Created in COMSOL Multiphysics 6.1

DC Characteristics of a MOS Transistor (MOSFET)

This model calculates the DC characteristics of a MOS (metal-oxide semiconductor) transistor. In normal operation, a system turns on a MOS transistor by applying a voltage to the gate electrode. When the voltage on the drain increases, the drain current also increases until it reaches saturation. The saturation current depends on the gate voltage.

Introduction

The MOSFET (metal oxide semiconductor field-effect transistor) is by far the most common semiconductor device, and it is the primary building block in all commercial processors, memories, and digital integrated circuits. Since the first microprocessors were introduced approximately 40 years ago this device has experienced tremendous development, and today it is being manufactured with feature sizes of 22 nm and smaller.

The MOSFET is essentially a miniaturized switch. In this example the source and drain contacts (the input and output of the switch) are both ohmic (low resistance) contacts to heavily doped n-type regions of the device. Between these two contacts is a region of p-type semiconductor. The gate contact lies above the p-type semiconductor, slightly overlapping the two n-type regions. It is separated from the semiconductor by a thin layer of Silicon oxide, so that it forms a capacitor with the underlying semiconductor. Applying a voltage to the gate changes the local band structure beneath it through the Field Effect. A sufficiently high voltage can cause the semiconductor to change from p-type to n-type in a thin layer (the channel) underneath the gate. This is known as inversion and the channel is sometimes referred to as the inversion layer. The channel connects the two n-type regions of semiconductor with a thin n-type region under the gate. This region has a significantly lower resistance than the series resistance of the np/pn junctions that separated the source and the gate before the gate voltage produced the inversion layer. Consequently applying a gate voltage can be used to change the resistance of the device from a high to a low value. The gate voltage where a significant current begins to flow is called the threshold or turn-on voltage. Figure 1 shows a schematic MOSFET with the main electrical connections highlighted. Figure 2 shows an electron microscope image of a modern MOSFET device.

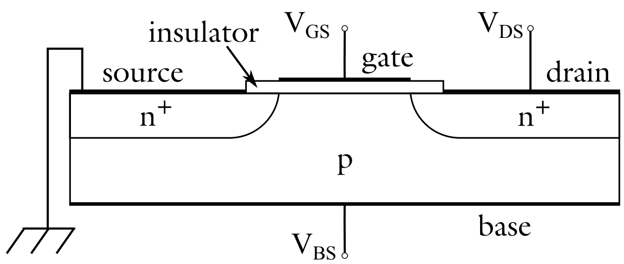


Figure 1: Schematic diagram of a typical MOSFET. The current flows from the source to the gate through a channel underneath the gate. The size of the channel is controlled by the gate voltage.

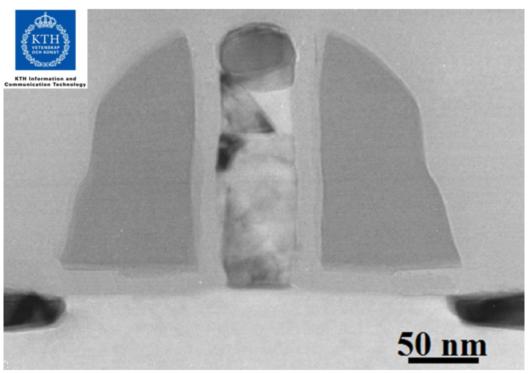


Figure 2: Cross-section TEM (transmission electron microscopy) image of a 50 nm gate length MOSFET fabricated at KTH Electrum laboratory by P.E Hellström and coworkers within the ERC advanced grant OSIRIS research project headed by Prof. M. Östling.

As the voltage between the drain and the source is increased the current carried by the channel eventually saturates through a process known as pinch-off, in which the channel narrows at one end due to the effect of the field parallel to the surface. The channel width is controlled by the gate voltage. Typically a larger gate voltage results in wider channel and consequently a lower resistance for a given drain voltage. Additionally the saturation current is larger for a higher gate voltage.

Model Definition

Figure 3 shows the model geometry, indicating how the geometry elements correspond to features in Figure 1 In this model both the source and the base are connected to ground and the voltages applied to the drain and the gate are varied. In the first study a small voltage (10 mV) is applied to the Drain and the Gate voltage is swept from 0 to 5 V. A plot of the current flowing between the source and the drain is used to determine the turn-on voltage of the device. The second study sweeps the drain voltage from 0 to 5 V at three different values of the gate voltage (2, 3, and 4 V). The drain current vs. drain voltage is then plotted at several values of the gate voltage.

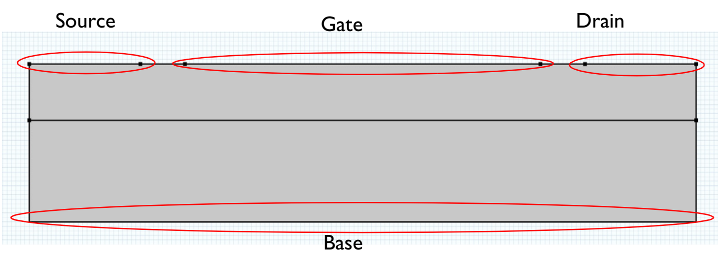


Figure 3: Model geometry showing the external connections.

Results and Discussion

Figure 4 shows the drain current vs gate voltage for a fixed drain voltage of 10 mV. From the plot it is clear that the threshold voltage, V_T, of the transistor is approximately 1.2 V. It is possible to compare this value with the theoretical value given in Ref. 1:

$$V_T \cong V_{FB} + 2\psi_B + \frac{d_{ox}(4\varepsilon_{r,s}\varepsilon_0 q N_a \psi_B)^{\frac{1}{2}}}{\varepsilon_{r,ox}\varepsilon_0}$$

where d_{ox} is the thickness of the oxide and $\varepsilon_{r,ox}$ is its relative permittivity, ε_0 is the permittivity of free space, $\varepsilon_{r,s}$ is the relative permittivity of the semiconductor, q is the electron charge, and N_a is the acceptor concentration under the gate. The flat band voltage V_{FB} and the potential difference between the intrinsic level and the Fermi-level, Ψ_B, are given by the following equations:

$$V_{FB} = \Phi_m - \chi + \frac{k_B T}{q}\ln\left(\frac{n_{eq}}{N_c}\right)$$

$$\psi_B = \frac{k_B T}{q}\ln\left(\frac{p_{eq}}{n_i}\right)$$

where Φ_m is the work function of the metal contact, χ is the semiconductor electron affinity, k_B is Boltzmann’s contact, T is the absolute temperature, N_c is the semiconductor density of states in the conduction band, and n_i is the intrinsic carrier density. The equilibrium electron (n_{eq}) and hole (p_{eq}) densities are given by:

$$n_{eq} = \frac{1}{2}(N_d - N_a) + \frac{1}{2}\sqrt{(N_d - N_a)^2 + 4n_i}$$
$$p_{eq} = -\frac{1}{2}(N_d - N_a) \pm \frac{1}{2}\sqrt{(N_d - N_a)^2 + 4n_i}$$

where N_d is the donor concentration under the gate. Note that these equations assume both complete ionization and Maxwell Boltzmann statistics (reasonable assumptions in the region under the gate). These equations give a threshold voltage of 1.18 V, in good agreement with the simulation value given the approximations required for the analytic approach.

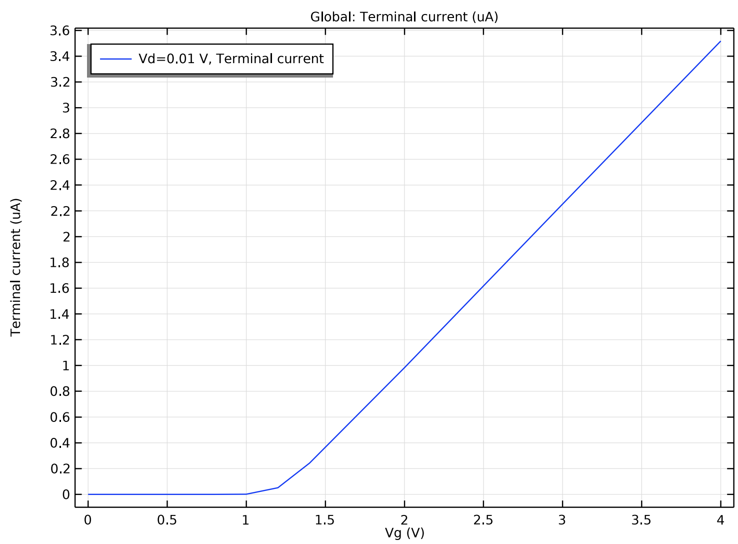


Figure 4: Drain current vs. gate voltage shown when a voltage of 10 mV is applied to the drain. The threshold voltage is approximately 1.2 V.

Figure 5 shows the drain current vs drain voltage curves for different values of the gate voltage. The curve shows three regions: a linear region at low voltages, a nonlinear region at intermediate voltages and an approximately constant region at higher voltages (the saturation region). For this device there is a slight gradient in the current at larger voltages due to the onset of short channel effects. Short channel effects mean that the standard analytic expressions for the saturation voltage and current are inaccurate, but the saturation voltages are of a similar magnitude to those predicted by the simple theory given in Ref. 1. The current saturation occurs due to a phenomenon known as pinch–off. As the drain voltage is increased more current flows along the channel and the potential drop along its length increases. The voltage between the gate and the semiconductor therefore changes as a function of position along the channel and the inversion layer width is no longer constant. Figure 6 shows the electron concentration and the electric potential at different values of the drain voltage for a gate voltage of 4 V. The pinch–off effect is apparent at 5 V.

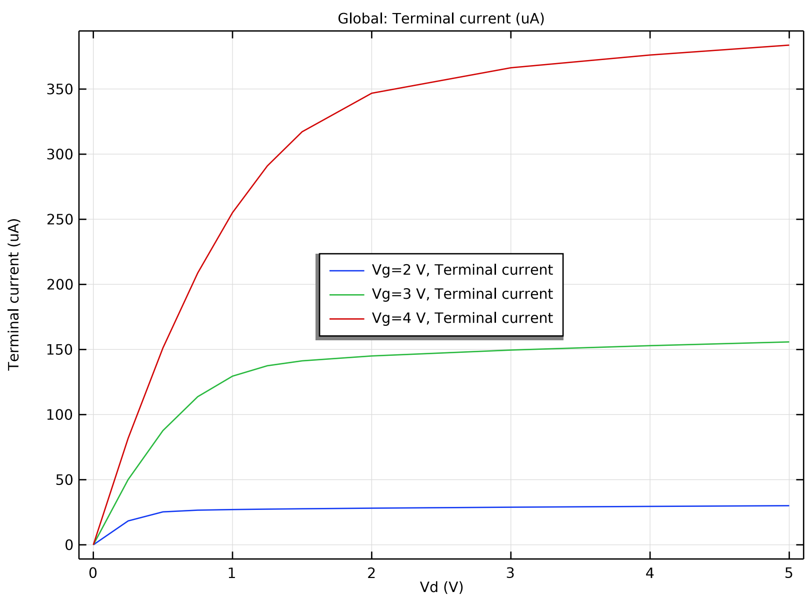


Figure 5: Drain current vs drain voltage for different values of the gate voltage.

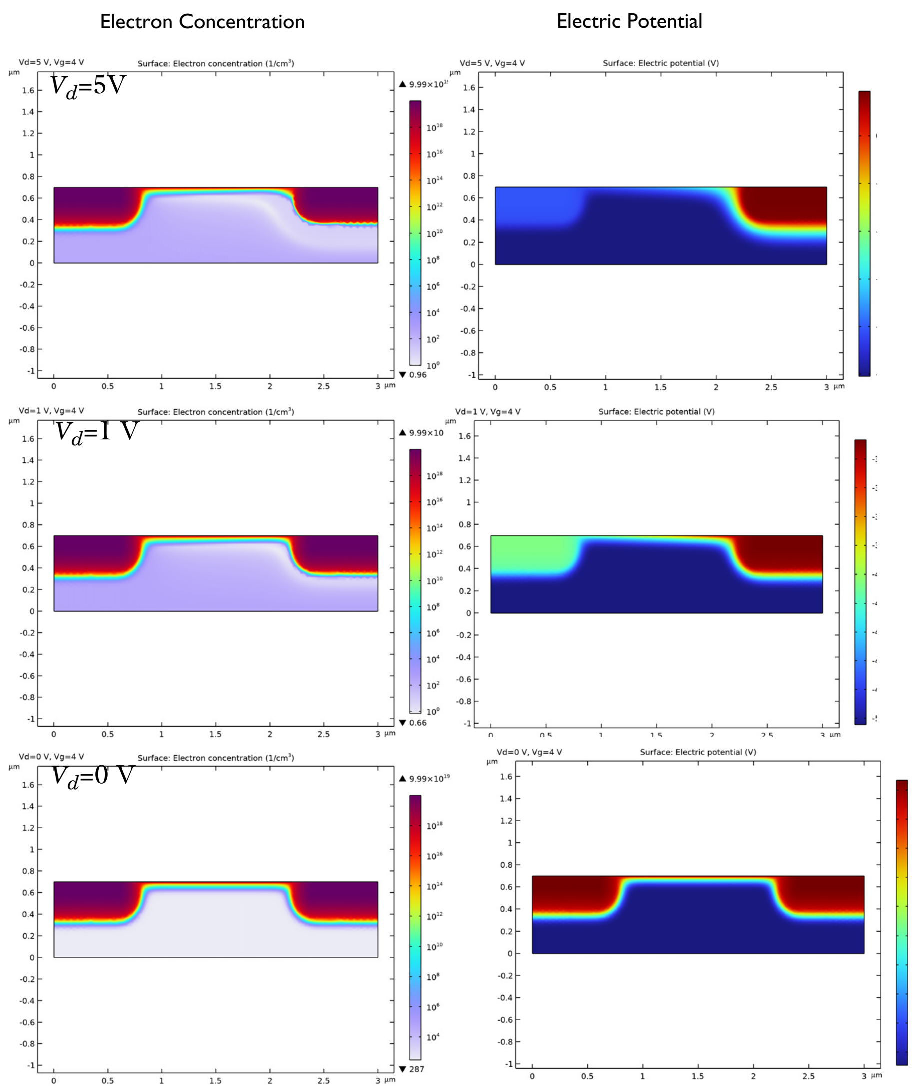


Figure 6: Left: Electron concentration and Right: Electric Potential for the MOSFET with an applied gate voltage of 4 V and with various applied drain voltages, V_d. Top: V_d=5 V, Middle: V_d=1 V, Bottom: V_d=0 V. The pinch-off effect is apparent from the plots.

Reference

1. S. M. Sze and K.K. Ng, *Physics of Semiconductor Devices,* 3rd ed., John Wiley & Sons, pp. 305–306, 2007.

Application Library path: `Semiconductor_Module/Transistors/mosfet`

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 **2D**.

2 In the **Select Physics** tree, select **Semiconductor>Semiconductor (semi)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **General Studies>Stationary**.

6 Click **Done**.

GLOBAL DEFINITIONS

Define parameters for the drain and gate voltages that you will later use when performing parametric sweeps.

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:

Name	Expression	Value	Description
Vd	10[mV]	0.01 V	Drain voltage
Vg	2[V]	2 V	Gate voltage

GEOMETRY 1

The geometry can be specified using COMSOL's built in tools. First choose to define geometry objects using micrometer units.

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**.

Next create a rectangle to define the geometry extents.

Rectangle 1 (r1)

1 In the **Geometry** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `3`.

4 In the **Height** text field, type `0.7`.

Add a polygon which will include points to define the source, drain and gate contacts. It will also include a line to help create the mesh.

Polygon 1 (pol1)

1 In the **Geometry** toolbar, click **Polygon**.

2 In the **Settings** window for **Polygon**, locate the **Object Type** section.

3 From the **Type** list, choose **Closed curve**.

4 Locate the **Coordinates** section. In the table, enter the following settings:

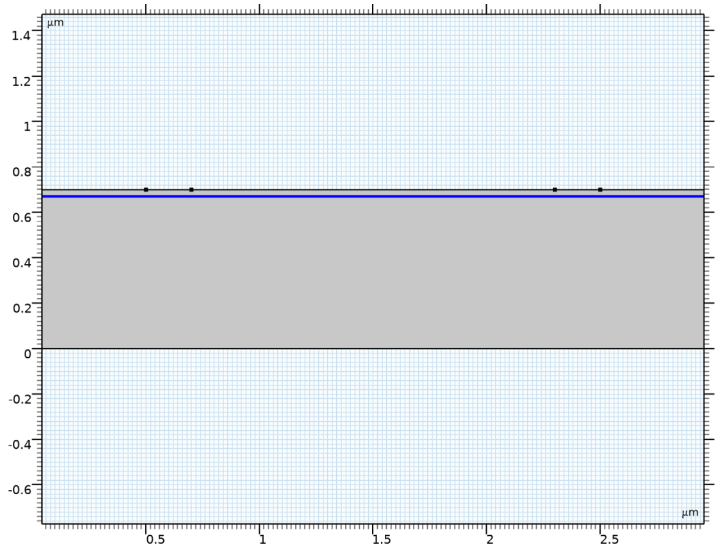
x (µm)	y (µm)
0	0.67
0	0.7
0.5	0.7
0.7	0.7
2.3	0.7
2.5	0.7
3	0.7
3	0.67

Mesh Control Edges 1 (mce1)

1 In the **Geometry** toolbar, click **Virtual Operations** and choose **Mesh Control Edges**.

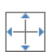
2 On the object **fin**, select Boundary 4 only.

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.)



3 Right-click **Mesh Control Edges 1 (mce1)** and choose **Build All Objects**.

Use the Zoom Extents button to zoom to the full geometry if desired.

4 Click the  **Zoom Extents** button in the **Graphics** toolbar.

MATERIALS

Next the material properties are added to the model.

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)

Next the physics settings must be defined. Start by defining the doping.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Semiconductor (semi)**.

2 In the **Settings** window for **Semiconductor**, locate the **Model Properties** section.

3 From the **Carrier statistics** list, choose **Fermi-Dirac**.

Analytic Doping Model 1

1 In the **Physics** toolbar, click **Domains** and choose **Analytic Doping Model**.

First a constant background acceptor concentration is defined.

2 In the **Settings** window for **Analytic Doping Model**, locate the **Impurity** section.

3 In the N_{A0} text field, type `1e17[1/cm^3]`.

4 Locate the **Domain Selection** section. From the **Selection** list, choose **All domains**.

Add a second doping feature to define the implanted doping profile for the source.

Analytic Doping Model 2

1 In the **Physics** toolbar, click **Domains** and choose **Analytic Doping Model**.

2 In the **Settings** window for **Analytic Doping Model**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **All domains**.

4 Locate the **Distribution** section. From the list, choose **Box**.

When defining a Gaussian doping distribution a rectangular region of constant doping is defined. The Gaussian drop off occurs away from the edges of this rectangular region.

First define the location of the lower left corner of the uniformly doped region.

5 Locate the **Uniform Region** section. Specify the r_0 vector as

0[um]	X
0.6[um]	Y

Then define the width and height of the uniformly doped region.

6 In the W text field, type `0.6[um]`.

7 In the D text field, type `0.1[um]`.

Choose the dopant type and the doping level in the uniformly doped region.

8 Locate the **Impurity** section. From the **Impurity type** list, choose **Donor doping (n-type)**.

9 In the N_{D0} text field, type `1e20[1/cm^3]`.

Next specify the length scale over which the Gaussian drop off occurs. If doping into a background dopant distribution of opposite type (as in this case), this setting specifies the junction depth. In this model different length scales are used in the x and y directions.

10 Locate the **Profile** section. Select the **Specify different length scales for each direction** check box.

11 Specify the d_j vector as

0.2[um]	X
0.25[um]	Y

Finally specify the constant background doping level.

12 From the N_b list, choose **Acceptor concentration (semi/adm1)**.

Add a similar Gaussian doping profile for the drain.

Analytic Doping Model 3

1 Right-click **Analytic Doping Model 2** and choose **Duplicate**.

2 In the **Settings** window for **Analytic Doping Model**, locate the **Uniform Region** section.

3 Specify the r_0 vector as

2.4[um]	X
0.6[um]	Y

Next set up boundary conditions for the contacts and gate.

First add a contact for the source.

Metal Contact 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Metal Contact**.

The Metal Contact feature is used to define Metal-Semiconductor interfaces of various types. In this instance, use the default Ideal ohmic contact to define the source.

2 Select Boundary 3 only.

Note that the Metal Contact feature in COMSOL Multiphysics is a so-called Terminal boundary condition. By default a fixed potential of 0 V is applied, which is appropriate in this instance, since the source is grounded. The terminal can also be set up to specify an input current, input power, or to connect to a voltage or current source from an external circuit.

Add a second Metal Contact feature to define the drain.

Metal Contact 2

1 In the **Physics** toolbar, click **Boundaries** and choose **Metal Contact**.

2 Select Boundary 7 only.

Set the drain voltage to be determined by the previously defined parameter.

3 In the **Settings** window for **Metal Contact**, locate the **Terminal** section.

4 In the V_0 text field, type `Vd`.

Add a third Metal Contact to set the body voltage to 0 V.

Metal Contact 3

1 In the **Physics** toolbar, click **Boundaries** and choose **Metal Contact**.

2 Select Boundary 2 only.

Set up the gate. The gate dielectric is not explicitly represented in the model, instead the Thin Insulator Gate boundary condition represents both the gate contact and the thin layer of oxide.

Thin Insulator Gate 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Thin Insulator Gate**.

The Thin Insulator Gate feature is also a terminal, but in this instance it is possible to fix the voltage or charge on the terminal, as well as to connect it to a circuit. Note that the charge setting determines the charge on the conductor and does not relate to trapped charge at the oxide-semiconductor interface.

The voltage applied to the gate is determined by the parameter previously added.

2 In the **Settings** window for **Thin Insulator Gate**, locate the **Terminal** section.

3 In the V_0 text field, type `Vg`.

4 Locate the **Gate Contact** section. In the ε_{ins} text field, type `4.5`.

5 In the d_{ins} text field, type `30[nm]`.

6 Select Boundary 5 only.

A range of recombination/generation mechanisms are available to be added to the model. In this case, simply add trap-assisted recombination, using the default Shockley-Read-Hall model.

Trap-Assisted Recombination 1

1 In the **Physics** toolbar, click **Domains** and choose **Trap-Assisted Recombination**.

2 In the **Settings** window for **Trap-Assisted Recombination**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **All domains**.

Semiconductor Material Model 1

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

2 In the **Settings** window for **Semiconductor Material Model**, click to expand the **Band Gap Narrowing** section.

3 From the **Band gap narrowing** list, choose **Jain-Roulston model**.

We will use a user-defined mesh for this model.

MESH 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

2 In the **Settings** window for **Mesh**, locate the **Sequence Type** section.

3 From the 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 growth rate** text field, type `1.05`.

Size 1

In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** right-click **Size 1** and choose **Delete**.

Size 2

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

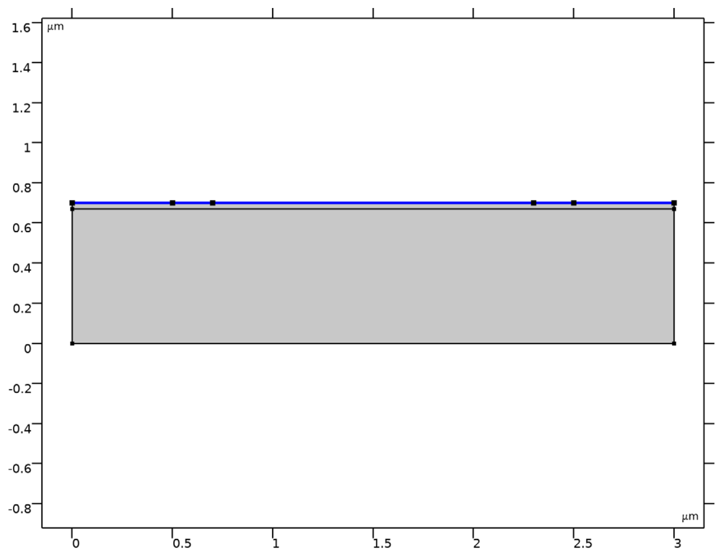
Free Triangular 1

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

3 From the **Calibrate for** list, choose **Semiconductor**.

4 Click the **Custom** button.

5 Locate the **Element Size Parameters** section.

6 Select the **Maximum element size** check box. In the associated text field, type `0.03`.

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 8.

6 In the **Element ratio** text field, type 9.

7 From the **Growth rate** list, choose **Exponential**.

8 Select the **Reverse direction** check box.

Free Triangular 1

1 In the **Mesh** toolbar, click **Free Triangular**.

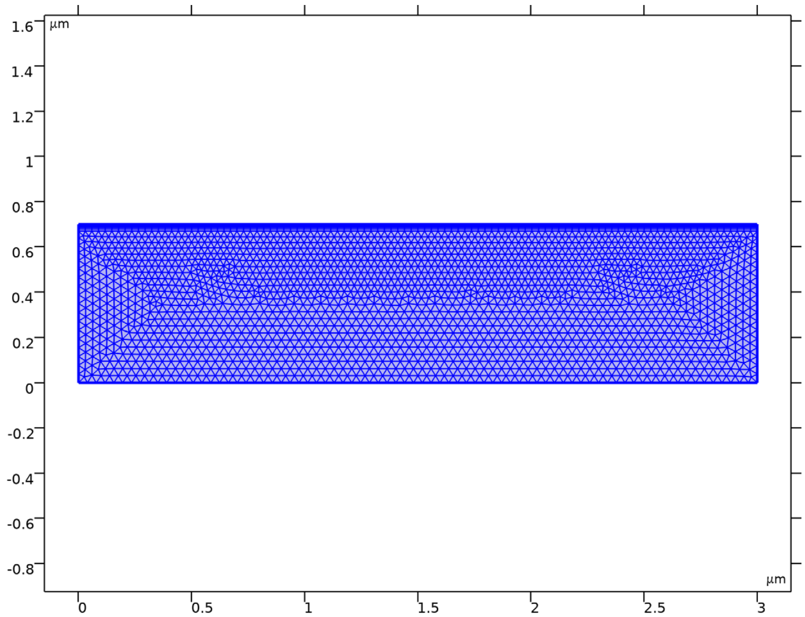
2 In the **Settings** window for **Free Triangular**, click to expand the **Control Entities** section.

3 Clear the **Smooth across removed control entities** check box.

4 Click **Build All**.

5 Click the **Zoom Extents** button in the **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 needs to be resolved by the mesh.



STUDY 1

Before setting up the study, check that the doping was set up correctly. To do this, first get the initial value for the study.

1 In the **Model Builder** window, click **Study 1**.

2 In the **Settings** window for **Study**, locate the **Study Settings** section.

3 Clear the **Generate default plots** check box.

Disable the default plots since these are not required.

4 In the **Study** toolbar, click **Get Initial Value**.

RESULTS

Add a 2D plot group to check the dopant distribution in the model.

2D Plot Group 1

In the **Home** toolbar, click **Add Plot Group** and choose **2D Plot Group**.

Surface 1

1 Right-click **2D Plot Group 1** and choose **Surface**.

Plot the signed dopant concentration (Nd-Na). This quantity is positive for net donor doping and negative for net acceptor doping.

2 In the **Settings** window for **Surface**, locate the **Expression** section.

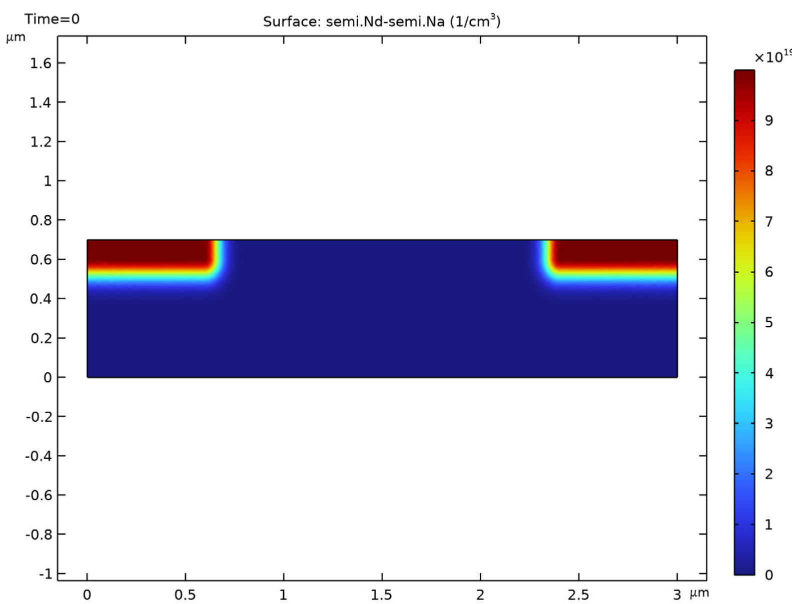
3 In the **Expression** text field, type `semi.Nd-semi.Na`.

4 In the **Unit** field, type `1/cm^3`.

5 In the **2D Plot Group 1** toolbar, click **Plot**.

6 Click the **Zoom Extents** button in the **Graphics** toolbar.

The doping distribution is shown below.



Signed Dopant Concentration

1 In the **Model Builder** window, right-click **2D Plot Group 1** and choose **Rename**.

2 In the **Rename 2D Plot Group** dialog box, type `Signed Dopant Concentration` in the **New label** text field.

3 Click **OK**.

STUDY 1

Step 1: Stationary

Now set up a Stationary study to determine the turn-on voltage for the transistor. In this study, set Vd to 10 mV and sweep over Vg.

1 In the **Model Builder** window, under **Study 1** click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, click to expand the **Study Extensions** section.

The study extensions panel can be used to set up a parametric sweep.

3 Select the **Auxiliary sweep** check box.

4 From the **Sweep type** list, choose **All combinations**.

Choose all combinations for the sweep to sweep over every combination of the specified parameters.

5 Click + **Add**.

6 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Vd (Drain voltage)	`0.01`	V

The drain voltage is fixed at a constant value.

7 Click + **Add**.

8 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Vg (Gate voltage)	`range(0,0.2,1.4) 2 3 4`	V

The gate voltage is swept between 0 and 4 V with uneven step sizes to reduce computation time and file size.

Running continuation for the Vg parameter configures the solver to use the solution for the previous continuation parameter step as the initial guess for the solution. It also allows the solver to take intermediate steps at values of Vg not specified in the list if necessary.

9 In the **Home** toolbar, click = **Compute**.

RESULTS

Add a 1D plot group to plot the source current versus the gate voltage.

1D Plot Group 2

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 **Legend** section.

3 From the **Position** list, choose **Upper left**.

Global 1

1 Right-click **1D Plot Group 2** and choose **Global**.

 The postprocessing menus contain a wide range of quantities available for plotting. Choose the current flowing into terminal 2.

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 **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
`semi.I0_2`	`uA`	`Terminal current`

4 In the **1D Plot Group 2** toolbar, click **Plot**.

 From the plot it is clear that the turn on voltage of the transistor is approximately 1.2 V.

5 Click the **Zoom Extents** button in the **Graphics** toolbar.

Id vs. Vg (Vd=10mV)

1 In the **Model Builder** window, right-click **1D Plot Group 2** and choose **Rename**.

2 In the **Rename 1D Plot Group** dialog box, type `Id vs. Vg (Vd=10mV)` in the **New label** text field.

3 Click **OK**.

ROOT

Now add an additional study to plot the source current as a function of drain voltage at a range of different gate voltages.

ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies>Stationary**.

4 Click **Add Study** in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Stationary

1 In the **Settings** window for **Stationary**, click to expand the **Values of Dependent Variables** section.

2 Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.

3 From the **Method** list, choose **Solution**.

4 From the **Study** list, choose **Study 1, Stationary**.

5 From the **Parameter value (Vg (V),Vd (V))** list, choose **9: Vg=2 V, Vd=0.01 V**.

6 Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.

7 From the **Sweep type** list, choose **All combinations**.

8 Click **Add**.

In the table, select Vg as the Auxiliary Parameter.

Now set up the study to sweep over Vg.

9 Click **Range**.

10 In the **Range** dialog box, type `2` in the **Start** text field.

11 In the **Step** text field, type `1`.

12 In the **Stop** text field, type `4`.

13 Click **Replace**.

14 In the **Settings** window for **Stationary**, locate the **Study Extensions** section.

15 Click **Add**.

In this case the default Auxiliary Parameter, Vd, is the desired parameter for the sweep.

16 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Vd (Drain voltage)	`range(0,0.25,1.5) 2 3 4 5`	V

The inner sweep over `Vd`, the last parameter, should be used for the continuation solver since the solution will only change slightly between close values of Vd. Configure the solver to reuse the solution from the last step of the continuation parameter sweep as the initial value for the next step for the outer sweep parameter `Vg`.

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

18 In the **Home** toolbar, click **Compute**.

RESULTS

Electron Concentration (semi)

By looking at the electron concentration at Vd values of 0, 1, and 5 V the pinch-off of the channel can be clearly seen.

1 Click the **Zoom Extents** button in the **Graphics** toolbar.

   By default the plot shows the results for the case Vd=5 V and Vg=4 V.

2 In the Settings window for **2D Plot Group**, locate the **Data** section. Change the Vd parameter value to 1 V and then to 0 V, each time clicking the **Plot** button to see how the results change.

3 In the **Model Builder** window, under **Results** click **Electric Potential (semi)**.

   Once again look at the plot for Vd values of 5 V, 1 V, and 0 V.

   Add another 1D plot group to plot the drain current versus the drain voltage.

1D Plot Group 6

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 **Dataset** list, choose **Study 2/Solution 2 (sol2)**.

4 Locate the **Legend** section. From the **Position** list, choose **Center**.

Global 1

1 Right-click **1D Plot Group 6** 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 **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
semi.I0_2	uA	Terminal current

4 In the **1D Plot Group 6** toolbar, click **Plot**.

   The drain current versus drain voltage diagram takes the usual form. Short channel effects can be seen at the larger gate voltages.

5 Click the **Zoom Extents** button in the **Graphics** toolbar.

Id vs. Vd

1 In the **Model Builder** window, right-click **1D Plot Group 6** and choose **Rename**.

2 In the **Rename 1D Plot Group** dialog box, type `Id vs. Vd` in the **New label** text field.

3 Click **OK**.