Created in COMSOL Multiphysics 6.0

Programming of a Floating Gate EEPROM Device

This model calculates the current and charge characteristics of a floating gate Electrically Erasable Programmable Read-Only Memory (EEPROM) device. A stationary study computes the current-voltage response of the device for a charged and uncharged floating gate. This demonstrates how the state of the memory can be read via measurements of the device resistance. Time dependent studies are then used to simulate the effects of transient voltage pulses on the control gate. These pulses cause current to tunnel between the floating gate and the semiconductor material, allowing charge to be stored or removed from the floating gate. A write-erase cycle is performed, where charge is first stored on the floating gate by an initial voltage pulse before a subsequent pulse discharges the device, returning it to its original state.

Introduction

EEPROM devices are the building blocks of modern non-volatile memory, which is becoming an increasingly important storage medium for computers and mobile devices. The structure of an EEPROM device is similar to that of a MOSFET, except that the single gate contact is replaced by two electrically isolated gates: a floating gate and a control gate (see Figure 1).

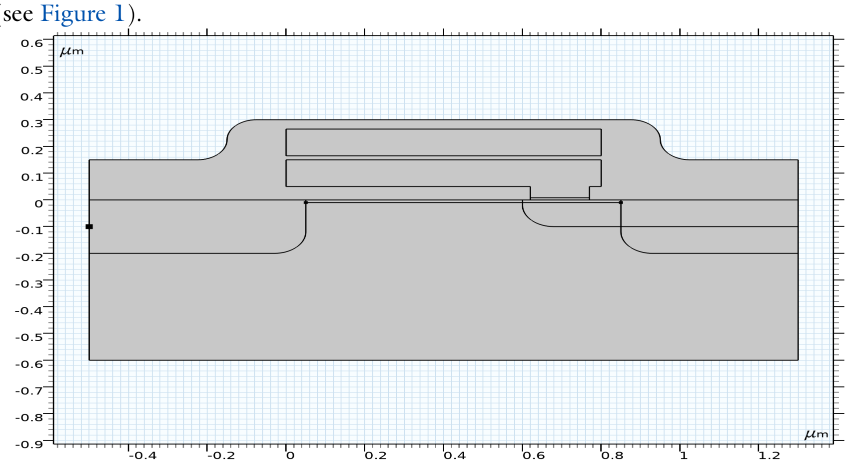


Figure 1: Model geometry showing key components of the EEPROM. The tunnel barrier is highlighted in blue.

The floating gate is electrically isolated from the rest of the device and a fixed charge is applied to it, which indicates the state of the memory. During normal operation, the control gate is used in a similar manner to the gate in a MOSFET device; its potential controls the channel width. However, the field applied to the channel depends on the charge stored on the floating gate, so at a fixed control gate bias the channel resistance varies depending on the charge applied to the floating gate (see Figure 4 below).

For this device, charge is added to the floating gate (known as programming) by applying a high field to the device (hot carrier injection is also used for this process in some EEPROM devices). The geometry of the floating gate is such that the electric field is concentrated in a small region immediately over a heavily doped part of the drain contact (known as the tunnel implant). In this region the electric field exceeds the threshold for a process known as Fowler-Nordheim tunneling, in which electrons tunnel directly into the conduction band of the insulator. For the silicon-silicon oxide system only the electron tunneling is significant and the tunnel current is given by:

$$J_{FN}^{n} = A_{FN}^{n} E_{ins}^{2} \exp\left(-\frac{B_{FN}^{n}}{E_{ins}}\right)$$

where E_{ins} is the electric field in the insulator, and A_{FN}^{n} and B_{FN}^{n} are constants related to the material properties of the insulator and semiconductor (see Ref. 1 for details). As current flows into the floating gate as a result of the applied field the charge on the gate builds up and this in turn acts to oppose the applied field. Thus the charging of the floating gate is self limiting process for a fixed applied bias, similar in nature to the charging a capacitor through a resistor.

The device presented here is based on that described in Ref. 2.

Model Definition

The model structure is shown in Figure 1. The device has a total length of 1.8 µm with a channel length, the distance between the highly doped n-type regions, of 0.55 µm. The source and drain contacts are 0.2 µm deep, with a shallower 0.1 µm deep tunnel implant protruding 0.25 µm from the drain region. The floating gate is separated from the channel by a 50 nm thick oxide layer, however directly above the tunnel implant the oxide thickness is only 8 nm. This 8 nm region serves a tunnel barrier between the MOSFET-like semiconductor device and the floating gate. When a voltage is applied to the control gate, the geometry of the floating gate serves to concentrate the resulting electric field in the region of the tunnel barrier. This can be seen in Figure 2, which shows the electric field during the programming voltage pulse. Sufficiently large control voltages generate an electric field capable of causing electron tunneling across the tunnel barrier.

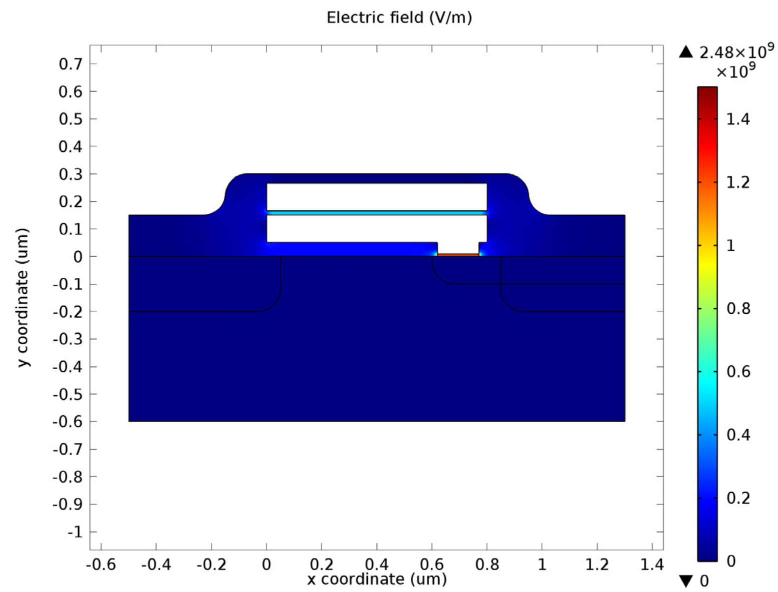


Figure 2: Surface plot showing the electric field during the control voltage pulse used to program the EEPROM device. Note how the field is concentrated in the region of the tunnel barrier.

The first study demonstrates the effect of varying the charge stored on the floating gate. For this study, the source and base contacts are grounded and a fixed voltage of 10 mV is applied to the drain. For two different values of stored charge, 0 and -2×10^{-15} C, the control gate voltage is swept from 0 to 3 V. The source current is plotted as a function of the control gate voltage for both values of stored charge.

The next two studies perform a program and erase cycle. As with the first study, the source and base contacts are grounded and a fixed voltage of 10 mV is applied to the drain. A time dependent voltage pulse is applied to the control gate, this pulse has positive sign for the program event and negative sign for the erase event, as shown below in Figure 3. For the duration of the voltage pulse electrons tunnel across the tunnel barrier. The positive program pulse causes electrons to accumulate on the floating gate. The subsequent negative pulse causes these electrons to tunnel back out again returning the floating gate near to its initial zero charge configuration. Note that the program event uses a solution from the first study as the initial condition; the erase event then takes the "programmed" state from the program event study as its initial condition.

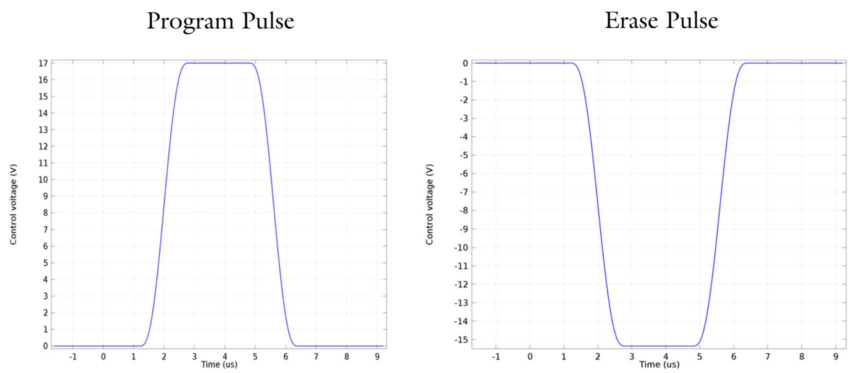


Figure 3: Time dependent control voltage pulses used for the program and erase event studies.

Results and Discussion

Figure 4 shows the current-voltage characteristics of the device for two different values of charge stored on the floating gate. As expected, the device behaves like a MOSFET, with no current flowing between the source and drain until a threshold "turn-on" control voltage is reached. This is because at the threshold voltage the electric field induces a thin inversion layer, in which the semiconductor changes from p-type to n-type, opening a conducting channel between the source and drain regions. As the control voltage increases past the threshold the width of the conducting channel increases, reducing the resistance between the source and drain contacts and allowing more current to flow for a given source-drain voltage. The stored charge changes the turn-on voltage, resulting in a different source-drain resistance for a given control voltage. By measuring the current at a given control and drain voltage it is thus possible to tell is charge is stored on the floating gate. For example, setting the control voltage to 1 V would result in no current if the device is in the erased configuration (zero stored charge) but approximately 0.5 µA if the device was charged to $-2 \cdot 10^{-15}$ C.

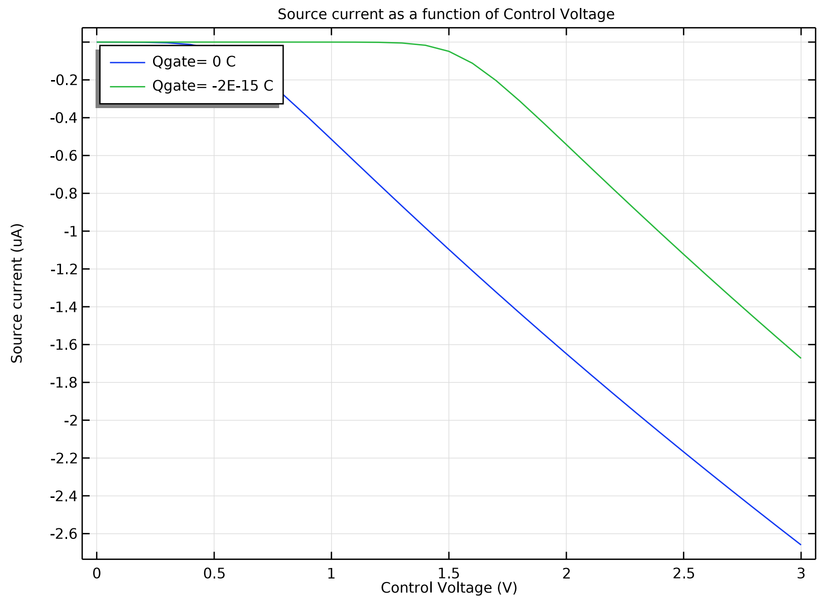


Figure 4: Source current as a function of control voltage for a fixed drain voltage of 10 mV. The blue line shows the curve when the device is in the erased state (zero stored charge). The green line shows the curve when the device is in the programed state.

Figure 5 shows the tunnel current as a function of time throughout the program and erase events. During the program event electrons tunnel onto the floating gate, resulting in a conventional current with negative sign. When electrons tunnel back out of the floating gate during the erase event there is a positive current of equal magnitude to the program event.

Figure 6 shows the charge stored on the floating gate as a function of time throughout the program and erase events. As the charge is due to electrons tunneling through the tunnel barrier, the program event results in the accumulation of a negative charge on the floating gate and the erase event returns the charge to near zero.

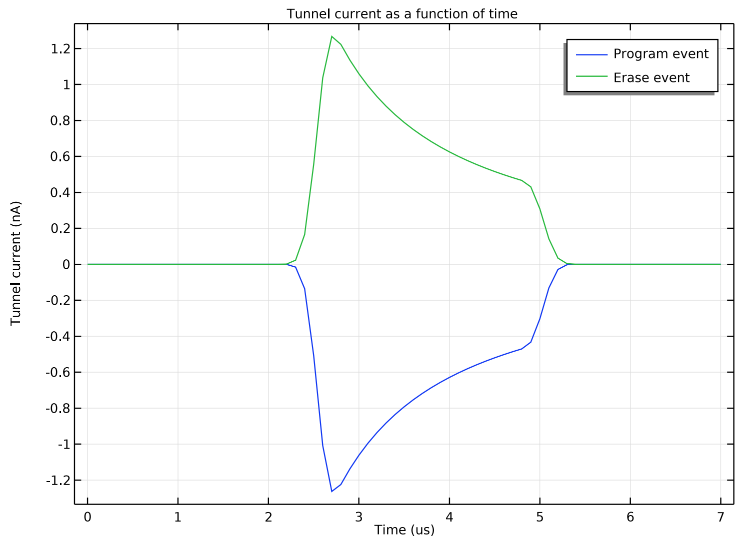


Figure 5: Tunnel current as a function of time for the program and erase events.

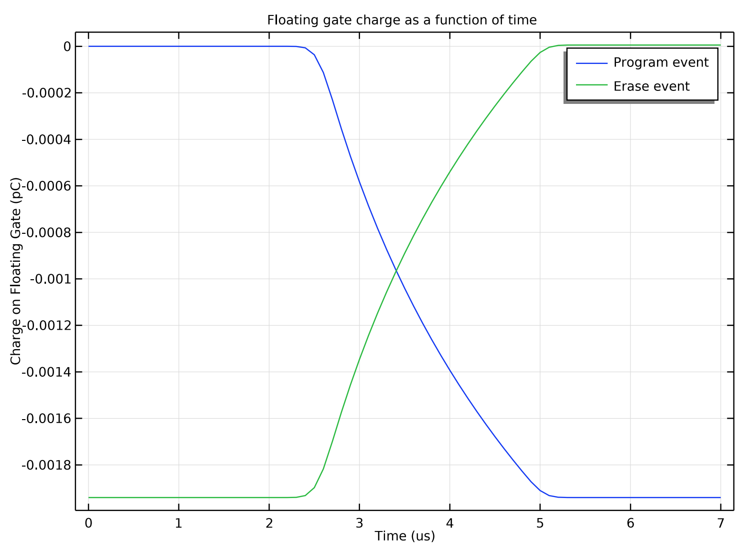


Figure 6: Charge on the floating gate as a function of time throughout the program and erase events.

References

1. M. Lenzlinger and E. H. Snow, “Fowler-Nordheim Tunneling into Thermally Grown SiO_2,” *J. Applied Physics*, vol. 40, no. 1, pp. 278–283, 1969.

2. A. Concannon, S. Keeney, A. Mathewson, and C. Lombardi, “Two-Dimensional Numerical Analysis of Floating-Gate EEPROM Devices,” *IEEE Transactions on Electron Devices,* vol. 40, no. 7, pp. 1258–1262, 1993.

Application Library path: `Semiconductor_Module/Transistors/eeprom`

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**.

GEOMETRY 1

For convenience, the device geometry will be inserted from an existing file. Once the geometry sequence is inserted it can be explored, in the usual way by clicking through the nodes in the Model Builder, if desired.

1 In the **Geometry** toolbar, click **Insert Sequence** and choose **Insert Sequence**.

2 Browse to the model’s Application Libraries folder and double-click the file `eeprom_geom_sequence.mph`.

Add a line to help make mesh later.

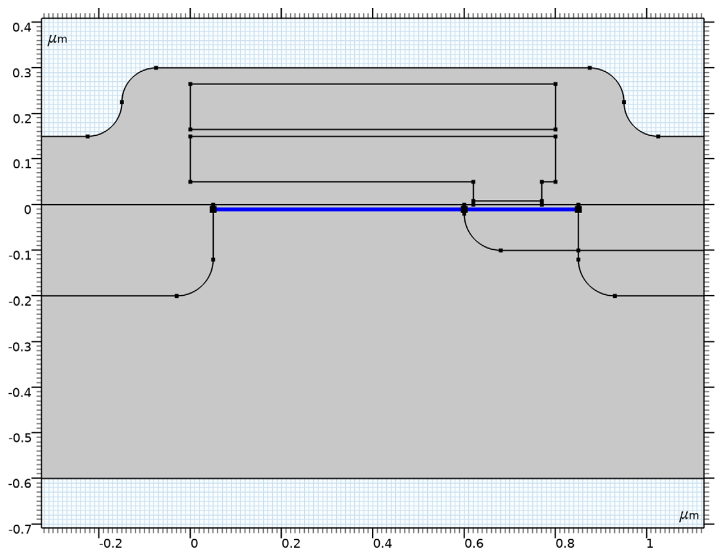
Line Segment 1 (ls1)

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 In the **x** text field, type `0.05`.
5 In the **y** text field, type `-0.01`.
6 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.
7 In the **x** text field, type `0.85`.
8 In the **y** text field, type `-0.01`.
9 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 Boundaries 18 and 22 only.

   It might be easier to select the correct boundaries 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 materials to the geometry, the Silicon (Si) material from the semiconductor material menu will be used for the semiconductor region and a blank material with the permittivity of Silicon Oxide (SiO2) will be used for the oxide layer.

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.

MATERIALS

Material 2 (mat2)

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.
2 Select Domains 3 and 7 only.
3 In the **Settings** window for **Material**, locate the **Material Contents** section.
4 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	4.2	1	Basic

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

GLOBAL DEFINITIONS

Enter some parameters which will be used to define the charge and voltages applied to the model.

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
Qgate	0[C]	0 C	Gate charge
Vcontrol	0.1[V]	0.1 V	Control voltage
Vd	10[mV]	0.01 V	Drain voltage
Vmax	23.7[V]	23.7 V	Transient voltage maximum

Name	Expression	Value	Description
A_fn	1.23e-6[A/V^2]	1.23E-6 A/V²	A tunneling coefficient
B_fn	237[MV/cm]	2.37E10 V/m	B tunneling coefficient

Create the time dependent voltage pulse which will be used in the program and erase event simulations.

Rectangle 1 (rect1)

1 In the **Home** toolbar, click f(X) **Functions** and choose **Global>Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Parameters** section.

3 In the **Lower limit** text field, type 2e-6.

4 In the **Upper limit** text field, type 5.6e-6.

5 Click to expand the **Smoothing** section. In the **Size of transition zone** text field, type 1.6e-6.

Control voltage pulse

1 In the **Model Builder** window, right-click **Global Definitions** and choose **Variables**.

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

3 In the table, enter the following settings:

Name	Expression	Unit	Description
Vcontrol_t	Vmax*rect1(t/1[s])	V	Time dependent voltage pulse

4 Right-click **Variables 1** and choose **Rename**.

5 In the **Rename Variables** dialog box, type Control voltage pulse in the **New label** text field.

6 Click **OK**.

Configure the physics in the Semiconductor interface. First remove the control and floating contacts from the semiconductor interface selection. This is equivalent to assuming that they are perfect conductors.

SEMICONDUCTOR (SEMI)

1 In the **Settings** window for **Semiconductor**, locate the **Domain Selection** section.

2 From the **Selection** list, choose **Manual**.

3 Select Domains 1–3 and 6–9 only.

Add a Charge Conservation feature to the oxide layer.

Charge Conservation 1

1. Right-click **Component 1 (comp1)>Semiconductor (semi)** and choose the domain setting **Electrostatics>Charge Conservation**.
2. Select Domains 3 and 7 only.

Next create the doping profile. The doping profile has three components: a background doping level throughout the entire semiconductor region; two doped regions, one at either side of the semiconductor region, which make up the source and drain contacts for the transistor; and a shallow doped region from which charge tunnels into the floating gate.

First apply a constant p-type background doping concentration.

Analytic Doping Model 1

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**.

Now create the n-type source and drain doping. Typically these doping regions would be created using an ion implantation process. This is approximated in the model by using an Analytical Doping Model feature to specify regions of constant doping and then using a Geometric Doping Model to create a Gaussian profile away from the edge of these regions.

Analytic Doping Model 2

1. In the **Physics** toolbar, click **Domains** and choose **Analytic Doping Model**.
2. Select Domains 2, 8, and 9 only.
3. In the **Settings** window for **Analytic Doping Model**, locate the **Impurity** section.
4. From the **Impurity type** list, choose **Donor doping (n-type)**.
5. In the N_{D0} text field, type `5e17[1/cm^3]`.

Geometric Doping Model 1

1. In the **Physics** toolbar, click **Domains** and choose **Geometric Doping Model**.
2. Select Domains 1 and 6 only.
3. In the **Settings** window for **Geometric Doping Model**, locate the **Impurity** section.
4. From the **Impurity type** list, choose **Donor doping (n-type)**.
5. In the N_{D0} text field, type `5e17[1/cm^3]`.
6. Locate the **Profile** section. From the **Specify profile length scale** list, choose **Decay length**.

7 In the l_d text field, type `0.02[um]`.

Boundary Selection for Doping Profile 1

1 In the **Model Builder** window, expand the **Geometric Doping Model 1** node, then click **Boundary Selection for Doping Profile 1**.

2 Select Boundaries 4, 16, 31, 32, 35, 43, and 45 only.

Now create the doped region below the tunnel barrier into the floating contact. As this doping region is shallower than the source and drain regions it would typically be added with a second implantation process. As before, a combination of a uniform region, specified with an Analytic Doping Model, and a Gaussian profile, specified with a Geometric Doping Model, are used.

Analytic Doping Model 3

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

2 Select Domains 6 and 9 only.

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

4 From the **Impurity type** list, choose **Donor doping (n-type)**.

5 In the N_{D0} text field, type `1e18[1/cm^3]`.

Geometric Doping Model 2

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

2 Select Domains 1, 2, and 8 only.

3 In the **Settings** window for **Geometric Doping Model**, locate the **Impurity** section.

4 From the **Impurity type** list, choose **Donor doping (n-type)**.

5 In the N_{D0} text field, type `1e18[1/cm^3]`.

6 Locate the **Profile** section. From the **Specify profile length scale** list, choose **Decay length**.

7 In the l_d text field, type `0.02[um]`.

Boundary Selection for Doping Profile 1

1 In the **Model Builder** window, expand the **Geometric Doping Model 2** node, then click **Boundary Selection for Doping Profile 1**.

2 Select Boundaries 18, 24, 33, and 44 only.

The boundary conditions for the semiconductor interface need to be specified, these will define the floating and control gates as well as the source and drain terminals and the tunneling barrier.

Add a Metal Contact boundary for the source.

Source

1 In the **Physics** toolbar, click **Boundaries** and choose **Metal Contact**.
2 Select Boundary 39 only.
3 Right-click **Metal Contact 1** and choose **Rename**.
4 In the **Rename Metal Contact** dialog box, type `Source` in the **New label** text field.
5 Click **OK**.

Add a Metal Contact boundary to ground the base of the device.

Base

1 In the **Physics** toolbar, click **Boundaries** and choose **Metal Contact**.
2 Select Boundary 2 only.
3 Right-click **Metal Contact 2** and choose **Rename**.
4 In the **Rename Metal Contact** dialog box, type `Base` in the **New label** text field.
5 Click **OK**.

Add a Metal Contact boundaries for the drain. Two boundary conditions are required, one for the stationary study and one for the time dependent study.

Drain (Stationary)

1 In the **Physics** toolbar, click **Boundaries** and choose **Metal Contact**.
2 Select Boundary 5 only.
3 In the **Settings** window for **Metal Contact**, locate the **Terminal** section.
4 In the V_0 text field, type `Vd`.
5 Right-click **Metal Contact 3** and choose **Rename**.
6 In the **Rename Metal Contact** dialog box, type `Drain (Stationary)` in the **New label** text field.
7 Click **OK**.

Drain (Time Dependent)

1 In the **Physics** toolbar, click **Boundaries** and choose **Metal Contact**.
2 Select Boundary 5 only.
3 In the **Settings** window for **Metal Contact**, locate the **Terminal** section.
4 In the V_0 text field, type `Vd`.
5 In the **Terminal name** text field, type `3`.
6 Right-click **Metal Contact 4** and choose **Rename**.

7 In the **Rename Metal Contact** dialog box, type `Drain (Time Dependent)` in the **New label** text field.

8 Click **OK**.

Add Terminal boundary conditions to the boundaries of the control contact. Two features are required, one for the stationary study and one for the time dependent study.

Control gate (Stationary)

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

2 Select Boundaries 13–15 and 30 only.

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

4 From the **Terminal type** list, choose **Voltage**.

5 In the V_0 text field, type `Vcontrol`.

6 Right-click **Terminal 1** and choose **Rename**.

7 In the **Rename Terminal** dialog box, type `Control gate (Stationary)` in the **New label** text field.

8 Click **OK**.

Control gate (Time Dependent)

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

2 Select Boundaries 13–15 and 30 only.

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

4 In the **Terminal name** text field, type `4`.

5 From the **Terminal type** list, choose **Voltage**.

6 In the V_0 text field, type `Vcontrol_t`.

7 Right-click **Terminal 2** and choose **Rename**.

8 In the **Rename Terminal** dialog box, type `Control gate (Time Dependent)` in the **New label** text field.

9 Click **OK**.

Add Insulator Tunneling boundary conditions to the boundary of the semiconductor material through which tunneling will occur.

Tunnel barrier

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

2 Select Boundary 21 only.

3 In the **Settings** window for **Insulator Interface**, locate the **Tunneling** section.

4. From the **Tunneling type** list, choose **Fowler-Nordheim tunneling**.
5. Locate the **Fowler-Nordheim Tunneling** section. In the $A^n{}_{FN}$ text field, type `A_fn`.
6. In the $B^n{}_{FN}$ text field, type `B_fn`.
7. Right-click **Insulator Interface 2** and choose **Rename**.
8. In the **Rename Insulator Interface** dialog box, type `Tunnel barrier` in the **New label** text field.
9. Click **OK**.

Add the Floating Gate boundary condition to the boundaries of the floating gate.

Floating Gate

1. In the **Physics** toolbar, click **Boundaries** and choose **Floating Gate**.
2. Select Boundaries 10–12, 22, 23, and 27–29 only.
3. In the **Settings** window for **Floating Gate**, locate the **Floating Gate** section.
4. In the Q_{init} text field, type `Qgate`.
5. Right-click **Floating Gate 1** and choose **Rename**.
6. In the **Rename Floating Gate** dialog box, type `Floating Gate` in the **New label** text field.
7. Click **OK**.

Configure the mesh to be finer around the regions of interest, in particular the mesh density must be very high in the channel region under the gate and in the tunnel barrier region.

MESH 1

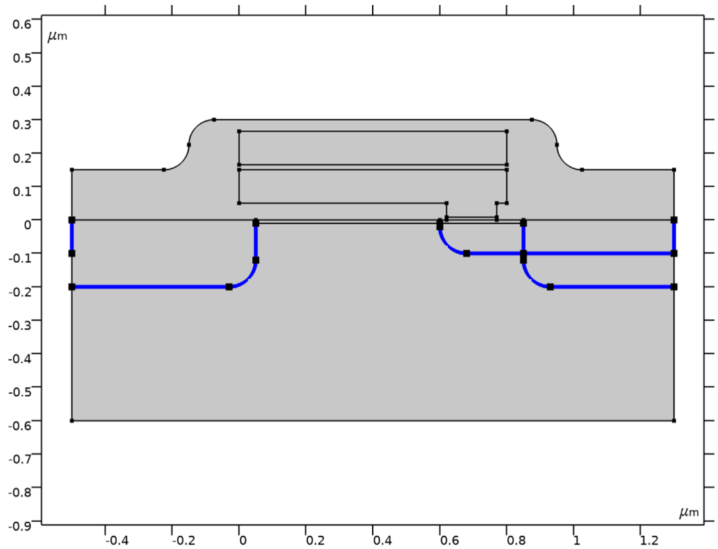
Size 1

1. In the **Model Builder** window, under **Component 1 (comp1)** right-click **Mesh 1** and choose **Size**.
2. In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
3. From the **Geometric entity level** list, choose **Domain**.
4. Select Domains 1 and 3 only.
5. Locate the **Element Size** section. From the **Predefined** list, choose **Finer**.

Size 2

1. In the **Model Builder** window, right-click **Mesh 1** and choose **Size**.
2. In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
3. From the **Geometric entity level** list, choose **Boundary**.

4 Select Boundaries 4, 5, 18, 24, 31–33, 35, 39, 43–45, and 48 only.



5 Locate the **Element Size** section. From the **Calibrate for** list, choose **Semiconductor**.

6 From the **Predefined** list, choose **Fine**.

Size 3

1 Right-click **Mesh 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Boundary**.

4 Select Boundaries 10–15 and 28–30 only.

5 Locate the **Element Size** section. 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 `0.01`.

Edge 1

1 In the **Mesh** toolbar, click **Edge**.

2 Select Boundaries 17, 19, 21, and 26 only.

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 From the **Predefined** list, choose **Extra fine**.

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 `0.01`.

Size 2

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

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Point**.

4 Select Points 18 and 22 only.

5 Locate the **Element Size** section. From the **Calibrate for** list, choose **Semiconductor**.

6 From the **Predefined** list, choose **Extra fine**.

7 Click the **Custom** button.

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

9 In the associated text field, type `0.002`.

10 Select the **Maximum element growth rate** check box.

11 In the associated text field, type `1.05`.

Copy Edge 1

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

2 Select Boundary 17 only.

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

4 Click to select the **Activate Selection** toggle button.

5 Select Boundary 51 only.

Copy Edge 2

1 Right-click **Mesh 1** and choose **Copying Operations>Copy Edge**.

2 Select Boundaries 19, 21, and 26 only.

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

4 Click to select the **Activate Selection** toggle button.

5 Select Boundary 52 only.

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 Domains 7, 10, and 11 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 16 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 3.
7. From the **Growth rate** list, choose **Exponential**.

Distribution 2

1. In the **Model Builder** window, right-click **Mapped 1** and choose **Distribution**.
2. Select Boundary 20 only.

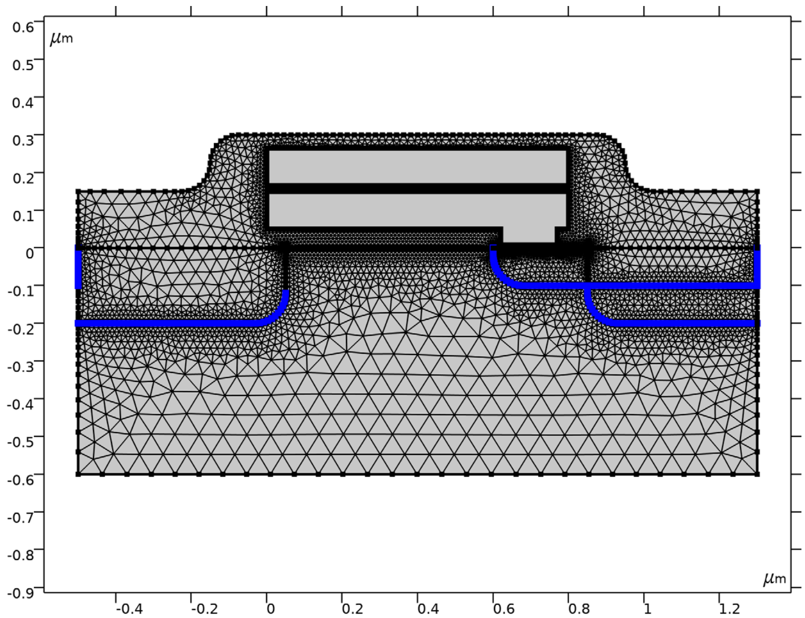
Free Triangular 1

1. In the **Mesh** toolbar, click **Free Triangular**.
2. In the **Settings** window for **Free Triangular**, locate the **Domain Selection** section.
3. From the **Geometric entity level** list, choose **Domain**.
4. Select Domains 1–3, 6, 8, and 9 only.
5. Click to expand the **Control Entities** section. Clear the **Smooth across removed control entities** check box.

Information

1 In the **Mesh** toolbar, click **Build Mesh**.

The resulting mesh is shown below.



Confirm that the doping profile is implemented as intended. This is achieved by getting the initial value from the default study settings and plotting a 2D surface plot of the net doping concentration.

STUDY 1

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.

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

RESULTS

2D Plot Group 1

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

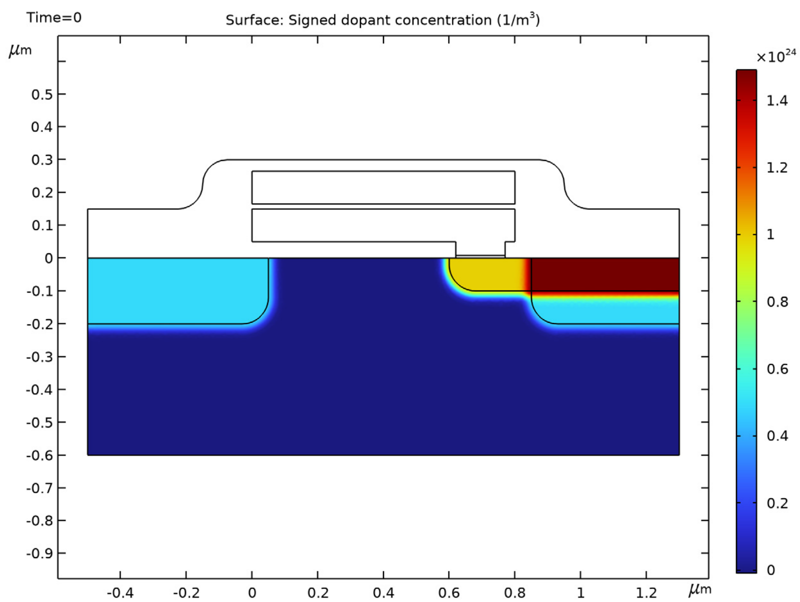
Surface 1

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

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

3 In the **Expression** text field, type `semi.Ndoping`.

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



Doping

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 `Doping` in the **New label** text field.

3 Click **OK**.

The desired doping profile is shown above.

With the physics configured and doping confirmed the main studies can be performed. Set the stationary study to sweep Vcontrol from 0 to 3 V for two different values of Qgate. Note that the time dependent boundary conditions are disabled for this study.

STUDY 1

Step 1: Stationary

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

2 In the **Settings** window for **Stationary**, locate the **Physics and Variables Selection** section.

3 Select the **Modify model configuration for study step** check box.

4 In the tree, select **Component 1 (Comp1)>Semiconductor (Semi)>Drain (Time Dependent)**.

5 Click **Disable**.

6 In the tree, select **Component 1 (Comp1)>Semiconductor (Semi)>Control Gate (Time Dependent)**.

7 Click **Disable**.

8 Click to expand the **Study Extensions** section. Select the **Auxiliary sweep** check box.

9 Click **Add**.

10 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Qgate (Gate charge)	`0 -2e-15`	`C`

11 Click **Add**.

12 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Vcontrol (Control voltage)	`range(0,0.1,3)`	`V`

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

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

Adjust scaling for better convergence.

Solution 1 (sol1)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 1 (sol1)** node, then click **Dependent Variables 1**.

3 In the **Settings** window for **Dependent Variables**, locate the **Scaling** section.

4 From the **Method** list, choose **None**.

5 In the **Model Builder** window, expand the **Study 1>Solver Configurations>Solution 1 (sol1)>Dependent Variables 1** node, then click **Electron solution variable (comp1.Ne)**.

6 In the **Settings** window for **Field**, locate the **Scaling** section.

7 From the **Method** list, choose **Manual**.

8 In the **Scale** text field, type `1.0e24`.

9 In the **Model Builder** window, under **Study 1>Solver Configurations>Solution 1 (sol1)>Dependent Variables 1** click **Hole solution variable (comp1.Ph)**.

10 In the **Settings** window for **Field**, locate the **Scaling** section.

11 From the **Method** list, choose **Manual**.

12 In the **Scale** text field, type `1.0e22`.

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

14 In the **Settings** window for **Study**, type `Stationary, sweep Vcontrol for fixed Qgate.` in the **Label** text field.

15 In the **Study** toolbar, click **Compute**.

Plot the I-V curves for each of the control voltages.

RESULTS

Current vs. Voltage

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

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

3 In the **Rename 1D Plot Group** dialog box, type `Current vs. Voltage` in the **New label** text field.

4 Click **OK**.

Global 1

1 Right-click **Current vs. Voltage** and choose **Global**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
semi.I0_1	uA	Source current

4 Click to expand the **Legends** section. From the **Legends** list, choose **Evaluated**.

5 In the **Legend** text field, type `Qgate= eval(Qgate, C) C`.

Current vs. Voltage

1 In the **Model Builder** window, click **Current vs. Voltage**.

2 In the **Settings** window for **1D Plot Group**, locate the **Plot Settings** section.

3 Select the **x-axis label** check box.

4 In the associated text field, type `Control Voltage (V)`.

5 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

6 In the **Title** text area, type `Source current as a function of Control Voltage`.

7 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

8 In the **Current vs. Voltage** toolbar, click **Plot**.

Add time dependent studies to perform the program and erase simulation.

The first time dependent study performs the Program event. In this study the control voltage pulse has positive sign and electrons tunnel out of the semiconductor across the tunnel barrier, resulting in negative charge being deposited on the floating contact.

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> Time Dependent**.

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: Time Dependent

1 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

2 In the **Output times** text field, type `range(0,0.1e-6,7e-6)`.

3 Click to expand the **Values of Dependent Variables** section. Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.

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

5 From the **Study** list, choose **Stationary, sweep Vcontrol for fixed Qgate., Stationary**.

6 From the **Parameter value (Vcontrol (V),Qgate (C))** list, choose **32: Vcontrol=0 V, Qgate=-2E-15 C**.

7 Click to expand the **Study Extensions** section. Select the **Auxiliary sweep** check box.

8 Click **Add**.

9 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Vmax (Transient voltage maximum)	16.8[V]	V

10 Click **Add**.

11 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
A_fn (A tunneling coefficient)	`1.23e-6[A/V^2]`	`A/V^2`

12 Click **Add**.

13 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
B_fn (B tunneling coefficient)	`237[MV/cm]`	`V/m`

14 In the **Model Builder** window, right-click **Study 2** and choose **Rename**.

15 In the **Rename Study** dialog box, type `Time dependent, Program event` in the **New label** text field.

16 Click **OK**.

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

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

Solution 2 (sol2)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 2 (sol2)** node, then click **Time-Dependent Solver 1**.

3 In the **Settings** window for **Time-Dependent Solver**, click to expand the **Time Stepping** section.

4 From the **Steps taken by solver** list, choose **Intermediate**.

5 In the **Study** toolbar, click **Compute**.

The second time dependent study performs the Erase event. This study starts with the device in the 'programmed' state and applies a control voltage pulse with negative sign. This causes electrons to tunnel out of the floating contact, reducing the magnitude of the floating gate charge near to zero.

ADD STUDY

1 In the **Study** 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> Time Dependent**.

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

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

STUDY 3

Step 1: Time Dependent

1 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

2 In the **Output times** text field, type `range(0,0.1e-6,7e-6)`.

3 Locate the **Values of Dependent Variables** section. Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.

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

5 From the **Study** list, choose **Time dependent, Program event, Time Dependent**.

6 From the **Selection** list, choose **Last**.

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

8 Click **Add**.

9 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Vmax (Transient voltage maximum)	-15.34	V

10 Click **Add**.

11 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
A_fn (A tunneling coefficient)	1.82e-7[A/V^2]	A/V^2

12 Click **Add**.

13 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
B_fn (B tunneling coefficient)	188[MV/cm]	V/m

14 In the **Model Builder** window, right-click **Study 3** and choose **Rename**.

15 In the **Rename Study** dialog box, type `Time dependent, Erase event` in the **New label** text field.

16 Click **OK**.

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

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

Solution 3 (sol3)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 3 (sol3)** node, then click **Time-Dependent Solver 1**.

3 In the **Settings** window for **Time-Dependent Solver**, locate the **Time Stepping** section.

4 From the **Steps taken by solver** list, choose **Intermediate**.

5 In the **Study** toolbar, click **Compute**.

Plot the tunnel current and the charge on the floating gate as functions of time during the Program and Erase events.

RESULTS

Tunnel Current

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 Right-click **1D Plot Group 3** and choose **Rename**.

3 In the **Rename 1D Plot Group** dialog box, type `Tunnel Current` in the **New label** text field.

4 Click **OK**.

5 In the **Settings** window for **1D Plot Group**, locate the **Data** section.

6 From the **Dataset** list, choose **None**.

7 Locate the **Title** section. From the **Title type** list, choose **Manual**.

8 In the **Title** text area, type `Tunnel current as a function of time`.

9 Locate the **Plot Settings** section. Select the **x-axis label** check box.

10 In the associated text field, type `Time (us)`.

11 Select the **y-axis label** check box.

12 In the associated text field, type `Tunnel current (nA)`.

Global 1

1 Right-click **Tunnel Current** and choose **Global**.

2 In the **Settings** window for **Global**, locate the **Data** section.

3 From the **Dataset** list, choose **Time dependent, Program event/Solution 2 (sol2)**.

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

Expression	Unit	Description
`semi.ii2.I_tun`	`nA`	`Tunnel current`

5 Locate the **x-Axis Data** section. From the **Unit** list, choose **µs**.

6 Locate the **Legends** section. From the **Legends** list, choose **Manual**.

7 In the table, enter the following settings:

Legends
`Program event`

Global 2

1 In the **Model Builder** window, right-click **Tunnel Current** and choose **Global**.

2 In the **Settings** window for **Global**, locate the **Data** section.

3 From the **Dataset** list, choose **Time dependent, Erase event/Solution 3 (sol3)**.

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

Expression	Unit	Description
`semi.ii2.I_tun`	`nA`	`Tunnel current`

5 Locate the **x-Axis Data** section. From the **Unit** list, choose **µs**.

6 Locate the **Legends** section. From the **Legends** list, choose **Manual**.

7 In the table, enter the following settings:

Legends
`Erase event`

8 In the **Tunnel Current** toolbar, click **Plot**.

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 **Dataset** list, choose **None**.

4 Locate the **Title** section. From the **Title type** list, choose **Manual**.

5 In the **Title** text area, type `Floating gate charge as a function of time`.

6 Locate the **Plot Settings** section. Select the **x-axis label** check box.

7 In the associated text field, type `Time (us)`.

8 Select the **y-axis label** check box.

9 In the associated text field, type `Charge on Floating Gate (pC)`.

Global 1

1 Right-click **1D Plot Group 4** and choose **Global**.

2 In the **Settings** window for **Global**, locate the **Data** section.

3 From the **Dataset** list, choose **Time dependent, Program event/Solution 2 (sol2)**.

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

Expression	Unit	Description
semi.fg1.Q0	pC	Charge

5 Locate the **x-Axis Data** section. From the **Unit** list, choose **µs**.

6 Locate the **Legends** section. From the **Legends** list, choose **Manual**.

7 In the table, enter the following settings:

Legends
Program event

Global 2

1 Right-click **Global 1** and choose **Duplicate**.

2 In the **Settings** window for **Global**, locate the **Data** section.

3 From the **Dataset** list, choose **Time dependent, Erase event/Solution 3 (sol3)**.

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

Legends
Erase event

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

Floating Gate Charge

1 In the **Model Builder** window, right-click **1D Plot Group 4** and choose **Rename**.

2 In the **Rename 1D Plot Group** dialog box, type `Floating Gate Charge` in the **New label** text field.

3 Click **OK**.