

Contents

| | | |
|----------|--|-----------|
| 1 | Introduction | 1 |
| | Exercise | 7 |
| 2 | Plasma Processes for Semiconductors | 8 |
| | 2.1 Plasmas | 9 |
| | 2.2 Plasma Interactions with Materials | 12 |
| | 2.3 The Hierarchy of Plasma Models | 15 |
| | 2.4 Plasma Electrostatics | 18 |
| | 2.5 Transport of Particles and Energy | 20 |
| | 2.5.1 Gas Phase Collisions | 20 |
| | 2.5.2 A Simple Random Walk | 21 |
| | 2.5.3 Random Walks of Electrons in a Low-Pressure Plasma | 22 |
| | 2.6 The Continuity Equation | 25 |
| | 2.7 The Particle Flux | 26 |
| | 2.8 Feedback in Plasmas | 28 |
| | Exercises | 28 |
| 3 | Plasma Electromagnetics and Circuit Models | 31 |
| | 3.1 Electromagnetic and Circuit Models | 31 |
| | 3.2 Plasma Electromagnetics | 31 |
| | 3.2.1 Electromagnetic Fields in an ICP | 33 |
| | 3.3 Circuit Model of an ICP – Negative Feedback in the Primary Circuit | 39 |
| | 3.4 Circuit Model of a Capacitive Discharge | 40 |
| | 3.5 Circuit Model of an Electron Cyclotron Resonance Discharge | 42 |
| | 3.6 Circuit Model for Damage Studies | 45 |
| | Exercises | 50 |
| 4 | Plasma Models | 51 |
| | 4.1 Plasma Models | 51 |
| | 4.2 Swarm Measurements | 51 |
| | 4.3 Capacitive rf Discharges | 52 |
| | 4.3.1 Local Heating in Capacitive Discharges | 53 |
| | 4.3.2 Nonlocal Heating in Capacitive Discharges | 55 |

| viii | Contents | |
|----------|--|-----------|
| 4.4 | Analytic Model of Transport in an ICP | 57 |
| 4.5 | Diffusion in Energy | 59 |
| 4.6 | Ambipolar Diffusion | 59 |
| 4.7 | Transport and the Plasma Density Profile | 62 |
| 4.8 | The Plasma Potential | 65 |
| 4.9 | Analytic Models of Electron Cyclotron Resonance Discharges | 65 |
| 4.10 | The Electron Distribution Function | 67 |
| | 4.10.1 Introduction | 67 |
| | 4.10.2 Physical Processes and the Electron Distribution | 67 |
| | 4.10.3 Electron Distribution Function Depending on Total Energy | 70 |
| | 4.10.4 Excitation and Ionization Rates | 72 |
| | 4.10.5 Higher Pressure Discharges | 73 |
| | 4.10.6 Inelastic “Holes” in the Electron Distribution Function | 74 |
| 4.11 | Computation of the Electron Distribution | 76 |
| | 4.11.1 Particle Motion | 77 |
| | 4.11.2 Collisions | 78 |
| | 4.11.3 Wall Losses | 79 |
| | 4.11.4 Heating Mechanisms | 79 |
| 4.12 | The Energy Distribution of the Flux | 80 |
| | Exercises | 82 |
| 5 | Plasma Chemistry | 85 |
| 5.1 | Plasma Chemistry | 85 |
| 5.2 | Rates of Reaction | 86 |
| 5.3 | Types of Reaction | 89 |
| 5.4 | Etching Recipes | 90 |
| | 5.4.1 Current Understanding of Etching Processes | 92 |
| 5.5 | The Chemistry of Film Deposition Using Plasmas | 92 |
| | 5.5.1 PECVD Recipes | 92 |
| | 5.5.2 Reactive Sputtering | 93 |
| 5.6 | The Gas Mixture in a Plasma: The Case of CF ₄ | 94 |
| | 5.6.1 Processes in the CF ₄ Plasma | 95 |
| | Exercises | 97 |
| 6 | Transport at Long Mean Free Path | 99 |
| 6.1 | Chemistry at Long Mean Free Path | 99 |
| | 6.1.1 Rates for CF ₄ | 100 |
| | 6.1.2 Rates at a Surface | 102 |
| | 6.1.3 Ion Chemistry | 103 |
| 6.2 | Ion Behavior Near the Surface and Evolution of Surface Features | 104 |
| 6.3 | Neutral Particle Kinetics at Surfaces | 106 |
| 6.4 | Neutral Particle Transport in a Trench | 108 |
| | 6.4.1 Computational Approach | 108 |
| | 6.4.2 Analytic Treatment of Neutral Transport in a Trench | 113 |
| | Exercises | 119 |

| | | |
|----------|--|------------|
| 7 | Evolution of the Trench | 121 |
| 7.1 | Evolution of the Trench | 121 |
| 7.1.1 | Etching by Neutrals | 121 |
| 7.2 | Computation of the Surface Shape | 126 |
| 7.3 | The Evolution of a Trench with Ion-Assisted Chemical Etching | 126 |
| 7.3.1 | Ion Motion in the Sheath | 127 |
| 7.4 | Charging of the Trench Walls | 131 |
| 7.4.1 | Electron and Ion Fluxes | 133 |
| 7.4.2 | Trench Electrostatics | 137 |
| 7.4.3 | Ion Motion in the Trench | 138 |
| 7.4.4 | Electron Motion in the Trench | 140 |
| | Exercises | 142 |
| 8 | Physical Description of the Plasma | 143 |
| 8.1 | Analytic Plasma Models | 143 |
| 8.1.1 | 1D Diffusion, Step Source | 143 |
| 8.1.2 | 2D Diffusion with “Simple” Sources | 145 |
| 8.1.3 | The Presheath | 147 |
| 8.1.4 | The Plasma Interior | 149 |
| 8.1.5 | Two-Dimensional Transport | 151 |
| 8.2 | Experimental Design | 154 |
| 8.2.1 | Measurements of Plasma Properties and Model Development | 157 |
| 8.3 | Computational Models of Plasmas | 158 |
| 8.3.1 | Fluid Models | 158 |
| 8.3.2 | Monte Carlo Simulations of Plasmas | 159 |
| 8.3.3 | Particle In Cell Simulations | 161 |
| 8.3.4 | PIC Simulation of an ECR Reactor | 164 |
| 8.3.5 | Hybrid Simulations | 165 |
| 8.3.6 | Construction of a Hybrid Simulation | 166 |
| 8.3.7 | Feedback in a Plasma Simulation | 167 |
| 8.3.8 | Direct Numerical Calculation of the Distribution Function | 168 |
| 8.3.9 | The Convected Scheme | 170 |
| 8.3.10 | Propagator for Diffusion | 175 |
| | Exercises | 177 |
| 9 | Going Further | 185 |
| 9.1 | Goals of Process Modeling | 186 |
| 9.2 | Detailed Description of Processing | 187 |
| 9.3 | Detailed Computations | 188 |
| | <i>Glossary</i> | 189 |
| | <i>Bibliography</i> | 205 |
| | <i>Index</i> | 213 |