Modeling PIN Photodiodes

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Abstract: This paper presents one approach to the modeling of an abrupt junction PIN photo-diode light sensor using COMSOL Multi-physics® software and the incorporated SPICE® capability. The current model is built using the capabilities of SPICE in COMSOL Multiphysics 4.0a. This model demonstrates the use of SPICE and the AC/DC Module to build a conduction current, rather than an electrostatic, model. This model is based on my earlier semiconductor modeling work using the COMSOL Multi-physics 3.X series software.

Keywords: PIN, Diode, SPICE, AC/DC, conduction current.

1. Introduction

Semiconductor device physics is complex, even under the best of circumstances. Multiphysics modeling of semiconductor device structures require that careful attention be paid to the specific details of those models in the areas of physics, mathematics and geometry. This PIN Diode model is a fundamentally simple model in the area of geometrical details. It is, however, somewhat more complex in the areas of physics and mathematics. This model is just somewhat complex in the detailed methodology used to implement the sequence of convergence in the Multiphysics and SPICE portions. The conceptual basis of this model derives from the semiconductor diode model [1] shipped with COMSOL Multiphysics 3.5a.

This multiphysics model has been built as a 2D approximation to what would normally be a 3D device, to ease calculation difficulties and facilitate more rapid convergence.

2. PIN Diode Model Overview

The initial PIN Diode model, without SPICE, as shown in the first Model Builder chart in Figure 1, approximates a silicon chip that has a 10μm footprint and a 7μm thickness. The lower portion of the chip (10μm by 10μm) has an enhanced N dopant level (cathode). The upper portion of the chip has a 2μm deep, P doped region (anode) with rounded corners, as is shown in the solution in Figure 2. The interfaces between the various doping regions, P-I-N, are lightly graded, as is standard practice (see Table 1 in the appendix) and is used herein to ease convergence calculations.

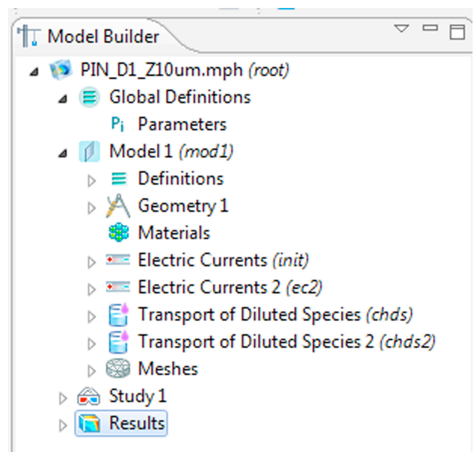

Figure 1. PIN Diode Model Builder

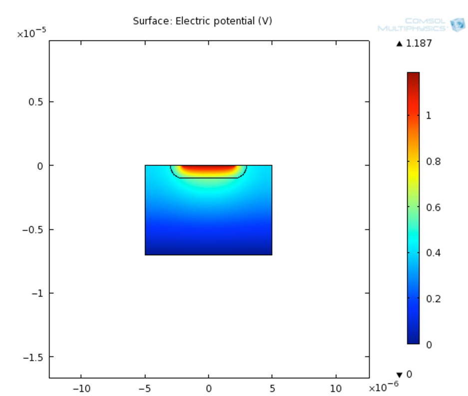

Figure 2. PIN Diode Solution

Figure 3, below, shows the geometrical configuration of the cross-section view of the semiconductor diode chip. Please note that two points have been added in the anode area to define the extent of the electrical contact on the upper anode surface. The anode contact on the upper surface does not extend to the boundary of the anode doping (P) volume. The electrical contact (Va applied voltage) extends between the two points. The remainder of the periphery, outside the anode electrical contact, is insulated, except for the cathode contact, on the bottom of the chip. The PIN Diode electrical contact on the bottom of the chip covers the entire lower surface.

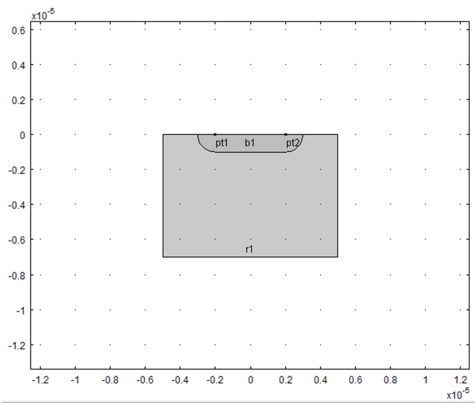

Figure 3. PIN Diode Geometry

3. PIN Diode Model Development

As can be seen in the Model Builder chart in Figure 1, the initial COMSOL Multiphysics PIN Diode Model requires calculations employing four (4) uniquely configured COMSOL sub-modules. The specific physical properties [2-10] of this PIN Diode semiconductor configuration are determined by the Parameters and Variables incorporated into the model and shown in the Parameters Table 1 and the Variables Table 2 in the appendix.

The first sub-module, Electric Currents (init), is calculated with sigma_sip assigned to the P-domain, sigma_sin assigned to the N-domain and V_psi_init, the charge neutrality voltage, applied to both the Anode and Cathode electrical contacts. Figure 4 shows the model Mesh. Failure to calculate the initialization conditions makes the calculation of the remainder of the model either extremely difficult or impossible.

Once the initialization conditions have been established, the Electric Currents 2 sub-module can be configured and calculated. However, in order to use any model subsequently with SPICE, that particular model must be configured so that one of that model's electrodes is connected specifically to GROUND. That condition is satisfied in the PIN Diode Model by connecting the electrical contact on the base of the chip (N-type) to GROUND. The Anode contact is set to Va+V_psi_init.

The Electric Currents 2 sub-module and the two Transport of Diluted Species sub-modules are next configured for the calculation of the simultaneous electron (cn0) and hole (cp0) densities. The density calculation treats the electrons and holes as a fluid, with one

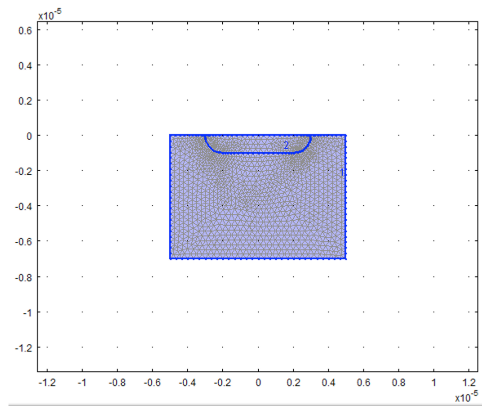

Figure 4. PIN Diode Model Mesh

density calculation for each carrier, over the entire volume of the device. The electron (cn0) – hole (cp0) recombination rate (-RSRH) is included as the built-in internal reaction. The PIN Diode Model is then meshed as shown in Figure 4 and the final result calculated. The final result is as shown in the PIN Diode Solution in Figure 2.

4. PIN Diode Model with SPICE

Once the PIN Diode Model has converged, as shown in Figure 2, the physics for the Electrical Circuit sub-module can be added. It is always best, as shown below in the Model Builder Chart in Figure 5, to save the converged model under a new name, so that the work on the converged model is not lost in the process of creating the new model.

After the Electrical Circuit sub-module is added to the model, the Anode contact needs to be changed to a Terminal contact and given a unique node name, in this case the name is “2”.

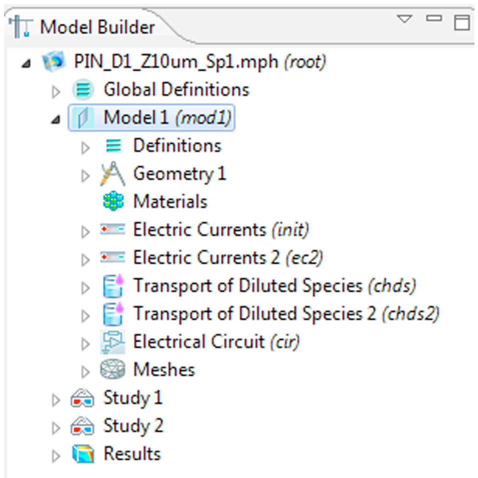

Figure 5. Model Builder Chart with SPICE

The SPICE circuit comprises a Voltage Source (0,1), a Resistor (1,2), the PIN Diode Model (0,2) and Ground (0), as shown in Figure 6.

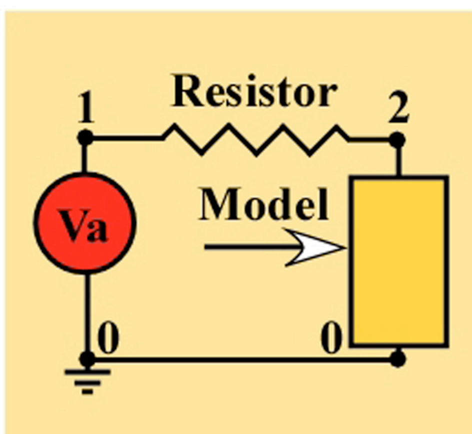

Figure 6. PIN Diode SPICE Circuit

The node numbers are shown in Figure 6 as assigned.

6. PIN Diode Model SPICE Results

Figure 7 below shows the current through the PIN Diode in the SPICE circuit for forward bias voltages (Va) in the range of 2V to 4V.

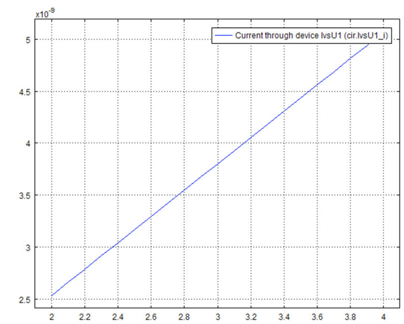

Figure 7. PIN Diode Current in SPICE Circuit

7. Conclusions

A PIN Diode model has been successfully built using the AC/DC conduction current module and incorporated into a simple SPICE circuit. This paper demonstrated the potential to build increasingly complex semiconductor models using the same methodology.

8. References

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9. Appendix

Table 1: PIN Diode Model Parameters

Parameter	Value	Description
q	1.602e-19[C]	Elementary charge
T	300[K]	Room temperature
k	1.38e-23[J/K]	Boltzmann's constant
epsilonr	11.8	Rel. permittivity for Si
ni	1.46e10[1/cm^3]	Intrinsic concentration for Si
mun	800[cm^2/(V*s)]	Electron mobility for Si
mup	200[cm^2/(V*s)]	Hole mobility for Si
Dn	k*T/q*mun	Electron diffusivity
Dp	k*T/q*mup	Hole diffusivity
taun	0.1[us]	Electron life time
taup	0.1[us]	Hole life time
c	q/(k*T)	Reciprocal thermal voltage
y1	7[um]	Diode dimension
x1	10[um]	Diode dimension
ju	1[um]	Junction depth
ac	4[um]	Anode dimension
NApmax	1e17[1/cm^3]	Maximum p-type doping
NDn	1e15[1/cm^3]	Drift layer n-type doping
NDnmax	1e17[1/cm^3]	Maximum n-type doping
ch	ju/sqrt(log(NApmax/NDn))	Doping fall-off constant
Va	0[V]	Applied voltage
Vt	k*T/q	Thermal voltage
Vpsi0	0[V]	Applied voltage (init)
q	1.602e-19[C]	Elementary charge
T	300[K]	Room temperature

Table 2: PIN Diode Model Variables

Variable	Expression	Description
N	NDn+NDnmax*exp(-((y+y1)/ch)^2)-NApmax*exp(-(y/ch)^2)*((abs(x)<ac/2)+(abs(x)>=ac/2)*exp(-((abs(x)-ac/2)/ch)^2))	Doping concentration
n_init	(abs(N)/2+sqrt(N^2/4+ni^2))*(N>=0)+ni^2/(abs(N)/2+sqrt(N^2/4+ni^2))*(N<0)	Charge neutrality electron concentration
p_init	(abs(N)/2+sqrt(N^2/4+ni^2))*(N<0)+ni^2/(abs(N)/2+sqrt(N^2/4+ni^2))*(N>=0)	Charge neutrality hole concentration
V_psi_init	1/c*(-log(p_init/ni)*(N<0)+log(n_init/ni)*(N>=0))	Charge neutrality voltage
RSRH	(cn[1/mol]*cp[1/mol]-ni^2)/(taup*(cn[1/mol]+ni)+taun*(cp[1/mol]+ni))	Recombination term
sigma_si	q*(cn[1/mol]*mun+cp[1/mol]*mup)	Conductivity of doped silicon

Variable	Expression	Description
cn0	ni*exp(-(V_psi0/Vt))	Thermal Eq electron concentration
cp0	ni*exp(-(V_psi0/Vt))	Thermal Eq hole concentration
sigma_sip	q*cp0*mup	P domain conductivity
sigma_sin	q*cn0*mun	N domain conductivity