Module 2 : MOSFET
Lecture 6 : MOSFET I-V characteristics

Objectives

In this course you will learn the following

- Derivation of I-V relationship
- Channel length modulation and body bias effect

6.1 derivation of I-V relationship

In this section, the relation between I_{DS} and V_{GS} is discussed. We assume that gate-body voltage drop is more than threshold voltage V_T, so that mobile electrons are created in the channel. This implies that the transistor is either in linear or saturation region.

Here we will derive some simple **I-V** characteristics of MOSFET, assuming that the device essentially acts as a variable resistor between source and drain, and only drift ohmic current needs to be calculated. Also note that the MOSFET is basically a two-dimensional device. The gate voltage V_{GS} produces a field in the vertical (**x**) direction, which induces charge in the silicon, including charge in the inversion layer. The voltage V_{DS} produces a field in the lateral (**y**) direction, and current flows (predominantly) in the y-direction. Strictly speaking, we must solve the 2-D Poisson and continuity equations to evaluate the **I-V** characteristics of the device. These are analytically intractable. We therefore resort to the gradual channel approximation described below.

To find the current flowing in the MOS transistor, we need to know the charge in the inversion layer. This charge, $\mathbf{Q_n(y)}$ (per sq. cm) is a function of position along the channel, since the potential varies going from source to drain. We assume that $\mathbf{Q_n(y)}$ can be found at any point y by solving the Poisson equation only in the **x** direction, that is treating the gate-oxide-silicon system in the channel region very much like a MOS capacitor. This is equivalent to assuming that vertical electric field E_x is much larger than the horizontal electric field E_y, so that the solution of the 1-dimensional Poisson equation is adequate. This gradual channel approximation (the voltage varies only gradually along the channel) is quite valid for long channel MOSFETs since E_y is small. For $\mathbf{Q_n(y)}$ using charge control relation at location **y** we have:

$$|Q_n(y)| = C_{ox}(V_{GS} - V_T - V(y)), \quad V_{GS} - V(y) > V_T \qquad (6.21)$$

Now we turn our attention to evaluate the resistance of the infinitesimal element of length d**y** along the channel (as shown in fig 6.21).

Assuming that only drift current is present and hence applying Ohm's law, we get :

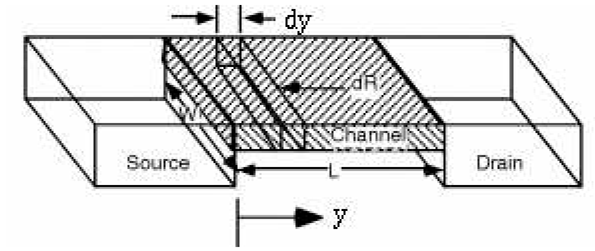

Fig 6.21: Cross Sectional View of channel

$$R = \rho\frac{l}{A} = \frac{l}{\sigma A} \quad (6.22)$$

Here we have l = dy, $\sigma = qn(x)\mu_n(x)$ and A=Wxi, where xi = inversion layer thickness.

Now using equation (6.22), We have: $\frac{dV_y}{I_{DS}(y)} = \frac{dy}{\sigma A} \quad (6.23)$

Since σ is varying along the transverse direction, we define σ_{av} as:

$$\sigma_{av} = \frac{1}{x_i}\int_0^{x_i} qn(x)\mu_n dx \qquad (6.24)$$

$$\Rightarrow \sigma_{av} x_i = \mu_n |Q_n(y)| \qquad (6.25)$$

Now using σ_{av} in eqn (6.23) and rearranging the terms, we will get:

$$I_{DS}(y)dy = |Q_n(y)|\ \mu_n W\ dV(y) \qquad (6.26)$$

Neglecting recombination-regeneration which implies **I_{DS}(y) = I_{DS}** i.e. current constant throughout the channel.
Integrating RHS of eqn (6.26) from **0** to **V_{DS}** and LHS from **0 to L**, we will get

$$I_{DS}L = \mu_n W \int_0^{V_{DS}} |Q_n(y)|\,dV(y) \qquad (6.27)$$

Now substituting **Q_n(y)** from eqn (6.21) in eqn (6.27), we will get:

$$I_{DS} = \mu_n \frac{W}{L} C_{ox} \int_0^{V_{DS}} (V_{GS} - V_T - V(y))\,dV(y) \qquad (6.28)$$

$$\Rightarrow I_{DS} = \mu_n \frac{W}{L} C_{ox}\,[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}] \qquad (6.29)$$

Eqn (6.29) holds true for $V_{GS} - V_T > V_{DS}$.

The drain current first increases linearly with the applied drain-to-source voltage, but then reaches a maximum value. This occurs due to the formation of depletion region between pinch-off point and drain. This behavior is known as **drain saturation** which is observed for $V_{GS} - V_T < V_{DS}$ as shown in figure below.

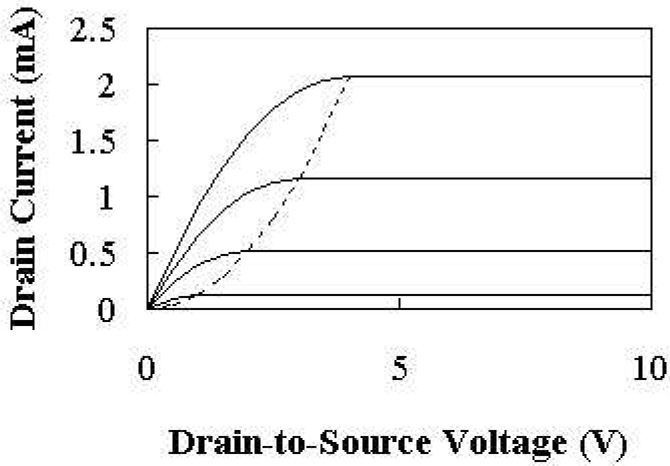

Fig 6.22: $\mathbf{I_{DS}}$-$\mathbf{V_{DS}}$ graph

The saturation current $\mathbf{I_{DSsat}}$ is given by eqn (6.210),

$$I_{DSSat} = \mu_n \frac{W}{L} C_{ox} \frac{(V_{GS} - V_T)^2}{2} \quad (6.210)$$

6.2 Channel length modulation and body bias effect

The observed current $\mathbf{I_{DS}}$ does not saturate, but has a small finite slope as shown in fig 6.31. This is attributed as **channel**

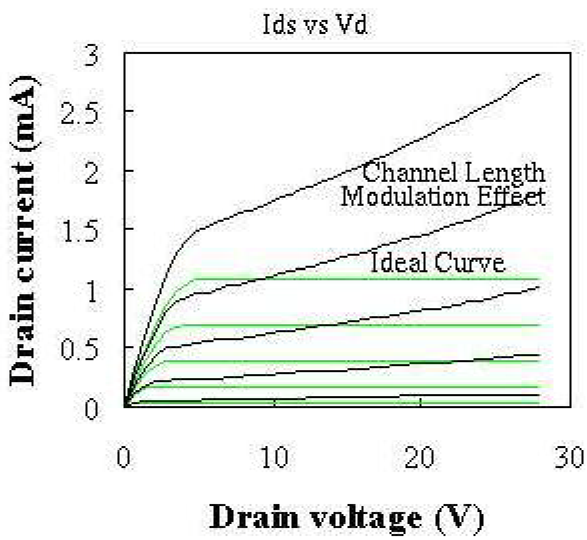

Fig 6.31: Actual vs Ideal I_{DS}-V_{DS} graph

Length modulation. This in MOSFET is caused by the increase in depletion layer width at the drain as the drain voltage is increased. This leads to a shorter channel length (reduced by ΔL) and increased drain current. When the channel length of MOSFET is decreased and MOSFET is operated beyond channel pinch-off, the relative importance of pinchoff length ΔL with respect to physical length is increased. This effect can be included in saturation current as :

$$I'_{DSSat} = \frac{I_{DSSat}}{1 - \frac{\Delta L}{L}} \qquad (6.31)$$

$$I_{DSSat} = \mu_n \frac{W}{L} C_{ox} \frac{(V_{GS} - V_T)^2}{2} (1 + \lambda V_{DS}) \qquad (6.32)$$

Here λ is called channel length modulation coefficient.

Till now we assumed that the body of MOSFET is to be grounded. We will now take effect of **body bias** into account i.e. body being applied a negative voltage in case of n-MOSFET. Application of VSB > 0 increases the potential build up across the semiconductor. Depletion region widens in order to compensate for the extra required field, which implies higher $\mathbf{V_T}$. Viewing it from the point of energy band diagram, a higher potential needs to be applied to the gate in order to bend the bands by the same amount in order to create the same electron concentration in the channel. With the application to the body bias, it modulates to the threshold voltage governed by the threshold voltage governed by the following equations:

$$V_T = V_{T0} + \gamma[(2\varphi_F + V_{SB})^{\frac{1}{2}} - (2\varphi_F)^{\frac{1}{2}}] \quad \text{where } \gamma = \frac{(2\varepsilon q N_a)^{1/2}}{C_{ox}} \qquad (6.33)$$

where γ is known as the **body coefficient**.

Recap

In this lecture you have learnt the following:

- Derivation of I-V relationship
- Channel length modulation and body bias effect