INTRODUCTION

COMSOL Multiphysics software is a powerful, Partial Differential Equation (PDE) solution engine. The basic COMSOL Multiphysics 5.x software has over twenty-five (25) add-on modules that expand the capabilities of the basic software into a broad collection of application areas: AC/DC, acoustics, batteries and fuel cells, CFD, chemical reaction engineering, electrodeposition, geomechanics, heat transfer, MEMS, microfluidics, plasma, RF, structural mechanics and subsurface flow, to name a few. The COMSOL Multiphysics software also has other supporting software, such as the Optimization Module, the Material Library Module, the CAD Import Module and LiveLink™ interfaces for several engineering software programs.

In this book, scientists, engineers, and others interested in exploring the behavior of different physical device structures through computer modeling are introduced to the techniques of hands-on building and solving models through the direct application of the basic COMSOL Multiphysics software, along with some samples using the AC/DC, heat transfer, rf, semiconductor, and structural mechanics modules. The next to the last technical chapter explores the use of Perfectly Matched Layers in the RF Module. The final technical chapter explores the use of the Bioheat Equation in the Heat Transfer and RF Modules.

The models presented herein are built within the context of the physical world (applied physics) and are presented in light of First Principle Analysis techniques. The demonstration models emphasize the fundamental concept that the information derived from the modeling solutions through the use of these computer simulations is only as good as the materials coefficients and the fundamental assumptions employed in building the models.

The combination of computer simulation and First Principle Analysis gives the modeler the opportunity to try a variety of approaches to the solution of the same problem as needed in order to get the design right or nearly right in the workshop or laboratory before the first device components are fabricated and tested. The modeler can also use the physical device test results to modify the model parameters and arrive at an improved solution more rapidly than by simply using the cut and try methodology.

CHAPTER TOPICS

The eleven (11) technical chapters in this book demonstrate to the reader the hands-on technique of model building and solving. The COMSOL concepts and techniques used in these chapters are shown in Figure Int.1. The COMSOL modules employed in the various models in specific chapters are shown in Figure Int.2, and the physics concepts and techniques employed in the various models in specific chapters are shown in Figure Int.3.

Concept/Technique Chapter:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
0D Modeling			•								
1D Modeling	•	•		•							
2D Axisymmetric Coordinates								•			•
2D Axisymmetric Modeling						•		•			•
2D Modeling					•		•	•		•	
3D Modeling									•		
Animation				•	•	•					
Bioheat Equation											•
Boolean Operations – geometry					•	•		•	•	•	•
Boundary Conditions	•	•		•	•	•	•	•	•	•	•
Conductive Media DC				•	•	•		•	•	•	
Coupled Multiphysics Analysis				•				•	•	•	•

Concept/Technique Chapter:	1	2	3	4	5	6	7	8	9	10	11
Cylindrical Coordinates						•		•		•	
Deformed Mesh – Moving Mesh					•						
Domain Plot Parameter								•	•	•	•
Electromagnetics				•	•			•	•	•	•
Electronic Circuit Modeling			•								
Electrostatic Potentials				•					•		
Fillet corners									•		
Floating Contacts					•						
Free Mesh Parameters					•	•	•	•	•	•	•
Frequency Domain							•	•	•	•	•
Global Equations					•		•	•	•	•	•
Heat Transfer Coefficient	•	•		•		•	•		•		•
Laplacian Operator							•				
Lumped Parameters			•						•		
Magnetostatic Modeling					•			•	•		
Materials Library	•	•					•	•	•	•	
Mathematics – Coefficient Form PDE				•							
Mathematics – General Form PDE				•							
Maximum Element Size				•			•	•		•	•
Mixed Materials Modeling								•			•
Mixed Mode Modeling							•	•			

(continued)

Concept/Technique Chapter:	1	2	3	4	5	6	7	8	9	10	11
Out-of-Plane Thickness				•	•		•	•		•	
Parametric Solutions				•	•	•	•	•	•		
Perfectly Matched Layers										•	
Pointwise constraints					•		•		•		
Quasi-Static Solutions					•	•	•				
Scalar Expressions							•				
Scalar Variables							•		•		
Spherical Coordinates				•							
Static Solutions			•			•	•		•		
Streamline Plot									•		
Terminal Boundary Condition					•				•		
Transient Analysis			•		•		•	•			
Triangular Mesh					•	•	•	•		•	•
Work Plane									•		

Figure Int.1 COMSOL Concepts and Techniques

Module Chapter:	1	2	3	4	5	6	7	8	9	10	11
Basic	•	•	•	•	•	•	•	•	•	•	•
AC/DC			•	•	•		•	•	•		
Heat Transfer	•	•		•		•	•		•		•
RF								•		•	•
Semiconductor				•							
Structural Mechanics									•		

Figure Int.2 COMSOL Modules Employed

Physics Concepts Chapter:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Anisotropic Conductivity					•						
Antennas											•
Bioheat Equation											•
Boltzmann Thermodynamics						•					
Complex AC Theory							•	•			
Concave Mirror										•	
Distributed Resistance			•				•		•		
Electrochemical Polishing					•						
Electromagnetic induction (Inductance)				•			•		•		
Electrostatic Potentials in Different Geometric Configurations				•					•		
Energy Concentrator										•	
Faraday's Law			•		•				•		
Fick's Laws						•	•				
First Estimate Review	•			•	•	•	•	•	•	•	•
Fourier Analysis						•	•				
Fourier's Law						•	•				
Free-Space Permittivity								•	•		
Good First Approximation	•		•	•	•	•	•	•	•	•	•

(continued)

Physics Concepts Chapter:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Hall Effect					•						
Heat Conduction	•	•	•	•		•	•		•	•	•
Information Transmission				•				•			
Insulated Containers						•					
Joule Heating						•	•		•		•
Kirchoff's Laws (Current, Voltage)			•								
Lorentz Force					•						
Magnetic Field					•				•		
Magnetic Permeability					•				•		
Magnetic Vector Potential					•			•	•		
Magnetostatics									•		
Maxwell-Faraday Equation			•								
Maxwell's Equations			•			•		•	•	•	
Microwave Irradiation											•
Newton's Law of Cooling						•					
Ohm's Law			•				•	•	•		•
Optical (Laser) Irradiation											•
Pennes Equation											•
Perfectly Matched Layers: 2D Planar, 3D Cartesian Cylindrical and Spherical										•	
Perfusion											•
Planck's Constant						•					

Physics Concepts Chapter:	1	2	3	4	5	6	7	8	9	10	11
Semiconductor Dual Carrier Types				•	•						
Semiconductor, Density-Gradient (DG) Theory				•							
Semiconductor, Schrodinger-Poisson (SP) Theory				•							
Soliton Waves				•							
Telegraph Equation				•							
Vector Dot Product Current				•	•			•	•		

Figure Int.3 Physics Concepts

The information in these three figures link the overall presentation of this book to the underlying modeling, mathematical and physical concepts. In this book, in contrast to other books with which the reader may be familiar, key ancillary information is, in most cases, contained in the notes.

NOTE *Please be sure to read, carefully consider, and apply, as needed, each note.*

CHAPTER 1 MODELING METHODOLOGY

Chapter 1 provides an overview of the modeling process by discussing the fundamental considerations involved: the hardware (computer platform), the coordinate systems (physics), the implicit assumptions (lower dimensionality considerations), and First Principles Analysis (physics). Three relatively simple 1D models are presented that build and solve, for comparison, single-, double- and triple-pane thermal insulation window structures. Comments are also included on common sources of modeling errors.

CHAPTER 2 MATERIALS PROPERTIES

Chapter 2 discusses various sources of materials properties data, including the COMSOL Material Library, basic and expanded module, as well as print and Internet sources. A multi-pane thermal insulation window structure model demonstrates three techniques for entering material properties: user-defined direct entry, user-defined parameters, and material definitions. Also included are instructions for building a user-defined material library for storage within COMSOL 5.x.

CHAPTER 3 0D ELECTRICAL CIRCUIT INTERFACE

COMSOL 5.x uses zero-dimensional models to provide for the modeling of electrical circuitry. The models in this chapter illustrate techniques for modeling various basic circuits: a resistor-capacitor series circuit, an inductor-resistor series circuit, and a series resistor, parallel inductor-capacitor circuit. Considerations for the proper setup of the circuits are discussed along with the basics of problem formulation and the implicit assumptions built into COMSOL 5.x relative to electrical circuit modeling.

CHAPTER 4 1D MODELING

The first part of Chapter 4 models the 1D KdV Equation. The KdV Equation is a powerful tool that is used to model soliton wave propagation in diverse media (e.g., physical waves in liquids, electromagnetic waves in transparent media, etc.). It is easily and simply modeled with a 1D PDE mode model.

The second part of Chapter 4 models the 1D Telegraph Equation. The Telegraph Equation is a powerful tool that is used to model wave propagation in diverse transmission lines. The Telegraph Equation can be used to thoroughly characterize the propagation conditions of coaxial lines, twin pair lines, microstrip lines, etc. The Telegraph Equation is easily and simply modeled with a 1D PDE mode model.

The third part of Chapter 4 is a 1D Spherically Symmetric Transport model that illustrates the technique of simplifying models with spherical components from 3D to 1D by assuming that they are essentially symmetrical.

The fourth part of Chapter 4 is an Advanced 1D Silicon Inversion Layer Model using DG and SP Theory Methodologies. It is the purpose of this model to demonstrate the modeling techniques needed to reproduce the calculated inversion layer electron density below the gate oxide, as a function of depth curves.

CHAPTER 5 2D MODELING

The first half of Chapter 5 models the surface smoothing process by using a 2D Electrochemical Polishing Model. This model is a powerful tool that can be used for diverse surface smoothing projects (e.g., microscope samples, precision metal parts, medical equipment and tools, large and small metal drums, thin analytical samples, vacuum chambers, etc.).

The second half of Chapter 5 models Hall Effect magnetic sensors. The 2D Hall Effect Model is a powerful tool that can be used to model such sensors when used for sensing fluid flow, rotating and/or linear motion, proximity, current, pressure, orientation, etc.

CHAPTER 6 2D AXISYMMETRIC MODELING

Modeling a 3D device that is symmetrical on one axis by treating it as a 2D Axisymmetric object simplifies the model for quicker first approximation results.

The first half of Chapter 6 discusses a 2D Axisymmetric Heat Conduction in a Cylinder Model and demonstrates the use of contour plotting of the solver results to show non-linear temperature distribution in the cylinder.

The second half of Chapter 6 models transient heat transfer in a niobium sphere immersed in a medium of constant temperature by using a 2D Axisymmetric model.

CHAPTER 7 2D SIMPLE AND ADVANCED MIXED-MODE MODELING

In this chapter, simple and advanced mixed-mode 2D models are presented. Such 2D models are typically more conceptually complex than the models that were presented in earlier chapters of this text. 2D simple and advanced mixed-mode models have proven to be very valuable to the science and engineering communities, both in the past and currently, as first-cut evaluations of potential systemic physical behavior under the influence of mixed external stimuli. The 2D mixed-mode model responses and other such ancillary information can be gathered and screened early in a project for a first-cut evaluation. That initial information can potentially be used later as guidance in building higher-dimensionality (3D) field-based (electrical, magnetic, etc.) models.

The first part of Chapter 7 uses a 2D Electrical Impedance Sensor Model to demonstrate this technique. The concept of electrical impedance, as used in alternating current (AC) theory, is an expansion on the basic concept of resistance as illustrated by Ohm's Law, in direct current (DC) theory.

The second part of Chapter 7 uses a 2D Axisymmetric Metal Layer on a Dielectric Block Model to demonstrate more aspects of the technique. The modeler was introduced to Fick's laws for the diffusion (mass transport) of a first item (e.g., a gas, a liquid, etc.) through a second item (e.g., another gas, liquid, etc.). In the case of this model, the diffusing item is heat.

In the first part of Chapter 7 implemented above, a copper layer was approximated by the Thin Conductive Layer function in the Heat Transfer in Solids Interface. In this, Advanced Model, the third study implemented in this chapter, the copper layer will be a geometrical copper layer. The modeler will now be able to compare the results of the earlier models, to the results of this Advanced model calculation, on nominally the same modeling problem, employing diamond as the substrate. The modeler can now determine the relative trade-offs required when he chooses different materials to model one methodology or another.

These models are examples of the Good First Approximation type of models because they demonstrate the significant power of relatively simple physical principles, such as Ohm's Law, Joule's Laws, and Fick's Laws, when applied in the COMSOL Multiphysics Modeling environment. The equations can, of course, be modified by the addition of new terms, insulating materials, heat loss through convection, etc.

CHAPTER 8 2D COMPLEX MIXED MODE MODELING

In this chapter, three new primary analysis concepts are introduced to the modeler: 2D electromagnetic impedance calculation for a planar, two-wire geometry (side by side), for a concentric two-wire geometry (coaxial cable), and a 2D Axisymmetric model of the transient behavior of a Concentric 2 Wire Geometry (Coaxial Cable).

CHAPTER 9 3D MODELING

In this chapter, the modeler is introduced to three new modeling concepts: the Terminal boundary condition lumped parameters and coupled thermal, electrical and structural multiphysics analysis. The Terminal boundary condition and the lumped parameter concepts are employed in the solution of the 3D Spiral Coil Microinductor Model. The fully coupled multiphysics solution is employed in the 3D Linear Microresistor Beam Model.

The lumped parameter (lumped element) modeling approach approximates a spatially distributed collection of diverse physical elements by a collection of topologically (series and/or parallel) connected discrete elements.

This technique is commonly employed for first approximation models in electrical, electronic, mechanical, heat transfer, acoustic and other physical systems.

CHAPTER 10 PERFECTLY MATCHED LAYER MODELS

One of the fundamental difficulties underlying electromagnetic wave equation calculations is dealing with a propagating wave after the wave interacts with a boundary (reflection). If the boundary of a model domain is terminated in an abrupt fashion, unwanted reflections will typically be incorporated into the solution, potentially creating undesired and possibly erroneous model solution values. Fortunately, for the modeler of today, there is a methodology that works sufficiently well that it essentially eliminates reflection problems at the domain boundary. That methodology is the Perfectly Matched Layer.

Chapter 10 includes two models, the 2D Concave Metallic Mirror PML Model and the 2D Energy Concentrator PML Model, to demonstrate the use of the Perfectly Matched Layer methodology.

CHAPTER 11 BIOHEAT MODELS

The Bioheat Equation plays an important role in the development and analysis of new therapeutic medical techniques (e.g., killing of tumors). If the postulated method raises the local temperature of the tumor cells, without excessively raising the temperature of the normal cells, then the proposed method will probably be successful. The results (estimated time values) from the model calculations will significantly reduce the effort needed to determine an accurate experimental value. The guiding principle needs to be that tumor cells die at elevated temperatures. The literature cites temperatures that range from 42 °C (315.15 K) to 60 °C (333.15 K).

The first half of Chapter 11 models the Bioheat Equation as applied with a photonic heat source (laser).

The second half of Chapter 11 models the Bioheat Equation as applied with a microwave heat source.