MOSFET Transistor

DC Analysis

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March 18, 2008
Outline

1. MOSFET DC Analysis Procedure
2. Examples
3. MOSFET As A Current Source
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Procedure

1. Apply KVL at the gate source loop to find $V_{GS}$
2. If $V_{GS} < V_{TN}$, the transistor is off. Otherwise, assume an operating region (usually saturation)
3. Use $V_{GS}$ from step 1 to calculate $I_D$ using the transistor current equation
4. Apply KVL at the drain source loop and use $I_D$ from step 3 to find $V_{DS}$
5. Check the validity of assumed region by comparing $V_{DS}$ to $V_{DSAT}$
6. Change assumptions and analyze again if required.

- An enhancement-mode device with $V_{DS} = V_{GS}$ is always in saturation
- If we have a source resistance, we need to solve the equations in steps 1 and 3 together to find $I_D$ and $V_{GS}$.
- If we include channel length modulation or we are in the triode region, we will solve the equations in steps 3 and 4 together
- If we include channel length modulation or we are in the triode region and we have a source resistance, we will solve the equations in steps 1, 3, and 4 together
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Example 1
Biasing in Triode Region

Example
- Find the Q-pt \((I_D, V_{DS})\) assuming that \(V_{TN} = 1\, V\), and \(K_n = 250\, \mu A/V^2\)

Solution
- Assumption: Transistor is saturated, and \(I_G = I_B = 0\)
- Analysis: From input loop \(V_{GS} = V_{DD} = 4\, V\)
- Since the transistor at saturation we can use:
  \[I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 = \frac{250}{2} \frac{\mu A}{V^2} (4 - 1)^2 = 1.13\, mA\]
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Solution

- Applying KVL at D-S Loop: \( V_{DD} = I_D R_D + V_{DS} \)

- Substitute by the given values:
  \[ 4 = 1.6 \times 1.3 + V_{DS} \rightarrow V_{DS} = 2.19 \text{V} \]

- But \( V_{DS} < V_{GS} - V_{TN} \). Hence, saturation region assumption is incorrect and the transistor is in triode region.

- Using triode region equation,
  \[ 4 - V_{DS} = 1600 \times 250 \frac{I_D}{V_T^2} (4 - 1 - \frac{V_{DS}}{2}) V_{DS} \]

- Solving the last equation \( \therefore V_{DS} = 2.3 \text{V} \), and \( I_D = 1.06 \text{mA} \)

- \( V_{DS} < V_{GS} - V_{TN} \), transistor is in triode region

- Q-pt: (1.06 m.A, 2.3 V) with \( V_{GS} = 4 \text{V} \)
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Biasing in Saturation Region

Example

- Find the Q-pt \((I_D, V_{DS})\)
  assuming that \(V_{TN}=1\text{V}\), and \(K_n = 25\mu\text{A/V}^2\)

Solution

- Approach: Assume operation region, find Q-point, check to see if result is consistent with operation region
- Assumption: Transistor is saturated, \(I_G = I_B = 0\)
- Analysis: First, simplify circuit, split \(V_{DD}\) into two equal-valued sources and apply Thevenin’s transformation to find \(V_{EQ}\) and \(R_{EQ}\) for the gate-bias voltage
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Solution

- Apply KVL at G-S Loop:
  \[ V_{EQ} = V_{GS} + I_D R_S \]
- Using \[ I_D = \frac{K_n}{2} \left( V_{GS} - V_{TN} \right)^2 \]
- \[ \therefore V_{EQ} = V_{GS} + \frac{K_n R_S}{2} \left( V_{GS} - V_{TN} \right)^2 \]

- Substitute by given values
  \[ 4 = V_{GS} + \frac{(25 \times 10^{-6})(39 \times 10^3)}{2} \left( V_{GS} - 1 \right)^2 \]

- Solving the quadratic equation results in \( V_{GS} = -2.71 \text{ V}, +2.66 \text{ V} \)
- Since \( V_{GS} < V_{TN} \) for \( V_{GS} = -2.71 \text{ V} \), we will ignore it
- Substituting with \( V_{GS} = +2.66 \text{ V} \) results in \( I_D = 34.4 \mu \text{A} \)
- Applying KVL at D-S loop, \[ V_{DD} = I_D (R_D + R_S) + V_{DS} \rightarrow V_{DS} = 6.08 \text{ V} \]
- Since \( V_{DS} > V_{GS} - V_{TN} \). Hence saturation region assumption is correct.
- Q-pt: \( (34.4 \, \mu \text{A}, 6.08 \text{ V}) \) with \( V_{GS} = 2.66 \text{ V} \)
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Solution

Apply KVL at G-S Loop:
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Substitute by given values:
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- Since \( V_{GS} < V_{TN} \) for \( V_{GS} = -2.71 \, V \), we will ignore it
- Substituting with \( V_{GS} = +2.66 \, V \) results in \( I_D = 34.4 \, \mu A \)
- Applying KVL at D-S loop, \( V_{DD} = I_D (R_D + R_S) + V_{DS} \rightarrow V_{DS} = 6.08 \, V \)
- Since \( V_{DS} > V_{GS} - V_{TN} \). Hence saturation region assumption is correct.
- Q-pt: \( (34.4 \, \mu A, 6.08 \, V) \) with \( V_{GS} = 2.66 \, V \)
Example 2

Solution

- **Apply KVL at G-S Loop:**
  \[ V_{EQ} = V_{GS} + I_D R_S \]

- **Using**
  \[ I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 \]

- \[ \therefore V_{EQ} = V_{GS} + \frac{K_n R_S}{2} (V_{GS} - V_{TN})^2 \]

- **Substitute by given values**
  \[ 4 = V_{GS} + \frac{(25 \times 10^{-6})(39 \times 10^3)}{2} (V_{GS} - 1)^2 \]

- Solving the quadratic equation results in \( V_{GS} = -2.71 \text{V}, +2.66 \text{V} \)

- Since \( V_{GS} < V_{TN} \) for \( V_{GS} = -2.71 \text{V} \), we will ignore it

- Substituting with \( V_{GS} = +2.66 \text{V} \) results in \( I_D = 34.4 \mu A \)

- Applying KVL at D-S loop,
  \[ V_{DD} = I_D (R_D + R_S) + V_{DS} \rightarrow V_{DS} = 6.08 \text{V} \]

- Since \( V_{DS} > V_{GS} - V_{TN} \), hence saturation region assumption is correct.

- **Q-pt:** (34.4 \( \mu A \), 6.08 \text{V}) with \( V_{GS} = 2.66 \text{V} \)
Example 2
Solution

- Apply KVL at G-S Loop:
  \[ V_{EQ} = V_{GS} + I_D R_S \]
- Using \( I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 \)
- \[ \therefore V_{EQ} = V_{GS} + \frac{K_n R_S}{2} (V_{GS} - V_{TN})^2 \]

- Substitute by given values 4 = \( V_{GS} + \frac{(25 \times 10^{-6})(39 \times 10^3)}{2} (V_{GS} - 1)^2 \)
- Solving the quadratic equation results in \( V_{GS} = -2.71 \text{V, } +2.66 \text{V} \)
  - Since \( V_{GS} < V_{TN} \) for \( V_{GS} = -2.71 \text{V} \), we will ignore it
  - Substituting with \( V_{GS} = +2.66 \text{V} \) results in \( I_D = 34.4 \mu \text{A} \)
  - Applying KVL at D-S loop, \( V_{DD} = I_D (R_D + R_S) + V_{DS} \rightarrow V_{DS} = 6.08 \text{V} \)
  - Since \( V_{DS} > V_{GS} - V_{TN} \). Hence saturation region assumption is correct.
- Q-pt: (34.4 \( \mu \text{A}, 6.08 \text{V} \)) with \( V_{GS} = 2.66 \text{V} \)
Example 2
Solution

Apply KVL at G-S Loop:
\[ V_{EQ} = V_{GS} + I_D R_S \]

Using \( I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 \)
\[ \therefore V_{EQ} = V_{GS} + \frac{K_n R_S}{2} (V_{GS} - V_{TN})^2 \]

Substitute by given values
\[ 4 = V_{GS} + \left(\frac{25 \times 10^{-6}}{2}\right)\left(\frac{39 \times 10^3}{2}\right) (V_{GS} - 1)^2 \]

Solving the quadratic equation results in \( V_{GS} = -2.71 \text{ V}, +2.66 \text{ V} \)

Since \( V_{GS} < V_{TN} \) for \( V_{GS} = -2.71 \text{ V} \), we will ignore it

Substituting with \( V_{GS} = +2.66 \text{ V} \) results in \( I_D = 34.4 \mu\text{A} \)

Applying KVL at D-S loop, \( V_{DD} = I_D (R_D + R_S) + V_{DS} \rightarrow V_{DS} = 6.08 \text{ V} \)

Since \( V_{DS} > V_{GS} - V_{TN} \). Hence saturation region assumption is correct.

Q-pt: \((34.4 \ \mu\text{A}, 6.08 \text{ V})\) with \( V_{GS} = 2.66 \text{ V} \)
Example 2

Solution

- Apply KVL at G-S Loop:
  \[ V_{EQ} = V_{GS} + I_D R_S \]
- Using \( I_D = \frac{K_n}{2} \left( V_{GS} - V_{TN} \right)^2 \)
- \( \therefore V_{EQ} = V_{GS} + \frac{K_n R_S}{2} \left( V_{GS} - V_{TN} \right)^2 \)

- Substitute by given values \( 4 = V_{GS} + \left( \frac{25 \times 10^{-6}}{2} \right) \left( 39 \times 10^3 \right) \left( V_{GS} - 1 \right)^2 \)
- Solving the quadratic equation results in \( V_{GS} = -2.71 \text{V}, +2.66 \text{V} \)
- Since \( V_{GS} < V_{TN} \) for \( V_{GS} = -2.71 \text{V} \), we will ignore it
- Substituting with \( V_{GS} = +2.66 \text{V} \) results in \( I_D = 34.4 \mu A \)
  - Applying KVL at D-S loop, \( V_{DD} = I_D (R_D + R_S) + V_{DS} \to V_{DS} = 6.08 \text{V} \)
  - Since \( V_{DS} > V_{GS} - V_{TN} \). Hence saturation region assumption is correct.
- Q-pt: (34.4 \( \mu A \), 6.08 \text{V}) with \( V_{GS} = 2.66 \text{V} \)
Example 2

Solution

- Apply KVL at G-S Loop:
  \[ V_{EQ} = V_{GS} + I_D R_S \]
- Using \( I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 \)
- \( \therefore V_{EQ} = V_{GS} + \frac{K_n R_S}{2} (V_{GS} - V_{TN})^2 \)

- Substitute by given values 4 = \( V_{GS} + \frac{(25 \times 10^{-6})(39 \times 10^3)}{2} (V_{GS} - 1)^2 \)
- Solving the quadratic equation results in \( V_{GS} = -2.71 \text{ V}, +2.66 \text{ V} \)
- Since \( V_{GS} < V_{TN} \) for \( V_{GS} = -2.71 \text{ V} \), we will ignore it
- Substituting with \( V_{GS} = +2.66 \text{ V} \) results in \( I_D = 34.4 \mu A \)
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- Since \( V_{DS} > V_{GS} - V_{TN} \). Hence saturation region assumption is correct.
- Q-pt: \( (34.4 \mu A, 6.08 \text{ V}) \) with \( V_{GS} = 2.66 \text{ V} \)
Example 2
Solution

- **Apply KVL at G-S Loop:**
  \[ V_{EQ} = V_{GS} + I_D R_S \]
  
- **Using**
  \[ I_D = \frac{K_n}{2} \left( V_{GS} - V_{TN} \right)^2 \]
  
  \[ \therefore V_{EQ} = V_{GS} + \frac{K_n R_S}{2} \left( V_{GS} - V_{TN} \right)^2 \]

- **Substitute by given values**
  \[ 4 = V_{GS} + \left( \frac{25 \times 10^{-6}}{2} \right) \left( \frac{39 \times 10^3}{2} \right) \left( V_{GS} - 1 \right)^2 \]

- **Solving the quadratic equation results in**
  \[ V_{GS} = -2.71 \text{V}, +2.66 \text{V} \]

- **Since** \( V_{GS} < V_{TN} \) for \( V_{GS} = -2.71 \text{V} \), we will ignore it.

- **Substituting with** \( V_{GS} = +2.66 \text{V} \) results in \( I_D = 34.4 \mu\text{A} \)

- **Applying KVL at D-S loop,**
  \[ V_{DD} = I_D (R_D + R_S) + V_{DS} \rightarrow V_{DS} = 6.08 \text{V} \]

- **Since** \( V_{DS} > V_{GS} - V_{TN} \). Hence saturation region assumption is correct.

- **Q-pt:** \((34.4 \ \mu\text{A}, 6.08 \text{V}) \) with \( V_{GS} = 2.66 \text{V} \)
Example 2

Solution

Apply KVL at G-S Loop:
\[ V_{EQ} = V_{GS} + I_D R_S \]

Using \[ I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 \]

\[ \therefore V_{EQ} = V_{GS} + \frac{K_n R_S}{2} (V_{GS} - V_{TN})^2 \]

Substitute by given values 4 = \( V_{GS} + \frac{(25 \times 10^{-6})(39 \times 10^3)}{2} (V_{GS} - 1)^2 \)

Solving the quadratic equation results in \( V_{GS} = -2.71 \text{V}, +2.66 \text{V} \)

Since \( V_{GS} < V_{TN} \) for \( V_{GS} = -2.71 \text{V} \), we will ignore it

Substituting with \( V_{GS} = +2.66 \text{V} \) results in \( I_D = 34.4 \mu A \)

Applying KVL at D-S loop, \( V_{DD} = I_D (R_D + R_S) + V_{DS} \rightarrow V_{DS} = 6.08 \text{V} \)

Since \( V_{DS} > V_{GS} - V_{TN} \). Hence saturation region assumption is correct.

Q-pt: (34.4 \( \mu A \), 6.08 \text{V}) with \( V_{GS} = 2.66 \text{V} \)
Example 3
Bias Analysis with Body Effect

Example

- Find the Q-pt \((I_D, V_{DS})\) assuming that \(V_{TO} = 1\,V\), \(2\phi_F = 0.6\,V\), \(\gamma = 0.5\sqrt{V}\), and \(K_n = 25\mu A/V^2\)

Solution

- Approach: Assume operation region, find Q-point, check to see if result is consistent with operation region

- Assumption: Transistor is saturated, \(I_G = I_B = 0\)

- Analysis: First, using KVL at the G-S loop yields:
  \[V_{GS} = V_{EQ} - I_D R_S = 6 - 22,000I_D\]
Example 3
Bias Analysis with Body Effect

Solution

- **Approach:** Assume operation region, find Q-point, check to see if result is consistent with operation region
  - **Assumption:** Transistor is saturated, $I_G = I_B = 0$
  - **Analysis:** First, using KVL at the G-S loop yields:
    \[ V_{GS} = V_{EQ} - I_D R_S = 6 - 22,000 I_D \]

- **Example**
  - Find the Q-pt $(I_D, V_{DS})$ assuming that $V_{TO} = 1V$, $2\phi_F = 0.6V$, $\gamma = 0.5\sqrt{V}$, and $K_n = 25\mu A/V^2$
Example 3
Bias Analysis with Body Effect

Find the Q-pt \((I_D, V_DS)\) assuming that \(V_{TO} = 1\) V, \(2\phi_F = 0.6\) V, \(\gamma = 0.5\sqrt{V}\), and \(K_n = 25\mu A/V^2\)

Solution

- **Approach**: Assume operation region, find Q-point, check to see if result is consistent with operation region
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\[
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Bias Analysis with Body Effect

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- Analysis: First, using KVL at the G-S loop yields:
  \[ V_{GS} = V_{EQ} - I_D R_S = 6 - 22,000 I_D \]
Example 3

Solution

- Since $V_{SB} \neq 0$ then use $V_{TN} = V_{TO} + \gamma(\sqrt{V_{SB}} + 2\varphi_F - \sqrt{2\varphi_F})$
- $\therefore V_{TN} = 1 + 0.5(\sqrt{22000I_D} + 0.6 - \sqrt{0.6})$
- Using $I_D' = \left(\frac{25 \times 10^{-6}}{2}\right) (V_{GS} - V_{TN})^2$ we can solve the non-linear equation to find $I_D$ or use the iteration method below.

Iteration Method

- Estimate value of $I_D$ and use it to find $V_{GS}$ and $V_{TN}$
- Find $I_D'$ using $V_{GS}$ and $V_{TN}$ from the last step
- If $I_D'$ is not same as original $I_D$ estimate, start again.

- The iteration sequence leads to $I_D = 88.0 \, \mu A$
- Applying KVL at D-S loop,
  
  $V_{DS} = V_{DD} - I_D(R_D + R_S) = 10 - 40,000I_D = 6.48 V$
- Since $V_{DS} > V_{GS} - V_{TN}$. Hence saturation region assumption is correct.
- Q-pt: $(88 \, \mu A, 6.48 \, V)$ with $V_{GS} = 4.06 \, V$
Example 3
Solution

- Since $V_{SB} \neq 0$ then use $V_{TN} = V_{TO} + \gamma(\sqrt{V_{SB}} + 2\varphi_F - \sqrt{2}\varphi_F)$

- $\therefore V_{TN} = 1 + 0.5(\sqrt{22000I_D} + 0.6 - \sqrt{0.6})$

- Using $I_D' = \left(\frac{25 \times 10^{-6}}{2}\right) (V_{GS} - V_{TN})^2$ we can solve the non-linear equation to find $I_D$ or use the iteration method below

### Iteration Method

- Estimate value of $I_D$ and use it to find $V_{GS}$ and $V_{TN}$
- Find $I_D'$ using $V_{GS}$ and $V_{TN}$ from the last step
- If $I_D'$ is not same as original $I_D$ estimate, start again.

- The iteration sequence leads to $I_D = 88.0 \mu A$
- Applying KVL at D-S loop,
  $V_{DS} = V_{DD} - I_D(R_D + R_S) = 10 - 40,000I_D = 6.48 V$

- Since $V_{DS} > V_{GS} - V_{TN}$. Hence saturation region assumption is correct.
- Q-pt: $(88 \mu A, 6.48 V)$ with $V_{GS} = 4.06 V$
Example 3
Solution

- Since $V_{SB} \neq 0$ then use $V_{TN} = V_{TO} + \gamma(\sqrt{V_{SB}} + 2\phi_F - \sqrt{2\phi_F})$
- $\therefore V_{TN} = 1 + 0.5(\sqrt{22000I_D} + 0.6 - \sqrt{0.6})$
- Using $I_D' = \frac{(25 \times 10^{-6})}{2} (V_{GS} - V_{TN})^2$ we can solve the non-linear equation to find $I_D$ or use the iteration method below.

Iteration Method

- Estimate value of $I_D$ and use it to find $V_{GS}$ and $V_{TN}$
- Find $I_D'$ using $V_{GS}$ and $V_{TN}$ from the last step
- If $I_D'$ is not same as original $I_D$ estimate, start again.

- The iteration sequence leads to $I_D = 88.0 \, \mu A$
- Applying KVL at D-S loop,
  $V_{DS} = V_{DD} - I_D(R_D + R_S) = 10 - 40,000I_D = 6.48\, V$
- Since $V_{DS} > V_{GS} - V_{TN}$. Hence saturation region assumption is correct.
- Q-pt: $(88 \, \mu A, 6.48 \, V)$ with $V_{GS} = 4.06 \, V$
Example 3

Solution

- Since $V_{SB} \neq 0$ then use $V_{TN} = V_{TO} + \gamma(\sqrt{V_{SB}} + 2\varphi_F - \sqrt{2}\varphi_F)$
- $\therefore V_{TN} = 1 + 0.5(\sqrt{22000}I_D + 0.6 - \sqrt{0.6})$
- Using $I_D' = \frac{(25\times10^{-6})}{2} (V_{GS} - V_{TN})^2$ we can solve the non-linear equation to find $I_D$ or use the iteration method below

Iteration Method

- Estimate value of $I_D$ and use it to find $V_{GS}$ and $V_{TN}$
- Find $I_D'$ using $V_{GS}$ and $V_{TN}$ from the last step
- If $I_D'$ is not same as original $I_D$ estimate, start again.

- The iteration sequence leads to $I_D = 88.0 \ \mu A$
- Applying KVL at D-S loop,
  $$V_{DS} = V_{DD} - I_D(R_D + R_S) = 10 - 40,000I_D = 6.48V$$
- Since $V_{DS} > V_{GS} - V_{TN}$. Hence saturation region assumption is correct.
- Q-pt: (88 $\ \mu A, \ 6.48 \ \text{V}$) with $V_{GS} = 4.06 \ \text{V}$
Example 3
Solution

- Since \( V_{SB} \neq 0 \) then use \( V_{TN} = V_{TO} + \gamma(\sqrt{V_{SB}} + 2\varphi_F - \sqrt{2}\varphi_F) \)

- \( \therefore V_{TN} = 1 + 0.5(\sqrt{22000I_D} + 0.6) \)

- Using \( I_D' = \frac{(25 \times 10^{-6})}{2} (V_{GS} - V_{TN})^2 \) we can solve the non-linear equation to find \( I_D \) or use the iteration method below

**Iteration Method**

- Estimate value of \( I_D \) and use it to find \( V_{GS} \) and \( V_{TN} \)
- Find \( I_D' \) using \( V_{GS} \) and \( V_{TN} \) from the last step
- If \( I_D' \) is not same as original \( I_D \) estimate, start again.

- The iteration sequence leads to \( I_D = 88.0 \, \mu A \)
- Applying KVL at D-S loop,
  \[ V_{DS} = V_{DD} - I_D(R_D + R_S) = 10 - 40,000I_D = 6.48 \, V \]
- Since \( V_{DS} > V_{GS} - V_{TN} \). Hence saturation region assumption is correct.
- Q-pt: \( (88 \, \mu A, 6.48 \, V) \) with \( V_{GS} = 4.06 \, V \)
Example 3
Solution

- Since $V_{SB} \neq 0$ then use $V_{TN} = V_{TO} + \gamma(\sqrt{V_{SB}} + 2\varphi_F - \sqrt{2\varphi_F})$
- $\therefore V_{TN} = 1 + 0.5(\sqrt{22000i_D} + 0.6 - \sqrt{0.6})$
- Using $i'_D = \left(\frac{25 \times 10^{-6}}{2}\right) (V_{GS} - V_{TN})^2$ we can solve the non-linear equation to find $i_D$ or use the iteration method below

Iteration Method

- Estimate value of $i_D$ and use it to find $V_{GS}$ and $V_{TN}$
- Find $i'_D$ using $V_{GS}$ and $V_{TN}$ from the last step
- If $i'_D$ is not same as original $i_D$ estimate, start again.

- The iteration sequence leads to $i_D$ = 88.0 $\mu$A
- Applying KVL at D-S loop,
  $V_{DS} = V_{DD} - i_D(R_D + R_S) = 10 - 40,000i_D = 6.48$V
- Since $V_{DS} > V_{GS} - V_{TN}$. Hence saturation region assumption is correct.
- Q-pt: (88 $\mu$A, 6.48 V) with $V_{GS}$ = 4.06 V
Example 3

Solution

- Since $V_{SB} \neq 0$ then use $V_{TN} = V_{TO} + \gamma(\sqrt{V_{SB}} + 2\varphi_F - \sqrt{2\varphi_F})$

- $\therefore V_{TN} = 1 + 0.5(\sqrt{22000I_D} + 0.6 - \sqrt{0.6})$

- Using $I'_D = \left(\frac{25 \times 10^{-6}}{2}\right) (V_{GS} - V_{TN})^2$ we can solve the non-linear equation to find $I_D$ or use the iteration method below.

Iteration Method

- Estimate value of $I_D$ and use it to find $V_{GS}$ and $V_{TN}$
- Find $I'_D$ using $V_{GS}$ and $V_{TN}$ from the last step
- If $I'_D$ is not same as original $I_D$ estimate, start again.

- The iteration sequence leads to $I_D = 88.0 \mu A$
- Applying KVL at D-S loop,
  $V_{DS} = V_{DD} - I_D(R_D + R_S) = 10 - 40,000I_D = 6.48V$
- Since $V_{DS} > V_{GS} - V_{TN}$. Hence saturation region assumption is correct.
- Q-pt: $(88 \mu A, 6.48 V)$ with $V_{GS} = 4.06 V$
Example 3

Solution

- Since $V_{SB} \neq 0$ then use $V_{TN} = V_{TO} + \gamma (\sqrt{V_{SB} + 2\varphi_F} - \sqrt{2\varphi_F})$

- $\therefore V_{TN} = 1 + 0.5(\sqrt{22000I_D} + 0.6 - \sqrt{0.6})$

- Using $I_D' = \left(\frac{25\times10^{-6}}{2}\right) (V_{GS} - V_{TN})^2$ we can solve the non-linear equation to find $I_D$ or use the iteration method below

### Iteration Method

- Estimate value of $I_D$ and use it to find $V_{GS}$ and $V_{TN}$
- Find $I_D'$ using $V_{GS}$ and $V_{TN}$ from the last step
- If $I_D'$ is not same as original $I_D$ estimate, start again.

- The iteration sequence leads to $I_D = 88.0 \, \mu A$

- Applying KVL at D-S loop,
  
  $V_{DS} = V_{DD} - I_D (R_D + R_S) = 10 - 40,000I_D = 6.48 \, V$

- Since $V_{DS} > V_{GS} - V_{TN}$. Hence saturation region assumption is correct.

- Q-pt: $(88 \, \mu A, 6.48 \, V)$ with $V_{GS} = 4.06 \, V$
Example 3

Solution

Since $V_{SB} \neq 0$ then use $V_{TN} = V_{TO} + \gamma (\sqrt{V_{SB}} + 2\varphi_F - \sqrt{2}\varphi_F)$

\[ \therefore V_{TN} = 1 + 0.5(\sqrt{22000}\,i_D + 0.6 - \sqrt{0.6}) \]

Using $I'_D = \left(\frac{25\times10^{-6}}{2}\right)(V_{GS} - V_{TN})^2$ we can solve the non-linear equation to find $I_D$ or use the iteration method below.

Iteration Method

- Estimate value of $I_D$ and use it to find $V_{GS}$ and $V_{TN}$
- Find $I'_D$ using $V_{GS}$ and $V_{TN}$ from the last step
- If $I'_D$ is not same as original $I_D$ estimate, start again.

The iteration sequence leads to $I_D = 88.0 \, \mu A$

Applying KVL at D-S loop,

$V_{DS} = V_{DD} - I_D(R_D + R_S) = 10 - 40,000I_D = 6.48 \, V$

- Since $V_{DS} > V_{GS} - V_{TN}$. Hence saturation region assumption is correct.
- Q-pt: $(88 \, \mu A, 6.48 \, V)$ with $V_{GS} = 4.06 \, V$
Example 3
Solution

- Since $V_{SB} \neq 0$ then use $V_{TN} = V_{TO} + \gamma(\sqrt{V_{SB} + 2\varphi_F} - \sqrt{2\varphi_F})$

- $\therefore V_{TN} = 1 + 0.5(\sqrt{22000I_D} + 0.6 - \sqrt{0.6})$

- Using $I_D' = \left(\frac{25 \times 10^{-6}}{2}\right) (V_{GS} - V_{TN})^2$ we can solve the non-linear equation to find $I_D$ or use the iteration method below

### Iteration Method

- Estimate value of $I_D$ and use it to find $V_{GS}$ and $V_{TN}$
- Find $I_D'$ using $V_{GS}$ and $V_{TN}$ from the last step
- If $I_D'$ is not same as original $I_D$ estimate, start again.

- The iteration sequence leads to $I_D = 88.0 \mu A$
- Applying KVL at D-S loop,
  $V_{DS} = V_{DD} - I_D(R_D + R_S) = 10 - 40,000I_D = 6.48V$

- Since $V_{DS} > V_{GS} - V_{TN}$. Hence saturation region assumption is correct.

Q-pt: $(88 \mu A, 6.48 V)$ with $V_{GS} = 4.06 V$
Example 3

Solution

- Since $V_{SB} \neq 0$ then use $V_{TN} = V_{TO} + \gamma(\sqrt{V_{SB} + 2\varphi_F} - \sqrt{2\varphi_F})$

- $\therefore V_{TN} = 1 + 0.5(\sqrt{22000I'_D + 0.6} - \sqrt{0.6})$

- Using $I'_D = \frac{(25 \times 10^{-6})}{2} (V_{GS} - V_{TN})^2$ we can solve the non-linear equation to find $I_D$ or use the iteration method below

Iteration Method

- Estimate value of $I_D$ and use it to find $V_{GS}$ and $V_{TN}$

- Find $I'_D$ using $V_{GS}$ and $V_{TN}$ from the last step

- If $I'_D$ is not same as original $I_D$ estimate, start again.

- The iteration sequence leads to $I_D = 88.0 \, \mu A$

- Applying KVL at D-S loop,
  $V_{DS} = V_{DD} - I_D(R_D + R_S) = 10 - 40,000I_D = 6.48 V$

- Since $V_{DS} > V_{GS} - V_{TN}$. Hence saturation region assumption is correct.

- Q-pt: $(88 \, \mu A, 6.48 \, V)$ with $V_{GS} = 4.06 \, V$
Example 4
Bias with Feedback

Example
- Find the Q-pt \((I_D, V_{DS})\) assuming that \(V_{TN} = 1\) V, and \(K_n = 260\,\mu\text{A}/V^2\)

Solution
- Assumption: \(I_G = I_B = 0\)
- Analysis: Transistor is saturated since \(V_{DS} = V_{GS}\)
- Using KVL at the D-S loop yields: \(V_{DS} = V_{GS} = V_{DD} - I_D R_D\)
Example 4
Bias with Feedback

Example

- Find the Q-pt \((I_D, V_{DS})\) assuming that \(V_{TN} = 1\, \text{V}\), and \(K_n = 260\, \mu\text{A}/\text{V}^2\)

Solution

- Assumption: \(I_G = I_B = 0\)
- Analysis: Transistor is saturated since \(V_{DS} = V_{GS}\)
- Using KVL at the D-S loop yields: \(V_{DS} = V_{GS} = V_{DD} - I_D R_D\)
Example 4
Bias with Feedback

Example
- Find the Q-pt \((I_D, V_{DS})\) assuming that \(V_{TN} = 1\,\text{V}\), and \(K_n = 260\,\mu\text{A}/\text{V}^2\)

Solution
- Assumption: \(I_G = I_B = 0\)
- Analysis: Transistor is saturated since \(V_{DS} = V_{GS}\)
- Using KVL at the D-S loop yields: \(V_{DS} = V_{GS} = V_{DD} - I_D R_D\)
Example 4
Bias with Feedback

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- Analysis: Transistor is saturated since \(V_{DS} = V_{GS}\)
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Example 4
Solution

Since the transistor at saturation we can use: \( I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 \)

Substitute in the last KVL equation yields:
\[ V_{GS} = V_{DD} - \frac{K_n R_D}{2} (V_{GS} - V_{TN})^2 \]

Substitute by the given values:
\[ \therefore V_{GS} = 3.3 - \left(\frac{2.6 \times 10^{-4}}{2}\right)(10^4) (V_{GS} - 1)^2 \]

Solve the quadratic equation: \( \therefore V_{GS} = -0.769\,V, +2.00\,V \)

Since \( V_{GS} < V_{TN} \) for \( V_{GS} = -0.769\,V \) and MOSFET will be cut-off, it will be ignored.

Substitute in the current equation yields: \( I_D = 130\,\mu A \)

Q-pt: (130 \( \mu \)A, 2 V) with \( V_{GS} = 2\,V \)
Example 4

Solution

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Example 5
Enhancement PMOS

**Example**
- Find the Q-pt \((I_D, V_{DS})\) assuming that \(V_{TP} = -2\) V, and \(K_p = 50 \mu A/V^2\)

**Solution**
- **Assumption:** \(I_G = I_B = 0\)
- **Analysis:** Transistor is saturated since \(V_{SD} = V_{SG}\)
- **Applying KVL at D-S loop:** 
  \[ -15V + (220k\Omega)I_D + V_{SG} = 0 \]
- \(\therefore 15V - (220k\Omega)\frac{50}{2} \frac{\mu A}{V^2} (V_{SG} - 2)^2 - V_{SG} = 0 \)
- \(\therefore V_{SG} = 0.369\) V, 3.45 V
- Since \(V_{SG} = 0.369\) V < \(|V_{TP}| = 2\) V, \(\therefore V_{SG} = 3.45\) V and \(I_D = 52.5\) mA.
- **Q-pt:** (52.2 \(\mu A\), 3.45 V)
Example 5
Enhancement PMOS

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- \(\therefore 15\, \text{V} - (220\, \text{k}\Omega)\frac{50\, \mu\text{A}}{\text{V}^2} (V_{SG} - 2)^2 - V_{SG} = 0\)
- \(\therefore V_{SG} = 0.369\, \text{V}, 3.45\, \text{V}\)
- **Since** \(V_{SG} = 0.369\, \text{V} < |V_{TP}| = 2\, \text{V}\), \(\therefore V_{SG} = 3.45\, \text{V}\) and \(I_D = 52.5\, \text{mA}\).
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- Q-pt: \((52.2 \mu A, 3.45 V)\)
Example 6

Example

Design the shown circuit so that the transistor operates at $I_D = 0.3\, m\, A$ and $V_D = +0.4\, V$. The NMOS transistor has $V_t = 1\, V$, $\mu_n C_{ox} = 60\, \mu A/V^2$, $L = 3\, \mu m$, and $W = 120\, \mu m$.

Answer

- $R_S = 3.3\, k\Omega$, and $R_D = 7\, k\Omega$
Example 6

Design the shown circuit so that the transistor operates at $I_D = 0.3 \text{mA}$ and $V_D = +0.4 \text{V}$. The NMOS transistor has $V_t = 1 \text{V}$, $\mu_n C_{ox} = 60 \mu\text{A}/\text{V}^2$, $L = 3 \mu\text{m}$, and $W = 120 \mu\text{m}$.

Answer

- $R_S = 3.3k\Omega$, and $R_D = 7k\Omega$
Example 7

Example

Design the shown circuit so that the transistor operates at $I_D = 80 \mu A$. The NMOS transistor has $V_t = 0.6 V$, $\mu_n C_{ox} = 200 \mu A/V^2$, $L = 0.8 \mu m$, and $W = 4 \mu m$. Also, find the drain voltage $V_D$.

Answer

- $R = 25k\Omega$, and $V_D = +1V$
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**Example**

Design the shown circuit so that the transistor operates at $I_D = 80 \mu A$. The NMOS transistor has $V_t = 0.6 V$, $\mu_n C_{ox} = 200 \mu A/V^2$, $L = 0.8 \mu m$, and $W = 4 \mu m$. Also, find the drain voltage $V_D$.

**Answer**

- $R = 25 k\Omega$, and $V_D = +1 V$
Example 8

Design the shown circuit to establish $V_D$ of 0.1 V. The NMOS transistor has $V_t = 1 V$, and $k'_n W/L = 1 mA/V^2$. What is the effective resistance between drain and source at this operating point?

Answer

- $R_D = 12.4 k\Omega$, and $r_{ds} = 253\Omega$
Example 8

Design the shown circuit to establish $V_D$ of 0.1 V. The NMOS transistor has $V_t = 1\, \text{V}$, and $k'_n W/L = 1\, \text{mA/V}^2$. What is the effective resistance between drain and source at this operating point?

Answer

- $R_D = 12.4k\Omega$, and $r_{ds} = 253\Omega$
Example 9

Analyze the circuit shown to determine the voltages at all nodes and the currents through all branches. The NMOS transistor has $V_t = 1\, V$, and $k'_n W/L = 1\, mA/V^2$.

Answer

- $I_G = 0\, mA$, $I_{RG} = 0.5\, \mu A$, $I_D = 0.5\, mA$, $V_G = 5\, V$, $V_S = +3\, V$, and $V_D = +7\, V$
Example 9

**Example**

Analyze the circuit shown to determine the voltages at all nodes and the currents through all branches. The NMOS transistor has \( V_t = 1 \text{V} \), and \( k'_n W/L = 1 \text{mA/V}^2 \).

**Answer**

- \( I_G = 0 \text{mA} \), \( I_{RG} = 0.5 \mu \text{A} \), \( I_D = 0.5 \text{mA} \), \( V_G = 5 \text{V} \), \( V_S = +3 \text{V} \), and \( V_D = +7 \text{V} \).
Example 10

Design the shown circuit to obtain the indicated current and voltage values. The NMOS transistor has $V_t = 1\, V$, $\mu_n C_{ox} = 120\, \mu A/V^2$, $\lambda = 0$, and $L_1 = L_2 = 1\, \mu m$.

Answer

- $R = 12.5\, k\Omega$, $W_1 = 8\, \mu m$, and $W_1 = 2\, \mu m$
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Example 11

For the shown circuit calculate the shown current and voltage values for \( v_I = 0V, +2.5V, \) and \(-2.5V\). Assuming matched transistors with \( V_{TN} = V_{TP} = 1V, \) \( k_n = k_p = 1mA/V^2 \), and \( \lambda = 0 \).

Answer

- \( I_{DN} = I_{DP} = 1.125mA \), and \( v_o = 0V \)
- \( I_{DN} = 0.244mA, I_{DP} = 0mA, \) and \( v_o = -2.44V \)
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Outline

1. MOSFET DC Analysis Procedure
2. Examples
3. MOSFET As A Current Source
MOSFET As A Current Source

- Ideal current source gives fixed output current regardless of the voltage across it.
- MOSFET behaves as an ideal current source if biased in the pinch-off region (output current depends on terminal voltage).

Notes

- \( V_{DS} \) should be greater than \( V_{DSAT} \) for proper operation.
- If the channel length modulation isn’t neglected, a finite source resistance will exist = \( [\lambda I_D]^{-1} \)
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MOSFET DC Analysis Procedure

**MOSFET As A Current Source**

理想的电流源在给定电压下提供固定的输出电流。

- MOSFET 在压缩区时行为类似于理想的电流源（输出电流取决于端电压）。

**Notes**

- $V_{DS}$ 应该大于 $V_{DSAT}$ 以保证正常操作。
- 如果忽视了电荷长度调制，有限的源电阻将存在，为：$\lambda I_D$。
Assumptions: \( M_1 \) and \( M_2 \) have identical \( V_{TN}, K'_n, \lambda \) and are in saturation.

Analysis

\[ I_{REF} = \frac{K'_n}{2} \left( \frac{W}{L} \right) M_1 (V_{GS1} - V_{TN})^2 (1 + \lambda V_{DS1}) \]

\[ I_O = \frac{K'_n}{2} \left( \frac{W}{L} \right) M_2 (V_{GS2} - V_{TN})^2 (1 + \lambda V_{DS2}) \]

But \( V_{GS2} = V_{GS1} \), \( \therefore I_O = I_{REF} \left( \frac{W}{L} \right) M_2 \left( \frac{1 + \lambda V_{DS2}}{1 + \lambda V_{DS1}} \right) \approx \left( \frac{W}{L} \right) M_2 I_{REF} \left( \frac{W}{L} \right) M_1 \]

Thus, output current mirrors reference current if \( V_{DS1} = V_{DS2} \) or \( \lambda = 0 \), and both transistors have the same \((W/L)\).
Assumptions: $M_1$ and $M_2$ have identical $V_{TN}$, $K'_n$, $\lambda$ and are in saturation.

Analysis

- $I_{REF} = \frac{K'_n}{2} \left( \frac{W}{L} \right)_{M1} (V_{GS1} - V_{TN})^2 (1 + \lambda V_{DS1})$
- $I_O = \frac{K'_n}{2} \left( \frac{W}{L} \right)_{M2} (V_{GS2} - V_{TN})^2 (1 + \lambda V_{DS2})$
- But $V_{GS2} = V_{GS1}$, $\therefore I_O = I_{REF} \left( \frac{W}{L} \right)_{M2} \left( \frac{1 + \lambda V_{DS2}}{1 + \lambda V_{DS1}} \right) \approx \left( \frac{W}{L} \right)_{M2} I_{REF} \left( \frac{W}{L} \right)_{M1}$
- Thus, output current mirrors reference current if $V_{DS1} = V_{DS2}$ or $\lambda = 0$, and both transistors have the same (W/L).
Assumptions: $M_1$ and $M_2$ have identical $V_{TN}$, $K'_n$, $\lambda$ and are in saturation.

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- $I_{REF} = \frac{K'_n}{2} \left( \frac{W}{L} \right)_{M1} (V_{GS1} - V_{TN})^2 (1 + \lambda V_{DS1})$
- $I_O = \frac{K'_n}{2} \left( \frac{W}{L} \right)_{M2} (V_{GS2} - V_{TN})^2 (1 + \lambda V_{DS2})$

- But $V_{GS2} = V_{GS1}$, ∴ $I_O = I_{REF} \left( \frac{W}{L} \right)_{M2} (1 + \lambda V_{DS2}) \approx \left( \frac{W}{L} \right)_{M2} I_{REF}$
- Thus, output current mirrors reference current if $V_{DS1} = V_{DS2}$ or $\lambda = 0$, and both transistors have the same ($W/L$).
MOSFET As A Current Source

Assumptions: $M_1$ and $M_2$ have identical $V_{TN}$, $K_n^\prime$, $\lambda$ and are in saturation.

Analysis

\[ I_{REF} = \frac{K_n^\prime}{2} \left( \frac{W}{L} \right) M_1 (V_{GS1} - V_{TN})^2 (1 + \lambda V_{DS1}) \]

\[ I_O = \frac{K_n^\prime}{2} \left( \frac{W}{L} \right) M_2 (V_{GS2} - V_{TN})^2 (1 + \lambda V_{DS2}) \]

But $V_{GS2} = V_{GS1}$, $\therefore I_O = I_{REF} \frac{\left( \frac{W}{L} \right) M_2}{\left( \frac{W}{L} \right) M_1 (1 + \lambda V_{DS2})} \approx \left( \frac{W}{L} \right) M_2 I_{REF} \]

Thus, output current mirrors reference current if $V_{DS1} = V_{DS2}$ or $\lambda = 0$, and both transistors have the same $(W/L)$. 
MOSFET As A Current Source

Current Mirror

Assumptions: \( M_1 \) and \( M_2 \) have identical \( V_{TN}, K'_n, \lambda \) and are in saturation.

Analysis

\[ I_{REF} = \frac{K'_n}{2} \left( \frac{W}{L} \right) M_1 (V_{GS1} - V_{TN})^2 (1 + \lambda V_{DS1}) \]

\[ I_O = \frac{K'_n}{2} \left( \frac{W}{L} \right) M_2 (V_{GS2} - V_{TN})^2 (1 + \lambda V_{DS2}) \]

But \( V_{GS2} = V_{GS1}, \therefore I_O = I_{REF} \left( \frac{W}{L} \right) M_2 \frac{(1+\lambda V_{DS2})}{(1+\lambda V_{DS1})} \approx \left( \frac{W}{L} \right) M_2 I_{REF} \]

Thus, output current mirrors reference current if \( V_{DS1} = V_{DS2} \) or \( \lambda = 0 \), and both transistors have the same \((W/L)\).
Example 12
Current Mirror

Find the output current and the minimum output voltage $v_o$ to maintain the given current mirror in proper operation. Assume, $I_{REF} = 50 \, \mu A$, $V_O = 12 \, V$, $V_{TN} = 1 \, V$, $K'_n = 75 \, \mu A/V^2$, $\lambda = 0 \, V^{-1}$, $(W/L)_{M1} = 2$, $(W/L)_{M2} = 10$

Analysis

$\therefore I_O = I_{REF} \frac{(W/L)_{M2}}{(W/L)_{M1}} = 250 \, \mu A$

$V_{GS} = V_{TN} + \sqrt{\frac{2I_{REF}}{K'_n \frac{W}{L}(1+\lambda V_{DS1})}} = 1 \, V + \sqrt{\frac{2(50 \, \mu A)}{2 * 75 \, \mu A/V^2}} = 1.82 \, V$

Hence, $V_{omin} = V_{GS} - V_{TN} = 0.82 \, V$
Example 12
Current Mirror

Find the output current and the minimum output voltage \( v_o \) to maintain the given current mirror in proper operation. Assume, \( I_{REF} = 50 \mu A, V_O = 12 \text{ V}, V_{TN} = 1 \text{ V}, K'_n = 75 \mu A/V^2, \lambda = 0V^{-1}, (W/L)_{M1} = 2, (W/L)_{M2} = 10 \)

**Analysis**

\[ I_O = I_{REF} \left( \frac{W}{L} \right)_{M2} = 250 \mu A \]

\[ V_{GS} = V_{TN} + \sqrt{\frac{2I_{REF}}{K'_n \left( \frac{W}{L} \right)_{M1}(1+\lambda V_{DS1})}} = 1 \text{ V} + \sqrt{\frac{2(50\mu A)}{2*75 \frac{\mu A}{V^2}}} = 1.82 \text{ V} \]

Hence, \( V_{omin} = V_{GS} - V_{TN} = 0.82 \text{ V} \).
Example 12

Current Mirror

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**Analysis**

1. $I_O = I_{REF} \left( \frac{W}{L} \right)_{M2} = 250 \, \mu A$
2. $V_{GS} = V_{TN} + \sqrt{\frac{2I_{REF}}{K'_n \left( \frac{W}{L} \right)_{M1}(1+\lambda V_{DS1})}} = 1 \, V + \sqrt{\frac{2(50 \, \mu A)}{2*75 \, \mu A/V^2}} = 1.82 \, V$
3. Hence, $V_{omin} = V_{GS} - V_{TN} = 0.82 \, V$. 
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Current Mirror

Example

Find the output current and the minimum output voltage $v_o$ to maintain the given current mirror in proper operation. Assume, $I_{REF} = 50 \, \mu A$, $V_O = 12 \, V$, $V_{TN} = 1 \, V$, $K_n' = 75 \, \mu A/V^2$, $\lambda = 0 V^{-1}$, $(W/L)_{M1} = 2$, $(W/L)_{M2} = 10$

Analysis

1. $I_O = I_{REF} \left(\frac{W}{L}\right)_{M2} = 250 \, \mu A$

2. $V_{GS} = V_{TN} + \sqrt{\frac{2I_{REF}}{K_n'\left(\frac{W}{L}\right)(1+\lambda V_{DS1})}} = 1 \, V + \sqrt{\frac{2(50 \, \mu A)}{2 \times 75 \, \mu A/V^2}} = 1.82 \, V$

3. Hence, $V_{omin} = V_{GS} - V_{TN} = 0.82 \, V$. 