

# List of Figures

Figure 1.1	Evolution of Materials Processing.....	3
Figure 1.2	Engineering materials via PVD. ....	4
Figure 1.3	Dissertation organization. ....	9
Figure 2.1	Multicrucible e-beam deposition. ....	14
Figure 2.2	Vapor distribution in an e-beam system.....	16
Figure 2.3	Vapor distribution in a high vacuum e-beam system. ....	22
Figure 2.4	Background gas pressure modifies vapor density distribution. ....	27
Figure 2.5	The effect of clustering upon deposited film morphology.....	34
Figure 2.6	Molecular beam deposition.....	35
Figure 2.7	Structure of a continuum free-jet. ....	38
Figure 2.8	Thornton's zone diagram. ....	47
Figure 2.9	Vacancy concentration as a function of adatom energy. ....	48
Figure 3.1	A preferred embodiment of Directed Vapor Deposition.....	51
Figure 4.1	Electron beam propagation in low vacuum. ....	62
Figure 4.2	Electron generating mechanism for the DVD evaporator.....	65
Figure 4.3	Overall e-beam gun configuration for DVD.....	66
Figure 4.4	A possible e-beam scanning pattern. ....	68
Figure 4.5	The electron beam system delivered from Germany. ....	69
Figure 4.6	Chamber design facilitated simultaneous use of multiple gas streams.....	73
Figure 4.7	Pathways for reactive material deposition in DVD. ....	74
Figure 4.8	DVD's unique crucible design. ....	75
Figure 4.9	Transfer of mechanical motion into the process chamber.....	77
Figure 4.10	A schematic showing the DVD system configuration.....	78
Figure 4.11	The graphical user interface developed for the DVD system. ....	86
Figure 4.12	Object-oriented programming for the DVD computer interface. ....	87
Figure 4.13	The assembled DVD system in the laboratory.....	89
Figure 5.1	The general DVD system configuration for all experiments described.....	91
Figure 5.2	Available processing range (Mach number vs. chamber pressure).....	93
Figure 5.3	Available processing range (Mach number vs. carrier gas flux). ....	94
Figure 5.4	Available processing range for argon / helium using a 1.27 cm nozzle.....	95
Figure 5.5	Initial system configuration for flow visualization.....	98
Figure 5.6	Gas flow structure. ....	101
Figure 5.7	Vapor entrainment into carrier gas fluxes. ....	104
Figure 5.8	Constant carrier gas flux. ....	107

---

Figure 5.9	Constant chamber pressure. ....	108
Figure 5.10	Effect of e-beam power variations in helium. ....	110
Figure 5.11	Effect of e-beam power variations in argon. ....	111
Figure 5.12	Flow interactions with substrates and crucible. ....	113
Figure 6.1	System configuration for material synthesis experiments. ....	117
Figure 6.2	An Auger electron spectroscopy scan of DVD deposited copper. ....	120
Figure 6.3	Optical absorption coefficient analysis of DVD deposited silicon. ....	122
Figure 7.1	The general dimensions of all deposition efficiency experiments. ....	130
Figure 7.2	Flat substrate deposition efficiency as a function of chamber pressure and Mach number. ....	134
Figure 7.3	Two distinct regions of material deposit for high gas flows. ....	139
Figure 7.4	Formation of a deposition halo at high gas flows. ....	141
Figure 7.5	The effect of e-beam power upon deposition efficiency. ....	143
Figure 7.6	Crucible to nozzle separation effects upon deposition efficiency. ....	148
Figure 7.7	Effect of initial vapor distribution upon deposition efficiency. ....	150
Figure 7.8	Material utilization efficiency during DVD fiber coating. ....	153
Figure 7.9	Evidence of non line-of-sight coating. ....	156
Figure 7.10	Vapor density distribution during transport. ....	157
Figure 7.11	Scenarios to explain the effect of clustering upon deposit appearance. ..	159
Figure 7.12	Cluster probability as a function of process conditions. ....	162
Figure 8.1	Vapor transport modeling of DVD. ....	167
Figure 8.2	A flowchart summary of Bird's DSMC code. ....	171
Figure 8.3	An overlay of the DSMC modeling grid onto the experimental setup. ...	172
Figure 8.4	Specifications for the DSMC modeling grid. ....	172
Figure 8.5	The computational flow of the BCT code. ....	178
Figure 8.6	Calculation of the initial vapor atom trajectory. ....	180
Figure 8.7	Spatial distribution of deposited vapor. ....	181
Figure 8.8	Impact parameter / deflection angle vs. energy of collision event. ....	185
Figure 8.9	Log-linear fits for $\chi_{\text{cutoff}}$ . ....	190
Figure 8.10	Summary of steps required to determine atomic mean free path $\lambda$ . ....	190
Figure 8.11	Parameters factoring into a collision calculation. ....	193
Figure 8.12	Determination of the post-collision velocity vector. ....	194
Figure 8.13	Steps to compute new vapor atom velocity vector after a collision. ....	196
Figure 9.1	Comparison of flowfield simulation with experimental result. ....	199
Figure 9.2	Random walk on an atomic surface. ....	201
Figure 9.3	Persistent random walk during vapor phase diffusion. ....	203

---

Figure 9.4	Pure vs. persistent random walk. ....	204
Figure 9.5	Energy distribution of atoms leaving a sputtering target. ....	206
Figure 9.6	Energy loss at 2.5 cm. ....	207
Figure 9.7	Energy loss at 5.0 cm. ....	208
Figure 10.1	Vapor atom transport at low chamber pressure. ....	214
Figure 10.2	Vapor atom transport at intermediate chamber pressure. ....	215
Figure 10.3	Vapor atom transport at high chamber pressure. ....	216
Figure 10.4	Vapor atom energy during transport. ....	219
Figure 10.5	Vapor atom orientation during transport. ....	221
Figure 10.6	Flowfield temperature profile at intermediate chamber pressure. ....	222
Figure 10.7	Chamber pressure variation at intermediate pressure. ....	223
Figure 10.8	Predicted deposition efficiency trends with chamber pressure. ....	224
Figure 10.9	Effect of dilute limit approximation upon modeling results. ....	227
Figure 10.10	Distributions of impact energies for various conditions. ....	229
Figure 10.11	Distributions of impact angle for various conditions. ....	230
Figure 10.12	Simulated vapor distributions. ....	232
Figure 10.13	Line scans across simulated thickness profiles. ....	233
Figure 11.1	A reconfigured DVD system. ....	236
Figure 11.2	Grid for modeling of reconfigured system. ....	239
Figure 11.3	Close-up of reconfigured system. ....	240
Figure 11.4	Simulation of vapor transport in the reconfigured system. ....	241
Figure 11.5	Nozzle geometry can affect gas focus. ....	244
Figure 12.1	Multicrucible vapor stream mixing in DVD. ....	254
Figure A.1	Wehnelt cup assembly which generates the e-beam. ....	276
Figure A.2	Overview drawing of traditional components of DVD e-beam gun. ....	277
Figure A.3	Beam Generating Assembly, top portion of DVD e-beam gun. ....	278
Figure A.4	Beam Guidance System, center section of DVD e-beam gun. ....	279
Figure A.5	Pressure Decoupling Chamber, bottom section of DVD e-beam gun. ....	280
Figure A.6	Stainless steel processing chamber with 2.54 cm thick walls. ....	281
Figure A.7	Specially designed DVD water-cooled crucible. ....	282
Figure A.8	Estimation of chamber pumping requirements. ....	284
Figure A.9	Achievable gas flow velocity for various pumping configurations. ....	285
Figure B.1	Cluster size as a function of time. ....	286
Figure E.1	Distribution of Ti-6-4 on substrate located directly above evaporant. ....	350
Figure E.2	Ti-6-4 distribution on substrate directly above evaporant. ....	350