# ASPECTS OF THRESHOLD VOLTAGE

The threshold voltage of a MOSFET is usually defined as the gate voltage where an inversion layer forms at the interface between the insulating layer (oxide) and the substrate (body) of the transistor. The purpose of the inversion layer's forming is to allow the flow of electrons through the gate-source junction. The creation of this layer is described next.

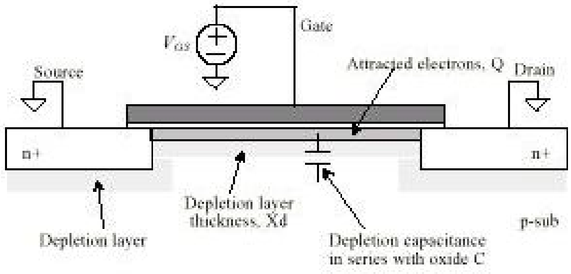



Fig. 2

When $V_{GS} > V_{THN}$ (*n*MOSFET), the semiconductor/oxide interface is inverted, i.e., the inversion layer is formed. In an n-MOSFET the substrate of the transistor is composed of p-type silicon (see doping (semiconductor)), which has positively charged mobile holes as carriers. When a positive voltage is applied on the gate, an electric field causes the holes to be repelled from the interface, creating a depletion region containing immobile negatively charged acceptor ions. A further increase in the gate voltage eventually causes electrons to appear at the interface, in what is called an inversion layer, or channel. Historically the gate voltage at which the electron density at the interface is the same as the hole density in the neutral bulk material is called the threshold voltage. Practically speaking the threshold voltage is the voltage at which there are sufficient electrons in the inversion layer to make a low resistance conducting path between the MOSFET source and drain.

In the figures, the source (left side) and drain (right side) are labeled $n+$ to indicate heavily doped (blue) n-regions. The depletion layer dopant is labeled $N_A^-$ to indicate that the ions in the (pink) depletion layer are negatively charged and there are very few holes. In the (red) bulk the number of holes $p = N_A$ making the bulk charge neutral.

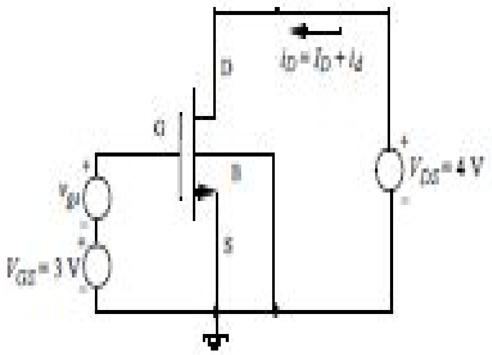
If the gate voltage is below the threshold voltage (top figure), the transistor is turned off and ideally there is no current from the drain to the source of the transistor. In fact, there is a current even for gate biases below threshold (subthreshold leakage) current, although it is small and varies exponentially with gate bias.

If the gate voltage is above the threshold voltage (lower figure), the transistor is turned on, due to there being many electrons in the channel at the oxide-silicon interface, creating a low-resistance channel where charge can flow from drain to source. For voltages significantly above threshold, this situation is called strong inversion. The channel is tapered when $V_D > 0$ because the voltage drops due to the current in the resistive channel reduces the oxide field supporting the channel as the drain is approached.

## Transistor Transconductance gm

The small-signal drain current due to $v_{gs}$ is therefore given by

$$i_d = g_m v_{gs}.$$



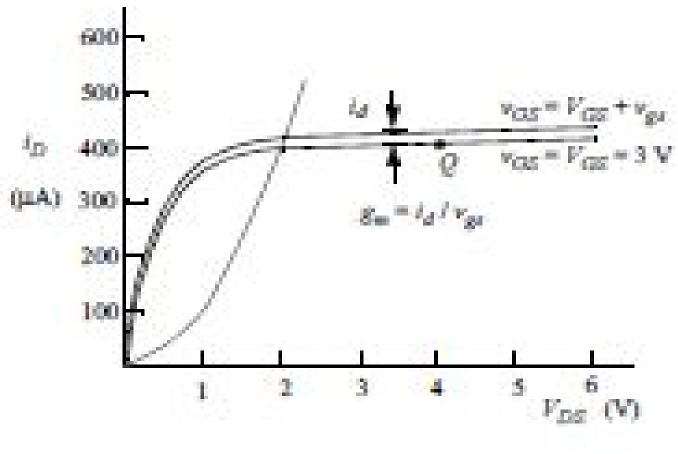



**Fig. 3 Transistor Model and Characteristics of MOS**

- Evaluating the partial derivative:

$$g_m = \mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS} - V_{Tn})(1 + \lambda_n V_{DS})$$

- In order to find a simple expression that highlights the dependence of $g_m$ on the DC drain current, we neglect the (usually) small error in writing:

$$g_m = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right) I_D} = \frac{2I_D}{V_{GS} - V_{Tn}}$$

For typical values $(W/L) = 10$, $I_D = 100\ \mu A$, and $\mu_n C_{ox} = 50\ \mu AV^{-2}$ what find that

$$g_m = 320\ \mu AV^{-1} = 0.32\ mS$$