ECE 480 DESIGN TEAM 6

Designing a Capacitive Sensor using COMSOL

Application Note

Arslan Qaiser

April 4th, 2010

Executive Summary:

Capacitive sensors can be virtually designed using a powerful 3D modeling software, COMSOL. It provides the user with the flexibility to model the sensor using a simple 2D user interface that can be easily transformed into a 3D model. With this software, the sensor can be modeled for any type of application like touch sensing, water sensing and pressure sensing. This application note focuses on a general capacitive sensor design that can be altered easily to fit any application.

Keywords: COMSOL, Capacitive Sensor

Table of Contents

Introduction:

Sensors are used in many important applications like medical equipment, industrial control systems, air-conditioning systems, aircrafts and satellites. They work by converting physical parameters such as temperature, pressure and wind speed into an electrical output that can be visualized by an observer. Capacitive sensors provide an alternative to the traditional mechanical buttons and sliders in electronics. These sensors work by sensing a conductive object nearby rather than detecting the physical state of the device. This application note will instruct the user on how to design a capacitive sensor using a 3D modeling software called COMSOL.

Objective:

The objective of this application note is to provide the reader with sufficient information on how to design a simple capacitive sensor. Specifically, a 3D modeling software known as COMSOL Multiphysics will be used to design and test the sensor before fabricating it. The software can predict the base capacitance and sensitivity of the sensor and this will be discussed in detail in this application note.

Background:

Capacitive Sensors:

Capacitive sensors are used in a variety of products and applications today, including popular handheld devices such as the iPod. The “scroll-wheel” interface of the iPod consists of an array of capacitive sensors laid out in a circular pattern. Many appliances and products now use capacitive sensors instead of traditional mechanical buttons or switches.

Capacitors are basically two conductors separated by a non-conductive material called a dielectric. A voltage is applied to one plate and the other plate is held at low potential or ground. This creates an electric field between the two plates. Normally capacitors are designed to maximize the mutual capacitance between the two plates and minimize any stray electric field lines also known as ‘fringe fields’. Compared to a standard capacitor, a capacitive sensor is designed to maximize the fringe fields between closely spaced conductors. Fringe fields loop away from the plane of the conductors as they connect one to the other, as shown in Figure 1. The way in which these fringe fields extend away from the conductor makes it useful for objects to interfere with the fringe fields without physically coming in contact with the sensor.

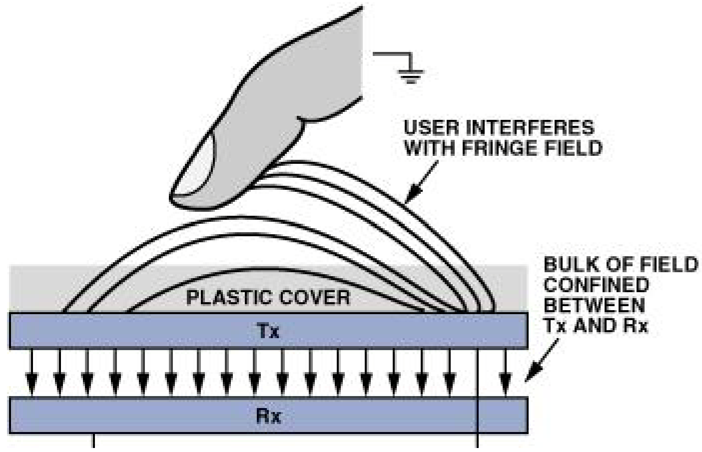


Figure 1: Finger interfering with fringe fields

Interference with the fringe fields by a conductive or dielectric object will change the capacitance of the system. The capacitance of the system can be monitored via circuitry. The conductors of a capacitive sensor are often laid out flat as copper traces on a printed circuit board (PCB). Depending on the application of the sensor, the traces can take on a variety of different sizes and patterns. The layout of the traces is often designed to maximize the fringing fields over a given area. These traces also form the base capacitance of the system, typically along the order of 2 – 20 pico-Farads in magnitude.

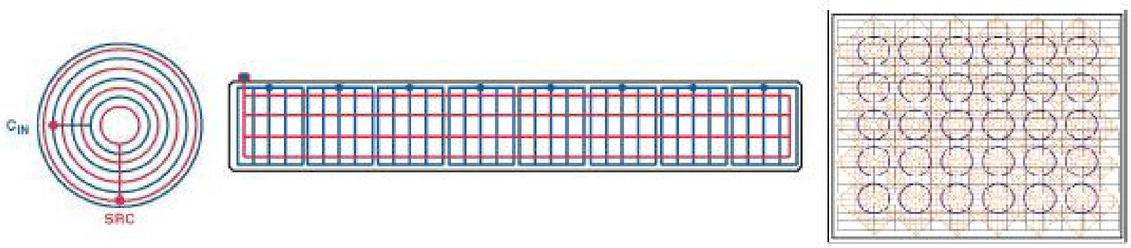


Figure 2: Sensor trace layouts for (from left to right) a button, slider, and touchpad

For the purpose of this application note, only the button sensor layout will be discussed when designing the layout on COMSOL. A comb structure will be used that consists of two metal traces interweaved together.

COMSOL:

COMSOL Multiphysics is an interactive engineering and physics tool that performs equation based modeling in a visual interface. This software allows the modeling and simulation of any physical phenomena in a way that's easy to implement. It comes pre-installed with different model libraries that can be readily used. Some of the libraries include modules such as Chemical Engineering Modules, MEMS Modules, RF Modules and Structural Mechanics Module.

In this application note, only the Electrostatics part of MEMS module will be discussed. Specifically it will be shown how to approach a 3D electrostatics problem by first creating a 2D geometry using the array tools and then extrude it to a 3D geometry, perform Mesh analysis and compute the capacitance using the Electrostatics application mode's port boundary conditions.

Implementation:

In order to design a capacitive sensor (also called a comb drive) in COMSOL, a series of steps need to be followed:

A. Model Navigator

1. Start by opening the **Model Navigator** after running COMSOL
2. Select the **MEMS Module → Electrostatics → Electrostatics** as shown in the following figure:

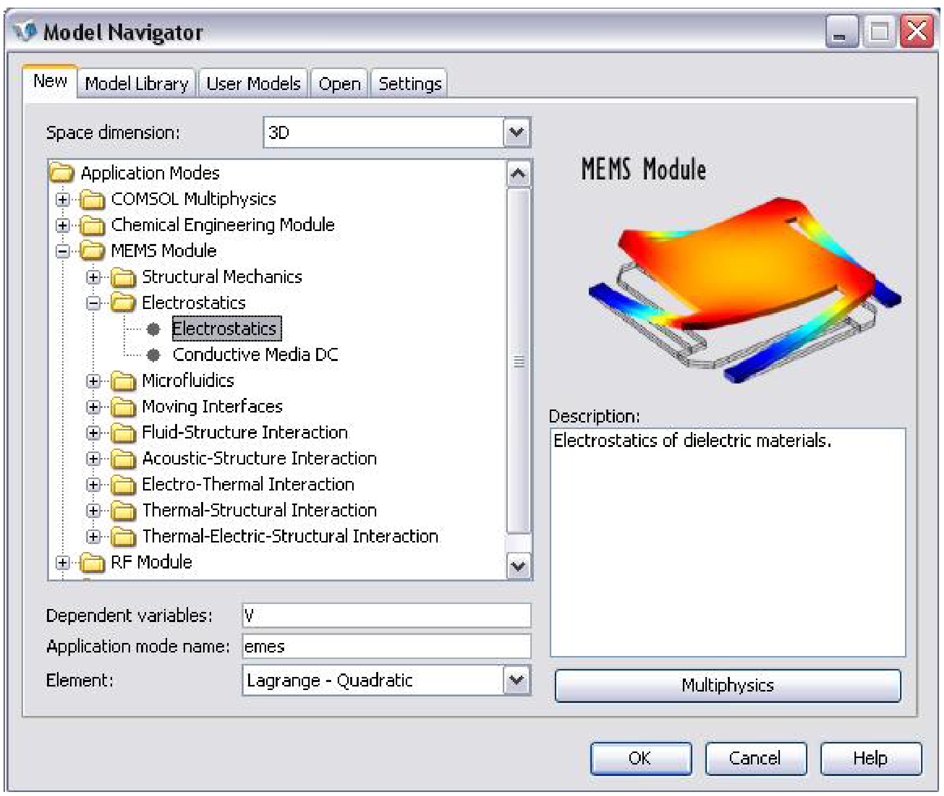


Figure 3

B. Geometry Modeling

1. To draw a 2D geometry, click on **Work-Plane Setting** under **Draw** and select z=0

2. Draw a rectangle by clicking on the **Rectangle/Square** icon in the draw toolbar. Once drawn, it is labeled as 'R1'.

3. Similarly, draw a series of rectangles by copy/paste and shift in the y-direction by $8x10^{-6}$ as shown:

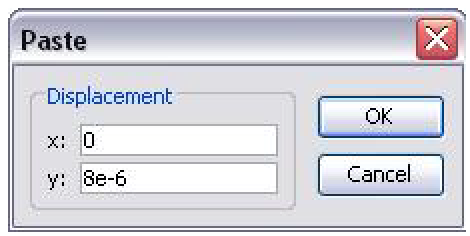


Figure 4

Note: The displacement can be different from $8x10^{-6}$ depending on the size of the sensor that is desired. For this application note, this size was chosen to make it easy for the reader to follow.

4. Select all the rectangles by using Ctrl+A then copy/paste again, this time adding both x-displacement and y-displacement to get the following: (x: $14x10^{-6}$, y: $4x10^{-6}$)

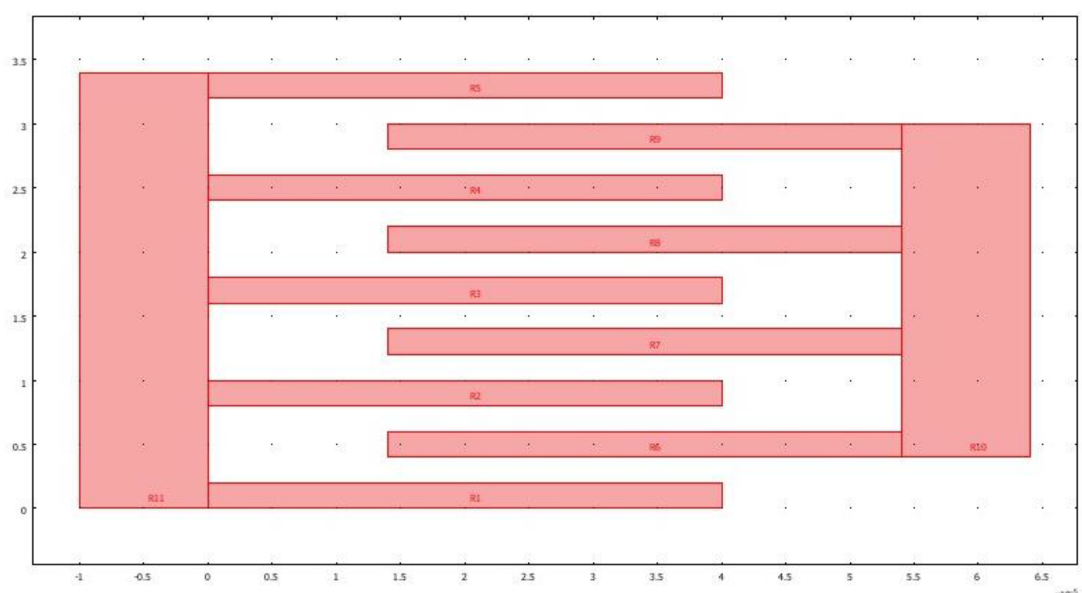


Figure 5

5. Use the **Union** and **Delete Interior Boundaries** button to merge all the rectangles (from R1-R11) and get to uniform 'comb like' structures as shown. These are called composite objects (CO2 and CO3 below)

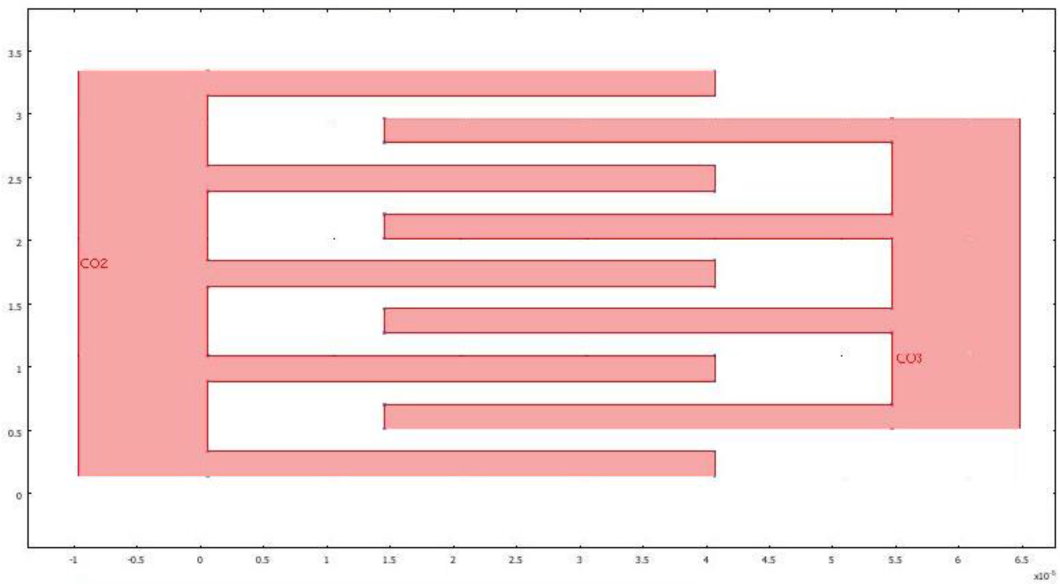


Figure 6

6. Draw a rectangle that covers the comb structure (labeled as R1). This will serve as the substrate and bounding air space for the analysis. This will be helpful in the 3D analysis when a top and bottom layer will be added to the comb structure.

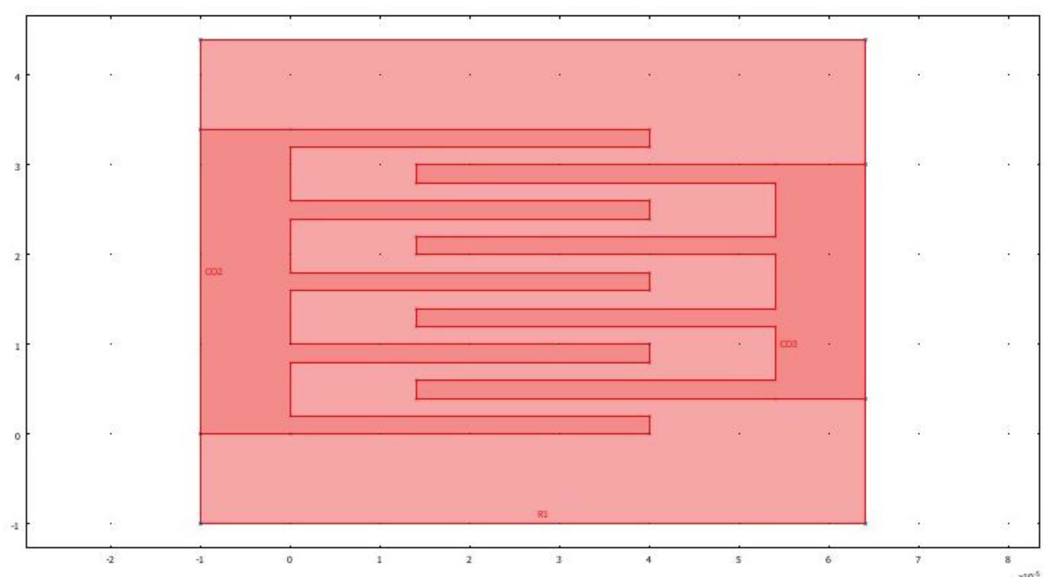


Figure 7

C. Extruding to 3D Geometry

1. The first step is to extrude the two comb drives to a 3D geometry. Select **Extrude** from the **Draw** menu and select the composite objects (CO2 and CO3).

2. Type in 2×10^{-6} in the distance field. The distance field corresponds to the height of the comb in the 3D geometry. This value can change based on the application of the capacitive sensor. The 3D comb drive can be seen in Figure 9 below.

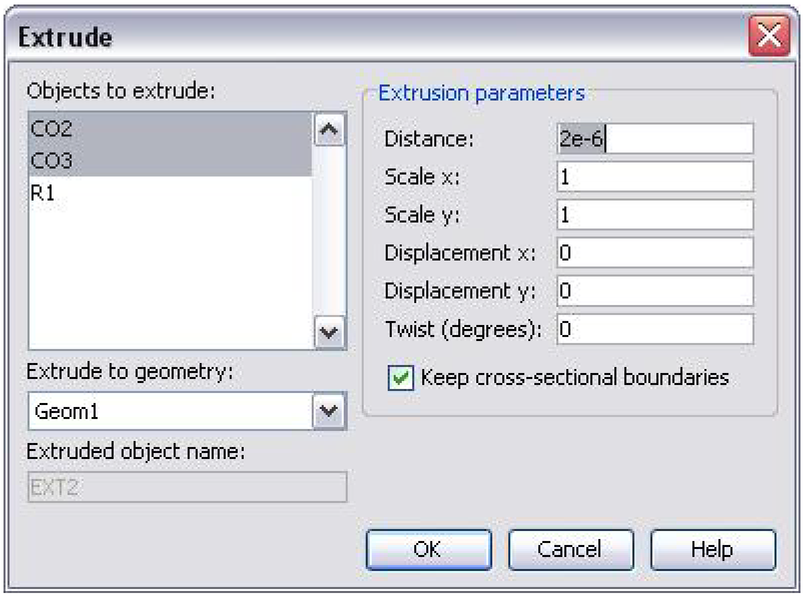


Figure 8

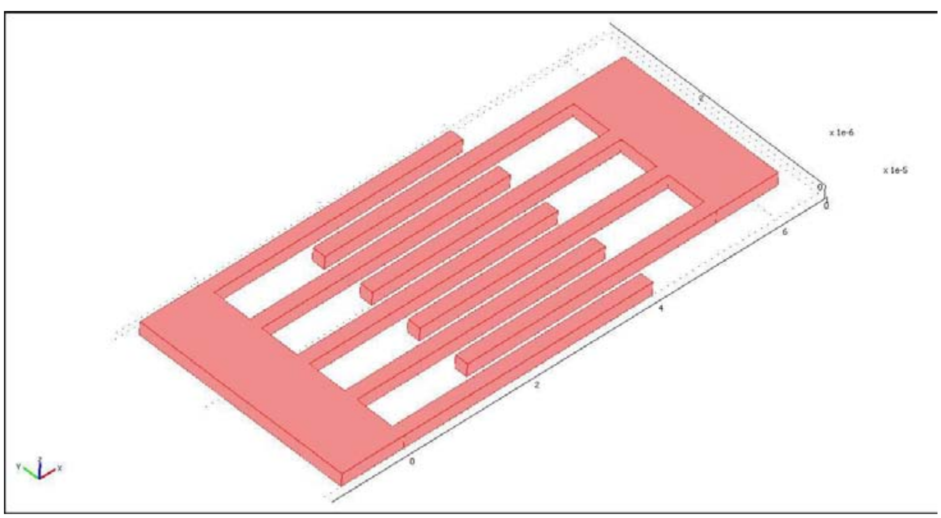


Figure 9

3. Next step is to include a layer of air on the top layer of the 3D comb. To do this, the rectangle R1 will be extruded in a similar manner as CO2 and CO3. But in this case, the distance is set to $12x10^{-6}$.

4. Once the top layer has been added, the bottom substrate layer can be extruded in the same way. To add the bottom layer, set the distance to $-10x10^{-6}$. The negative sign indicates that the bottom layer will be extruded in the –z-direction. The following figure shows the complete 3D comb geometry.

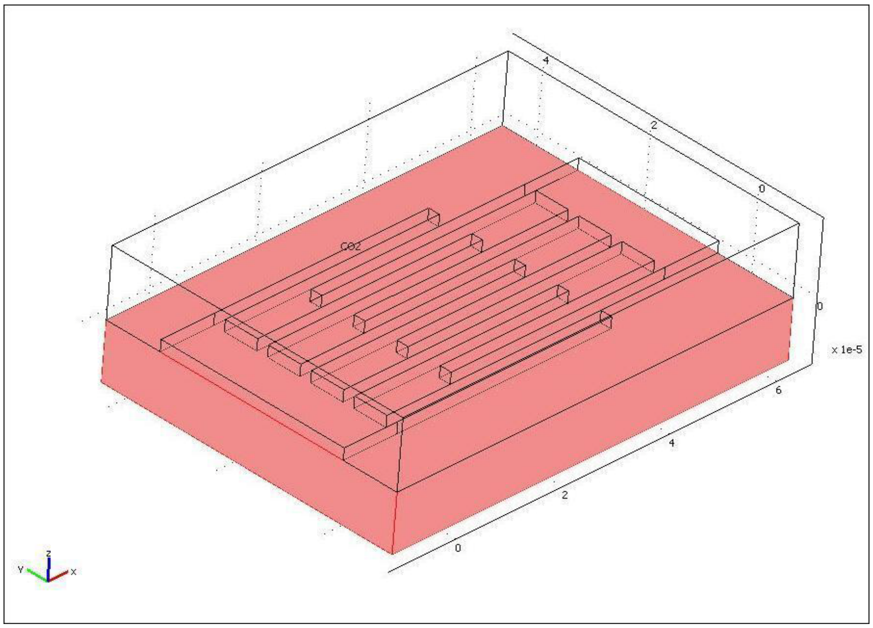


Figure 10

D. Physics Settings

1. ***Subdomain Settings:***
The 3D comb geometry shown in Figure 10 consists of two sub-domains. First is the top layer of air and second is the bottom silicon substrate layer. Select **Subdomain** from the **Physics** menu.

   Note: These layers can represent different materials. For example, the top layer could be glass or plastic and the bottom layer can be a substrate made of Teflon, FR4 instead of silicon. The way COMSOL identifies these different materials is through a property called 'Dielectric permittivity' (ϵ_r) of the material. A list of different Dielectric permittivity is given in Table 3 (Appendix).

In this case, the following values are used:

Settings	Subdomain 1 (Silicon)	Subdomain 2 (Air)
ϵ_r	11.9	1.0
ρ	0	0

Table 1

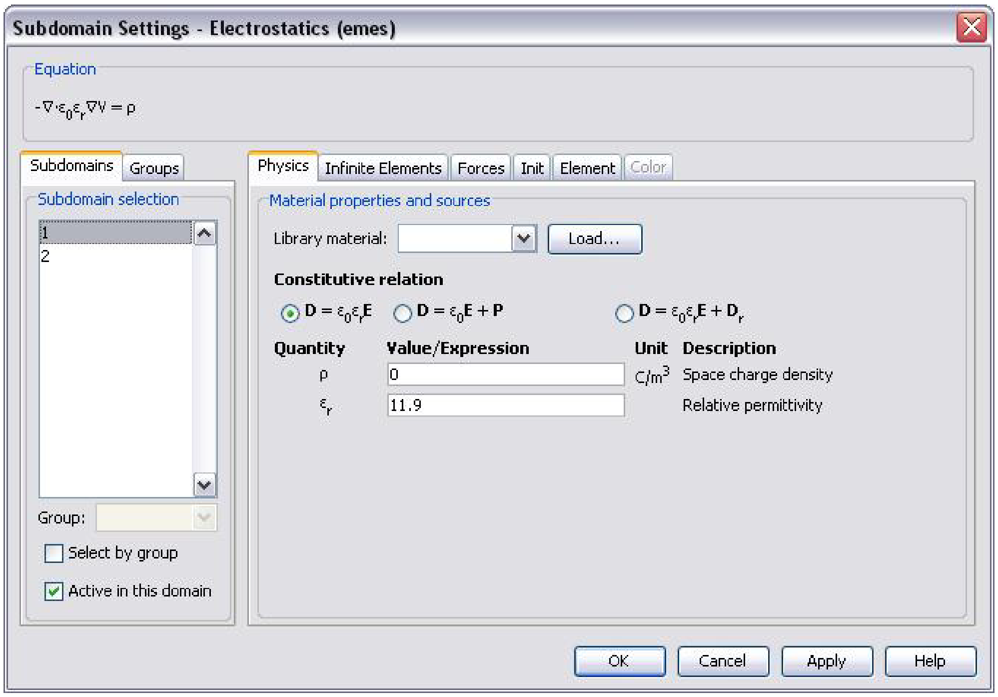


Figure 11

2. ***Boundary Conditions:***
   There are three boundary conditions that need to be defined. First is the ground, second is the port (voltage) and third is the symmetry or zero charge condition. To access boundary conditions, select **Boundary Settings** under the **Physics** menu.

Settings	Boundary: 1-5, 7,12,13,52,53	Boundary: 8-11, 14-27, 42-46	Boundary: 28-41, 47-51
Boundary Condition	Symmetry/ Zero Charge	Ground	Port (voltage)

Table 2

3. After applying the above boundary conditions, click on the **Port** tab and make sure the dialog box looks exactly like shown in figure 12.

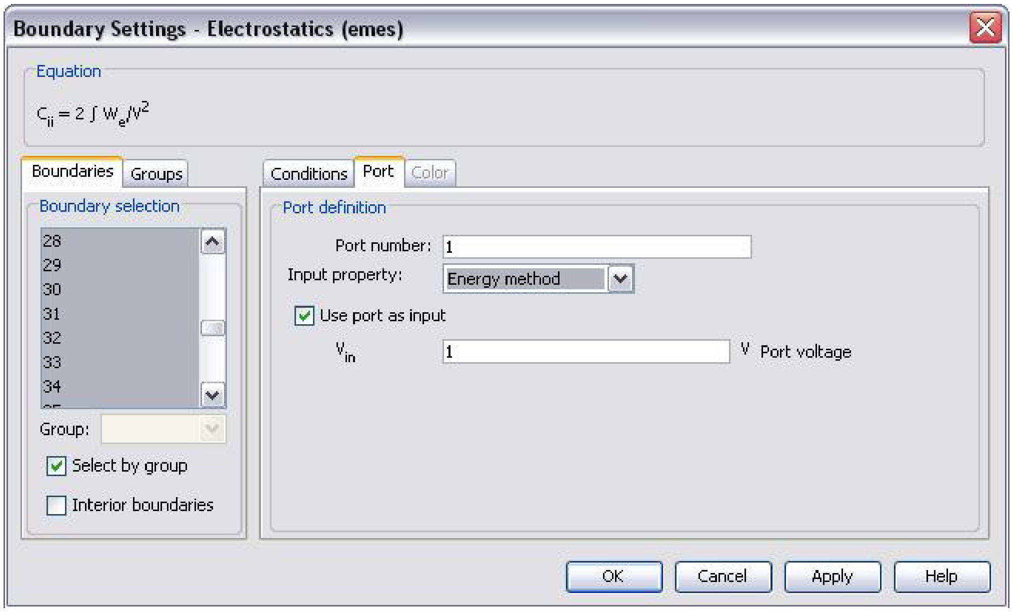


Figure 12

4. Make sure that the **Select by group** box is checked. Click on one set of Boundaries and make that it corresponds to the right comb. The following two figures show the comb geometries corresponding to different sets of Boundary conditions.

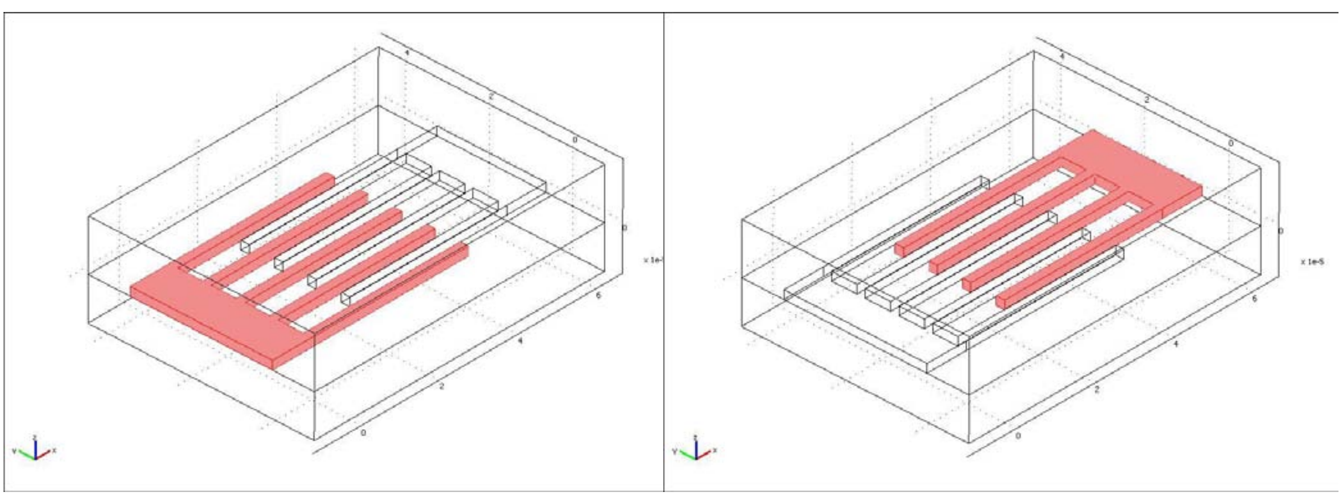


Figure 13: Left picture shows the comb that is grounded.
Right picture shows the comb that is a port.

E. Mesh Analysis

1. In order to do a Mesh Analysis, click on **Mesh → Initialize Mesh**.

2. The following Progress box appears:

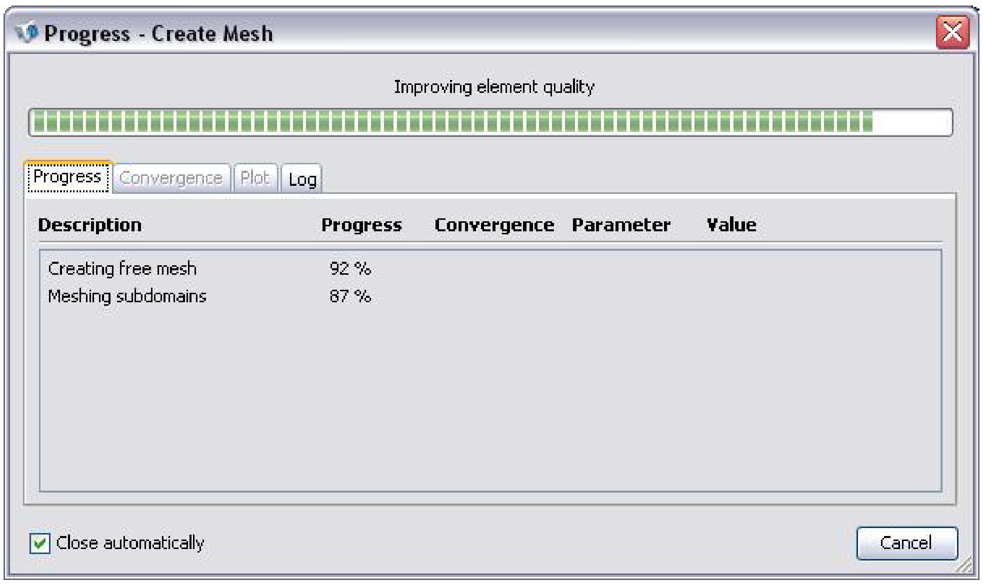


Figure 14

3. Once the Create Mesh Analysis is complete, the comb structure will look like the following figure:

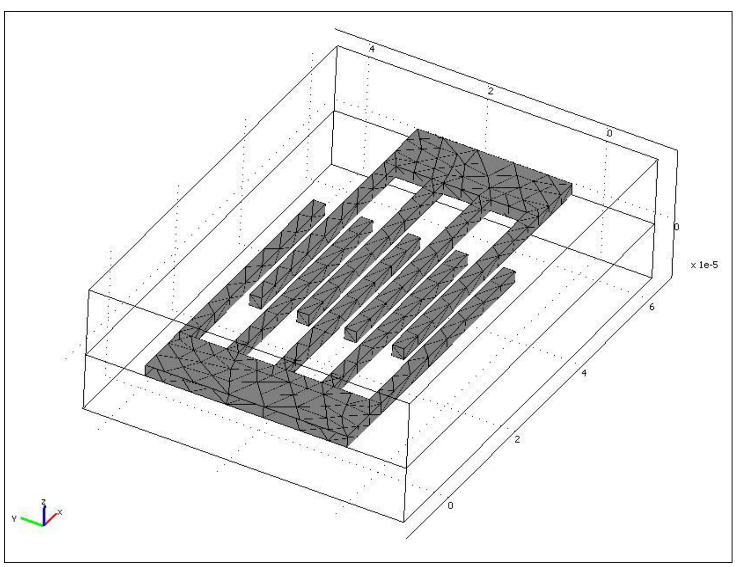


Figure 15

F. Solve Problem

1. In order to get a solution to the problem, click on **Solve → Solve Problem**

2. The following Progress box appears:

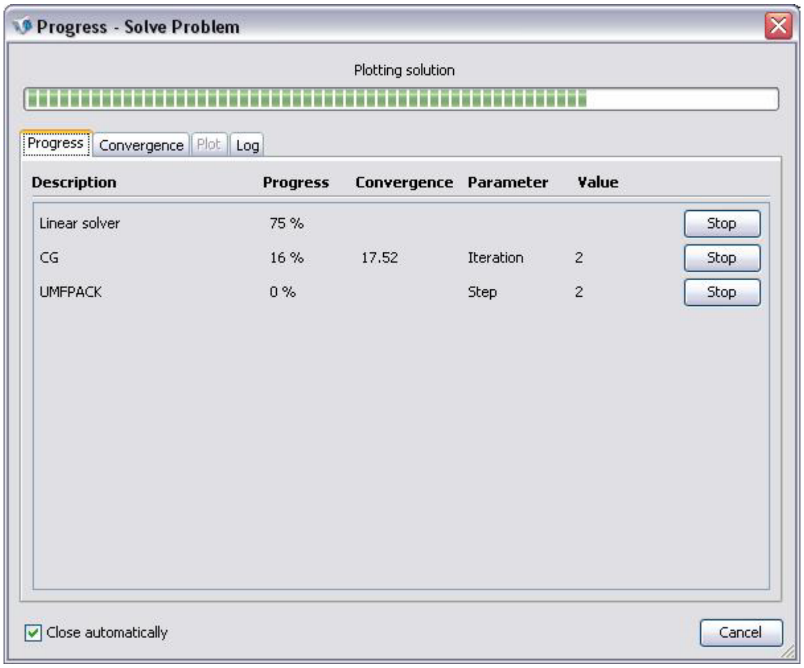


Figure 16

3. Once the Solve Problem Analysis is complete, the final capacitive sensor structure appears as follows:

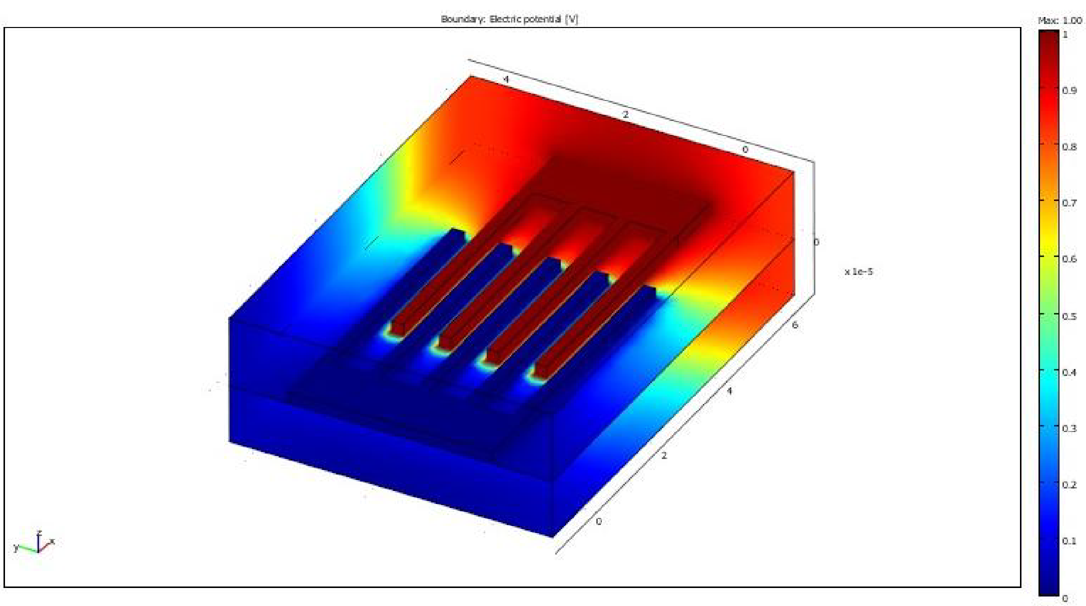
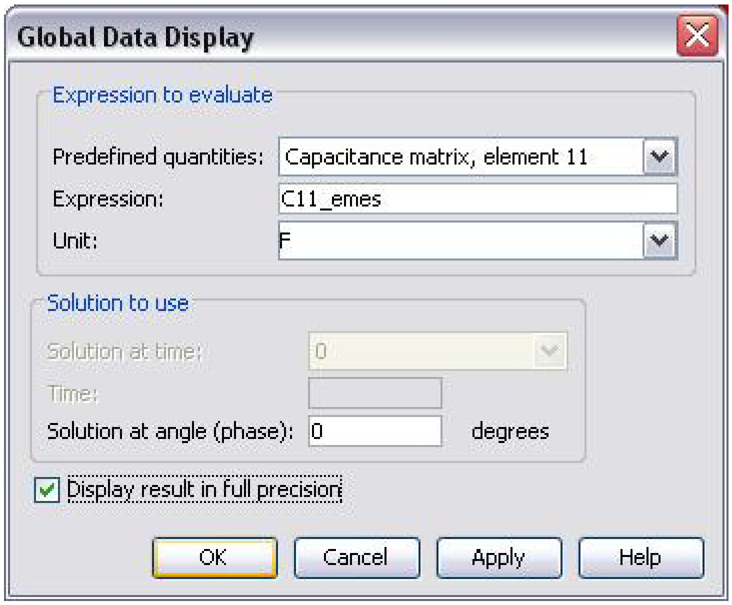


Figure 17: Red Color shows high voltage (1V) and blue color is low voltage (ground)

G. Compute Capacitance

1. In order to calculate the capacitance of the capacitive sensor, select **Postprocessing → Data Display → Global**. The following Global Data Display box appears:




```
Number of degrees of freedom solved for: 11708
Solution time: 0.594 s
Value: 2.1938850480665124E-14 [F], Expression: C11_emes, Phase: 0 degrees
```

Figure 18

2. Figure 18 shows the final results:

   Capacitance = 2.19388 x 10^{-14} F = 0.0219388 pF

Conclusion

Capacitive sensor design using COMSOL provides the user with a wide variety of tools. The user can simulate a design, test for the capacitance and observe the effects on capacitance by changing parameters such as dielectric permittivity of materials. With COMSOL, it is also possible to observe the effects of temperature on the capacitance value. It is very useful software that can save a lot of time by simulating the design before actually fabricating it. ECE 480 Design Team 6 is using a similar capacitive sensor design to detect water. COMSOL proved to be quite useful in optimizing the design of the sensor.

Appendix

Material	Dielectric constant	Material	Dielectric constant
Air	1.0	Nylon	3.4-22.4
Amber	2.6-2.7	Paper (dry)	1.5-3.0
Asbestos Fiber	3.1-4.8	Paper (coated)	2.5-4.0
Epoxy Resin	3.4-3.7	Paraffin (solid)	2.0-3.0
Ethyl Alcohol (absolute)	6.5-25	Plexiglas	2.6-3.5
Fiber	5.0	Polystyrene	2.4-3.0
Formica	3.6-6.0	Quartz	5.0
Glass (electrical)	3.8-14.5	Quartz (fused)	3.78
Glass (Pyrex)	4.6-5.0	Rubber (hard)	2.0-4.0
Glass (window)	7.6	Styrofoam	1.03
Silicone (glass) (molding)	3.2-4.7	Teflon	2.1
Silicone (glass)	3.7-4.3	Titanium Dioxide	100
Soil (dry)	4.4	Vaseline	2.16
Mica (electrical)	4.0-9.0	Water (distilled)	34-78

Table 3: Dielectric Constant Table

References

Baxter, Larry K. *Capacitive Sensors: Design and Applications*. New York: IEEE, 1997. *Google ooks*. Web. 3 Apr. 2010. http://books.google.com/books?id=Tjd2laRnO4wC&dq=why+use+capacitive+sensors&printsec=frontcover&source=in&hl=en&ei=3LO3S7CfC4iGNOH1keIL&sa=X&oi=book_result&ct=result&resnum=11&ved=0CD8Q6AEwCg#v=onepage&q=why%20use%20capacitive%20sensors&f=false

"Capacitive Sensor Introduction." *School of Computer Science, Carnegie Mellon*. Web. http://www.cs.cmu.edu/~ram/capsense/intro.html

MEMS Module Model Library. COMSOL AB. November 2008.