1. For a fixed $V_D$, explain how the drain current in an N-channel JFET is reduced as the gate voltage is made more negative.
2. For a fixed gate voltage, explain how the drain current is increased as the drain voltage is increased.
3. What is the difference between pinch off voltage and threshold voltage.
4. Explain how there is a drain current after the channel is pinched off.
5. How is the work function of a metal determined?
6. The Fermi level of a metal does not change when electrons are added to metal. Why?
7. Why is there no diffusion (storage) capacitance in a Schottky-barrier diode?
8. Why is Schottky-barrier diode much faster in switching, than the PN diode?
MOS Capacitor

- Typical MOS capacitors and transistors in ICs today employ
  - heavily doped polycrystalline Si ("poly-Si") film as the gate-electrode material
    - n*-type, for "n-channel" transistors (NMOS)
    - p*-type, for "p-channel" transistors (PMOS)
  - SiO₂ as the gate dielectric
    - band gap = 9 eV
    - $\varepsilon_{r,\text{SiO}_2} = 3.9$
  - Si as the semiconductor material
    - p-type, for "n-channel" transistors (NMOS)
    - n-type, for "p-channel" transistors (PMOS)
Bulk Semiconductor Potential $\psi_B$

$$q \psi_B \equiv E_i (\text{bulk}) - E_F$$

- **p-type Si:**
  $$\psi_B = \frac{kT}{q} \ln\left(\frac{N_A}{n_i}\right) > 0$$

- **n-type Si:**
  $$\psi_B = -\frac{kT}{q} \ln\left(\frac{N_D}{n_i}\right) < 0$$
MOS Equilibrium Energy-Band Diagram

(a) N⁺ polysilicon

(b) 

- $E_c$ 
- $E_v$ 
- 3.1 eV 
- gate 
- body 
- $E_f$ 
- body 
- $E_v$
Guidelines for Drawing MOS Band Diagrams

- Fermi level $E_F$ is flat (constant with distance $x$) in the Si
  - Since no current flows in the $x$ direction, we can assume that equilibrium conditions prevail

- Band bending is linear in the oxide
  - No charge in the oxide $\Rightarrow d\varepsilon/dx = 0$ so $\varepsilon$ is constant
  $\Rightarrow dE_c/dx$ is constant

- From Gauss’ Law, we know that the electric field strength in the Si at the surface, $\varepsilon_{Si}$, is related to the electric field strength in the oxide, $\varepsilon_{ox}$:

$$\varepsilon_{ox} = \frac{\varepsilon_{Si}}{\varepsilon_{ox}} \varepsilon_{Si} \approx 3 \varepsilon_{Si} \Rightarrow \frac{dE_c}{dx}_{\text{oxide}} = 3 \times \frac{dE_c}{dx}_{\text{Si (at the surface)}}$$
MOS Band-Diagram Guidelines (cont.)

- The barrier height for conduction-band electron flow from the Si into SiO₂ is 3.1 eV
  - This is equal to the electron-affinity difference (\( \chi_{\text{Si}} \) and \( \chi_{\text{SiO}_2} \))

- The barrier height for valence-band hole flow from the Si into SiO₂ is 4.8 eV

- The vertical distance between the Fermi level in the metal, \( E_{FM} \), and the Fermi level in the Si, \( E_{FS} \), is equal to the applied gate voltage:
  \[
  qV_G = E_{FS} - E_{FM}
  \]
Voltage Drops in the MOS System

- In general,

\[ V_G = V_{FB} + V_{ox} + \psi_s \]

where

\[ qV_{FB} = \phi_{MS} = \phi_M - \phi_S \]

\( V_{ox} \) is the voltage dropped across the oxide
\( (V_{ox} = \text{total amount of band bending in the oxide}) \)

\( \psi_s \) is the voltage dropped in the silicon
\( (\text{total amount of band bending in the silicon}) \)

\[ q\psi_s = E_i(bulk) - E_i(surface) \]

For example: When \( V_G = V_{FB}, V_{ox} = \psi_s = 0 \)
\( i.e. \) there is no band bending
Special Case: Equal Work Functions

\[ \Phi_M = \Phi_S \]

What happens when the work function is different?
General Case: Different Work Functions

(a)

(b)
Flat-Band Condition

$E_0$: Vacuum level
$E_0 - E_f$: Work function
$E_0 - E_c$: Electron affinity
Si/SiO$_2$ energy barrier

$qq_M = 3.1 \text{ eV}$
$q\Phi_S = \chi_{Si} + (E_c - E_f)$
$9 \text{ eV}$
$4.8 \text{ eV}$
MOS Band Diagrams (n-type Si)

Decrease $V_G$ (toward more negative values)
-> move the gate energy-bands up, relative to the Si

- **Accumulation**
  - $V_G > V_{FB}$
  - Electrons accumulate at surface

- **Depletion**
  - $V_G < V_{FB}$
  - Electrons repelled from surface

- **Inversion**
  - $V_G < V_T$
  - Surface becomes p-type
Biasing Conditions for p-type Si

Energy band diagram

Applied dc voltage

$V_G = V_{FB}$

$V_G < V_{FB}$

$V_T > V_G > V_{FB}$

$V_G > V_T$

Charge diagram

Name: Flat band

Accumulation

$-Q$

Depletion

$+Q$

Inversion

Exposed acceptors

Electrons

$-Q$
Accumulation (n+ poly-Si gate, p-type Si)

\[ V_G < V_{FB} \]

Mobile carriers (holes) accumulate at Si surface

\[ E_c = E_{FM} \]

3.1 eV

4.8 eV

\[ |qV_{ox}| \]

\[ |qV_G| \]

\[ \text{is small, } \approx 0 \]

\[ V_G \approx V_{FB} + V_{ox} \]
Accumulation Layer Charge Density

\[ V_G < V_{FB} \]

\[ V_{ox} \equiv V_G - V_{FB} \]

From Gauss’ Law:

\[ \varepsilon_{ox} = -\frac{Q_{acc}}{\varepsilon_{SiO_2}} \]

\[ V_{ox} = \varepsilon_{ox} t_{ox} = -\frac{Q_{acc}}{C_{ox}} \]

where \( C_{ox} \equiv \frac{\varepsilon_{SiO_2}}{t_{ox}} \) (units: F/cm²)

\[ \Rightarrow Q_{acc} = -C_{ox} (V_G - V_{FB}) > 0 \]
Depletion (n+ poly-Si gate, p-type Si)

\[ V_T > V_G > V_{FB} \]

Si surface is depleted of mobile carriers (holes)
\[ => \] Surface charge is due to ionized dopants (acceptors)
Depletion Width $W_d$ (p-type Si)

- **Depletion Approximation:**
  The surface of the Si is depleted of mobile carriers to a depth $W_d$.

- The charge density within the depletion region is
  \[ \rho \equiv -qN_A \quad (0 \leq x \leq W_d) \]

- Poisson’s equation:
  \[ \frac{d}{dx} \frac{\varepsilon}{\varepsilon_{Si}} = \frac{\rho}{\varepsilon_{Si}} \equiv -\frac{qN_A}{\varepsilon_{Si}} \quad (0 \leq x \leq W_d) \]

- Integrate twice, to obtain $\psi_S$:
  \[ \psi_S = \frac{qN_A W_d^2}{2 \varepsilon_{Si}} \Rightarrow W_d = \sqrt{\frac{2 \varepsilon_{Si} \psi_S}{qN_A}} \]

To find $\psi_S$ for a given $V_G$, we need to consider the voltage drops in the MOS system...
Voltage Drops in Depletion (p-type Si)

From Gauss’ Law:

\[ \varepsilon_{ox} = -\frac{Q_{dep}}{\varepsilon_{SiO_2}} \]

\[ V_{ox} = \varepsilon_{ox} t_{ox} = -\frac{Q_{dep}}{C_{ox}} \]

\( Q_{dep} \) is the integrated charge density in the Si:

\[ Q_{dep} = -qN_A W_d = -\sqrt{2qN_A \varepsilon_{Si} \psi_s} \]

\[ V_G = V_{FB} + \psi_s + V_{ox} = V_{FB} + \psi_s + \frac{\sqrt{2qN_A \varepsilon_{Si} \psi_s}}{C_{ox}} \]
Surface Potential in Depletion (p-type Si)

\[ V_G = V_{FB} + \psi_s + \frac{\sqrt{2qN_A \varepsilon_{si}}\psi_s}{C_{ox}} \]

• Solving for \( \psi_s \), we have

\[ \sqrt{\psi_s} = \frac{\sqrt{qN_A \varepsilon_{si}}}{\sqrt{2C_{ox}}} \left[ \sqrt{1+ \frac{2C_{ox}^2 (V_G - V_{FB})}{qN_A \varepsilon_{si}}} - 1 \right] \]

\[ \psi_s = \frac{qN_A \varepsilon_{si}}{2C_{ox}^2} \left[ \sqrt{1+ \frac{2C_{ox}^2 (V_G - V_{FB})}{qN_A \varepsilon_{si}}} - 1 \right]^2 \]
Threshold Condition \((V_G = V_T)\)

- When \(V_G\) is increased to the point where \(\psi_s\) reaches \(2\psi_B\), the surface is said to be strongly inverted.
  
  (The surface is n-type to the same degree as the bulk is p-type.)

  This is the threshold condition.

\[
V_G = V_T \implies \psi_s = 2\psi_B
\]

\[
E_i(bulk) - E_i(surface) = 2[E_i(bulk) - E_F]
\]

\[
E_i(surface) - E_F = -[E_i(bulk) - E_F]
\]

\[
\implies n_{surface} = N_A
\]
MOS Band Diagram at Threshold (p-type Si)

\[ \psi_s = 2\psi_B = 2 \frac{kT}{q} \ln \left( \frac{N_A}{n_i} \right) \]

\[ W_d = W_{dm} = \sqrt{\frac{2\varepsilon_{Si} (2\psi_B)}{qN_A}} \]
Threshold Voltage

- For p-type Si:
  \[ V_G = V_{FB} + \psi_s + V_{ox} = V_{FB} + \psi_s + \frac{\sqrt{2qN_A \varepsilon_{Si} \psi_s}}{C_{ox}} \]
  \[ V_T = V_{FB} + 2\psi_B + \frac{\sqrt{2qN_A \varepsilon_{Si} (2\psi_B)}}{C_{ox}} \]

- For n-type Si:
  \[ V_T = V_{FB} + 2\psi_B - \frac{\sqrt{2qN_D \varepsilon_{Si} |2\psi_B|}}{C_{ox}} \]
Strong Inversion (p-type Si)

As $V_G$ is increased above $V_T$, the negative charge in the Si is increased by adding mobile electrons (rather than by depleting the Si more deeply), so the depletion width remains ~constant at $W_d = W_{dm}$.

Significant density of mobile electrons at surface (surface is n-type)

$$\psi_s \approx 2\psi_B$$

$$W_d \approx W_{dm} = \sqrt{\frac{2\varepsilon\psi_B}{qN_A}}$$
Inversion Layer Charge Density (p-type Si)

\[ V_G = V_{FB} + \psi_s + V_{ox} \]

\[ = V_{FB} + 2\psi_B - \frac{(Q_{dep} + Q_{inv})}{C_{ox}} \]

\[ = V_{FB} + 2\psi_B + \frac{\sqrt{2qN_A \varepsilon_s (2\psi_B)}}{C_{ox}} - \frac{Q_{inv}}{C_{ox}} \]

\[ = V_T - \frac{Q_{inv}}{C_{ox}} \]

\[ \therefore \quad Q_{inv} = -C_{ox} (V_G - V_T) \]