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.

Demetre J. Economou
Dept. of Chemical Engineering
University of Houston
Houston, TX 77204

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 microbial growth kinetics, with additional coverage of mass-transfer aspects and ideal bioreactors. The material presented in this book is appropriate for a senior/graduate-level engineering course on microbial growth kinetics. While there are already some textbooks available for a course on biochemical or bioprocess engineering, this book is focused more on the fundamental analysis of mathematical modeling of cellular growth processes. Even with its higher level of mathematical sophistication (with their justifiable usage of matrices and vectors when analyzing multiple intracellular reactions), the book gives due importance to the exposition of biochemical details as well as microbial diversity. The authors' favored microbial species may appear to be *Escherichia coli* and *Saccharomyces cerevisiae*, as evidenced by their recurrent appearance in numerous examples throughout the text and problems at the end of each chapter; however, their mathematical treatments are easily extended to other species such as lactic acid bacteria, *Corynebacterium*, and filamentous fungi.

Beginning with a summarized introduction to the major catabolic and energy-generating pathways, the authors develop the systematic approach to stoichiometry of microbial reactions (Chapter 2) in the order of elemental balances, degree of reduction balance, yield coefficients, energy balance for growth and maintenance for aerobic and nonaerobic growth processes and heat generation during microbial growth. Chapter 3 is devoted to the analysis of reaction rates, ranging from the more primitive extreme of a black box description of fermentation process to the more sophisticated applications of metabolic flux analysis and control theory to determine bottlenecks within a multienzymatic reaction pathway. Practical and quantitative examples are used often to illustrate these more abstract analytical methods. The remainder of Chapter 3 discusses the consistency analysis of overdetermined systems and identification of gross measurement errors with illustrative examples.

Chapter 4 on modeling of reaction kinetics is a thorough analysis of the usefulness and limitations of the unstructured Monod model for correlating the growth rate as a function of substrate. Modifications to this classical model, such as the inclusion of maintenance energy term or the multiple substrate terms, are detailed. The rationale for bringing structure into the growth models to predict the chemostat dynamics, as well as to analyze the growth on multiple substrates, are brought out very analytically. Chapters 5 and 6 on morphologically structured and population balance models involve more complicated mathematical formulations, but address interesting, experimentally observed phenomena such as oscillating yeast cultures and plasmid stability in recombinant bacteria and yeast cells from uncommon perspectives.

Chapter 7 provides a well-organized treatment of mass-transfer aspects, drawing heavily from the classical chemical engineering literature as should be expected. Chapter 8 presents the interplay of unstructured and structured growth models in ideal bioreactors, such as batch, continuous, and semi- or fed-batch stirred-tank reactors. The analysis extends from single wild-type organisms to more interesting mixed microbial populations, illustrated with examples ranging from the traditional predator-prey interactions to the more recent plasmid-containing microorganisms reverting to the wild type. The shorter final chapter highlights the issues involved in scaling up from the smaller ideal bioreactors to the larger industrial-scale bioreactors, with short sections on rheology, mixing, and impellers.

The major strength of this textbook is its uniformly high-quality exposition and discussion of the fundamentals of reaction engineering applied to cellular growth processes. It would have been more satisfying to see their systematic analyses extended to more modern biotechnological applications, such as the growth kinetics and metabolism of recombinant microbes and animal cell cultures, rather than focus predominantly on the more traditional cases of wild-type microorganisms. A significant omission in this book is lack of any discussion on cell immobilization methods and their effects on the cellular growth kinetics. This textbook turns out to be an extensive and thorough review of several decades of published literature on the mathematical modeling of wild-type microorganisms, which is suitable for a more advanced course focused on mathematical modeling of cellular growth, rather than for an introductory biochemical engineering course with broader coverage.

Bioreactor System Design edited by Juan A. Asenjo and Jose C. Merchuk is Volume 21 in a series on *Bioprocess Technology* edited by W. Coutney McGregor. This book deals with the core subject of bioreactor design in 11 chapters, augmented by three chapters at the beginning on the host organism selection and media design and by two chapters at the end on bioreactor support systems, such as sterilization, containment, and supplies. This volume, with 16 chapters and 29 authors, covers broadly most of the issues relevant to bioprocess engineers. The coverage by various expert authors often overlaps and differs widely in quality, ranging from a few excellent chapters to some mediocre ones. There are also inconsistencies in style, such as different referencing patterns with occasional titles, absence of problem sections in a few chapters. This lack of uniformity makes it difficult to use as a textbook.

Chapters 2–4 on the host organism selection and media design provide most of the biological background, with not as much detail on metabolic pathways as covered in the book reviewed above. A surprising inclusion in Chapter 2 is the selective listing of addresses, phone and fax numbers of commercial organizations that provide collection, testing or expression services. While this listing may contain some useful contact information for those listed, a large number of other providers as well as more traditional and commonly used expression systems are not included. The discussion in these three chapters have the tone of a summary, with pointers to a large number of more detailed original publications.

Chapter 5 on the Fundamentals of Bioreactor Design by the editors of this volume appears to be the anchor or originator of this whole effort. The sections on stoichiometry and kinetics are relatively weak, dated, and not discussed in sufficient detail (particularly in comparison to the other book reviewed above). Many different kinetic equations used in the literature are merely listed, with very limited discussion on the appropriateness or the limitations of any of these equations. The next section on mass transfer in bioreactors presents a much briefer version of the next two more detailed chapters. In light of the inclusion of those two following chapters, it seems unnecessary to repeat those same topics in the brief sections of this chapter by the editors, and more important to cover the kinetics and stoichiometry, as they are not covered in sufficient detail elsewhere in this book. The next two sections on heat transfer and shear are again very brief, even though there is no other chapter dedicated to them. The problems at the end of this important chapter are weak and do not test the material in any significant manner.

Chapters 6 and 7 on stirred-tank bioreactors and pneumatically agitated bioreactors treat these topics more thoroughly, but with no problems at the end of the chapters to illustrate or test any quantitative or qualitative understanding of the materials presented (as included in most other chapters). Chapter 13 on Bioreactor Operation Modes by Prof. Yamane is a well-written fundamental chapter on bioreactor engineering, probably a summarized version of his text on the same topic. This chapter belongs along with Chapters 5, 6 and 7 on suspension bioreactors, rather than as an add-on chapter toward the end of the book.

The following three chapters (8–10) on the different methods of immobilizing microorganisms and animal cells are written authoritatively by long-time practitioners of these fields. While the discussion is somewhat curtailed by the brevity of these chapters, they provide an important counterpoint to the common treatments of only the suspension cultures in stirred-tank reactors in many books (such as the one reviewed above). The references at the end of these chapters provide useful pointers to more detailed discussions on these topics for more interested readers. Chapters 11 and 12 on plant cell bioreactors and photobioreactors provide further examples of the diversity of bioreactor designs for more specialized or less common cell cultures. The last three chapters (14–16) on Scale-up, Sterilization and Containment, and Bioreactor System Supplies provide many useful discussions relevant to the practitioners of large-scale bioreactor design and operation.

The major strength of this book is its relatively broad coverage of many different types of bioreactor system by various experts, many of whom are long-time practitioners of these technologies. Another strength is the vast amount of original articles referenced at the end of each chapter, which provide more detailed information on the topics treated briefly in this book. Its relative weakness is the lack of critical analysis or comparative discussion of these methods or technologies. Consequently, we are left with smörgasbord treatment of many topics, compared with the gourmet treatment of a focused area of kinetics in the book reviewed above. Thus, the second book will provide a quick introduction to many different areas of bioreactor system design, with helpful pointers to the original sources for more detailed elaboration.

Dhinakar Kompala
Chemical Engineering Dept.
University of Colorado
Boulder, CO 80309