Created in COMSOL Multiphysics 5.6

Electrodeposition on a Resistive Patterned Wafer

Introduction

This example models a cupplater reactor, where copper is electrodeposited on a patterned silicon wafer. It is also demonstrated how to make the deposited layer more uniform by the use of a current thief.

The deposition reaction occurs on a seed layer on an otherwise insulating wafer, with the effect that all current going into the metal layer is transported tangentially along the surface. As the deposition process progresses, and more metal is added to the surface, the tangential conductivity of the layer increases.

To cope with the very different geometric scales of the metal layer (tens of micrometers) and the electrolyte chamber (millimeters), which would otherwise pose problems in regard to mesh quality and problem size, the current conduction in the wafer metal layer is modeled using the Electrode, Shell interface, which uses a boundary formulation for the metal current conduction.

The model qualitatively reproduces the results of Purcar and others (Ref. 1).

Model Definition

The geometry is shown in Figure 1 and consists of one electrolyte domain. The top boundary is the anode. The bottom circular area represents the wafer surface, on top of which a metal seed layer has been deposited, followed by the application of a photoresist mask.

In the cell, the metal deposits on the patterned surface, which acts as cathode. The effect of the ring current thief is investigated by letting the surface be inactive as electrode in a first study, and then comparing the results to when letting also the current thief act as cathode. The area between the current thief and pattern is covered by a photoresist, and is inactive to the deposition reaction. A small edge segment of the current thief ring is used as current collector. The area outside the ring is insulating and does not conduct current in this model.

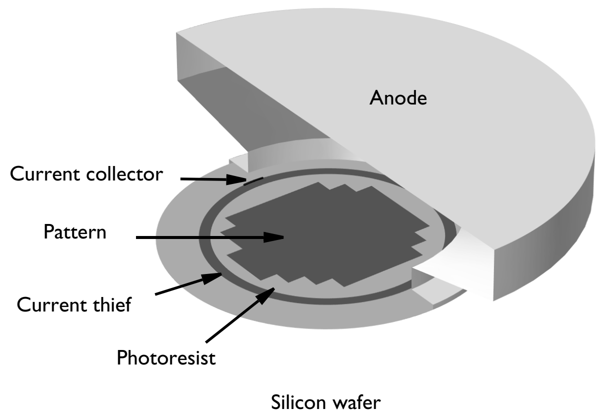

Figure 1: Model geometry.

The model is set up using two different interfaces: a Secondary Current Distribution interface, which solves for the electrolyte potential, ϕ_s , and the deposited concentration, c_{dep}, on the patterned wafer, and an Electrode, Shell interface, which solves for the electric potential on the metal layer on the wafer, $\phi_{s,wafer}$.

SECONDARY CURRENT DISTRIBUTION

The single domain is modeled as an Electrolyte domain. A constant conductivity of 20 S/m is used for the electrolyte.

The anode is assumed to a have a negligible polarization and an Electrolyte Current boundary condition, with a condition for the total current of 0.4 A, is used for the top boundary.

An Electrode Surface boundary node, with an added Dissolving-Depositing species, is used for the active cathode boundaries, with an electric potential for this electrode set to the electric potential of the Electrode, Shell interface. The kinetics are described by Butler-Volmer kinetics, and the thickness of the deposited layer is based on the molar mass and density of copper.

All other boundaries are isolated.

ELECTRODE SHELL

An Electrode boundary is used for the inactive parts of the surface, where only current conduction occurs. A constant conductivity value, $5.6 \cdot 10^7$ S/m, is used for all parts of the surface. On the inactive parts, the metal layer thickness is equal to the seed layer thickness, 0.1 µm.

For the active parts of the wafer surface, the cathode, a Depositing Electrode boundary node is used. Here, the metal layer thickness is set to the seed layer thickness plus the electrode thickness change (due to the cathode depositing reaction), which is coupled to the Electrode Surface node in the Secondary Current Distribution interface.

The electrode reactions also give rise to a current source on the cathode boundaries, these are also coupled to the Electrode Surface node in the Secondary Current Distribution interface.

The current collector edge is grounded, whereas all other edges are isolated.

STUDIES

The problem is solved using a Time-dependent with Initialization, Fixed Geometry study type, simulating the deposition process for 600 s.

By using a study type for a fixed geometry, the change in geometry, which is expected to be in the range of micrometers, is not included in the variables that are solved for by the solver.

Two studies are performed. In the first, Study 1, only the pattern is used as active electrode on the wafer. In Study 2 both the ring current thief and the wafer pattern is used as cathodes.

Discussion

Figure 2 shows the electrolyte potential at the end of the Study 1, without the current thief. The potential in the outer parts of the patterned area is almost 40 mV higher than in the central parts.

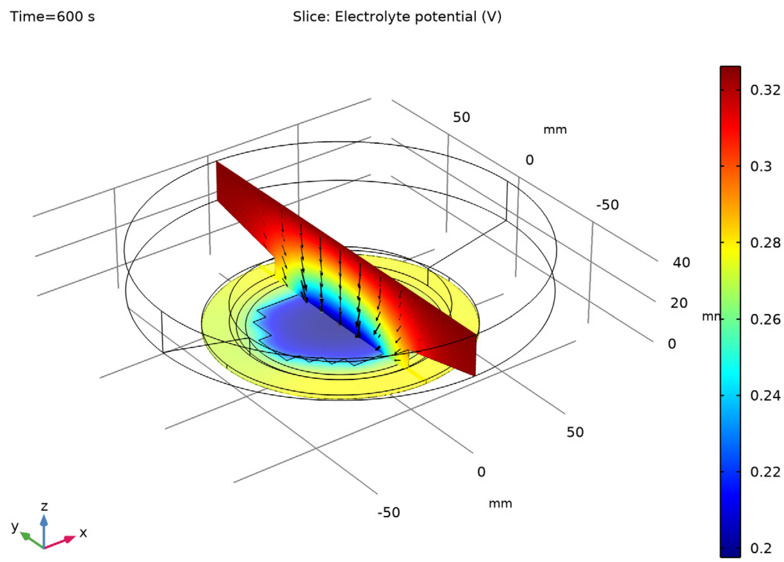

Figure 2: Electrolyte currents and potential at the end of the simulation without a current thief.

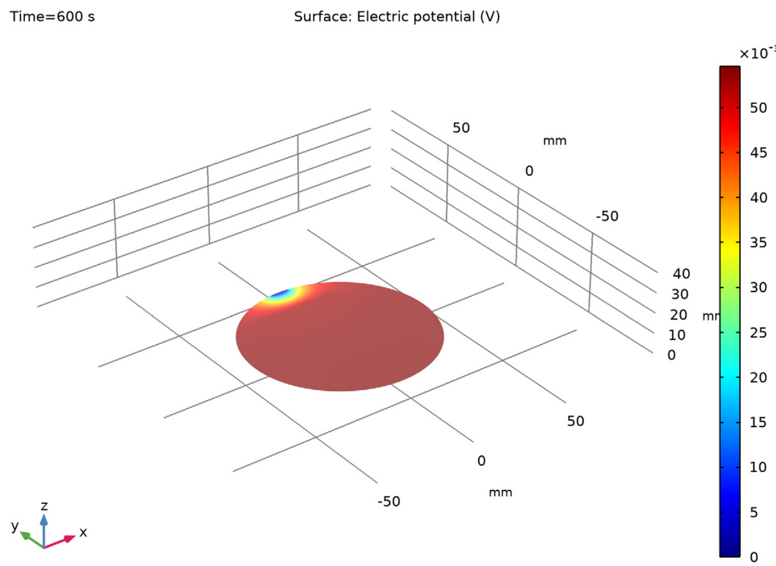

Figure 3: Electric potential in the copper layer at the end of the simulation without a current thief.

Figure 3 shows the potential in the metal on the wafer at the end of the Study 1. Close to the current collector there is a significant potential drop. The potential is however fairly uniform for the active part of the wafer.

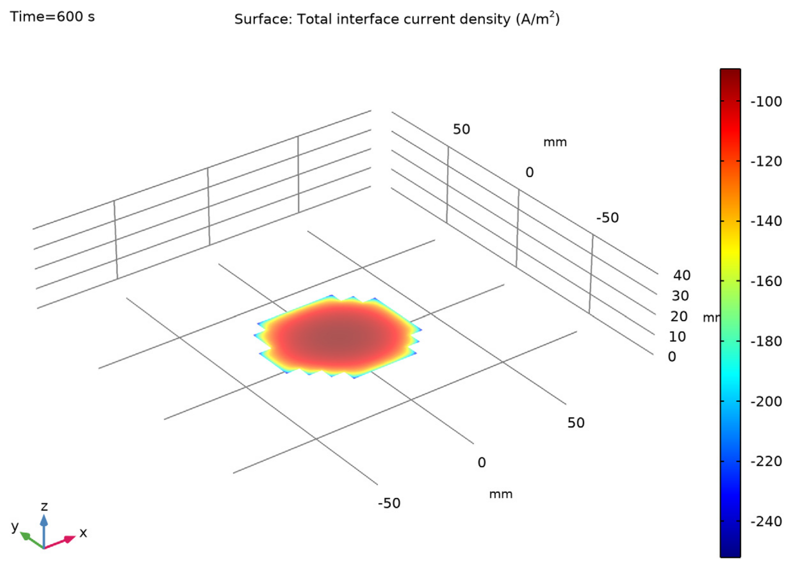

Figure 4: Electrode reaction current density at the end of the simulation without a current thief.

Figure 4 shows the electrode currents at the end of the Study 1. The reaction currents are significantly higher in the outer parts of the patterned area, especially in the corners. This is mainly an effect of the large differences in electrolyte potential seen in Figure 2.

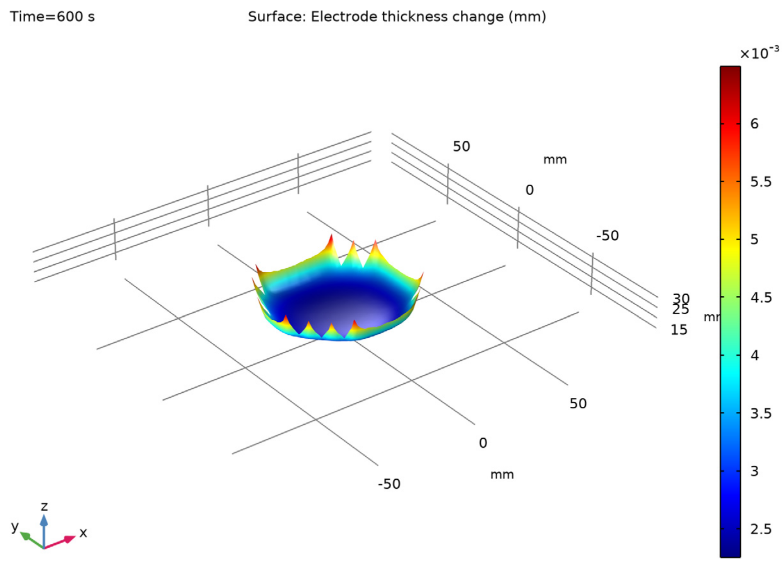

Figure 5: Deposited thickness at the end of the simulation without a current thief. The surface is deformed in the z direction according to the layer thickness.

Figure 5 shows the resulting electrode thickness change at the end of Study 1. As a result of the higher electrode currents seen in Figure 4, the deposited thickness is nonuniform with higher thickness toward the outer rim of the pattern.

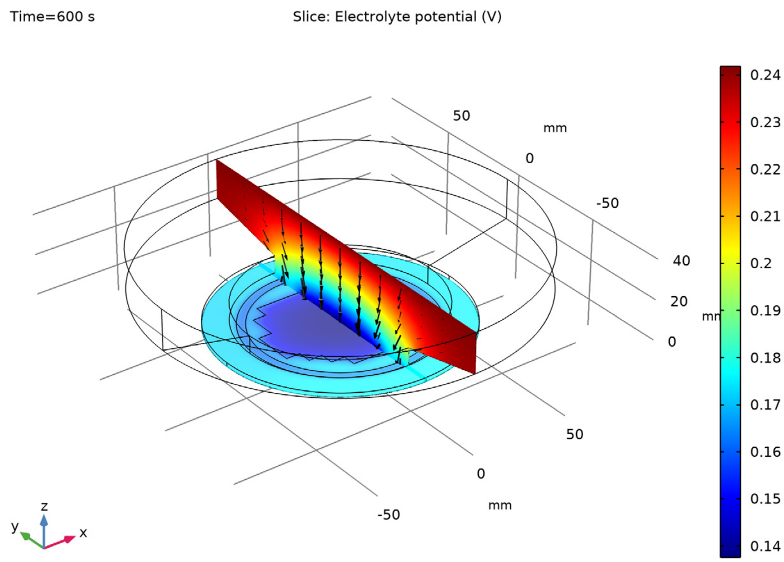

Figure 6: Electrolyte currents and potential at the end of the simulation with a current thief.

Figure 6 shows the electrolyte potential at the end of Study 2. Compared to Figure 2 the potential distribution is more uniform on the patterned surface.

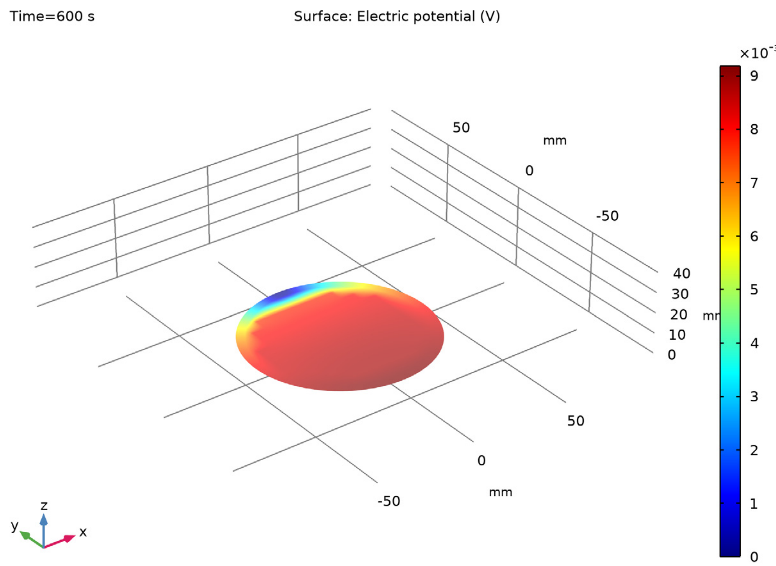

Figure 7: Electric potential in the copper layer at the end of the simulation with a current thief.

Figure 7 shows the electric potential distribution at the end of Study 2 when using a current thief. The deposit build-up results in less steeper potential gradients close to the current collector. The potential over the patterned area is still fairly uniform.

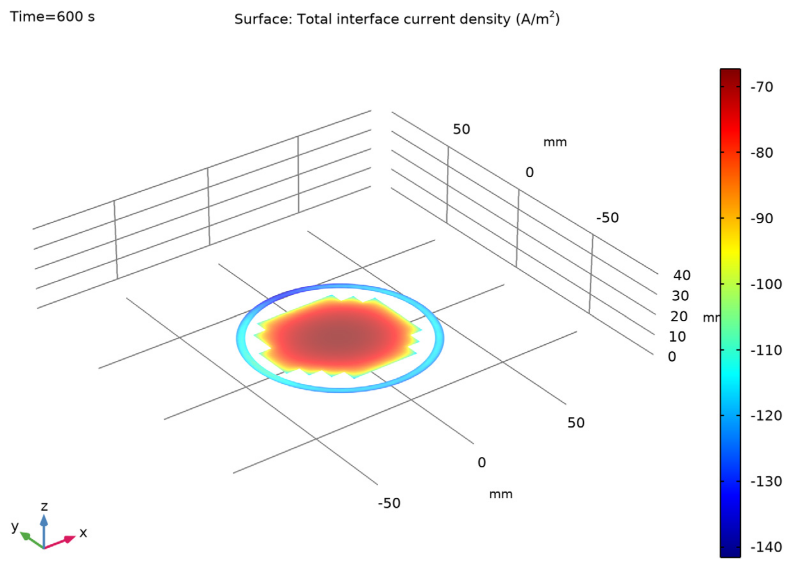

Figure 8: Electrode reaction current density at the end of the simulation with a current thief.

Figure 8 shows the electrode current distribution at the end of Study 2. Compared Figure 4 to the electrode currents are more uniform on the patterned wafer. It can also be seen that the electrode currents densities are higher on the current thief than on the pattern, with a maximum at the current collector.

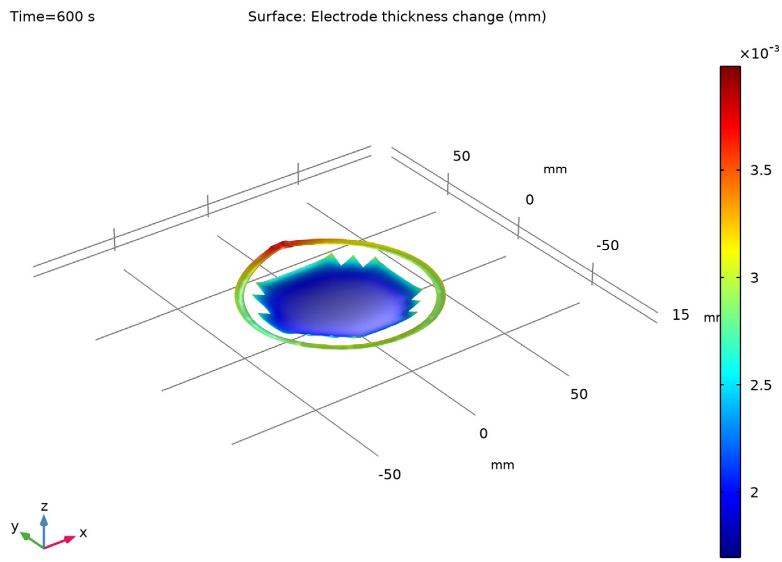

Figure 9: Deposited thickness at the end of the simulation without a current thief.

Figure 9 shows the deposited layer thickness at the end of Study 2. Compared to Figure 5 the deposited thickness is more uniform, all though the deposited thickness still is significantly higher in the corners of the pattern than in the central parts.

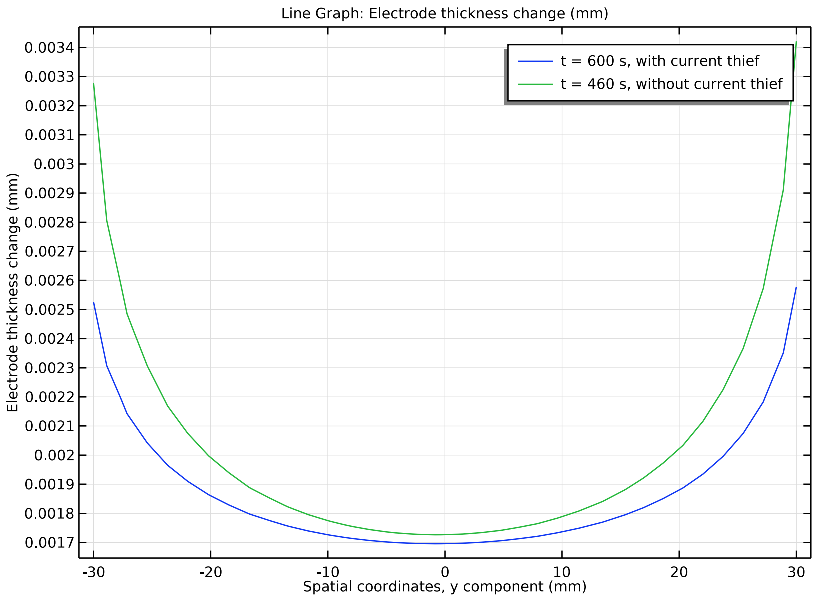

Figure 10: Comparison of deposited thicknesses, with current thief at t = 600 s, without current thief at t = 460 s.

Finally, the deposit uniformity effect of using a current thief is shown in Figure 10, where the deposit profile along the *y*-axis is compared for the two studies. The current thief results in a more uniform deposit, but also results in a longer deposition time due to the lower electrode current on the wafer pattern.

Reference

1. M. Purcar, B. Van den Bossche, L. Bortels, J. Deconninck, and G. Nelissen, "Three-Dimensional Current Density Distribution Simulations for a Resistive Patterned Wafer", *J. Electrochem.Soc.*, vol. 151, no. 9, pp. D78–D86, 2004.

Application Library path: `Electrodeposition_Module/Tutorials/resistive_wafer`

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 **3D**.

2 In the **Select Physics** tree, select **Electrochemistry>Primary and Secondary Current Distribution>Secondary Current Distribution (cd)**.

3 Click **Add**.

4 In the **Select Physics** tree, select **Electrochemistry>Electrode, Shell (els)**.

5 Click **Add**.

6 In the **Electric potential** text field, type `phis_wafer`.

7 Click **Study**.

8 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Secondary Current Distribution>Time Dependent with Initialization**.

9 Click **Done**.

GEOMETRY 1

This model utilizes a premade geometry file for which the length unit is millimeters. The model geometry is available as a parameterized geometry sequence in a separate MPH-file. If you want to build it from scratch, follow the instructions in the section Appendix — Geometry Modeling Instructions. Otherwise load it from file with the following steps.

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

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

GLOBAL DEFINITIONS

Load the parameter values for this model from a text file.

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 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `resistive_wafer_parameters.txt`.

DEFINITIONS

Make selections in the geometry, to be used later when setting up the physics.

Wafer surface

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, locate the **Input Entities** section.

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

4 Select Boundaries 15–17 only.

5 Right-click **Explicit 1** and choose **Rename**.

6 In the **Rename Explicit** dialog box, type `Wafer surface` in the **New label** text field.

7 Click **OK**.

Cathode

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, locate the **Input Entities** section.

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

4 Select Boundary 17 only.

In the first study, use the patterned part of the wafer surface as the cathode. Later, you will add the outer ring as current thief.

5 Right-click **Explicit 2** and choose **Rename**.

6 In the **Rename Explicit** dialog box, type `Cathode` in the **New label** text field.

7 Click **OK**.

Anode

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, locate the **Input Entities** section.

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

4 Select Boundary 6 only.

5 Right-click **Explicit 3** and choose **Rename**.

6 In the **Rename Explicit** dialog box, type `Anode` in the **New label** text field.

7 Click **OK**.

SECONDARY CURRENT DISTRIBUTION (CD)

Electrolyte 1

Now start setting up the physics, beginning with the current distribution in the electrolyte.

1 In the **Settings** window for **Electrolyte**, locate the **Electrolyte** section.

2 From the σ_l list, choose **User defined**. In the associated text field, type `sigma`.

Electrolyte Current 1

In this model you do not model the anode reactions explicitly. Use a total current condition instead.

1 In the **Model Builder** window, right-click **Secondary Current Distribution (cd)** and choose **Electrolyte>Electrolyte Current**.

2 In the **Settings** window for **Electrolyte Current**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Anode**.

4 Locate the **Electrolyte Current** section. In the $I_{l,total}$ text field, type `I_cell`.

Electrode Surface 1

Use the Electrode Surface to model the wafer electrode reaction and the deposit growth.

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

2 In the **Settings** window for **Electrode Surface**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Cathode**.

The electric potential of the Electrode Surface is equal to phis_wafer, which is the potential solved for by the Electrode, Shell interface (which you will set up shortly).

4 Locate the **Electrode Phase Potential Condition** section. In the $\phi_{s,ext}$ text field, type `phis_wafer`.

5 Click to expand the **Dissolving-Depositing Species** section. Click + **Add**.

6 In the table, enter the following settings:

Species	Density (kg/m^3)	Molar mass (kg/mol)
s1	rho	M

Electrode Reaction 1

1 In the **Model Builder** window, expand the **Electrode Surface 1** node, then click **Electrode Reaction 1**.

2 In the **Settings** window for **Electrode Reaction**, locate the **Stoichiometric Coefficients** section.

3. In the n text field, type `2`.
4. In the **Stoichiometric coefficients for dissolving-depositing species:** table, enter the following settings:

Species	Stoichiometric coefficient (1)
s1	1

5. Locate the **Equilibrium Potential** section. In the E_{eq} text field, type `Eeq_cathode`.
6. Locate the **Electrode Kinetics** section. From the **Kinetics expression type** list, choose **Butler-Volmer**.
7. In the i_0 text field, type `i0_cathode`.
8. In the α_{a} text field, type `alpha_a`.
9. In the α_{c} text field, type `alpha_c`.

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 *phil* text field, type `-Eeq_cathode`.

ELECTRODE, SHELL (ELS)

Now set up the Electrode, Shell interface, which models the electric currents in the thin copper layer on the wafer.

1. In the **Model Builder** window, under **Component 1 (comp1)** click **Electrode, Shell (els)**.
2. In the **Settings** window for **Electrode, Shell**, locate the **Boundary Selection** section.
3. From the **Selection** list, choose **Wafer surface**.

Depositing Electrode 1

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

   The Depositing Electrode is coupled to the Secondary Current Distribution interface via the thickness of the electrode and the electrode currents.
2. In the **Settings** window for **Depositing Electrode**, locate the **Boundary Selection** section.
3. From the **Selection** list, choose **Cathode**.
4. Locate the **Depositing Electrode** section. In the s_0 text field, type `s_init`.
5. From the Δs list, choose **Total electrode thickness change (cd/es1)**.
6. From the σ list, choose **User defined**. In the associated text field, type `W`.

7 Locate the **Electrode Current Density** section. From the i_n list, choose **Local current density, Electrode Reaction 1 (cd/es1/er1)**.

Electrode 1

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

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

3 In the s text field, type `s_init`.

4 From the σ list, choose **User defined**. In the associated text field, type `w`.

Ground 1

1 In the **Physics** toolbar, click **Edges** and choose **Ground**.

2 Select Edge 34 only.

GLOBAL DEFINITIONS

Default Model Inputs

Set up the temperature value used in the entire model.

1 In the **Model Builder** window, under **Global Definitions** click **Default Model Inputs**.

2 In the **Settings** window for **Default Model Inputs**, locate the **Browse Model Inputs** section.

3 In the tree, select **General>Temperature (K) - minput.T**.

4 Find the **Expression for remaining selection** subsection. In the **Temperature** text field, type `T`.

MESH 1

Edit the default mesh to make the mesh finer in the domain and on the wafer surface.

Size

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

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

3 From the **Predefined** list, choose **Finer**.

Size 1

1 In the **Model Builder** window, right-click **Free Tetrahedral 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 From the **Selection** list, choose **Wafer surface**.

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 `2[mm]`.

8 In the **Model Builder** window, right-click **Mesh 1** and choose **Build All**.

STUDY 1

The problem is now ready for solving. Use the secondary current distribution initialization and set the time range. Modify the default solver sequence to use the fully coupled solver.

Solution 1 (sol1)

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

Step 1: Current Distribution Initialization

1 In the **Model Builder** window, click **Step 1: Current Distribution Initialization**.

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

3 From the **Current distribution type** list, choose **Secondary**.

Step 2: Time Dependent

1 In the **Model Builder** window, click **Step 2: Time Dependent**.

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

3 In the **Output times** text field, type `range(0,20,600)`.

Solution 1 (sol1)

1 In the **Model Builder** window, expand the **Solution 1 (sol1)** node.

2 In the **Model Builder** window, expand the **Study 1>Solver Configurations>Solution 1 (sol1)>Stationary Solver 1** node.

3 Right-click **Stationary Solver 1** and choose **Fully Coupled**.

4 In the **Model Builder** window, expand the **Study 1>Solver Configurations>Solution 1 (sol1)>Time-Dependent Solver 1** node.

5 Right-click **Time-Dependent Solver 1** and choose **Fully Coupled**.

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

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

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

RESULTS

Reproduce Figure 2 through Figure 5 by following the instructions below.

3D Plot Group 1

In the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.

Slice 1

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

The electrolyte potential is the default plot variable. Keep it for this slice plot.

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

3 In the **Planes** text field, type 1.

4 In the **3D Plot Group 1** toolbar, click **Plot**.

Arrow Volume 1

1 In the **Model Builder** window, right-click **3D Plot Group 1** and choose **Arrow Volume**.

2 In the **Settings** window for **Arrow Volume**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Secondary Current Distribution>cd.Ilx,...,cd.Ilz - Electrolyte current density vector**.

3 Click to expand the **Title** section. From the **Title type** list, choose **None**.

4 Locate the **Arrow Positioning** section. Find the **X grid points** subsection. In the **Points** text field, type 1.

5 Find the **Y grid points** subsection. In the **Points** text field, type 13.

6 Locate the **Coloring and Style** section. From the **Color** list, choose **Black**.

Slice 2

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

2 In the **Settings** window for **Slice**, click to expand the **Title** section.

3 From the **Title type** list, choose **None**.

4 Locate the **Plane Data** section. From the **Plane** list, choose **XY-planes**.

5 From the **Entry method** list, choose **Coordinates**.

6 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Slice 1**.

7 In the **3D Plot Group 1** toolbar, click **Plot**.

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

Study 1/Solution 1 (3) (sol1)

1 In the **Model Builder** window, expand the **Results>Datasets** node.

2 Right-click **Results>Datasets>Study 1/Solution 1 (sol1)** and choose **Duplicate**.

Selection

1 In the **Results** toolbar, click **Attributes** and choose **Selection**.

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

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

4 From the **Selection** list, choose **Wafer surface**.

3D Plot Group 2

1 In the **Results** toolbar, click **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, locate the **Plot Settings** section.

3 Clear the **Plot dataset edges** check box.

Surface 1

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

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Electrode, Shell> ElectricGroup>phis_wafer - Electric potential - V**.

3 In the **3D Plot Group 2** toolbar, click **Plot**.

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

3D Plot Group 3

In the **Model Builder** window, under **Results** right-click **3D Plot Group 2** and choose **Duplicate**.

Surface 1

1 In the **Model Builder** window, expand the **3D Plot Group 3** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)> Secondary Current Distribution>Electrode kinetics>cd.itot - Total interface current density - A/m²**.

3 In the **3D Plot Group 3** toolbar, click **Plot**.

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

3D Plot Group 4

In the **Model Builder** window, under **Results** right-click **3D Plot Group 3** and choose **Duplicate**.

Surface 1

1 In the **Model Builder** window, expand the **3D Plot Group 4** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Electrode, Shell> MaterialPropsGroup>els.deltas - Electrode thickness change - m**.

3 In the **3D Plot Group 4** toolbar, click **Plot**.

Deformation 1

1 Right-click **Surface 1** and choose **Deformation**.

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

3 In the **Z component** text field, type `els.deltas`.

4 Locate the **Scale** section. Select the **Scale factor** check box.

5 In the associated text field, type `5000`.

6 In the **3D Plot Group 4** toolbar, click **Plot**.

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

STUDY 1

Solution 1 (sol1)

Now modify the problem to use the ring on the wafer as current thief. First store the current solution to be able to compare the results later.

1 In the **Model Builder** window, under **Study 1>Solver Configurations** right-click **Solution 1 (sol1)** and choose **Solution>Copy**.

DEFINITIONS

Cathode

1 In the **Model Builder** window, under **Component 1 (comp1)>Definitions>Selections** click **Cathode**.

2 Select Boundaries 15 and 17 only.

STUDY 1

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

RESULTS

The following creates a plot for comparing the deposited thicknesses between the two studies.

Cut Line 3D 1

1 In the **Results** toolbar, click **Cut Line 3D**.

2 In the **Settings** window for **Cut Line 3D**, locate the **Line Data** section.

3 In row **Point 1**, set **Y** to `-30`.

4 In row **Point 2**, set **Y** to `30`.

5 Select the **Snap to closest boundary** check box.

Cut Line 3D 2

1 Right-click **Cut Line 3D 1** and choose **Duplicate**.

2 In the **Settings** window for **Cut Line 3D**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 1/Solution 1 - Copy 1 (sol3)**.

1D Plot Group 5

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

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

3 From the **Dataset** list, choose **Cut Line 3D 1**.

Line Graph 1

1 Right-click **1D Plot Group 5** and choose **Line Graph**.

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

3 From the **Dataset** list, choose **Cut Line 3D 1**.

4 From the **Time selection** list, choose **From list**.

5 In the **Times (s)** list, select **600**.

6 Locate the **y-Axis Data** section. In the **Expression** text field, type `els.deltas`.

7 Click to expand the **Legends** section. Select the **Show legends** check box.

8 From the **Legends** list, choose **Manual**.

9 In the table, enter the following settings:

Legends
`t = 600 s, with current thief`

10 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

11 In the **Expression** text field, type `y`.

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

Line Graph 2

1 Right-click **Line Graph 1** and choose **Duplicate**.

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

3 From the **Dataset** list, choose **Cut Line 3D 2**.

4 In the **Times (s)** list, select **460**.

5 Click to expand the **Title** section. From the **Title type** list, choose **None**.

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

Legends
`t = 460 s, without current thief`

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

Appendix — Geometry Modeling Instructions

From the **File** menu, choose **New**.

NEW

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

ADD COMPONENT

In the **Home** toolbar, click **Add Component** and choose **3D**.

GEOMETRY 1

1 In the **Settings** window for **Geometry**, locate the **Units** section.

2 From the **Length unit** list, choose **mm**.

Cylinder 1 (cyl1)

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

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

3 In the **Radius** text field, type `60`.

4 In the **Height** text field, type `2`.

Cylinder 2 (cyl2)

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

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

3 In the **Radius** text field, type `48`.

4 In the **Height** text field, type `8.808`.

5 Locate the **Position** section. In the **z** text field, type `2`.

Cone 1 (cone1)

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

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

3 In the **Bottom radius** text field, type `48`.

4 In the **Height** text field, type `9.192`.

5 In the **Top radius** text field, type `92`.

6 Locate the **Position** section. In the **z** text field, type `10.808`.

Cylinder 3 (cyl3)

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

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

3 In the **Radius** text field, type `92`.

4 In the **Height** text field, type `20`.

5 Locate the **Position** section. In the **z** text field, type `20`.

Wafer surface

1 In the **Geometry** toolbar, click **Work Plane**.

2 In the **Settings** window for **Work Plane**, type `Wafer surface` in the **Label** text field.

3 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** check box.

Wafer surface (wp1)>Plane Geometry

In the **Model Builder** window, click **Plane Geometry**.

Wafer surface (wp1)>Circle 1 (c1)

1 In the **Work Plane** toolbar, click **Circle**.

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

3 In the **Radius** text field, type `45`.

Wafer surface (wp1)>Rectangle 1 (r1)

1 In the **Work Plane** toolbar, click **Rectangle**.

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

3 In the **Width** text field, type `7.844`.

4 Locate the **Object Type** section. From the **Type** list, choose **Curve**.

5 Locate the **Position** section. In the **yw** text field, type `45`.

6 From the **Base** list, choose **Center**.

Wafer surface (wp1)>Partition Edges 1 (pare1)

1 In the **Work Plane** toolbar, click **Booleans and Partitions** and choose **Partition Edges**.

2 On the object **c1**, select Boundaries 3 and 4 only.

3 In the **Settings** window for **Partition Edges**, locate the **Positions** section.

4 From the **Type of specification** list, choose **Vertex projection**.

5 On the object **r1**, select Points 3 and 4 only.

6 In the tree, select **r1**.

7 Click **Build Selected**.

Wafer surface (wp1)>Delete Entities 1 (del1)

1 In the **Work Plane** toolbar, click **Delete**.

2 In the **Settings** window for **Delete Entities**, locate the **Entities or Objects to Delete** section.

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

4 Select the object **r1** only.

Wafer surface (wp1)>Circle 2 (c2)

1 In the **Work Plane** toolbar, click **Circle**.

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

3 In the **Radius** text field, type `41`.

4 Click the **Select Points** button in the **Graphics** toolbar.

Wafer surface (wp1)>Rectangle 2 (r2)

1 In the **Work Plane** toolbar, click **Rectangle**.

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

3 In the **Width** text field, type `6.8`.

4 In the **Height** text field, type `20.4`.

5 Locate the **Position** section. In the **xw** text field, type `-36.04`.

6 In the **yw** text field, type `-10.2`.

7 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. Click **New**.

8 In the **New Cumulative Selection** dialog box, type `Wafer` in the **Name** text field.

9 Click **OK**.

Wafer surface (wp1)>Rectangle 3 (r3)

1 In the **Work Plane** toolbar, click **Rectangle**.

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

3 In the **Width** text field, type `54.4`.

4 In the **Height** text field, type `40.8`.

5 Locate the **Position** section. In the **xw** text field, type `-29.24`.

6 In the **yw** text field, type `-17`.

7 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. From the **Contribute to** list, choose **Wafer**.

Wafer surface (wp1)>Rectangle 4 (r4)

1 In the **Work Plane** toolbar, click **Rectangle**.

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

3 In the **Width** text field, type `40.8`.

4 In the **Height** text field, type `6.8`.

5 Locate the **Position** section. In the **xw** text field, type `-22.44`.

6 In the **yw** text field, type `23.8`.

7 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. From the **Contribute to** list, choose **Wafer**.

Wafer surface (wp1)>Rectangle 5 (r5)

1 In the **Work Plane** toolbar, click **Rectangle**.

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

3 In the **Width** text field, type `6.8`.

4 In the **Height** text field, type `34`.

5 Locate the **Position** section. In the **xw** text field, type `25.16`.

6 In the **yw** text field, type `-17`.

7 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. From the **Contribute to** list, choose **Wafer**.

Wafer surface (wp1)>Rectangle 6 (r6)

1 In the **Work Plane** toolbar, click **Rectangle**.

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

3 In the **Width** text field, type `47.6`.

4 In the **Height** text field, type `6.8`.

5 Locate the **Position** section. In the **xw** text field, type `-22.44`.

6 In the **yw** text field, type `-23.8`.

7 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. From the **Contribute to** list, choose **Wafer**.

Wafer surface (wp1)>Rectangle 7 (r7)

1 In the **Work Plane** toolbar, click **Rectangle**.

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

3 In the **Width** text field, type `34`.

4 In the **Height** text field, type `6.8`.

5 Locate the **Position** section. In the **xw** text field, type `-15.64`.

6 In the **yw** text field, type `-30.6`.

7 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. From the **Contribute to** list, choose **Wafer**.

Wafer surface (wp1)>Union 1 (uni1)

1 In the **Work Plane** toolbar, click **Booleans and Partitions** and choose **Union**.

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

3 From the **Input objects** list, choose **Wafer**.

4 Clear the **Keep interior boundaries** check box.

Ignore Vertices 1 (igv1)

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Virtual Operations>Ignore Vertices**.

2 On the object **fin**, select Point 31 only.

Anode

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Anode` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 On the object **igv1**, select Boundary 6 only.

Cathode

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Cathode` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 Click the **Wireframe Rendering** button in the **Graphics** toolbar.

5 On the object **igv1**, select Boundaries 15 and 17 only.