Semiconductor Device Modeling - Video course

COURSE OUTLINE

Course Learning Outcomes

At the end of this course you should be able to

1. **Explain** the equations, approximations and techniques available for deriving a model with specified properties, for a general device characteristic with *known qualitative theory*
2. **Apply** suitable approximations and techniques to derive the model referred to above starting from drift-diffusion transport equations (assuming these equations hold)
3. **Offer clues** to qualitative understanding of the physics of a new device and conversion of this understanding into equations
4. **Simulate** characteristics of a simple device using MATLAB, SPICE and ATLAS / SYNOPSYS
5. **Explain** how the equations get lengthy and parameters increase in number while developing a compact model
6. **List** mathematical functions representing various non-linear shapes

COURSE DETAIL

Module no.	Module Learning Outcomes	No. of (Total) Hours
0	**Motivation, Contents and Learning Outcomes**	1
1	**Introduction** At the end of this module you should be able to • State the constituents of a device model • Recognize the importance of approximations in a model • Recognize the various stages of IC design where device models are used • Distinguish among activities of analysis, modeling, simulation and design • Transform the equivalent circuit form of a device model into a mathematical form, and vice-versa • Recognize how the equations get lengthy and parameters increase in number while developing a model	1
2	**Semi-classical Bulk Transport – Qualitative Model** At the end of this module you should be able to explain qualitatively the following in semiconductors ▪ The reason for terming certain mechanisms of carrier motion as semi-clasical ▪ The concepts of scattering, effective mass and carrier	5

NPTEL

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Electronics & Communication Engineering

Pre-requisites:

Solid State Devices (NPTEL course)

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Additional Reading:

1. T.A. Fjeldly, T. Ytterdal and M. Shur, “Introduction to Device Modeling and Circuit Simulation”, John Wiley, 1998.
2. Y. Taur and T. H. Ning, “Fundamentals of Modern VLSI Devices”, Cambridge University Press, 1998.

Coordinators:

Prof. S. Karmalkar
Department of Electrical EngineeringIIT Madras

	temperature ▪ The phenomena of ohmic transport, velocity saturation, velocity overshoot and ballistic transport of carriers ▪ The series of approximations leading to the drift-diffusion carrier transport formulation starting from the concept of carriers as particles in random thermal motion		

3	**Semi-classical Bulk Transport – EM field and Transport Equations**
	
	At the end of this module you should be able to
	
	• Write the equations of electromagnetic field driving the device current, namely
	  ▪ Maxwell's wave equations and their quasi-static approximation
	  ▪ Lorentz force equation
	
	• Recognize the four approaches of determining the device current, developed out of the individual carrier and ensemble viewpoints, in each of which the carrier can be treated either as a particle or as a wave
	
	• Recognize that the equations of carrier transport in semiconductor devices have a common form which manifests conservation of some physical quantity
	
	• Write the fundamental equations of determining the device current based on each of the following: Schrodinger equation, Newton's second law and Boltzmann Transport Equation (BTE)
	
	• Write the equation for lattice temperature or heat flux, and recognize its necessity for determining the device current from the ensemble point of view
	
	• Derive the approximations of the BTE, namely:
	  ▪ carrier, momentum and energy balance equations
	  ▪ drift-diffusion and thermoelectric current equation
	
	• Apply the balance equations to derive expressions for the velocity-field and velocity overshoot characteristics
		8	

4	**Drift-Diffusion Transport Model – Equations, Boundary Conditions, Mobility and Generation / Recombination** At the end of this module, you should be able to write, for the widely used drift-diffusion transport model, • its three coupled equations in electron concentration, *n*, hole concentration, *p*, and potential ψ • the conditions imposed on *n*, *p* and ψ at the contacted and non-contacted boundaries of the device, to solve he coupled equations • the equations for field dependent mobility in bulk and inversion layers • the equations for different generation-recombination mechanisms	5	

5	**Characteristic times and lengths**
	
	At the end of this module, you should be able to
	
	• State the characteristic times and lengths associated with
	  ▪ the bulk carrier population under equilibrium
	  ▪ the relaxation of disturbance in
	    * carrier momentum and energy
	    * excess EHP concentration
	    * space-charge
	  ▪ the transit of an average carrier across the device length
	
	• State the conditions (including those at the boundary) and the defining differential equation associated with each characteristic time and length
	
	• State the order of magnitude of, and factors governing, the characteristic times and lengths
	
	• State how the characteristic times and lengths are useful in
	  ▪ qualitative description of device phenomena
	  ▪ simulation and characterization of devices
	  ▪ validation of approximations
	
	• Derive the defining equations associated with the various characteristic times and lengths
	
	• Identify approximations which will simplify, decouple or eliminate any of the equations of carrier transport, e.g. DD equations, balance equations etc.
	
	• Express the qualitative analysis using graphs of n, p, J_n, J_p, E, ψ versus x, t
		6	

6	**Energy band diagrams**
	
	At the end of this module you should be able to
	
	• Explain how the wave nature of electrons restricts the allowed energy, ε, of electrons subjected to a periodic potential, to certain energy bands
	
	• Outline the features, methods of determination and utilities of ε-k and ε-x diagrams of a semiconductor
	
	• Explain the concept of crystal momentum
	
	• Determine the effective mass, group velocity and crystal momentum of an electron, having an energy ε, from theε-k diagram
	
	• Sketch and explain the ε-k diagrams of Si and GaAs
	
	• Determine and sketch the ε-x diagram of a uniform semiconductor under the following conditions:
	  ▪ equilibrium, for any doping and temperature
	  ▪ uniform volume generation
	  ▪ applied bias
	
	• Determine and sketch the ε-x diagram of a spatially non-uniform semiconductor under equilibrium, in
		7	

	which the doping and composition change ▪ abruptly at a point (hetero-junction) ▪ gradually • Explain how the energy band diagram can be used to derive the exponential increase in the diode current with forward bias • Sketch and explain the *ε-x* diagram of a p+ n junction under high forward bias • Sketch the 1-D band diagram (*ε-x*) and interpret a 2-D band diagram (*ε -x*, *y*) of any device		
7	**SQEBASTIP: The Nine Steps of Deriving a Device Model** At the end of this module, you should be able to • Describe the nine steps for deriving a device model • Apply the nine steps to derive the model of a spreading resistance • Name the requirements of an elegant model • Identify the variables, constants and parameters of a model • Organize the approximations associated with a device model into a specific tabular form • Express an equation in a normalized form	3	
8	**Types of Device Models** At the end of this module, you should be able to • describe the classification of device models based on the ▪ time rate of change or frequency of voltage / current variation ▪ amplitude of voltage / current variation ▪ starting point of the derivation ▪ attributes of the solution technique ▪ attributes of the mathematical function ▪ attributes of the parameters and constants ▪ - application • interpret, from the jargon employed, the type of model being addressed in any literature on device modeling • use the appropriate jargon to convey a particular type of device model	2	
9	**MOSFET Model: Structure and Characteristics, Qualitative Model** ---- Under development ---		
10	**MOSFET Model: Equations, Boundary Conditions and Approximations** ---- Under development ---		
11	**MOSFET Model: Surface Potential based and**		

	Threshold based solutions ---- Under development ---	
12	**MOSFET Model: Testing, Improvement and Parameter Extraction** ---- Under development ---	

References:

1. M. Lundstrom, "Fundamentals of Carrier Transport", Cambridge University Press, 2000.
2. C. Snowden, "Introduction to Semiconductor Device Modeling", World Scientific, 1986.
3. Y. Tsividis and C. McAndrew, "MOSFET modeling for Circuit Simulation", Oxford University Press, 2011.
4. BSIM Manuals available on BSIM homepage on the internet.