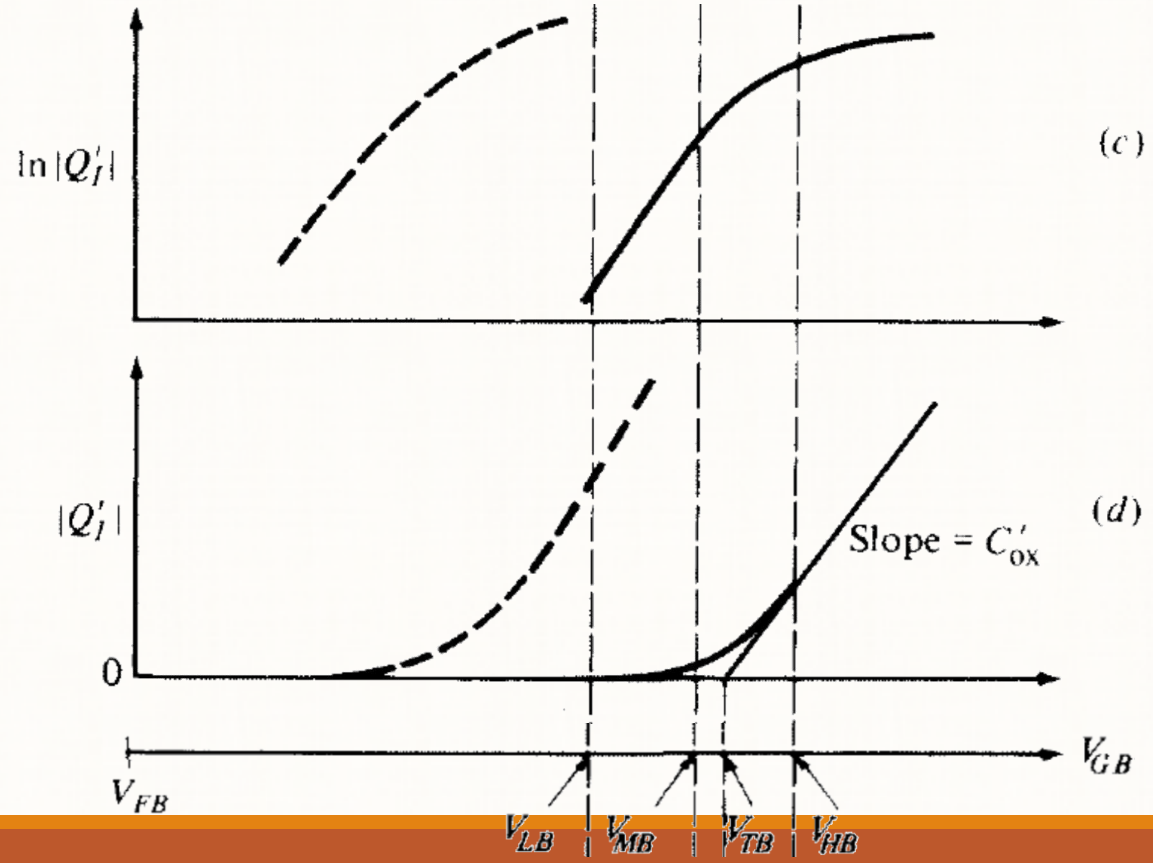
$$C_i' = \sqrt{2q\epsilon_s N_A}\frac{\phi_T e^{\frac{\psi_s-(2\phi_F+V_{CB})}{\phi_T}}}{2\sqrt{\psi_s + \phi_T e^{\frac{\psi_s-(2\phi_F+V_{CB})}{\phi_T}}}}$$

$$C_C' = C_b' + C_i'$$

Inversion

- Results: broken line for $\boldsymbol{V_{CB} = 0}$. In this case as the inversion charges (electron) can interact with outside world through the n+ region it can response to high frequency (not extremely high) input.





Inversion

- The behavior seen for $\boldsymbol{V_{CB} > 0}$ is qualitatively similar to that for $\boldsymbol{V_{CB} = 0}$.
- Weak (V_{LB})-, moderate (V_{MB})-, and strong (V_{HB})-inversion regions are again defined for this structure.
- Weak inversion → exponential dependency between Q_C' and V_{GB}
- Strong inversion → linear dependency between Q_C' and V_{GB}
- Increasing $\boldsymbol{V_{CB}}$ tends to make the level of inversion lighter; increasing $\boldsymbol{V_{GB}}$ tends to make that level heavier.

Inversion

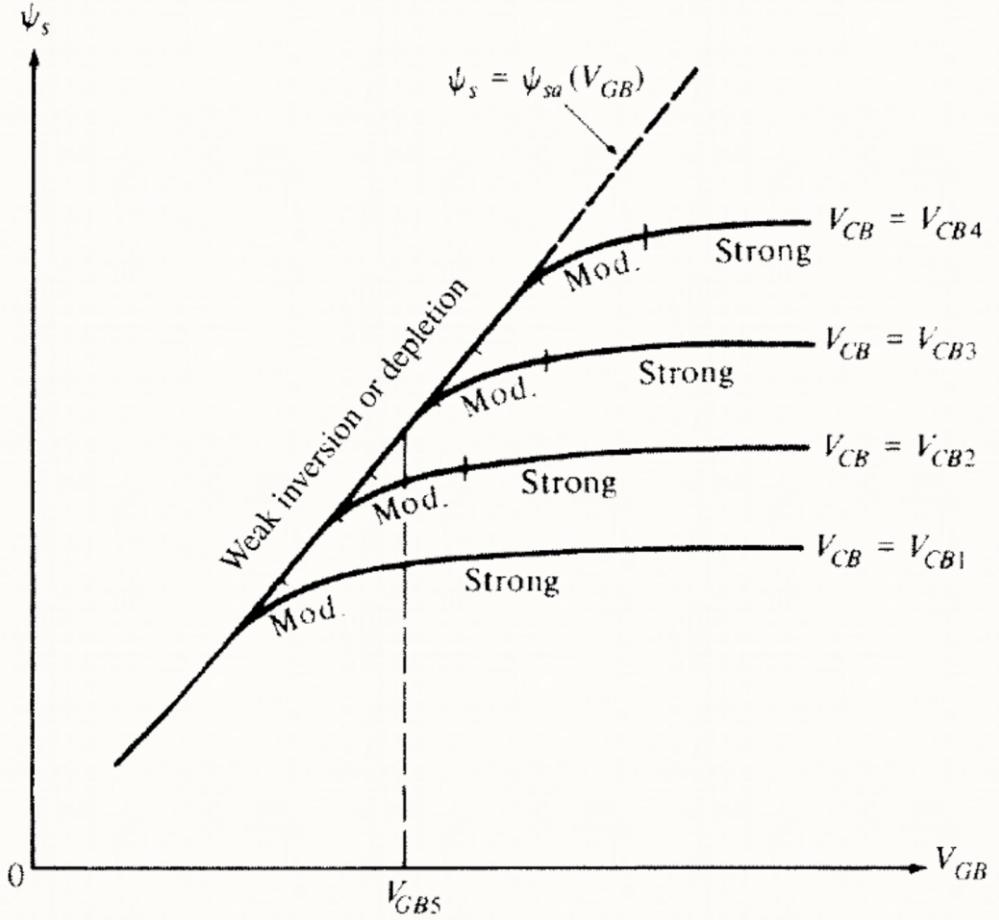
- Surface potential ψ_S vs $\boldsymbol{V_{GB}}$ in presence of $\boldsymbol{V_{CB}}$
  - increasing $\boldsymbol{V_{CB}}$ "postpones" the tendency of $\psi_S$to "flatten out" until larger $\boldsymbol{V_{GB}}$ values.
  - This is because it "postpones" the formation of an inversion layer.
  - In deep depletion regime as discussed before:

$$\psi_s \approx \psi_{sa} = \left(-\frac{\gamma}{2} + \sqrt{\frac{\gamma^2}{4} + V_{GB} - V_{FB}} \right)^2$$

  - There is no dependency to $\boldsymbol{V_{CB}}$, which means that when there is no inversion layer, this voltage has not any significant effect on surface potential and can be ignored in this region.
  - The inverse of this slope *n* is:

$$n = \left(\frac{d\psi_{sa}}{dV_{GB}} \right)^{-1} = 1 + \frac{\gamma}{2\sqrt{\psi_{sa}(V_{GB})}}$$

This quantity is a weak function of $\boldsymbol{V_{GB}}$. Typical values for *n* are between I and 1.5.



Inversion

- In this structure for given value of V_{GB} like V_{GB5}, one can not state the level of inversion which the three terminal MOS is work!
- New look → new footnotes B→C $V_{GB} = V_{CB} + V_{GC}$