



Model created in COMSOL Multiphysics 6.4

Electrolyte-Gated Organic Field-Effect Transistor



Introduction

An Electrolyte-Gated Organic Field-Effect Transistor, for short EGOFET, is a type of field-effect transistor where the gate dielectric layer is replaced by an electrolyte and the semiconductor is an organic material. Just like a traditional field-effect transistor, an EGOFET comprises three electrodes, including source, drain, and gate electrode.

In an EGOFET constructed with a p-type organic semiconductor, the gate is negatively polarized, causing the positive ions of the electrolyte to accumulate at the gate–electrolyte interface. Concurrently, the negative ions accumulate at the electrolyte–organic semiconductor interface. This ends up in the formation of electrical double layer at the two aforementioned interfaces.

In this example, we are going to show how to model the static characteristics of this device based on a general Drift–Diffusion model.

Model Definition

The materials and geometry of this model are a simplified version of the device described in [Ref. 1](#). The model uses the following configuration: source and drain electrodes positioned on the two side ends of the organic semiconductor domain and the gate electrode placed at the top boundary of the electrolyte domain. The total depth of the transistor is 1 cm with a width of 30 μm . [Figure 1](#) shows the configuration of the modeled device.

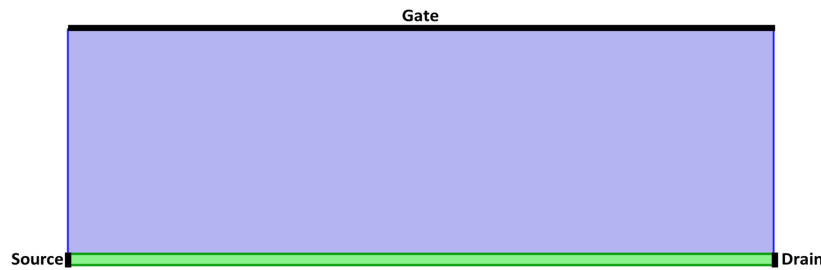


Figure 1: Configuration of the modeled EGOFET, with the organic semiconductor domain in green and the electrolyte in blue.

In a p-type organic semiconductor, the charge carriers are holes, while in the electrolyte domain, ions serve as the charge carriers. The model uses the Transport of Charge Carriers interface for defining transport phenomena ([Equation 1](#)) and the Electrostatics interface to describe the motion of the charges under the applied electric field ([Equation 2](#)):

$$\nabla \cdot \mathbf{J}_c = \nabla \cdot \left(-D_c \nabla c - z_c \frac{D_c}{RT} F c \nabla V \right) = 0 \quad (1)$$

$$-\nabla \cdot (\epsilon_0 \epsilon_r \nabla V) = c \times F \quad (2)$$

In the equations above, \mathbf{J}_c , D_c , and z_c , are flux, diffusion coefficient, and charge of the charge carriers, respectively. R is the ideal gas constant, T the temperature, F the Faraday constant, and V the electric potential. ϵ_0 and ϵ_r are the permittivity of vacuum and relative permittivity of the material, respectively.

Since there are three different types of charge carriers in this device, we use the same set of equations for each, namely the holes, positive ions and negative ions. The procedure of the implementation is described in detail in the [Modeling Instructions](#) section.

Results and Discussion

[Figure 2](#) shows the electric field profile at the cross-section of the device (along the y direction) for zero drain voltage and gate voltage varying from 0 to -0.5 V. The profile shows a high electric field at the two interfaces, corresponding to the gate–electrolyte and electrolyte–organic semiconductor interface. This is due to the accumulation of charges at these interfaces.

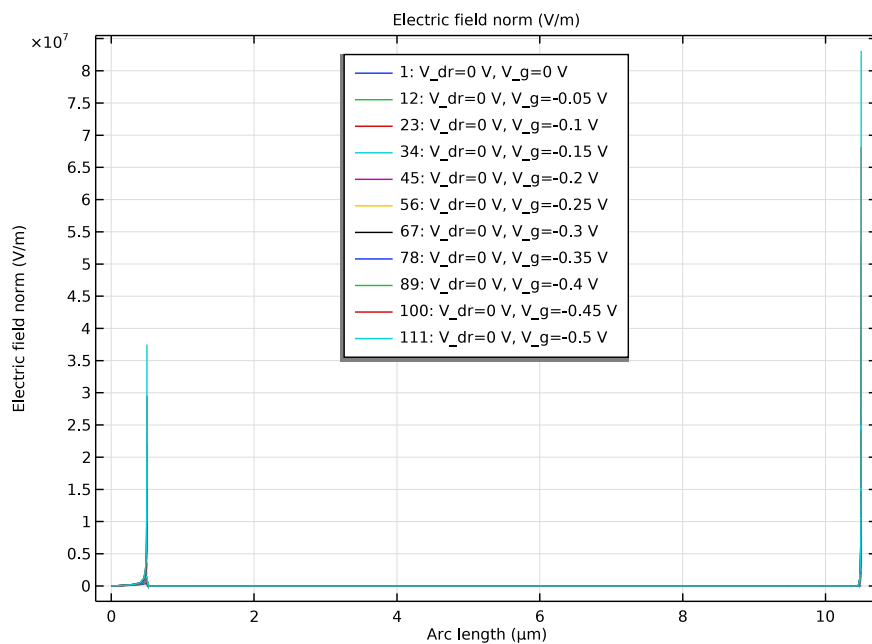


Figure 2: Electric field along the cross section of the EGOFET.

Figure 3 shows the transfer curve of the EGOFET which is drain current versus the gate voltage.

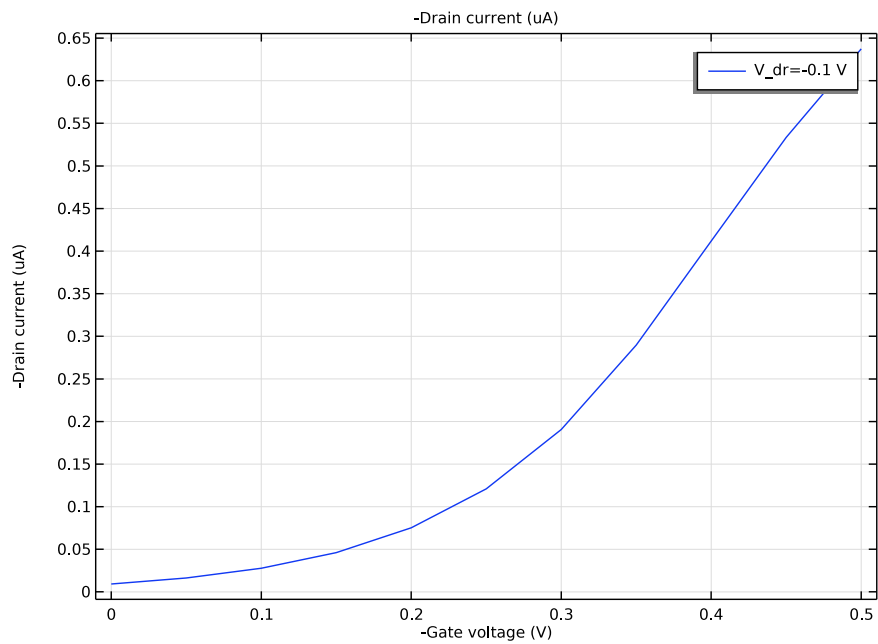


Figure 3: Drain current versus gate voltage curve.

Reference


I. N. Delavari, K. Tybrandt, M. Berggren, B. Piro, V. Noël, G. Mattana, and I. Zozoulenko, “Nernst–Planck–Poisson analysis of electrolyte-gated organic field-effect transistors,” *J. Phys. D: Appl. Phys.*, vol. 54, no. 41, 415101, 2021.

Application Library path: Semiconductor_Module/Transistors/egofet


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 **Electric Discharge > Transport of Charge Carriers (tcc)**.
- 3 Click **Add**.
- 4 In the **Charge carriers (1/m³)** table, enter the following settings:

h

- 5 Click **Add**.
- 6 In the **Number of charge carriers** text field, type 2.
- 7 In the **Charge carriers (1/m³)** table, enter the following settings:

p
n
- 8 In the **Select Physics** tree, select **AC/DC > Electric Fields and Currents > Electrostatics (es)**.
- 9 Click **Add**.
- 10 Click  **Study**.
- 11 In the **Select Study** tree, select **General Studies > Stationary**.
- 12 Click **Done**.

GLOBAL DEFINITIONS

Parameters I

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

Name	Expression	Value	Description
w_dom	30[um]	3E-5 m	Domain width
h_semi	500[nm]	5E-7 m	Organic semiconductor thickness
h_electrolyte	10[um]	1E-5 m	Electrolyte thickness
V_dr	0[V]	0 V	Drain electrode Voltage

Name	Expression	Value	Description
V_g	0[V]	0 V	Gate electrode voltage
D_h	1e-6[m ² /s]	1E-6 m ² /s	Diffusion coefficient for holes
D_p	15e-10[m ² /s]	1.5E-9 m ² /s	Diffusion coefficient for positive ions
D_n	D_p	1.5E-9 m ² /s	Diffusion coefficient for negative ions
T	300[K]	300 K	Temperature
d	1[cm]	0.01 m	depth
z_h	+1	1	charge of hole
z_p	+1	1	charge of positive ions
z_n	-1	-1	charge of negative ions
ch0	1e-3[mol/m ³]	0.001 mol/m ³	Holes initial concentration
cp0	1[mol/m ³]	1 mol/m ³	Positive ions initial concentration
cn0	1[mol/m ³]	1 mol/m ³	Negative ions initial concentration


GEOMETRY 1

1 In the **Model Builder** window, expand the **Component 1 (comp1) > Geometry 1** node, then 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  **Rectangle**.

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


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

4 In the **Height** text field, type h_semi.

Rectangle 2 (r2)

- 1 Right-click **Rectangle 1 (r1)** and choose **Duplicate**.
- 2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
- 3 Clear the **Height** text field.
- 4 Locate the **Position** section. In the **y** text field, type h_{semi} .
- 5 Locate the **Size and Shape** section. In the **Height** text field, type $h_{\text{electrolyte}}$.
- 6 Click  **Build All Objects**.

TRANSPORT OF HOLES

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Transport of Charge Carriers (tcc)**.
- 2 In the **Settings** window for **Transport of Charge Carriers**, type Transport of Holes in the **Label** text field.
- 3 Locate the **Domain Selection** section. Click  **Clear Selection**.
- 4 Select Domain 1 only.
- 5 Locate the **Physical Model** section. In the d_z text field, type d .


Transport Properties 1

- 1 In the **Model Builder** window, under **Component 1 (comp1)** > **Transport of Holes (tcc)** click **Transport Properties 1**.
- 2 In the **Settings** window for **Transport Properties**, locate the **Electric Field** section.
- 3 From the **E** list, choose **Electric field (es/fsp1)**.
- 4 Locate the **Drift** section. In the z_h text field, type z_h .
- 5 In the μ_h text field, type $D_h * F_{\text{const}} / (R_{\text{const}} * T)$.
- 6 Locate the **Diffusion** section. In the D_h text field, type D_h .



Initial Values 1

- 1 In the **Model Builder** window, click **Initial Values 1**.
- 2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.
- 3 In the n_h text field, type $ch0 * F_{\text{const}} / e_{\text{const}}$.

No Flux 1

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **No Flux**.
- 2 In the **Settings** window for **No Flux**, locate the **Boundary Selection** section.
- 3 From the **Selection** list, choose **All boundaries**.


Number Density 1

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Number Density**.
- 2 In the **Settings** window for **Number Density**, locate the **Boundary Selection** section.
- 3 Click  **Paste Selection**.
- 4 In the **Paste Selection** dialog, type 1 6 in the **Selection** text field.
- 5 Click **OK**.
- 6 In the **Settings** window for **Number Density**, locate the **Number Density** section.
- 7 Select the **Carrier h** checkbox.
- 8 In the $n_{0,h}$ text field, type $ch_0 * F_const / e_const$.

Current Calculation 1

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Current Calculation**.
- 2 Select Boundary 6 only.

TRANSPORT OF IONS

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Transport of Charge Carriers 2 (tcc2)**.
- 2 In the **Settings** window for **Transport of Charge Carriers**, type Transport of Ions in the **Label** text field.
- 3 Locate the **Domain Selection** section. Click  **Clear Selection**.
- 4 Select Domain 2 only.
- 5 Locate the **Physical Model** section. In the d_z text field, type d.


Transport Properties 1

- 1 In the **Model Builder** window, under **Component 1 (comp1)** > **Transport of Ions (tcc2)** click **Transport Properties 1**.
- 2 In the **Settings** window for **Transport Properties**, locate the **Electric Field** section.
- 3 From the **E** list, choose **Electric field (es/fsp1)**.
- 4 Locate the **Drift** section. In the z_p text field, type z_p .
- 5 In the z_n text field, type z_n .
- 6 In the μ_p text field, type $D_p * F_const / (R_const * T)$.
- 7 In the μ_n text field, type $D_n * F_const / (R_const * T)$.
- 8 Locate the **Diffusion** section. In the D_p text field, type D_p .
- 9 In the D_n text field, type D_n .



Initial Values 1

- 1 In the **Model Builder** window, click **Initial Values 1**.
- 2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.
- 3 In the n_p text field, type $cp0 * F_const / e_const$.
- 4 In the n_n text field, type $cn0 * F_const / e_const$.

No Flux 1

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **No Flux**.
- 2 In the **Settings** window for **No Flux**, locate the **Boundary Selection** section.
- 3 From the **Selection** list, choose **All boundaries**.


Number Density 1

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Number Density**.
- 2 In the **Settings** window for **Number Density**, locate the **Boundary Selection** section.
- 3 Click  **Paste Selection**.
- 4 In the **Paste Selection** dialog, type 3 7 in the **Selection** text field.
- 5 Click **OK**.
- 6 In the **Settings** window for **Number Density**, locate the **Number Density** section.
- 7 Select the **Carrier p** checkbox.
- 8 In the $n_{0,p}$ text field, type $cp0 * F_const / e_const$.
- 9 Select the **Carrier n** checkbox.
- 10 In the $n_{0,n}$ text field, type $cn0 * F_const / e_const$.

ELECTROSTATICS (ES)

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Electrostatics (es)**.
- 2 In the **Settings** window for **Electrostatics**, locate the **Thickness** section.
- 3 In the d text field, type d .



Charge Conservation in Fluids 1

- 1 In the **Physics** toolbar, click  **Domains** and choose **Charge Conservation in Fluids**.
- 2 In the **Settings** window for **Charge Conservation in Fluids**, locate the **Domain Selection** section.
- 3 From the **Selection** list, choose **All domains**.
- 4 Locate the **Constitutive Relation D-E** section. From the ϵ_r list, choose **User defined**. In the associated text field, type 3.



Charge Conservation in Fluids 2

- 1 Right-click **Charge Conservation in Fluids I** and choose **Duplicate**.
- 2 Select Domain 2 only.
- 3 In the **Settings** window for **Charge Conservation in Fluids**, locate the **Constitutive Relation D-E** section.
- 4 In the ϵ_r text field, type 79.



V_s

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Electric Potential**.
- 2 In the **Settings** window for **Electric Potential**, type V_s in the **Label** text field.
- 3 Locate the **Boundary Selection** section. Click  **Paste Selection**.
- 4 In the **Paste Selection** dialog, type 1 in the **Selection** text field.
- 5 Click **OK**.


V_{dr}

- 1 Right-click V_s and choose **Duplicate**.
- 2 In the **Settings** window for **Electric Potential**, type V_{dr} in the **Label** text field.
- 3 Locate the **Boundary Selection** section. Click  **Clear Selection**.
- 4 Click  **Paste Selection**.
- 5 In the **Paste Selection** dialog, type 6 in the **Selection** text field.
- 6 Click **OK**.
- 7 In the **Settings** window for **Electric Potential**, locate the **Electric Potential** section.
- 8 In the V_0 text field, type V_{dr} .


V_g

- 1 Right-click V_{dr} and choose **Duplicate**.
- 2 In the **Settings** window for **Electric Potential**, type V_g in the **Label** text field.
- 3 Locate the **Boundary Selection** section. Click  **Clear Selection**.
- 4 Click  **Paste Selection**.
- 5 In the **Paste Selection** dialog, type 5 in the **Selection** text field.
- 6 Click **OK**.
- 7 In the **Settings** window for **Electric Potential**, locate the **Electric Potential** section.
- 8 In the V_0 text field, type V_g .

Space Charge Density 1

- 1 In the **Physics** toolbar, click  **Domains** and choose **Space Charge Density**.
- 2 Select Domain 1 only.
- 3 In the **Settings** window for **Space Charge Density**, locate the **Space Charge Density** section.
- 4 In the ρ_v text field, type $h \cdot e_{\text{const}}$.


Space Charge Density 2

- 1 Right-click **Space Charge Density 1** and choose **Duplicate**.
- 2 In the **Settings** window for **Space Charge Density**, locate the **Domain Selection** section.
- 3 Click  **Clear Selection**.
- 4 Select Domain 2 only.
- 5 Locate the **Space Charge Density** section. In the ρ_v text field, type $(p-n) \cdot e_{\text{const}}$.


MESH 1

In the **Model Builder** window, under **Component 1 (comp1)** right-click **Mesh 1** and choose **Edit Physics-Induced Sequence**.

Size 1



- 1 In the **Model Builder** window, expand the **Component 1 (comp1) > Mesh 1 > Free Triangular 1** node.
- 2 Right-click **Free Triangular 1** and choose **Size**.
- 3 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
- 4 From the **Geometric entity level** list, choose **Domain**.
- 5 Click  **Paste Selection**.
- 6 In the **Paste Selection** dialog, type 1 in the **Selection** text field.
- 7 Click **OK**.
- 8 In the **Settings** window for **Size**, locate the **Element Size** section.
- 9 Click the **Custom** button.
- 10 Locate the **Element Size Parameters** section.
- 11 Select the **Maximum element size** checkbox. In the associated text field, type $1e-7$ [m].

Distribution 1

- 1 In the **Model Builder** window, right-click **Free Triangular 1** and choose **Distribution**.
- 2 In the **Settings** window for **Distribution**, locate the **Boundary Selection** section.
- 3 Click  **Paste Selection**.

- 4 In the **Paste Selection** dialog, type 5 in the **Selection** text field.
- 5 Click **OK**.
- 6 In the **Settings** window for **Distribution**, locate the **Distribution** section.
- 7 In the **Number of elements** text field, type 1000.


Distribution 2

- 1 Right-click **Distribution 1** and choose **Duplicate**.
- 2 In the **Settings** window for **Distribution**, locate the **Boundary Selection** section.
- 3 Click  **Clear Selection**.
- 4 Click  **Paste Selection**.
- 5 In the **Paste Selection** dialog, type 16 in the **Selection** text field.
- 6 Click **OK**.
- 7 In the **Settings** window for **Distribution**, locate the **Distribution** section.
- 8 In the **Number of elements** text field, type 50.

Boundary Layers 1

In the **Mesh** toolbar, click  **Boundary Layers**.


Boundary Layer Properties

- 1 In the **Model Builder** window, click **Boundary Layer Properties**.
- 2 In the **Settings** window for **Boundary Layer Properties**, locate the **Boundary Selection** section.
- 3 Click  **Paste Selection**.
- 4 In the **Paste Selection** dialog, type 45 in the **Selection** text field.
- 5 Click **OK**.
- 6 In the **Settings** window for **Boundary Layer Properties**, locate the **Layers** section.
- 7 In the **Number of layers** text field, type 4.
- 8 In the **Stretching factor** text field, type 1.05.
- 9 In the **Model Builder** window, right-click **Mesh 1** and choose **Build All**.

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**, click to expand the **Study Extensions** section.
- 3 Select the **Auxiliary sweep** checkbox.

4 Click  **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
V _g (Gate electrode voltage)		V

6 In the table, click to select the cell at row number 1 and column number 2.

7 Click  **Range**.

8 In the **Range** dialog, type 0 in the **Start** text field.

9 In the **Step** text field, type -0.05.

10 In the **Stop** text field, type -0.5.

11 Click **Replace**.

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

13 Click  **Add**.

14 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
V _{dr} (Drain electrode Voltage)		V

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


16 Click  **Range**.

17 In the **Range** dialog, type 0 in the **Start** text field.

18 In the **Step** text field, type -0.05.


19 In the **Stop** text field, type -0.5.

20 Click **Replace**.

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

RESULTS

Cut Line 2D 1

1 In the **Results** toolbar, click  **Cut Line 2D**.

2 In the **Settings** window for **Cut Line 2D**, locate the **Line Data** section.

3 From the **Line entry method** list, choose **Point and direction**.


4 Find the **Point** subsection. In the **x** text field, type $w_{\text{dom}}/2$.

5 Find the **Direction** subsection. In the **x** text field, type 0.

6 In the **y** text field, type 1.

7 Click  **Plot**.

V-y

1 In the **Results** toolbar, click  **ID Plot Group**.

2 In the **Settings** window for **ID Plot Group**, type V-y in the **Label** text field.

3 Locate the **Data** section. From the **Parameter selection (V_dr)** list, choose **First**.

Line Graph 1

Right-click **V-y** and choose **Line Graph**.

V-y


From the **Dataset** list, choose **Cut Line 2D 1**.

Line Graph 1

1 In the **Model Builder** window, click **Line Graph 1**.

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

3 In the **Expression** text field, type V.

4 In the **V-y** toolbar, click  **Plot**.

E-y

1 In the **Model Builder** window, right-click **V-y** and choose **Duplicate**.

2 In the **Settings** window for **ID Plot Group**, type E-y in the **Label** text field.


3 Locate the **Legend** section. From the **Position** list, choose **Upper middle**.

Line Graph 1

1 In the **Model Builder** window, expand the **E-y** node, then click **Line Graph 1**.

2 In the **Settings** window for **Line Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1) > Electrostatics > Electric > es.normE - Electric field norm - V/m**.

3 Click to expand the **Legends** section. Select the **Show legends** checkbox.

4 In the **E-y** toolbar, click  **Plot**.



h-y

1 In the **Model Builder** window, right-click **E-y** and choose **Duplicate**.

2 In the **Settings** window for **ID Plot Group**, type h-y in the **Label** text field.

Line Graph 1


1 In the **Model Builder** window, expand the **h-y** node, then click **Line Graph 1**.

- 2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
- 3 In the **Expression** text field, type h.
- 4 In the **h-y** toolbar, click  **Plot**.
- 5 Click the  **y-Axis Log Scale** button in the **Graphics** toolbar.

p-y

- 1 In the **Model Builder** window, right-click **h-y** and choose **Duplicate**.
- 2 In the **Settings** window for **ID Plot Group**, type p-y in the **Label** text field.


Line Graph 1

- 1 In the **Model Builder** window, expand the **p-y** node, then click **Line Graph 1**.
- 2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
- 3 In the **Expression** text field, type p.
- 4 In the **p-y** toolbar, click  **Plot**.



n-y

- 1 In the **Model Builder** window, right-click **p-y** and choose **Duplicate**.
- 2 In the **Settings** window for **ID Plot Group**, type n-y in the **Label** text field.

Line Graph 1

- 1 In the **Model Builder** window, expand the **n-y** node, then click **Line Graph 1**.
- 2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
- 3 In the **Expression** text field, type n.
- 4 In the **n-y** toolbar, click  **Plot**.

I_dr-V_dr


- 1 In the **Results** toolbar, click  **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type I_dr-V_dr in the **Label** text field.
- 3 Locate the **Data** section. From the **Parameter selection (V_g)** list, choose **Manual**.
- 4 Click  **Range**.
- 5 In the **Integer Range** dialog, type 2 in the **Step** text field.
- 6 In the **Stop** text field, type 11.
- 7 Click **Replace**.

Global 1

- 1 Right-click **I_dr-V_dr** 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 I (comp I) > Transport of Holes > Electric > tcc.IO_0 - Conduction current - A**.
- 3 Locate the **y-Axis Data** section. In the table, enter the following settings:


Expression	Unit	Description
-tcc.IO_0	uA	-Drain current

- 4 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 5 In the **Expression** text field, type -V_dr.
- 6 Select the **Description** checkbox. In the associated text field, type -Drain voltage.
- 7 Click to expand the **Legends** section. Find the **Include** subsection. Clear the **Description** checkbox.
- 8 In the **I_dr-V_dr** toolbar, click  **Plot**.

I_dr-V_g

- 1 In the **Model Builder** window, right-click **I_dr-V_dr** and choose **Duplicate**.
- 2 In the **Settings** window for **ID Plot Group**, type **I_dr-V_g** in the **Label** text field.
- 3 Locate the **Data** section. From the **Parameter selection (V_g)** list, choose **All**.
- 4 From the **Parameter selection (V_dr)** list, choose **From list**.
- 5 In the **Parameter values (V_dr (V))** list box, select **-0.1**.

Global I

- 1 In the **Model Builder** window, expand the **I_dr-V_g** node, then click **Global I**.
- 2 In the **Settings** window for **Global**, locate the **x-Axis Data** section.
- 3 From the **Axis source data** list, choose **V_g**.
- 4 In the **Expression** text field, type -V_g.
- 5 In the **Description** text field, type -Gate voltage.
- 6 In the **I_dr-V_g** toolbar, click  **Plot**.