First-Time User Guide to MOSCAP*

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Introduction: What is a MOS Capacitor?

MOS Capacitor: Metal Oxide Semiconductor\[^1\] Capacitor

- Metal: metal or poly-silicon material
- Oxide: SiO\(_2\) or high-\(\kappa\) dielectric material
- Semiconductor: p-type or n-type semiconductor material

• Importance of MOS Capacitors
  » Essential for understanding MOSFET*\[^2\]
  » Basic structural part of MOSFET

[\(^1\) Dragica Vasileska (2008), "MOS Capacitors Description," http://nanohub.org/resources/5087

*MOSFET: Metal Oxide Semiconductor Field Effect Transistor has a source and a drain as an additional contacts to the gate contact as shown in the picture above.

For more information, refer to the following reference [2]

[\(^2\) Dragica Vasileska (2008), "MOSFET Operation Description," https://nanohub.org/resources/5085

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Introduction: What Can Be Measured in MOS Capacitors?

Capacitance-Voltage Characteristics\[^{[3]}\]

- Measurement
  - Simulation


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What Can Be Simulated by MOSCAP? (input):

MOS Capacitor with different geometry

Single Gate

- Insulator
- Semiconductor
- Gate insulator thickness: 2nm
- Gate insulator layer nodes: 4
- Semiconductor thickness: 500nm
- Semiconductor layer nodes: 100

Double Gate

- Insulator
- Semiconductor
- Insulator
- Left gate insulator thickness: 2nm
- Left gate insulator layer nodes: 4
- Semiconductor thickness: 50nm
- Semiconductor layer nodes: 25
- Right gate insulator thickness: 2nm
- Right gate insulator layer nodes: 4
What Can Be Simulated by MOSCAP? (input):

- Insulator dielectric constant
- Gate electrode type
- Gate workfunction* specification
- Semiconductor doping type
- Semiconductor doping density

*MOS Capacitor with different doping and material

*Workfunction is the minimum energy that is needed to remove an electron from a solid to a point immediately outside the solid surface - http://en.wikipedia.org/wiki/Work_function
What Can Be Simulated by MOSCAP? (input):

- Environment parameters
- Special parameters (charge density in the insulator)

Simulation starts with the default input parameters!!
**What If You Just Hit the “Simulate” Button? (output):**

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<th>C-V characteristic</th>
<th>[C-V Characteristics] : Gate capacitance vs Voltage characteristics</th>
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<td>[C/Cox-V Characteristics] : Gate capacitance divided by oxide capacitance vs Voltage characteristics</td>
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<td>Energy band diagram (at VG = 0)</td>
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<td>[Electron density] : electron density in the semiconductor</td>
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<td>Hole density (at VG = 0)</td>
<td>[Hole density] : hole density in the semiconductor</td>
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<tr>
<td>Net charge density (at VG = 0)</td>
<td>[Net charge density] : $\rho = q(N_A-N_D+n-p)$</td>
</tr>
<tr>
<td>Electrostatic potential (at VG = 0)</td>
<td>[Electrostatic potential] : $V = \text{const} - q \cdot E_c$</td>
</tr>
<tr>
<td>Electric field (at VG = 0)</td>
<td>[Electric field] : $E = -\nabla V$</td>
</tr>
</tbody>
</table>

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\[ \rho : \text{charge density} \]
\[ N_A/N_D : \text{acceptor/Donor density} \]
\[ n/p : \text{electron/hole density} \]
\[ q : \text{electron charge} \]
\[ E_c : \text{conduction band edge} \]
\[ E : \text{electric field} \]
\[ V : \text{electrostatic potential} \]
Example of Simulation (if the doping is changed)

C_{tot} \mid V_{G}=0 \text{ decrease}

Example of Simulation (if the doping is changed)

\[ C_{\text{tot}} = \frac{1}{\frac{1}{C_{\text{ox}}} + \frac{1}{C_{\text{Depl}}}}, \quad C_{\text{depl}} = \frac{\varepsilon_S}{W_D}, \quad C_{\text{ox}} = \frac{\varepsilon_{\text{ox}}}{d_{\text{ox}}} \]

\[ \frac{C_{\text{tot}}}{C_{\text{ox}}}/C_{\text{depl}} : \text{total/oxide/depletion capacitance} \]
\[ \varepsilon_{\text{ox}}/\varepsilon_S : \text{dielectric constant of oxide/semi conductor} \]
\[ W_D : \text{depletion width}, d_{\text{ox}} : \text{oxide thickness} \]

\[ W_D \text{ increase} \rightarrow C_{\text{depl}} \text{ decrease} \rightarrow C_{\text{tot}} \text{ decrease} \]

Result: Hole density (at VG = 0)

Doping decrease

\[ \sim W_D \]

C_{\text{tot}} \text{ decrease}

Depletion

Doping decrease

Capacitance (F/cm²)

Gate voltage (V)
Example of Simulation (if the oxide thickness is changed)

\[ C_{tot} = \frac{1}{\frac{C_{ox} + C_S}{C_{ox}}} \quad \text{and} \quad C_{ox} = \frac{\varepsilon_{ox}}{d_{ox}} \]

- \( C_{tot} / C_{ox} / C_S \): total/oxide/semiconductor capacitance
- \( \varepsilon_{ox} / \varepsilon_S \): dielectric constant of oxide/semiconductor
- \( W_D \): depletion width, \( d_{ox} \): oxide thickness

**CV Characteristics**

**Electric field at the last applied bias**

- \( d_{ox} \) increase → \( C_{ox} \) decrease → \( C_{tot} \) decrease
- \( d_{ox} \) increase → \( E_{ox} \) decrease

<table>
<thead>
<tr>
<th>d_{ox} increase → C_{ox} decrease → C_{tot} decrease</th>
<th>d_{ox} increase → E_{ox} decrease</th>
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</table>

**Increasing oxide thickness**

\[ |E_{ox}| = \frac{dV}{dx} \approx \frac{\Delta V_{ox}}{d_{ox}} \]
PADRE\[^6\] : classical drift-diffusion simulator

- PADRE simulates the electrical behavior of devices under steady state, transient conditions or AC small-signal analysis\[^7\].

Self consistent simulation

\[ \text{Poisson equation} \]
\[ \text{Drift-diffusion equation} \]

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Limitations of the MOSCAP Tool

• MOSCAP does not model quantum mechanical effects
  » Confinement of carriers in the semiconductor
  » Tunneling from the gate to the semiconductor

• MOSCAP does not have sequence plots – users cannot see what happens in the intermediate steps between $V_G=0$ and the last applied bias*

• MOSCAP does not allow users to choose the frequency for AC analysis*

* These features may be upgraded in the next versions.
References

• MOS Capacitor/MOSFET basic theory

• MOS Capacitor C-V measurements

• Charges in oxide

• PADRE