Semiconductor devices

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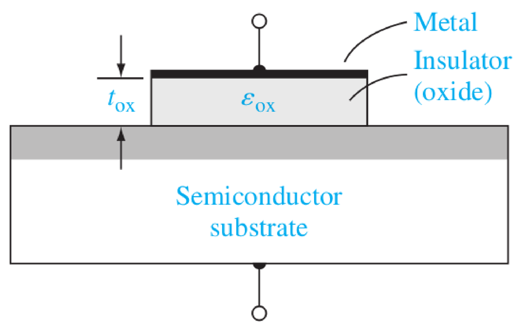
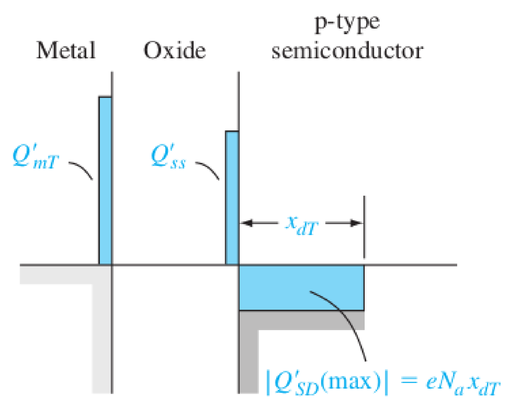
Fundamentals of the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)

The two-terminal MOS structure





The MOS structure is similar to that of the plate capacitor:

$$
\begin{aligned}
C &= \frac{\epsilon}{d}\\
Q' &= C'V\\
E &= \frac{V}{d}\\
\phi_{fp} &= V_t \ln\left(\frac{N_a}{n_i}\right)\\
x_d &= \sqrt{\frac{2\epsilon\phi_s}{eN_a}}\\
x_{dT} &= \sqrt{\frac{4\epsilon\phi_{fp}}{eN_a}}\\
n &= n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]\\
n_s &= n_i \exp\left[\frac{\phi_{fp} + \Delta\phi_s}{V_t}\right] = \underbrace{n_i \exp\left(\frac{\phi_{fp}}{V_t}\right)}_{n_{st}} \exp\left(\frac{\Delta\phi_s}{V_t}\right) \quad \Delta\phi_s > 2\phi_{fp}
\end{aligned}
$$

$$
e\phi'_m + eV_{ox0} = e\chi' + \frac{E_g}{2} - e\phi_{s0}e\phi_{Jfp}
$$

$V_{ox}0$ is the potential drop across the oxide, ϕ'_m the modified metal work function

$$
V_{ox0} + \phi_{s0} = -\left[\phi'_m - \left(\chi' + \frac{E_g}{2e} + \phi_{fp}\right)\right]
$$

The metal semiconductor workfunction is then:

$$
\begin{aligned}
\phi_{ms} &\equiv \left[\phi'_m - \left(\chi' + \frac{E_g}{2e} + \phi_{fp}\right)\right]\\
\phi_{ms_{np}} &= \pm\left(\frac{E_g}{2e} - \phi_{fp}\right)\\
V_{ox0} + \phi_{s0} &= -\phi_{ms}\\
V_g &= \Delta V_{ox} + \Delta\phi_s = (V_{ox} - V_{ox0}) + (\phi_{s0} - \phi_{s0})\\
&= V_{ox} + \phi_s + \phi_{ms}
\end{aligned}
$$

For flaatband

$$
\begin{aligned}
Q'_m + Q'_{ss} &= 0\\
V_{ox} &= \frac{Q'_m}{C_{ox}} = \frac{-Q'_{ss}}{C_{ox}}\\
V_G &= V_{FB} = \phi_{ms} - \frac{Q'_{ss}}{C_{ox}}\\
Q'_{mT} + Q'_{ss} &= |Q'_{SD}(\max)|\\
|Q'_{SD}(\max)| &= eN_a x_{dT}\\
V_G &= V_{ox} + \phi_s + \phi_{ms}
\end{aligned}
$$

at threshold $V_G = V_{TN}$

$$
\begin{aligned}
V_{TN} &= V_{xoT}02\phi_{fp} + \phi_{ms}\\
V_{oxT} &= \frac{Q'_{mT}}{C_{ox}}\\
&= \frac{1}{C_{ox}}\left(|Q'_{SD}(\max)| - Q'_{ss}\right)\\
V_{TN} &= \frac{1}{C_{ox}}\left(|Q'_{SD}(\max)| - Q'_{ss}\right) + \phi_{ms} + 2\phi_{fp}\\
&= \frac{t_{ox}}{\epsilon_{ox}}\left(|Q'_{SD}(\max)| - Q'_{ss}\right) + \phi_{ms} + 2\phi_{fp}\\
&= \frac{|Q'_{SD}(\max|}{C_{ox}} + V_{FB} + 2\phi_{fp}
\end{aligned}
$$

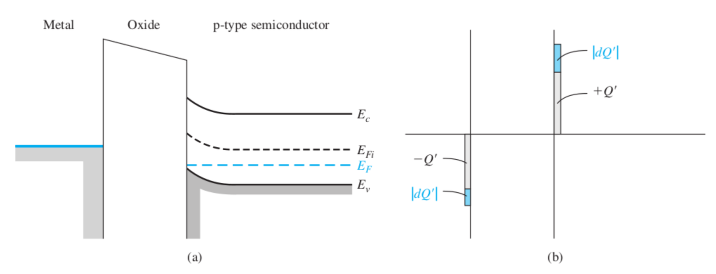
The same can be done with an n type conductor

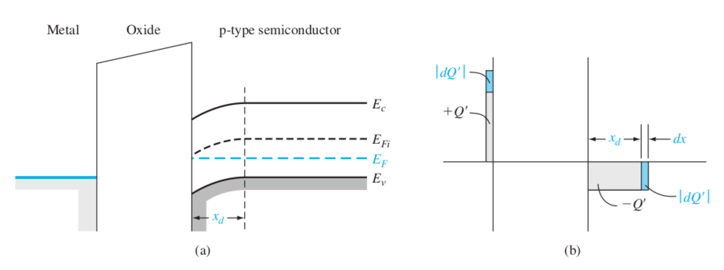
$$
V_{TP} = \frac{t_{ox}}{\epsilon_{ox}}\left(-|Q'_{SD}(\max)| - Q'_{ss}\right) + \phi_{ms} + 2\phi_{fn}
$$

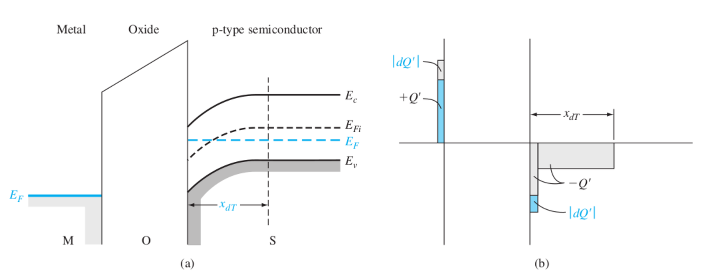
with

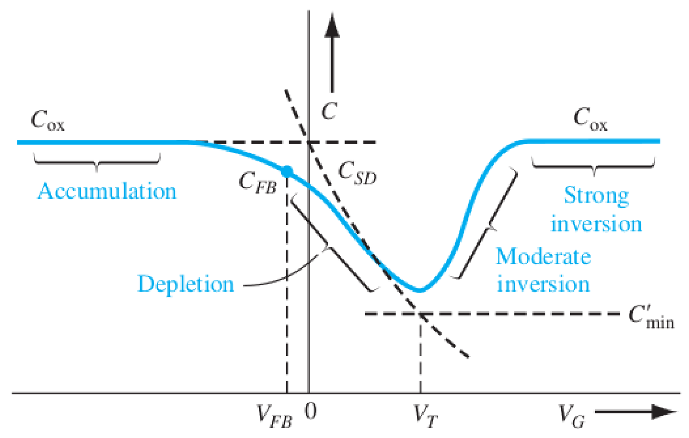
$$
\begin{aligned}
\phi_{ms} &= \phi'_m - \left(\chi' + \frac{E_g}{2e} - \phi_{fn}\right)\\
|Q'_{SD}(\max)| &= eN_d x_{dT}\\
x_{dT} &= \sqrt{\frac{4\epsilon_s\phi_{fn}}{eN_d}}\\
\phi_{fn} &= V_t \ln\left(\frac{N_d}{n_i}\right)
\end{aligned}
$$

Capacitance-voltage characteristics









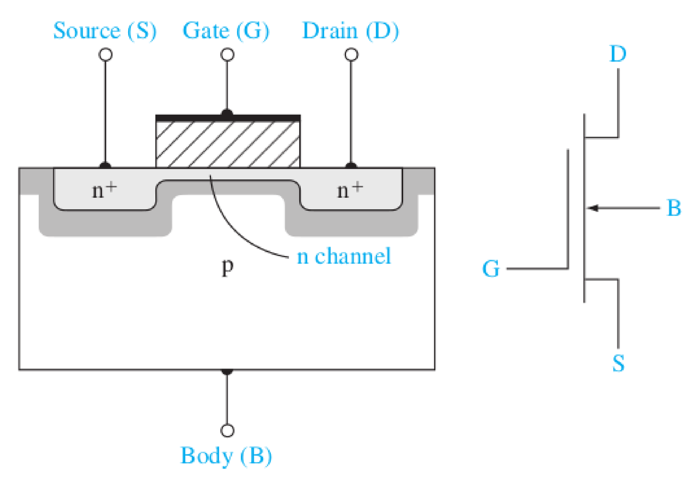
$$
C = \frac{dQ}{dV}
$$

dQ is the magnitude of differential change in charge

$$
\begin{aligned}
C'(acc) &= C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}\\
\frac{1}{C'(depl)} &= \frac{1}{C'_{ox}} + \frac{1}{C'_{SD}}\\
C'(depl) &= \frac{C_{ox}C'_{SD}}{C_{ox} + C'_{SD}}\\
&= \frac{C_{ox}}{1 + \frac{C_{ox}}{C'_{SD}}}\\
&= \frac{\epsilon_{ox}}{t_{ox} + \frac{\epsilon_{ox}}{\epsilon_s}x_d}\\
C'_{\min} &= \frac{\epsilon_{ox}}{t_{ox} + \frac{\epsilon_{ox}}{\epsilon_s}x_{dT}}\\
C'(inv) &= C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}\\
C'_{FB} &= \frac{\epsilon_{ox}}{t_{ox} + \frac{\epsilon_{ox}}{\epsilon_s}\sqrt{V_t\frac{\epsilon_s}{eN_a}}}
\end{aligned}
$$

Frequency effects Two sources of electrons changing the charge density of the inversion layer: Diffusion of minority carrier electrons and thermal generation of electron hole pairs inside the space charge region. Fixed oxide and interface charge effects $V_{FB} = \phi_{ms} - \frac{Q'_{SS}}{C_{ox}}$ This can move and smear out the C-V curve

The basic MOSFET operation



There are four MOSFET types: n and p types and each can be in either enhancement(auto off) mode and depletion(auto on).

$$
\begin{aligned}
I_d &= g_d V_{DS}\\
g_d &= \frac{W}{L}\mu_n|Q'_n|\\
V_{DS}(sat) &= V_{GS} - V_T
\end{aligned}
$$

for an n-chanel type in depletion

$$
\begin{aligned}
I_D &= \frac{W\mu_n C_{ox}}{2L}\left[2\left(V_{GS} - V_T\right)V_{DS} - V_{DS}^2\right]\\
&= \frac{k'_n}{2}\frac{W}{L}\left[2\left(V_{GS} - V_T\right)V_{DS} - V_{DS}^2\right]\\
&= K_n\left[2\left(V_{GS} - V_T\right)V_{DS} - V_{DS}^2\right]
\end{aligned}
$$

When the transistor is biased in the saturation region

$$
\begin{aligned}
I_D &= \frac{W\mu_n C_{ox}}{2L}\left(V_{GS} - V_T\right)^2\\
&= \frac{k'_n}{2}\frac{W}{L}\left(V_{GS} - V_T\right)^2\\
&= K_n\left(V_{GS} - V_T\right)^2
\end{aligned}
$$