on the phenomena of detonation uses the classic approach of Chapman-Jouguet. Formation of tridimensional structure is discussed. The phenomenon of supersonic combustion is also treated in this chapter because of its similarities with detonation. Chapter 8 gives a fresh view on the problem of ignition based on recent work on computer simulation of the ignition process by various sources of energy.

Chapter 9 is concerned with the combustion of liquids and particle clouds. Having treated the classical problem of burning a single liquid drop, the authors discuss the structure and calculation of the flames of particle clouds. Advances in this new territory of research reveal exotic structures such as group combustion, percolant combustion, and combustion in pockets. The book ends with a chapter on environmental consideration regarding the chemistry of pollutants (NO_x, SO_x, and particulate).

This 365-page-long book is consistent with the stated purpose of the authors to write only an introductory text but with the maximum rigor and clarity possible. Although this book, according to the authors, emphasizes the physical aspect of the combustion phenomena rather than their mathematical demonstration, the mathematics gives the book its special flavor and makes it interesting enough to read or to study.

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Computational Modeling in Semiconductor Manufacturing

Edited by M. Meyyappan, Artech House, Norwood, MA, 1995, 363 pp., $89.00 (hardcover).

It has been recognized that computer simulation can be a valuable tool for the design and optimization of equipment used in the fabrication of microelectronic devices. This edited volume fills the need for a reference book on the subject. It is meant for researchers and graduate students with some background in semiconductor manufacturing processes. The book consists of six chapters: (1) modeling of semiconductor manufacturing processes—an introduction; (2) outline of numerical methods; (3) crystal growth; (4) chemical vapor deposition processes; (5) plasma process modeling; and (6) rapid thermal processing.

Chapter 1 (by M. Meyyappan) is a short introduction giving the rationale for and utility of numerical modeling as applied to semiconductor fabrication. Chapter 2 (by T. R. Govindan and F. J. de Jong) briefly discusses finite-difference techniques used to solve the partial-differential equation systems resulting by applying the principles of conservation of mass, momentum and energy. Emphasis is placed on the compressible Navier-Stokes equations for pure fluids. Discussed are the basics of finite difference approximations, applications to complex domains and nonuniform meshes, linearization of the equations, and iterative schemes to solve the resulting system of linear equations. The important issue of convergence acceleration is also touched on. Reference to other numerical techniques such as finite element and finite volume is made in passing, but these techniques are covered in Chapter 4 on chemical vapor deposition (CVD) processes.

Chapter 3 (by Y. T. Chan) that starts with a description of different techniques for crystal growth from vapor, melt, and solution focuses exclusively on growth from the melt. Governing equations and boundary conditions are presented, and the important dimensionless groups that arise are tabulated, and their physical meaning discussed. Criteria for stability of rotating flows, the onset of natural convection over vertical and horizontal surfaces, as well as convection due to surface tension gradients are presented. Stress analysis in crystal growth with explicit expressions for GaAs is also discussed. It is followed by case studies on some popular crystal growth techniques, which shed much insight into the factors that control the crystal diameter, shape of the melt/crystal interface, impurity incorporation into the crystal, and radial and axial uniformity of crystal properties. However, comparisons with experimental data are not made, except for one isolated case. The first case study deals with liquid encapsulated Czochralski (LEC) growth of GaAs crystals. Results of a 3-D simulation are shown, and the effect of varying the operating conditions is analyzed under quasi-steady state and transient thermal conditions. The effect of applying a static magnetic field B is reported, although the governing equations given earlier in the chapter do not include B. The float zone process is the second case study applied to growth of TiC. Here an account is given of the equations and procedure to determine the effect of a radio frequency (RF) heating system on the temperature distribution and the melt/solid interface shape. The last case study is a vertical Bridgman growth of HgCdTe. This chapter is well written, but the most important material system, silicon growth from the melt, is not discussed.

Chapter 4 (by C. R. Kleijn) is well written and thoroughly explains (thermal) CVD with an extensive literature review up to July 1993 (containing 290 references). Plasma CVD is dealt with in the next chapter. The author orients the reader with the basic principles of CVD, and common reactor designs and applications in the IC industry. An overview of the modeling approach is given followed by a detailed review of modeling assumptions, basic equations for mass, momentum and energy conservation in multicomponent mixtures, a general formalism for gas-phase and surface chemistry, and the relevant boundary conditions. Then empirical and kinetic theory results are given for calculating the thermodynamic and transport properties of multicomponent gas mixtures including thermodiffusion coefficients. Modeling of chemical reaction kinetics (including RRKM and transition state theories) and of conjugate heat transport are presented in a clear and concise manner. The author then presents an account of finite-volume and finite-element methods used to solve the governing equations. A comparison of the strengths and weaknesses of each technique, as well as a short discussion on the capabilities and shortcomings of available commercial CFD software packages, is also given. The author then tabulates a long list of CVD studies reported in the literature (up to July 1993) in a quite informative format including the publication year, process studied (e.g., CVD of Si and GaAs), problem dimensionality (2-D, 3-D, etc.), and type (diffusion, convective-diffusion, boundary layer, elliptic, parabolic, etc.), solution method (such as finite differences), and relevant features of the model (detailed vs. simplified chemistry, full multicomponent diffusion, detailed conjugate heat transfer, comparison with experiments, etc.).

He classifies the literature according to operating pressure and reactor configuration and presents a table for each classification. The author also gives an informative discussion of some of the most important papers in the corresponding classification, making comparisons with experimental data when possible. The classifications he considers are: atmospheric pressure CVD (APCVD) in horizontal rectangular ducts, APCVD in vertical impinging jet and stagnation point reactors, APCVD in rotating disk reactors, hot-tube multiwafer low-pressure CVD (LPCVD) reactors, LPCVD in single-wafer and rapid thermal CVD reactors, and barrel, pancake, and other CVD reactors. This presentation format should be very useful to the reader who wants to know what exists out there in the CVD arena. A subsection is devoted to an overview of chemistry modeling that has been included in published CVD works from empirical Langmuir-Hinshelwood deposition models to multispecies (up to ~ 100) multireaction (up to ~ 350) models. A short account of microscopic feature modeling is then presented where models based on the "pseudo-continuum" approach are contrasted to the "ballistic deposition" and direct simulation Monte Carlo (DSMC) based models. Challenges facing the CVD community (chemistry, 3-D simulations with full chemistry and coupling of microscopic with reactor scale models) are enumerated in the conclusions section.

Chapter 5 (by M. Meyyappan) is also well written. It starts with a brief introduction on the uses of plasma etching and plasma-enhanced CVD (PECVD) in the IC industry, and gives elementary plasma reactions and reactor configurations. The goal of the simulation is presented as the link between equipment settings (pressure, power, gas flow, etc.) and process figures-of-merit (etch and deposition rate, uniformity, anisotropy, etc.). Plasma reactor modeling is divided into: (a) "discharge model" in which one is interested in the discharge physics neglecting neutral species transport and chemistry; (b) "reactor model" that computes the gas velocity, temperature and concentration distribution of reactive neutral species (much as in thermal CVD) based on assumed electron density and energy (i.e., assuming that the discharge model has been solved); and (c) "process model" in which discharge and reactor models are coupled, hopefully self-consistently. The discharge model starts with a brief introduction to the Boltzmann equation and the particle-in-cell Monte Carlo collisions (PIC-MCC) method for the kinetic simulation of plasmas.

The emphasis of this chapter, however, is on continuum or fluid simulations using the conservation equations derived as moments of the Boltzmann equation. The equations and boundary conditions are presented, and approximations made in the literature are scrutinized. Electron transport properties and electron-impact reaction rate coefficients from the electron energy distribution function are then discussed. Numerical solution issues, including the disparity of time and length scales associated with plasmas, and the need to accelerate convergence to the periodic steady state are emphasized. Discharge modeling results emphasize 1-D simulations since at the time the book was completed, 2-D simulations were just starting to emerge. Both electropositive (argon) and electronegative (chlorine) gases are considered and their behavior contrasted. Scaling relations of the plasma properties (e.g., electron density and "temperature") with reactor operating conditions are given. Qualitative comparisons with data are made where possible. Reactor model results include 2-D simulations of silicon nitride deposition in a radial flow reactor, BCl_3 etching of GaAs in a channel reactor, and CF_4 etching of silicon again in a radial flow reactor, all using highly simplified chemistry. The section on process model presents a hierarchy of models to couple the discharge physics with neutral transport and chemistry from elementary CSTR, to plug flow, to 0-D plasma coupled with 2-D neutral transport and chemistry models. Unfortunately, the tremendous developments in plasma modeling and simulation over the past 3 years could not have been incorporated into this chapter (the book includes developments up to late 1993). Currently, there exist 2-D fluid simulations that couple discharge physics and neutral transport and chemistry in a self-consistent and computationally efficient manner. Also, "particle" simulations in 2-D including PIC-MCC, DSMC, and hybrid fluid-particle simulations are available. 3-D plasma simulations are around the corner. Finally, high density plasmas are not discussed in this chapter.

Chapter 6 (by S. A. Campbell) on rapid thermal processing (RTP) has a considerable overlap with the CVD chapter. An abbreviated list of the fluid dynamics and transport equations are presented along with radiation heat transport (conjugate heat transfer) items that were also presented in the CVD chapter. Also, one of the central issues in RTP is uniform heating of the substrate which is also an issue in ordinary CVD. What distinguishes RTCVD from ordinary CVD is the rapid heating (heating the wafer by several hundred °C in a period of seconds), necessitating transient simulations, and the development of thermal stresses in the wafer. This is correctly emphasized in the chapter. The author presents a limited set of 2-D and 3-D results of temperature distribution on the wafer under the influence of fluid flow without chemistry. Again, this chapter has missed recent developments of RTP simulations including chemistry. However, RTP is still at a relatively early stage of development.

A revised version of the book might include computational simulation of other semiconductor fabrication processes such as lithography, oxidation, and dopant incorporation and diffusion. Special attention should be paid to comparison with laboratory experiments to enhance confidence in the simulations. Also, I believe that simulation of microscopic feature evolution should be included either by extending the chapters on CVD and plasma processing, or preferably as a separate chapter. In addition, more emphasis should be placed on "molecular simulations" (PIC-MCC, DSMC, molecular dynamics). These become progressively more important as the operating pressure is lowered (longer mean free path of gas species) and as the need to understand surface kinetics becomes progressively more compelling. Finally, the development of technology computer-aided design (TCAD) simulation tools needs to be further emphasized. However, limits on the length of a book of this kind may prevent including all the above mentioned subjects.

Overall this book is a commendable first of its kind attempt. It is useful not only for the newcomers who want to get started in the numerical simulation of some important semiconductor processes, but also for the researchers in the field who want to have an up-to-date (up to late 1993) account of the methodologies and published works in crystal growth, CVD, plasma processing, and RTP. I recommend the book enthusiastically.

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Bioreaction Engineering Principles

By Jens Nielsen and John Villadsen, Plenum Press, New York, 1994, 456 pp.

Bioreactor System Design

Edited by Juan A. Asenjo and Jose C. Merchuk, Marcel Dekker, New York, 1995, 620 pp., $195.

Bioreaction Engineering Principles by Jens Nielsen and John Villadsen is developed with a strong focus on mathematical modeling and analysis of micro-