COMSOL Multiphysics: simulation of a pinned photodiode

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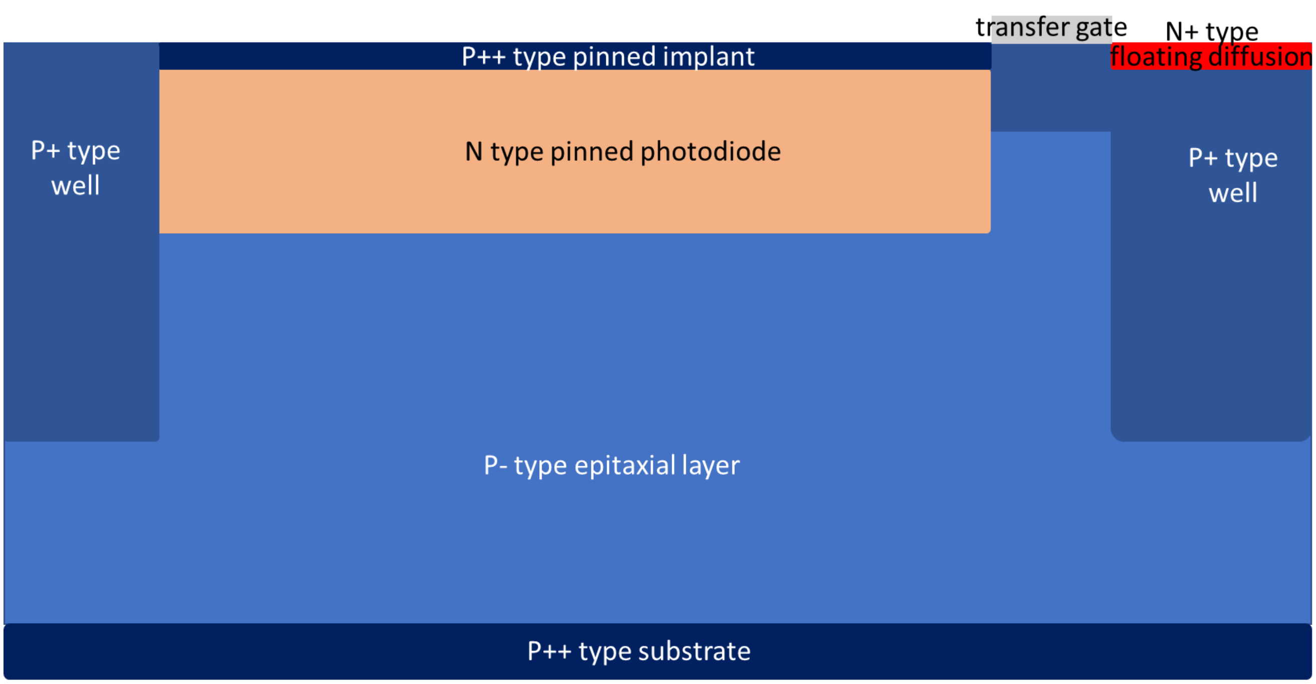
The pinned photodiode (not to be confused with the P-I-N photodiode) is the mostly adopted photodetector within modern digital cameras. We can estimate approximately at least 10^{14} of such photodetectors are operating every day in the world on mobile phones, digital still cameras, video cameras… You will study its working principle in detail in the next classes, but today we have a first glimpse at its structure.

The core concept of this device is to decouple the functions of (i) photons collection and (ii) electrons integration, which in a conventional PN photodiode are performed by the same structure, the junction itself. On the contrary, in a pinned photodiode the region where charge is gathered during exposure to photons (indicated as N-type pinned region below) does not correspond to the capacitance on which direct integration is performed (indicated as floating diffusion below).

The correct operation of such a structure is critically dependent on the right doping choices, which makes the design (and the simulation convergence) quite challenging.

Try designing the structure yourself and simulate it with the given voltages. Below a few hints on how to proceed.



Introduction

Begin by opening Comsol multiphysics. Choose a 2D model, then choose *Semiconductor* as the *Physics* to solve. Once this physics is added, choose the simulation study: select *Stationary*. Click on *Done*, and the main Comsol interface will open.

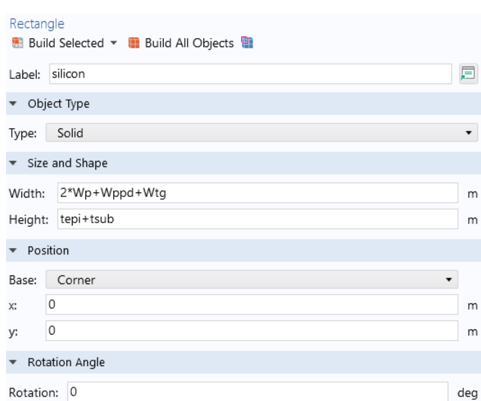
Like in the former CAD class, in order to simulate this structure, we rely on a symmetric 2D simulation in such a way that the left and right boundary conditions can be conditions of continuity (i.e. Neumann conditions, where we set that the derivative of our variables has a fixed value, in this case null. Indeed, a null derivative means a continuity of the solution at the boundaries).

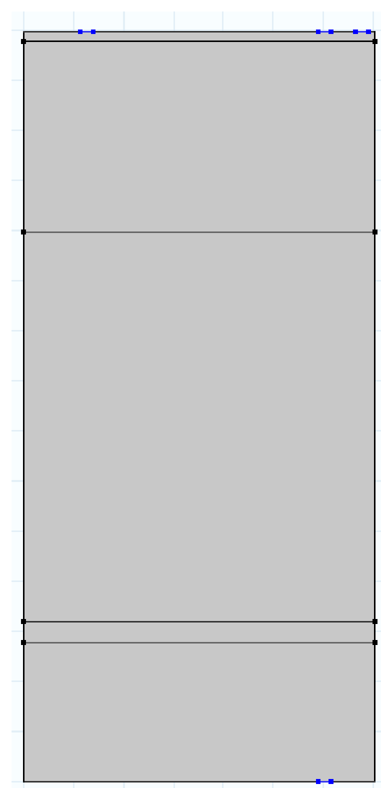
Name	Expression	Value	Description
Wp	500e-9	5E-7	width of the deep P well
Wppd	5e-6	5E-6	width of the pinned photodiode
Wtg	1e-6	1E-6	width of the transfer gate
tepi	12e-6	1.2E-5	thickness of the epitaxy
tsub	3e-6	3E-6	thickness of the substrate
timp	200e-9	2E-7	thickness of the thin implants
tppd	1.5e-6	1.5E-6	thickness of the pinned photodiode
tp	2e-6	2E-6	thickness of the p-type region under the gate
Wcont	250e-9	2.5E-7	width of the contacts
tox	10e-9	1E-8	oxide thickness
e_ox	4	4	oxide relative permittivity
V_fd	3	3	voltage at the floating diffusion

The set of parameters that we define to assist our design is also shown in the Table above, with an obvious meaning for almost all of them when compared to the structure design.

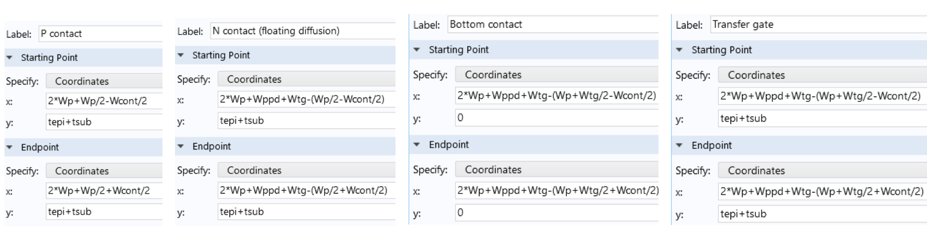
1. Structure design

The simulation starts by designing a rectangle corresponding to the structure above. As usual, doping profiles will be added later, so that we do not have to care about them now.



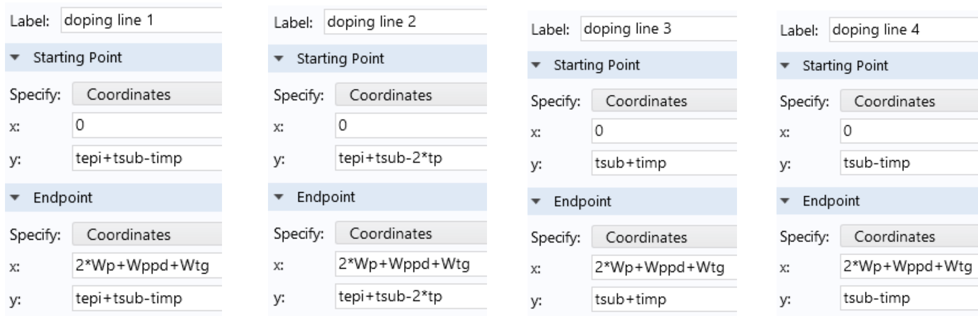


The definition of the contacts follows the steps below.



Note that we do not include the gate oxide, as this can be simplified later adding a specific type of boundary conditions for the electrode associated to the gate (see below).

Note also that we add a few lines in our geometry, which will help in optimizing the mesh.

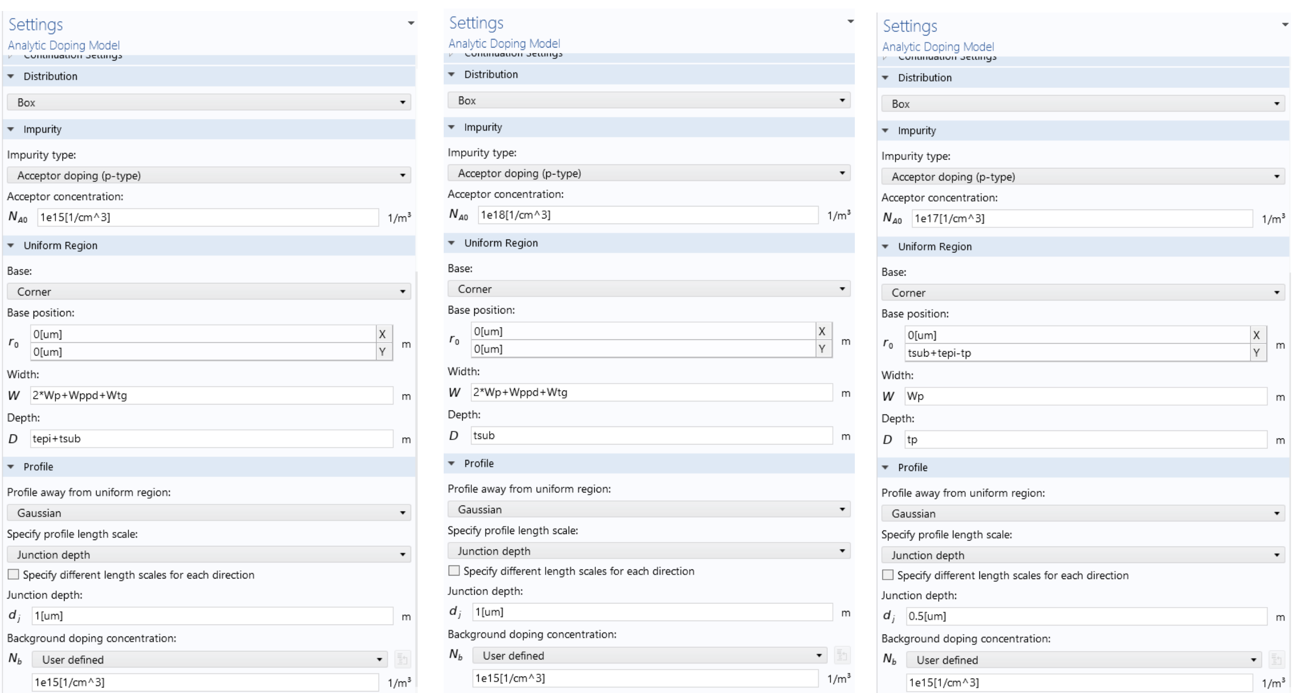


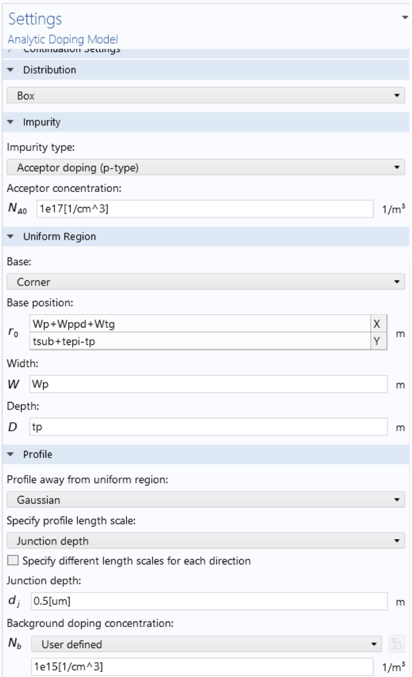
2. Materials and Boundary Settings

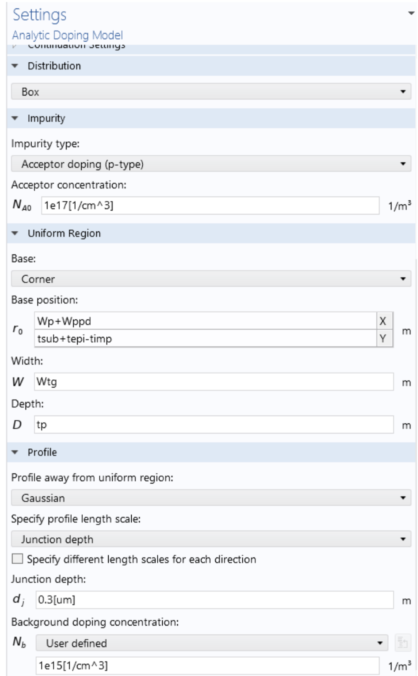
You can set silicon as the material of the entire rectangle.

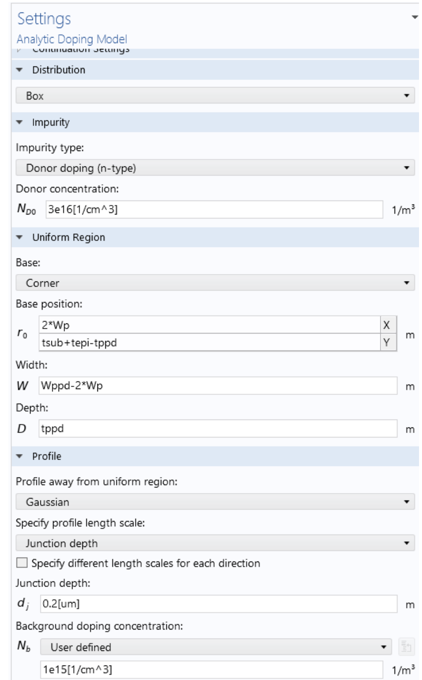
For what concerns boundary conditions, you have to input:

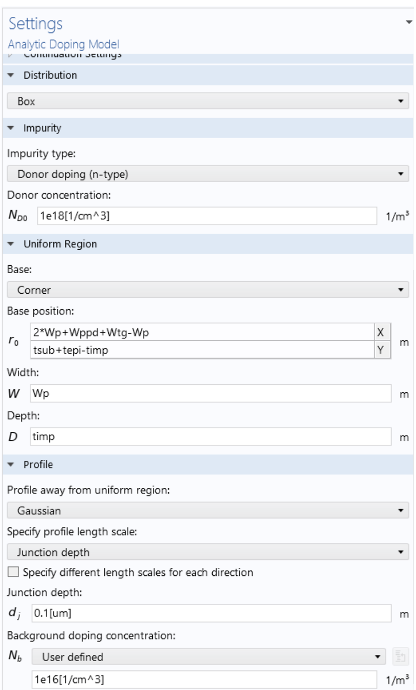
- all (8!) doping profiles
- 2 voltages at the metal contacts
- 1 thin insulator condition at the transfer gate (note: this avoids the need for designing the gate oxide)

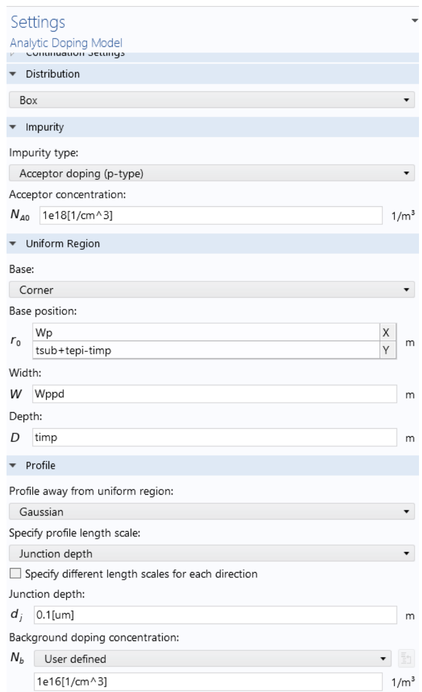


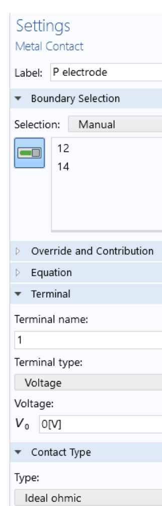


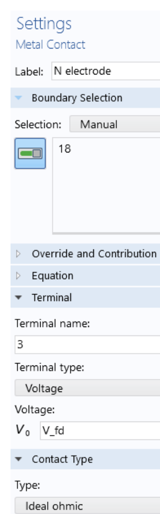


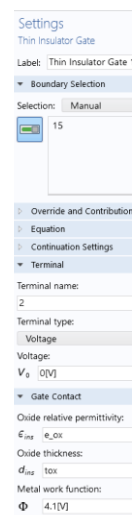






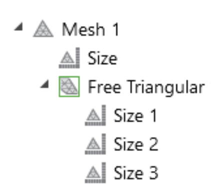


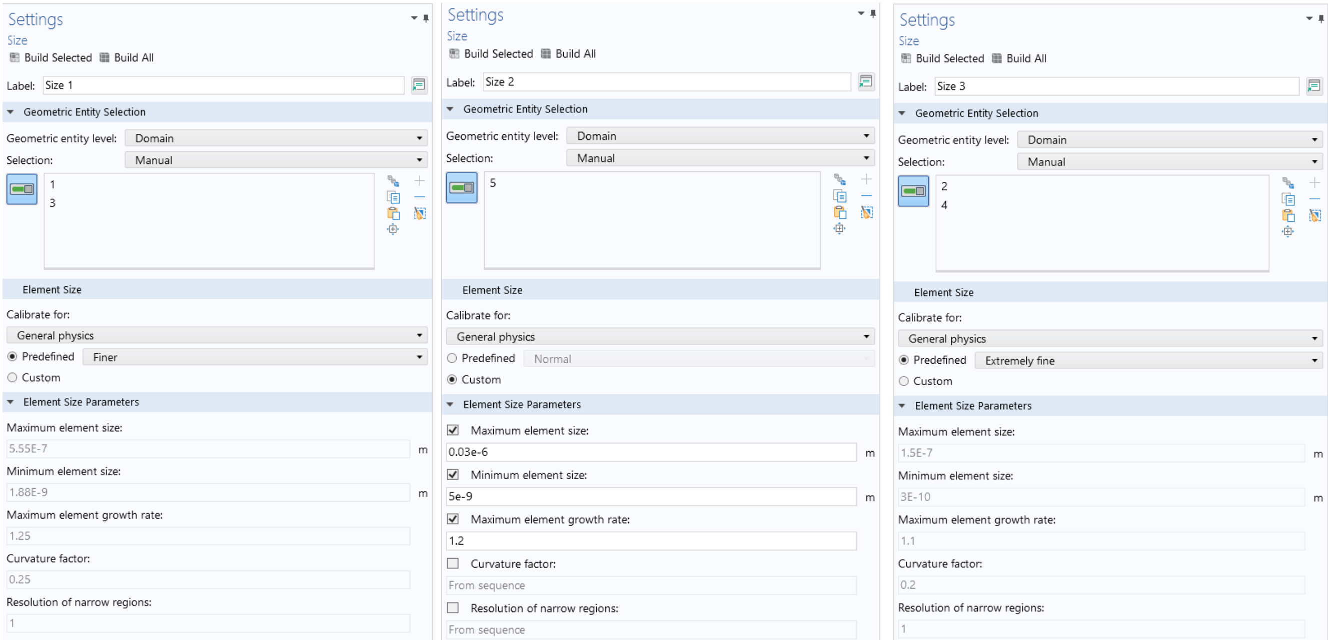




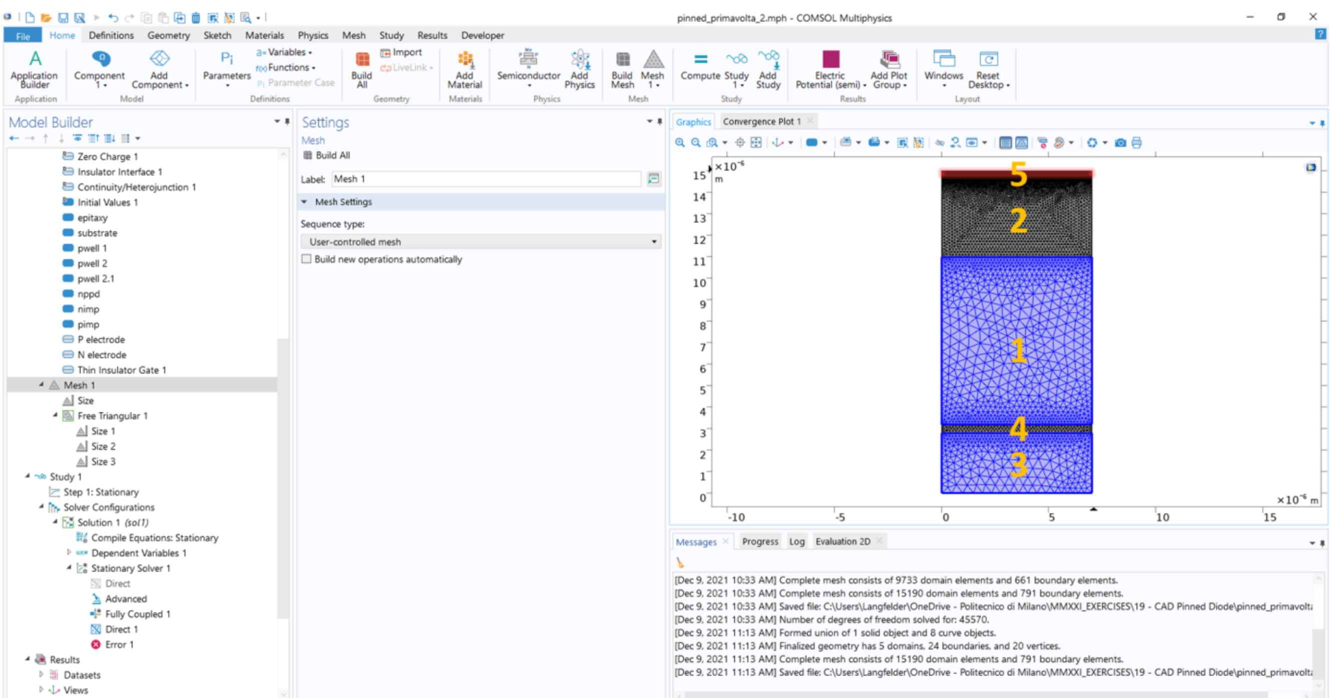
3. Mesh

In order to optimize the mesh around the regions where we expect the largest doping and electric field gradients, we have split the geometry through lines in the former geometrical definitions. As a consequence, you can now use a free triangular meshing, with three different meshing regions. Below is an example of a good mesh distribution.



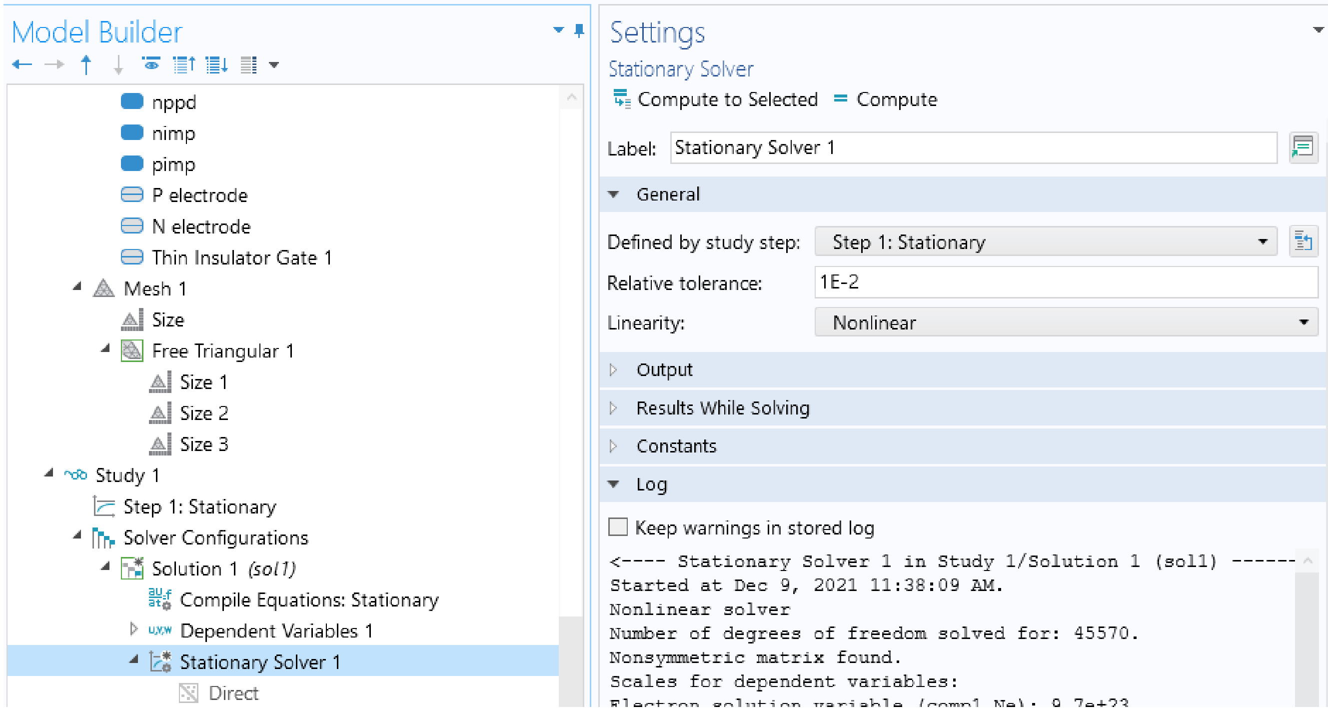


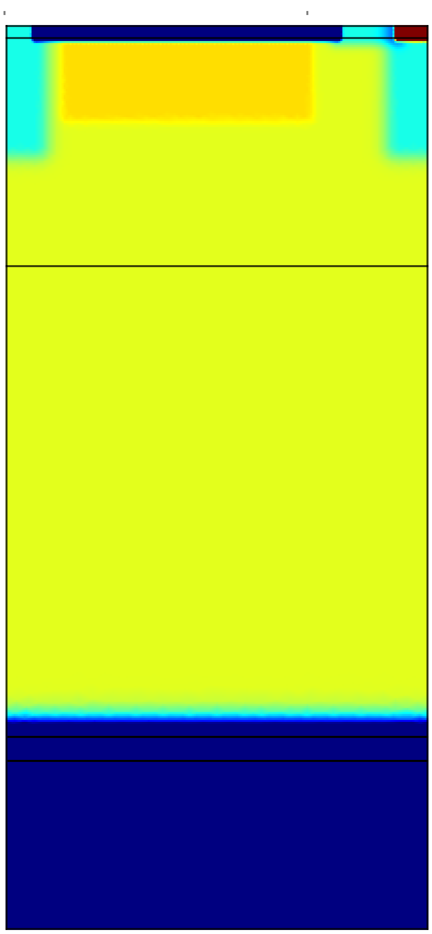
The resulting mesh is shown below, with colors separating the differently meshed regions, and the names of the "Size X" regions indicated in the boxes above.



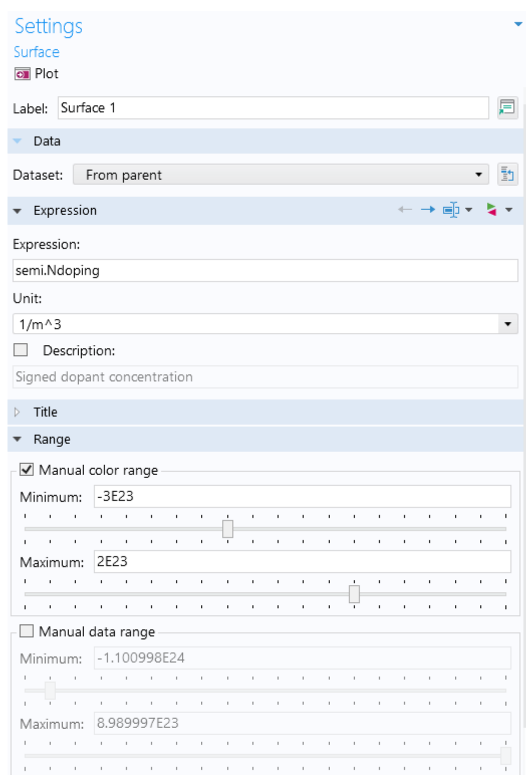
4. Study and results

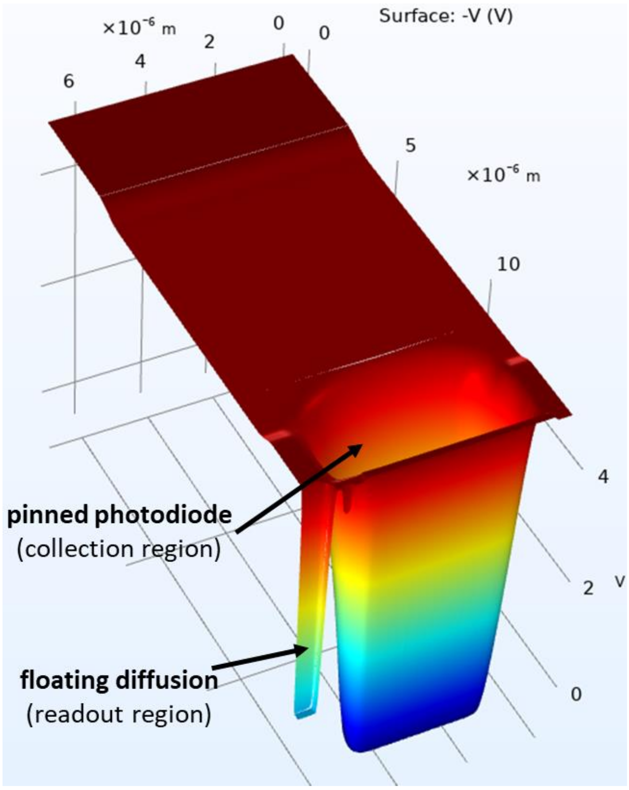
Set the stationary solver options as indicated below. Right click on *Study* and click on *Compute*. Regardless of the solution convergence, we can have a first look at the correctness of the doping profiles. This is independent of the actual solution, which computes electron and hole concentration, and voltages, but no the native doping values which are a boundary condition.





In order to properly visualize the results, it is better to adapt the color scale (set manual color range) as in the image below. On the left, you see the various doping regions that we have effectively added.





The study may or may not converge on your computer, depending mostly on doping profile and mesh implementation, on simulation settings, and on computer capabilities… Regardless of the convergence or not, you still may be able to see a decent solution (even if the convergence does not reach the expected target).

Qualitatively, you will be able to see an energy band graph as shown below (see also the plot settings, and enable Height Expression). We note two points, which you will deepen in future lectures: (i) the energy hole for electrons (where photogenerated carriers are gathered) is clearly visible. However, unlike for simple PN junctions, this hole is not in contact with the surface, avoiding the collection of dark electrons generated by impurities close to the surface, thus reducing the dark current; (ii) a second small valley for electrons is visible close to the left surface corner in the image. When activating the transfer gate, which essentially behaves like a transistor, you will be able to transfer all electrons gathered inside the pinned photodiode into the floating diffusion, thus separating the region of collection from the integration capacitance.