Lombardi Surface Mobility
This example demonstrates how to use the Lombardi surface mobility model for the electron mobility in a simple MOSFET. The current density profile and total current flowing into the terminal are compared with the constant mobility case.

**Introduction**

Surface acoustic phonons and surface roughness have an important effect on the carrier mobility, especially in the thin inversion layer under the gate in MOSFETs. The Lombardi surface mobility model adds surface scattering resulting from these effects to an existing mobility model using Matthiessen’s rule. The mobility model is based on the equations presented in Ref. 1.

The electron ($\mu_{n,lo}$) and hole ($\mu_{p,lo}$) mobilities are determined by the following equations:

$$
\frac{1}{\mu_{n,lo}} = \frac{1}{\mu_{in,n}} + \frac{1}{\mu_{ac,n}} + \frac{1}{\mu_{sr,n}}
$$

$$
\mu_{ac,n} = \frac{\mu_{1,n} + \mu_{2,n} (\frac{N}{N_{ref}})^{\beta_n}}{\frac{E_{\perp,n}}{E_{ref}}} \left( \frac{T}{T_{ref}} \right)^{\frac{1}{3}}
$$

$$
\mu_{sr,n} = \frac{\delta_n E_{\perp,n}^2}{2}
$$

$$
\frac{1}{\mu_{p,lo}} = \frac{1}{\mu_{in,p}} + \frac{1}{\mu_{ac,p}} + \frac{1}{\mu_{sr,p}}
$$

$$
\mu_{ac,p} = \frac{\mu_{1,p} + \mu_{2,p} (\frac{N}{N_{ref}})^{\beta_p}}{\frac{E_{\perp,p}}{E_{ref}}} \left( \frac{T}{T_{ref}} \right)^{\frac{1}{3}}
$$

$$
\mu_{sr,p} = \frac{\delta_p E_{\perp,p}^2}{2}
$$

where $T$ is the lattice temperature, $\mu_{in,n}$ and $\mu_{in,p}$ are the electron and hole input mobilities, $N_{a}^+$ is the ionized acceptor concentration, $N_{d}^+$ is the ionized donor concentration, $E_{\perp,n}$ is the component of the electric field perpendicular to the electron current and $E_{\perp,p}$ is the component of the electric field perpendicular to the hole current. All other parameters in the model are material properties (note that $\delta_n$ and $\delta_p$ have units of V/s). The material properties for silicon are also obtained from Ref. 1.

**Model Definition**

The model represents a 2D MOSFET where the n-doped drain and source contacts are located at the top right and top left of the geometry, respectively; see Figure 1. The gate is positioned above the p-doped silicon section which is located at the center of the device.

The model sweeps the drain voltage form 0 V to 1 V with an applied gate voltage of 1 V. We expect an important perpendicular (to the currents) electric field underneath the gate.
contact. In order to ensure convergence of the nonlinear model, a solver continuation parameter is used to ramp up the electron and hole perpendicular components of the field ($E_{\perp,n}$ and $E_{\perp,p}$) as the drain voltage is swept.

![Schematic of the modeled device.](image)

**Figure 1:** Schematic of the modeled device.

**Results and Discussion**

Figure 2 shows the effect of the Lombardi surface mobility model on the solution. The comparison of the constant mobility (the perpendicular fields are multiplied by $10^{-6}$) and the Lombardi surface mobility ($E_{\perp,n}$ and $E_{\perp,p}$ multiplied by 1) models shows a more pronounced saturation effect for the Lombardi surface mobility model than for the constant mobility model (without field dependent parameters).

Figure 3 shows that the electron current density varies substantially in the inversion layer depending on the used mobility model. The Lombardi surface mobility model (top) shows a lower current density in comparison to the one observed with the constant mobility model (bottom).

Figure 4 shows that the electron mobility also varies along the device. As a consequence of the inversion layer generated by the applied potential on the gate contact, the electron mobility is smaller in the vicinity of the gate junction.
Figure 2: Plot of terminal current for the constant mobility and surface mobility cases. The current is inhibited when the surface mobility model is active.
Figure 3: Plot of the electron current density on the same scale with the Lombardi surface mobility model active (top) and without (bottom).
Figure 4: Plot of the electron mobility for a drain-source voltage of 1 volt with the Lombardi surface mobility model active.

Reference


Application Library path: Semiconductor_Module/Transistors/lombardi_surface_mobility

Modeling Instructions

From the File menu, choose New.

NEW

In the New window, click Model Wizard.
**Model Wizard**

1. In the Model Wizard window, click \( \rightarrow \) 2D.
2. In the Select Physics tree, select Semiconductor> Semiconductor (semi).
3. Click Add.
4. Click \( \rightarrow \) Study.
5. In the Select Study tree, select General Studies>Stationary.
6. Click done.

**Global Definitions**

**Parameters 1**

1. In the Model Builder window, under Global Definitions click Parameters 1.
2. In the Settings window for Parameters, locate the Parameters section.
3. In the table, enter the following settings:

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vds</td>
<td>0 [V]</td>
<td>0 V</td>
<td>Drain-source voltage</td>
</tr>
<tr>
<td>Vgs</td>
<td>1 [V]</td>
<td>1 V</td>
<td>Gate-source voltage</td>
</tr>
<tr>
<td>ds</td>
<td>0</td>
<td>0</td>
<td>Continuation parameter</td>
</tr>
</tbody>
</table>

**Geometry 1**

1. In the Model Builder window, under Component 1 (comp1) click Geometry 1.
2. In the Settings window for Geometry, locate the Units section.
3. From the Length unit list, choose µm.

**Rectangle 1 (r1)**

1. In the Geometry toolbar, click \( \square \) Rectangle.
2. In the Settings window for Rectangle, locate the Size and Shape section.
3. In the Height text field, type 0.5.
4. Locate the Position section. In the x text field, type -0.5.
5. In the y text field, type -0.5.
6. Click to expand the Layers section. In the table, enter the following settings:

<table>
<thead>
<tr>
<th>Layer name</th>
<th>Thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>0.01</td>
</tr>
</tbody>
</table>

7. Clear the Layers on bottom check box.
8 Select the Layers on top check box.
9 Click Build All Objects.

**Line Segment 1 (ls1)**
1 In the Geometry toolbar, click More Primitives and choose Line Segment.
2 In the Settings window for Line Segment, locate the Starting Point section.
3 From the Specify list, choose Coordinates.
4 Locate the Endpoint section. From the Specify list, choose Coordinates.
5 Locate the Starting Point section. In the x text field, type -0.12.
6 Locate the Endpoint section. In the x text field, type 0.12.

**Line Segment 2 (ls2)**
1 In the Geometry toolbar, click More Primitives and choose Line Segment.
2 In the Settings window for Line Segment, locate the Starting Point section.
3 From the Specify list, choose Coordinates.
4 Locate the Endpoint section. From the Specify list, choose Coordinates.
5 Locate the Starting Point section. In the x text field, type -0.18.
6 Locate the Endpoint section. In the x text field, type -0.5.

**Line Segment 3 (ls3)**
1 In the Geometry toolbar, click More Primitives and choose Line Segment.
2 In the Settings window for Line Segment, locate the Starting Point section.
3 From the Specify list, choose Coordinates.
4 Locate the Endpoint section. From the Specify list, choose Coordinates.
5 Locate the Starting Point section. In the x text field, type 0.18.
6 Locate the Endpoint section. In the x text field, type 0.5.
7 Click Build All Objects.

**Mesh Control Edges 1 (mce1)**
1 In the Geometry toolbar, click Virtual Operations and choose Mesh Control Edges.
2 On the object fin, select Boundary 4 only.

It might be easier to select the correct boundary by using the Selection List window. To open this window, in the Home toolbar click Windows and choose Selection List. (If you are running the cross-platform desktop, you find Windows in the main menu.)

ADD MATERIAL

1 In the Home toolbar, click Add Material to open the Add Material window.
2 Go to the Add Material window.
3 In the tree, select Semiconductors>Si - Silicon.
4 Click Add to Component in the window toolbar.
5 In the Home toolbar, click Add Material to close the Add Material window.

SEMICONDUCTOR (SEMI)

1 In the Model Builder window, under Component 1 (comp1) click Semiconductor (semi).
2 In the Settings window for Semiconductor, click to expand the Continuation Settings section.
3 In the $C_p$ text field, type $ds$.

Metal Contact 1

1 In the Physics toolbar, click Boundaries and choose Metal Contact.
2 Select Boundaries 2 and 3 only.
Metal Contact 2
1 In the Physics toolbar, click Boundaries and choose Metal Contact.
2 Select Boundary 7 only.
3 In the Settings window for Metal Contact, locate the Terminal section.
4 In the $V_0$ text field, type $V_{ds}$.

Thin Insulator Gate 1
1 In the Physics toolbar, click Boundaries and choose Thin Insulator Gate.
2 Select Boundary 5 only.
3 In the Settings window for Thin Insulator Gate, locate the Terminal section.
4 In the $V_0$ text field, type $V_{gs}$.
5 Locate the Gate Contact section. In the $e_{ins}$ text field, type 4.2.
6 In the $d_{ins}$ text field, type 5[nm].
7 In the $\Phi$ text field, type 4.5[V].

Analytic Doping Model 1
1 In the Physics toolbar, click Domains and choose Analytic Doping Model.
2 Select Domain 1 only.
3 In the Settings window for Analytic Doping Model, locate the Impurity section.
4 In the $N_{A0}$ text field, type $5 \times 10^{17}[1/cm^3]$.

Analytic Doping Model 2
1 In the Physics toolbar, click Domains and choose Analytic Doping Model.
2 Select Domain 1 only.
3 In the Settings window for Analytic Doping Model, locate the Distribution section.
4 From the list, choose Box.
5 Locate the Uniform Region section. Specify the $r_0$ vector as

| 0.2[um] | X |
| 0[um]   | Y |

6 Locate the Impurity section. From the Impurity type list, choose Donor doping (n-type).
7 Locate the Uniform Region section. In the $W$ text field, type 0.3[um].
8 In the $D$ text field, type 0.2[um].
9 Locate the Impurity section. In the $N_{D0}$ text field, type $1 \times 10^{19}[1/cm^3]$.
10 Locate the Profile section. In the $d_j$ text field, type 0.1[um].
From the $N_B$ list, choose **Acceptor concentration (semi/adm1)**.

**Analytic Doping Model**

1. In the Physics toolbar, clickDomains and choose **Analytic Doping Model**.
2. Select Domain 1 only.
3. In the Settings window for Analytic Doping Model, locate the Distribution section.
4. From the list, choose Box.
5. Locate the Uniform Region section. Specify the $r_0$ vector as

<table>
<thead>
<tr>
<th>-0.5[um]</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>0[um]</td>
<td>Y</td>
</tr>
</tbody>
</table>

6. In the $W$ text field, type $0.3[um]$.
7. In the $D$ text field, type $0.2[um]$.
8. Locate the Impurity section. From the Impurity type list, choose Donor doping (n-type).
9. In the $N_D$ text field, type $1e19[1/cm^3]$.
10. Locate the Profile section. In the $d_j$ text field, type $0.1[um]$.
11. From the $N_B$ list, choose **Acceptor concentration (semi/adm1)**.

**Trap-Assisted Recombination**

1. In the Physics toolbar, clickDomains and choose **Trap-Assisted Recombination**.
2. Select Domain 1 only.

**Semiconductor Material Model**

In the Model Builder window, click **Semiconductor Material Model 1**.

**Lombardi Surface Mobility Model (S)**

1. In the Physics toolbar, clickAttributes and choose Lombardi Surface Mobility Model (S).
2. In the Settings window for Lombardi Surface Mobility Model (S), click to expand the Continuation Settings section.
3. From the Continuation type list, choose Use interface continuation parameter.

**Semiconductor Material Model**

1. In the Model Builder window, click Semiconductor Material Model 1.
2. In the Settings window for Semiconductor Material Model, locate the Mobility Model section.
3. From the $\mu_n$ list, choose **Electron mobility, Lombardi (semi/smm1/mmls1)**.
Set up a user-defined mesh.

**Mesh 1**
1. In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.
2. In the **Settings** window for **Mesh**, locate the **Mesh Settings** section.
3. From the **Sequence type** list, choose **User-controlled mesh**.

**Size**
1. In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** click **Size**.
2. In the **Settings** window for **Size**, locate the **Element Size** section.
3. Click the **Custom** button.
4. Locate the **Element Size Parameters** section. In the **Maximum element size** text field, type 0.04.
5. In the **Maximum element growth rate** text field, type 1.04.

**Size 1**
In the **Model Builder** window, right-click **Size 1** and choose **Delete**.

**Size 2**
In the **Model Builder** window, right-click **Size 2** and choose **Delete**.

**Free Triangular 1**
In the **Model Builder** window, right-click **Free Triangular 1** and choose **Delete**.

**Edge 1**
1. In the **Mesh** toolbar, click **Edge**.
2. Select Boundaries 3–7 only.
3. In the **Settings** window for **Edge**, click to expand the **Control Entities** section.
4. Clear the **Smooth across removed control entities** check box.

**Size 1**
1. Right-click **Edge 1** and choose **Size**.
2 Select Boundaries 4–6 only.

3 In the Settings window for Size, locate the Element Size section.

4 From the Calibrate for list, choose Semiconductor.

5 Click the Custom button.

6 Locate the Element Size Parameters section. Select the Maximum element size check box.

7 In the associated text field, type 0.005.

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Copy Edge 1

1 In the Model Builder window, right-click Mesh 1 and choose More Operations>Copy Edge.

2 In the Settings window for Copy Edge, locate the Source Boundaries section.

3 Click Paste Selection.

4 In the Paste Selection dialog box, type 3-7 in the Selection text field.

5 Click OK.

6 In the Settings window for Copy Edge, locate the Destination Boundaries section.

7 Select the Activate Selection toggle button.

8 Select Boundary 11 only.

9 Click to expand the Control Entities section. Clear the Smooth across removed control entities check box.
**Mapped 1**
1. In the Mesh toolbar, click ![Mapped].
2. In the Settings window for Mapped, locate the Domain Selection section.
3. From the Geometric entity level list, choose Domain.
4. Select Domain 2 only.
5. Click to expand the Control Entities section. Clear the Smooth across removed control entities check box.
6. Click to expand the Reduce Element Skewness section. Select the Adjust edge mesh check box.

**Distribution 1**
1. Right-click Mapped 1 and choose Distribution.
2. Select Boundary 9 only.
3. In the Settings window for Distribution, locate the Distribution section.
4. From the Distribution type list, choose Predefined.
5. In the Number of elements text field, type 6.
6. In the Element ratio text field, type 7.
7. From the Growth formula list, choose Geometric sequence.
8. Select the Reverse direction check box.

**Free Triangular 1**
1. In the Mesh toolbar, click ![Free Triangular].
2. In the Settings window for Free Triangular, click to expand the Control Entities section.
3. Clear the Smooth across removed control entities check box.
4. Click ![Build All].
5 Click the \( \textbf{Zoom Extents} \) button in the \textbf{Graphics} toolbar.

The user-defined mesh is shown in the image below. The mapped mesh with the specific distribution helps create layers of thin elements underneath the gate, where the large gradient of the carrier concentration should be resolved by the mesh.

\textbf{STUDY 1}

\textit{Step 1: Stationary}

Set up an auxiliary continuation sweep for the 'ds' parameter.

1 In the \textbf{Model Builder} window, under \textbf{Study 1} click \textbf{Step 1: Stationary}.

2 In the \textbf{Settings} window for \textbf{Stationary}, click to expand the \textbf{Study Extensions} section.

3 Select the \textbf{Auxiliary sweep} check box.

4 Click \( \text{Add} \).

5 Click \( \text{Add} \).
6 In the table, enter the following settings:

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Parameter value list</th>
<th>Parameter unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vds (Drain-source voltage)</td>
<td>range(0, 0.2, 1)</td>
<td>V</td>
</tr>
<tr>
<td>ds (Continuation parameter)</td>
<td>0 1e-6 0.1 0.5 0.999 1 1.001</td>
<td></td>
</tr>
</tbody>
</table>

7 From the Sweep type list, choose All combinations.

8 From the Reuse solution from previous step list, choose Auto.

Solution 1 (sol1)
1 In the Study toolbar, click Show Default Solver.
2 In the Model Builder window, expand the Solution 1 (sol1) node.
3 In the Model Builder window, expand the Study 1>Solver Configurations>
   Solution 1 (sol1)>Stationary Solver 1 node.
4 Right-click Parametric 1 and choose Previous Solution.
5 In the Settings window for Previous Solution, locate the Previous Solution section.
6 Under Variables, click Add.
7 In the Add dialog box, in the Variables list, choose
   Electric field magnitude perpendicular to electron current density (comp1.semi.smm1.mmls1.Edn)
   and
   Electric field magnitude perpendicular to hole current density (comp1.semi.smm1.mmls1.Edp).
8 Click OK.
9 In the Study toolbar, click Compute.

RESULTS

Electron Concentration (semi)
Click the Zoom Extents button in the Graphics toolbar.

1D Plot Group 4
1 In the Home toolbar, click Add Plot Group and choose 1D Plot Group.
2 In the Settings window for 1D Plot Group, locate the Data section.
3 From the Parameter selection (ds) list, choose From list.
4 In the Parameter values (ds) list, choose 1E-6 and 1.001.
Global 1
1 Right-click 1D Plot Group 4 and choose Global.
2 In the Settings window for Global, click Replace Expression in the upper-right corner of the y-Axis Data section. From the menu, choose Component 1 (comp1)>Semiconductor>Terminals>semi.I0_2 - Terminal current - A.
3 Locate the x-Axis Data section. From the Axis source data list, choose Vds.
4 In the 1D Plot Group 4 toolbar, click Plot.
5 Click to expand the Legends section. From the Legends list, choose Manual.
6 In the table, enter the following settings:

<table>
<thead>
<tr>
<th>Legends</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant mobility</td>
</tr>
<tr>
<td>Lombardi surface mobility</td>
</tr>
</tbody>
</table>

1D Plot Group 4
1 In the Model Builder window, click 1D Plot Group 4.
2 In the Settings window for 1D Plot Group, locate the Legend section.
3 From the Position list, choose Lower right.

Electron current density comparison
1 In the Home toolbar, click Add Plot Group and choose 2D Plot Group.
2 In the Settings window for 2D Plot Group, type Electron current density comparison in the Label text field.
3 Locate the Data section. From the Parameter value (ds) list, choose 1E-6.
   For this plot group, we will zoom in to a region underneath the gate to look at the current density profile. In order not to interfere with the zoom settings of other plot groups, we use a different view setting for this plot group by selecting "New".
4 Locate the Plot Settings section. From the View list, choose New view.
5 Clear the Plot dataset edges check box.

Surface 1
1 Right-click Electron current density comparison and choose Surface.
2 In the Settings window for Surface, click Replace Expression in the upper-right corner of the Expression section. From the menu, choose Component 1 (comp1)>Semiconductor>Currents and charge>Electron current>Electron current density - A/m²>semi.jnX - Electron current density, X component.
Filter 1
1 Right-click **Surface 1** and choose **Filter**.
2 In the **Settings** window for **Filter**, locate the **Element Selection** section.
3 In the **Logical expression for inclusion** text field, type \((y>-0.05\text{[um]}) \&\& (x>-0.1\text{[um]}) \&\& (x<0.1\text{[um]})\).
4 In the **Electron current density comparison** toolbar, click ![Plot](image).

Surface 2
1 In the **Model Builder** window, under **Results>Electron current density comparison** right-click **Surface 1** and choose **Duplicate**.
2 In the **Settings** window for **Surface**, locate the **Data** section.
3 From the **Dataset** list, choose **Study 1/Solution 1 (sol1)**.
4 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

Deformation 1
1 Right-click **Surface 2** and choose **Deformation**.
2 In the **Settings** window for **Deformation**, locate the **Expression** section.
3 In the **X component** text field, type 0.
4 In the **Y component** text field, type 0.06.
5 Locate the **Scale** section. Select the **Scale factor** check box.
6 In the associated text field, type 1.
7 In the **Electron current density comparison** toolbar, click ![Plot](image).
8 Click the ![Zoom Extents](image) button in the **Graphics** toolbar.

2D Plot Group 6
In the **Home** toolbar, click ![Add Plot Group](image) and choose **2D Plot Group**.

Surface 1
1 Right-click **2D Plot Group 6** and choose **Surface**.
2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Semiconductor>Mobility>semi.mun_ls - Electron mobility, Lombardi - m²/(V·s)**.
3 In the **2D Plot Group 6** toolbar, click ![Plot](image).
4 Click the ![Zoom Extents](image) button in the **Graphics** toolbar.