MOSFET Operation

Lecture Outline

- Last lecture examined the MOSFET structure and required processing steps

- Now move on to basic MOSFET operation, some of which may be familiar

- First consider <u>drift</u>, the movement of carriers due to an electric field – this is the basic conduction mechanism in the MOSFET

- Then review basic regions of operation and charge mechanisms in MOSFET operation

Drift

- The movement of charged particles under the influence of an electric field is termed drift

- The current density due to conduction by drift can be written in terms of the electron and hole velocities v_n and v_p (cm/sec) as

$$J = qnv_n + qpv_p$$

- This relationship is general in that it merely accounts for particles passing a certain point with a given velocity

Mobility and Velocity Saturation

- At low values of electric field
  E, the carrier velocity is
  proportional to E - the
  proportionality constant is the
  mobility μ

- At low fields, the current
  density can therefore be written

$$J = qn\underbrace{\mu_n E}_{v_n} + qp\underbrace{\mu_p E}_{v_p}$$

- At high E, scattering limits the
  velocity to a maximum value
  and the relationship above no
  longer holds - this is termed
  velocity saturation
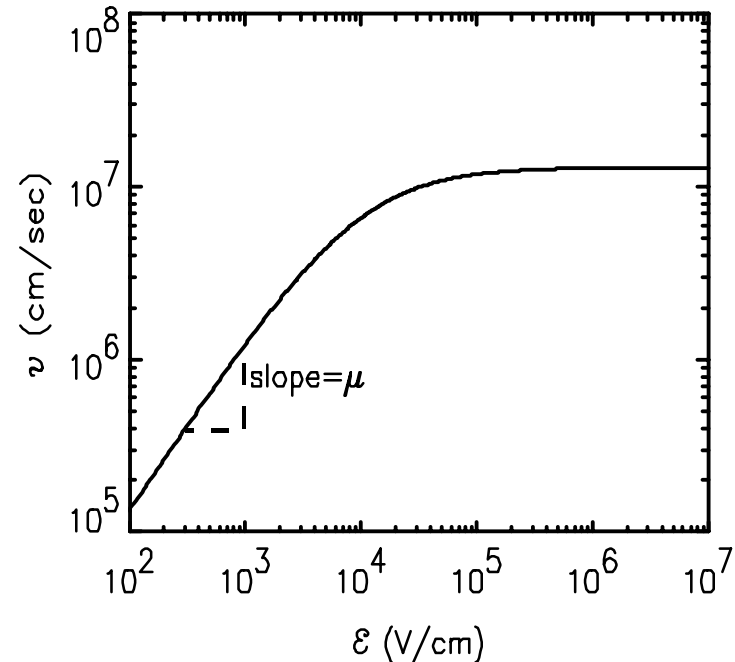
Factors Influencing Mobility

- The value of mobility (velocity per unit electric field) is influenced by several factors

  – The mechanisms of conduction through the valence and conduction bands are different, and so the mobilities associated with electrons and holes are different. The value for electrons is more than twice that for holes at low values of doping

  – As the density of dopants increases, more scattering occurs during conduction - mobility therefore decreases as doping increases

  – At low temperatures, electrons and holes gain more energy than the lattice with increasing T, therefore mobility increases. At high temperatures, lattice scattering dominates, and thus mobility falls

  – Conduction through bulk material (diodes, BJTs) experiences less scattering than conduction along a surface (MOSFET), hence bulk mobility is higher than surface mobility (see Table 21.1)

Resistivity and Conductivity

- The expression for *J* in terms of μ and *E* can be written as

$$J = (qn\mu_n + qp\mu_p)E$$

- The first term is the conductivity σ, in $(\Omega\text{cm})^{-1}$, and its inverse is the resistivity ρ, already used in the calculation of series resistance in the diode structure

$$\sigma = \frac{1}{\rho} \equiv qn\mu_n + qp\mu_p$$

MOS Structure in Depletion

- A +ve V_{GB} applied to the gate of a MOS structure whose substrate is grounded produces E penetrating into the substrate

- For a p-type substrate, E repels majority holes from the surface, creating a depletion region

- Some minority electrons are attracted to the surface, but at low values of V_{GB} their numbers are not sufficient to cause much effect

- Charge balance is primarily +ve holes on gate, -ve ionized acceptors

- This is termed depletion operation
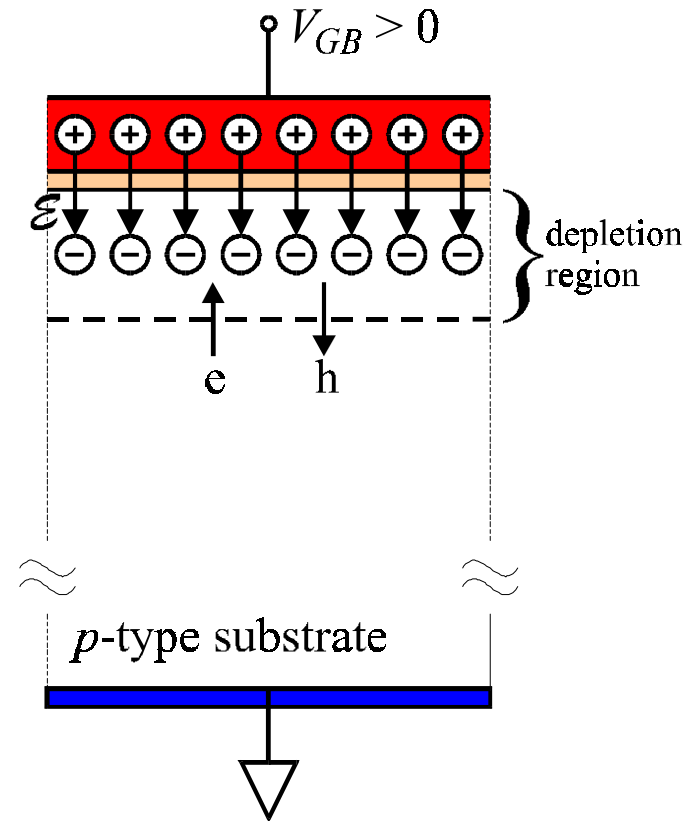
MOS Structure in Inversion

- At large V_{GB}, a dense inversion layer of electrons forms under the surface

- Further increases in V_{GB} only change the density of the inversion layer

- The potential at which the inversion layer dominates the substrate behaviour is the threshold voltage V_T

- This inversion layer will form the conductive channel between the source and drain of the MOSFET
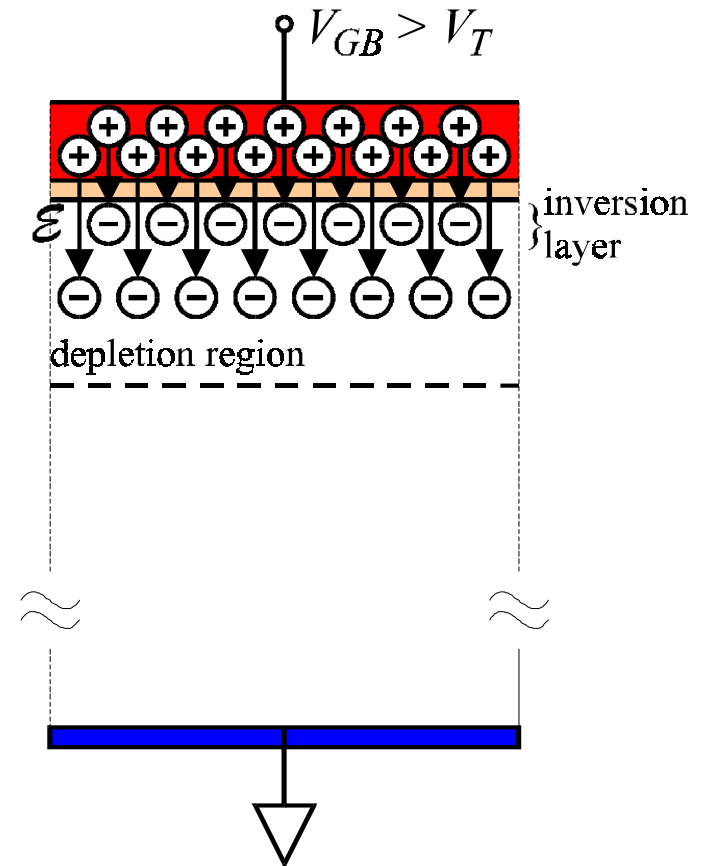
Electric Fields in the MOSFET

- Two distinct electric field distributions exist in the MOSFET structure
  - The transverse field is caused by the potential difference between the conductive gate and the substrate. This field is supports the substrate depletion region and inversion layer
  - The lateral field arises due to a non-zero source to drain potential, and is (in the simple model) the main mechanism for current flow in the MOSFET
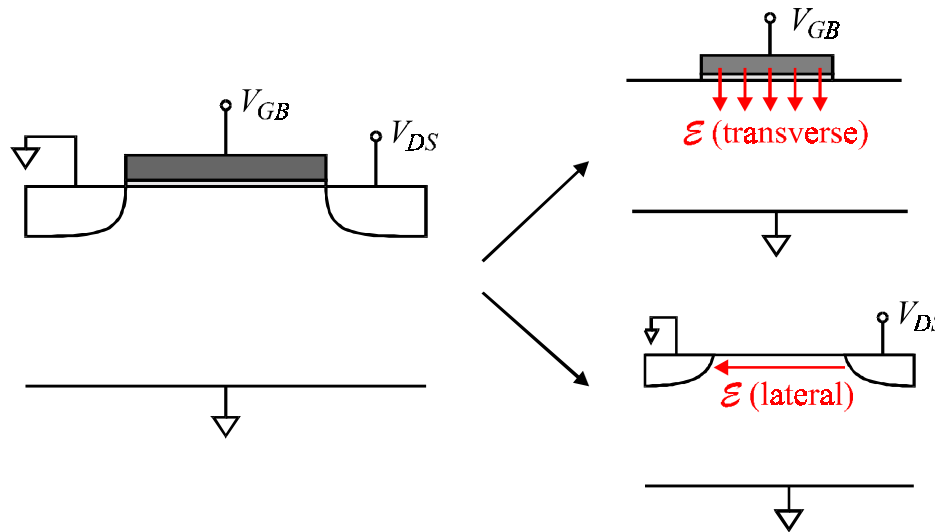
Qualitative MOSFET Operation

- Assume an n-channel MOSFET, i.e. n^+ source and drain regions in a uniformly doped p-type substrate

- Source and substrate are grounded

- Results discussed here apply to p-channel (n-type substrate) devices with reversal of polarities
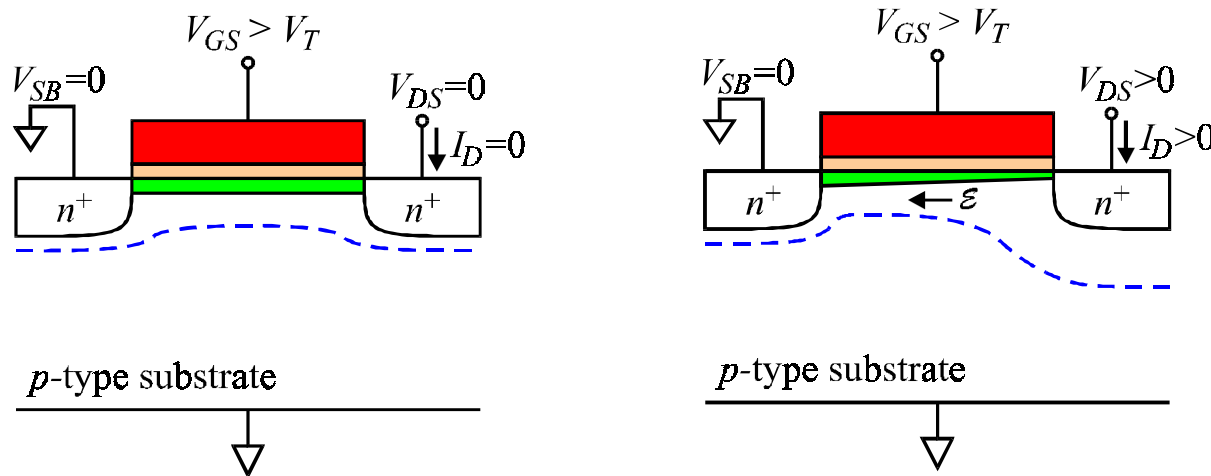
n-Channel MOSFET With $V_{GS} < V_T$

- With $V_{GS} < V_T$, there is no inversion layer present under the surface
- At $V_{DS} = 0$, the source and drain depletion regions are symmetrical
- A positive V_{DS} reverse biases the drain substrate junction, hence the depletion region around the drain widens, and since the drain is adjacent to the gate edge, the depletion region widens in the channel
- No current flows even for $V_{DS} > 0$, since there is no conductive channel between the source and drain for $V_{GS} < V_T$
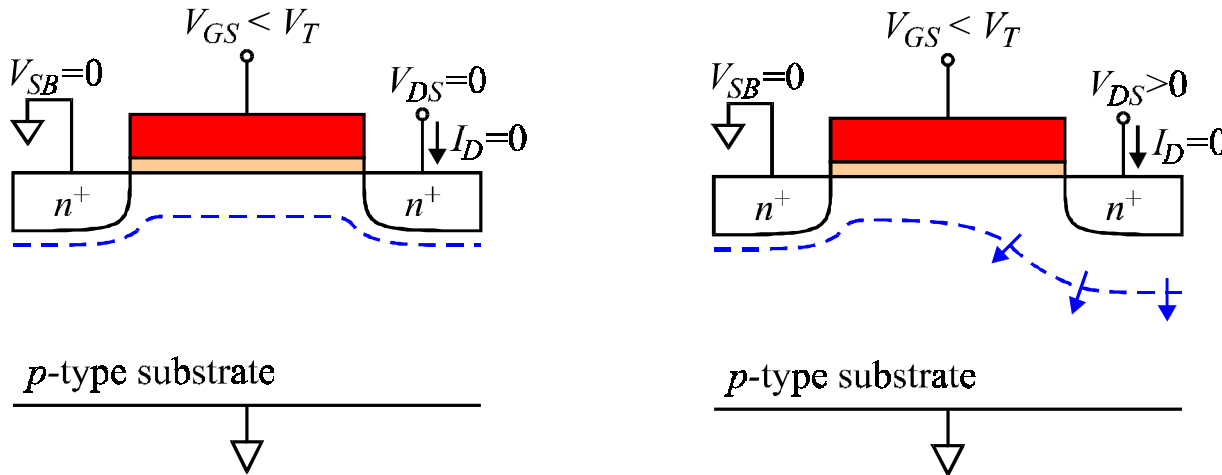
n-Channel MOSFET With $V_{GS} > V_T$, small V_{DS}

- With $V_{GS} > V_T$, a conductive channel forms under the surface - a non-zero transverse field is present

- I_D is zero for $V_{DS} = 0$ since no lateral field is present

- For $V_{DS} > 0$, transverse E is present and current flows

- The increased reverse bias on the drain substrate junction in contact with the inversion layer causes inversion layer density to decrease

97.398*, *Physical Electronics:*
MOSFET Operation (21)

n-Channel MOSFET With $V_{GS} > V_T$, large V_{DS}

- The point at which the inversion layer density becomes very small (essentially zero) at the drain end is termed pinch-off

- The value of V_{DS} at pinchoff is denoted $V_{DS,sat}$

- Past pinchoff, further increases in lateral electric field are absorbed by the creation of a narrow high field region with low carrier density ($J_n = q n \mu_n E$, so if n is small E is large)
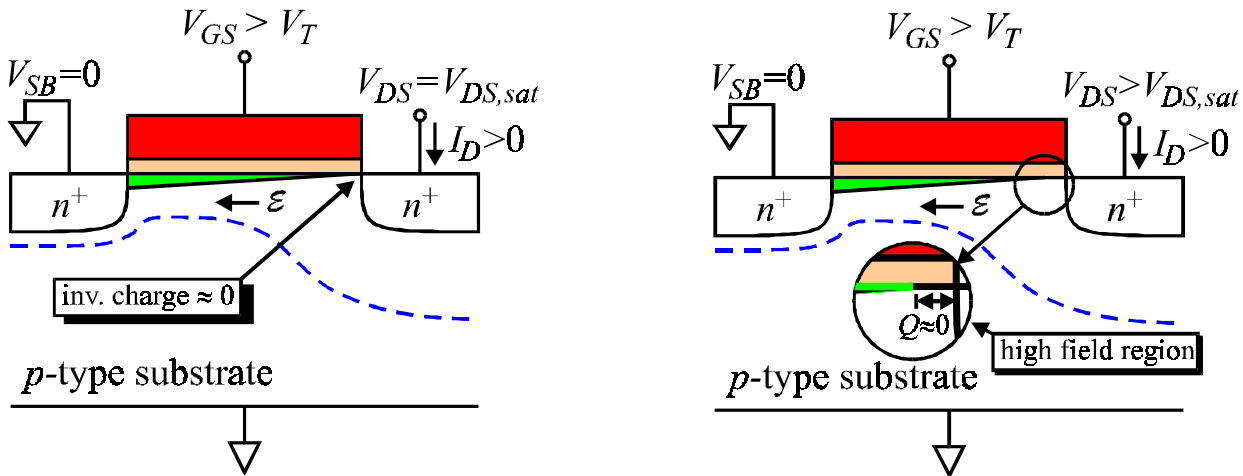
MOSFET Regions of Operation

- There are three regions of operation in the MOSFET
  - When $V_{GS} < V_T$, no conductive channel is present and $I_D = 0$, the cutoff region
  - If $V_{GS} < V_T$ and $V_{DS} < V_{DS,sat}$, the device is in the triode region of operation. Increasing V_{DS} increases the lateral field in the channel, and hence the current. Increasing V_{GS} increases the transverse field and hence the inversion layer density, which also increases the current
  - If $V_{GS} < V_T$ and $V_{DS} > V_{DS,sat}$, the device is in the saturation region of operation. Since the drain end channel density has become small, the current is much less dependent on V_{DS}, but is still dependent on V_{GS}, since increased V_{GS} still increases the inversion layer density

MOSFET I_D-V_{DS} Characteristic

- For $V_{GS} < V_T$, $I_D = 0$

- As V_{DS} increases at a fixed V_{GS}, I_D increases in the triode region due to the increased lateral field, but at a decreasing rate since the inversion layer density is decreasing

- Once pinchoff is reached, further V_{DS} increases only increase I_D due to the formation of the high field region

- The device starts in triode, and moves into saturation at higher V_{DS}
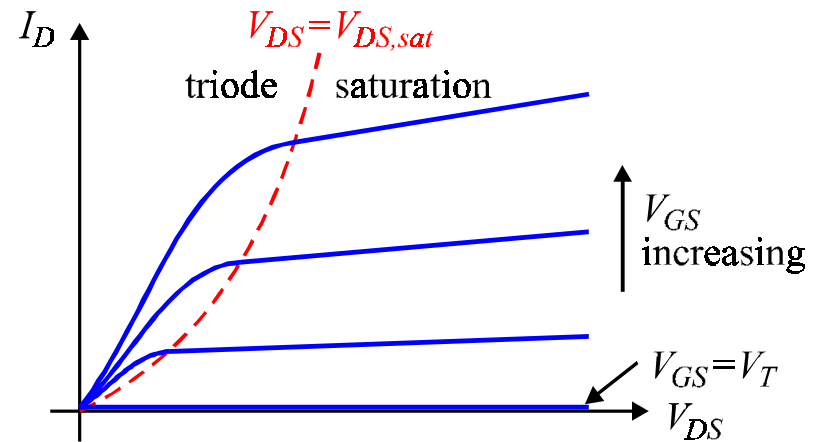
MOSFET I_D-V_{GS} Characteristic

- As I_D is increased at fixed V_{DS}, no current flows until the inversion layer is established

- For V_{GS} slightly above threshold, the device is in saturation since there is little inversion layer density (the drain end is pinched off)

- As V_{GS} increases, a point is reached where the drain end is no longer pinched off, and the device is in the triode region

- A larger V_{DS} value postpones the point of transition to triode
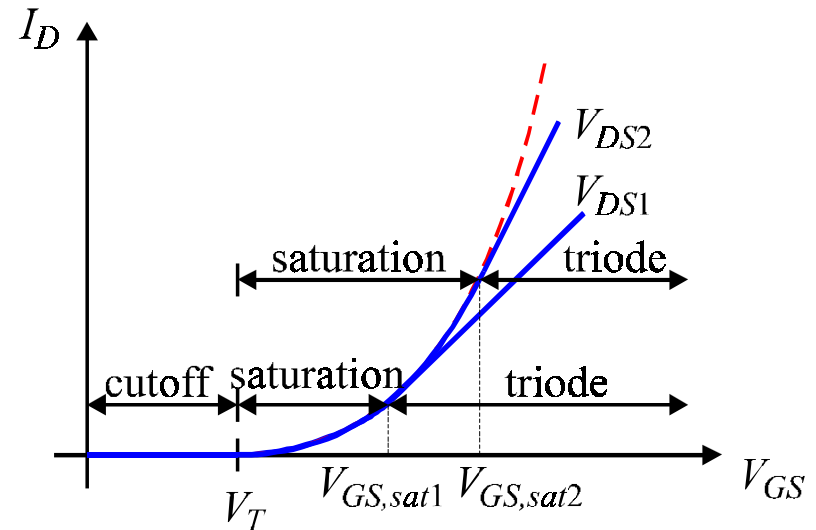
Lecture Summary

- Examined <u>drift</u>, the movement of carriers under the influence of an electric field

- <u>Mobility</u> characterizes the ease with which carriers can move by drift (velocity per unit electric field), and is influenced by dopant density, temperature, surface vs bulk conduction and the type of carrier

- Mobility is the proportionality constant between velocity and electric field for low field magnitudes - for high fields, carrier velocity is limited to a maximum value, referred to as <u>velocity saturation</u>

- Qualitative MOSFET operation in cutoff, triode and saturation regions was described