

Contents

	<i>Preface</i>	<i>page xv</i>
1	Thin-film applications to microelectronic technology	1
	1.1 Introduction	1
	1.2 Metal-oxide-semiconductor field-effect-transistor (MOSFET) devices	1
	1.2.1 Self-aligned silicide (salicide) contacts and gate	5
	1.3 Thin-film under-bump-metallization in flip-chip technology	7
	1.4 Why do we seldom encounter reliability failure in our computers?	11
	1.5 Trend and transition from micro to nano electronic technology	11
	1.6 Impact on microelectronics as we approach the end of Moore's law	12
	References	12
2	Thin-film deposition	14
	2.1 Introduction	14
	2.2 Flux equation in thin-film deposition	15
	2.3 Thin-film deposition rate	17
	2.4 Ideal gas law	17
	2.5 Kinetic energy of gas molecules	19
	2.6 Thermal equilibrium flux on a surface	20
	2.7 Effect of ultrahigh vacuum on the purity of the deposited film	20
	2.8 Frequency of collision of gas molecules	21
	2.9 Boltzmann's velocity distribution function and ideal gas law	22
	2.10 Maxwell's velocity distribution function and kinetic energy of gas molecules	24
	2.11 Parameters of nucleation and growth that affect the microstructure of thin films	26
	References	28
	Problems	28
3	Surface energies	30
	3.1 Introduction	30
	3.2 Pair potential energy, bond energy, and binding energy	31

viii	Contents		
	3.3	Short-range interaction and quasi-chemical assumption	33
	3.4	Surface energy and latent heat	35
	3.5	Surface tension	36
	3.6	Liquid surface energy measurement by capillary effect	38
	3.7	Solid surface energy measurement by zero creep	41
	3.8	Surface energy systematics	44
	3.9	Magnitudes of surface energies	46
	3.9.1	Thermodynamic approach	46
	3.9.2	Mechanical approach	46
	3.9.3	Atomic approach	49
	3.10	Surface structure	51
	3.10.1	Crystallography and notation	51
	3.10.2	Directions and planes	54
	3.10.3	Surface reconstruction	54
		References	56
		Problems	57
4		Atomic diffusion in solids	60
	4.1	Introduction	60
	4.2	Jump frequency and diffusional flux	61
	4.3	Fick's first law (flux equation)	64
	4.4	Diffusivity	65
	4.5	Fick's second law (continuity equation)	66
	4.5.1	Derivation of the continuity equation	69
	4.6	A solution of the diffusion equation	71
	4.7	Diffusion coefficient	73
	4.8	Calculation of the diffusion coefficient	74
	4.9	Parameters in the diffusion coefficient	76
	4.9.1	Atomic vibrational frequency	76
	4.9.2	Activation enthalpy	79
	4.9.3	The pre-exponential factor	81
		References	83
		Problems	84
5		Applications of the diffusion equation	86
	5.1	Introduction	86
	5.2	Application of Fick's first law (flux equation)	87
	5.2.1	Zener's growth model of a planar precipitate	87
	5.2.2	Kidson's analysis of planar growth in layered thin films	89
	5.3	Applications of Fick's second law (diffusion equation)	93
	5.3.1	Effect of diffusion on composition homogenization	93
	5.3.2	Interdiffusion in a bulk diffusion couple	95
	5.4	Analysis of growth of a solid precipitate	108

Contents

ix

	5.4.1	Ham's model of growth of a spherical precipitate (C_r is constant)	109
	5.4.2	Mean-field consideration	112
	5.4.3	Growth of a spherical nanoparticle by ripening	113
		References	116
		Problems	117
6		Elastic stress and strain in thin films	118
	6.1	Introduction	118
	6.2	Elastic stress–strain relationship	120
	6.3	Strain energy	123
	6.4	Biaxial stress in thin films	124
	6.5	Stoney's equation of biaxial stress in thin films	127
	6.6	Measurement of thermal stress in Al thin films	131
	6.7	Application of Stoney's equation to thermal expansion measurement	133
	6.8	Anharmonicity and thermal expansion	134
	6.9	The origin of intrinsic stress in thin films	134
	6.10	Elastic energy of a misfit dislocation	135
		References	138
		Problems	138
7		Surface kinetic processes on thin films	141
	7.1	Introduction	141
	7.2	Adatoms on a surface	143
	7.3	Equilibrium vapor pressure above a surface	145
	7.4	Surface diffusion	146
	7.5	Step-mediated growth in homoepitaxy	149
	7.6	Deposition and growth of an amorphous thin film	152
	7.7	Growth modes of homoepitaxy	153
	7.8	Homogeneous nucleation of a surface disc	155
	7.9	Mass transport on a patterned surface	159
		7.9.1 Early stage of diffusion on a patterned surface	159
		7.9.2 Later stage of mass transport on a patterned structure	161
	7.10	Ripening of a hemispherical particle on a surface	163
		References	167
		Problems	167
8		Interdiffusion and reaction in thin films	170
	8.1	Introduction	170
	8.2	Silicide formation	172
		8.2.1 Sequential Ni silicide formation	172
		8.2.2 First phase in silicide formation	178
	8.3	Kinetics of interfacial-reaction-controlled growth in thin-film reactions	180
	8.4	Kinetics of competitive growth of two-layered phases	185

x	Contents	
	8.5	Marker analysis in intermetallic compound formation 186
	8.6	Reaction of a monolayer of metal and a Si wafer 189
		References 189
		Problems 190
9	Grain-boundary diffusion	192
	9.1	Introduction 192
	9.2	Comparison of grain-boundary and bulk diffusion 194
	9.3	Fisher's analysis of grain-boundary diffusion 197
	9.3.1	Penetration depth 200
	9.3.2	Sectioning 200
	9.4	Whipple's analysis of grain-boundary diffusion 202
	9.5	Diffusion in small-angle grain boundaries 206
	9.6	Diffusion-induced grain-boundary motion 207
		References 209
		Problems 210
10	Irreversible processes in interconnect and packaging technology	212
	10.1	Introduction 212
	10.2	Flux equations 214
	10.3	Entropy generation 216
	10.3.1	Heat conduction 217
	10.3.2	Atomic diffusion 218
	10.3.3	Electrical conduction 218
	10.4	Conjugate forces with varying temperature 220
	10.4.1	Atomic diffusion 221
	10.4.2	Electrical conduction 222
	10.5	Joule heating 222
	10.6	Electromigration, thermomigration, and stress-migration 223
	10.7	Irreversible processes in electromigration 225
	10.7.1	Electromigration and creep in Al strips 226
	10.8	Irreversible processes in thermomigration 229
	10.8.1	Thermomigration in unpowered composite solder joints 229
	10.9	Irreversible processes in thermo-electric effects 232
	10.9.1	Thomson effect and Seebeck effect 233
	10.9.2	Peltier effect 235
		References 235
		Problems 235
11	Electromigration in metals	237
	11.1	Introduction 237
	11.2	Ohm's law 242

Contents

xi

11.3	Electromigration in metallic interconnects	243
11.4	Electron wind force of electromigration	246
11.5	Calculation of the effective charge number	249
11.6	Effect of back stress and measurement of critical length, critical product, and effective charge number	251
11.7	Why is there back stress in an Al interconnect?	252
11.8	Measurement of back stress induced by electromigration	254
11.9	Current crowding	256
11.10	Current density gradient force of electromigration	259
11.11	Electromigration in an anisotropic conductor of beta-Sn	261
11.12	Electromigration of a grain boundary in anisotropic conductor	264
11.13	AC electromigration	266
	References	267
	Problems	268
12	Electromigration-induced failure in Al and Cu interconnects	270
12.1	Introduction	270
12.2	Electromigration-induced failure due to atomic flux divergence	271
12.3	Electromigration-induced failure due to electric current crowding	271
12.3.1	Void formation in the low-current density region	272
12.4	Electromigration-induced failure in Al interconnects	276
12.4.1	Effect of microstructure in Al on electromigration	276
12.4.2	Wear-out failure mode in multilayered Al lines and W vias	277
12.4.3	Solute effect of Cu on electromigration in Al	277
12.4.4	Mean-time-to-failure in Al interconnects	277
12.5	Electromigration-induced failure in Cu interconnects	279
12.5.1	Effect of microstructure on electromigration	281
12.5.2	Effect of solute on electromigration	282
12.5.3	Effect of stress on electromigration	285
12.5.4	Effect of nanotwins on electromigration	286
	References	287
	Problems	288
13	Thermomigration	289
13.1	Introduction	289
13.2	Thermomigration in flip-chip solder joints of SnPb	291
13.2.1	Thermomigration in unpowered composite solder joints	291
13.2.2	In-situ observation of thermomigration	292
13.2.3	Random states of phase separation in the two-phase eutectic structure	293
13.2.4	Thermomigration in unpowered eutectic SnPb solder joints	295
13.3	Analysis of thermomigration	298
13.3.1	Driving force of thermomigration	299

xii	Contents	
	13.3.2 Thermomigration in eutectic two-phase alloys	301
	13.4 Thermomigration under DC or AC stressing in flip-chip solder joints	302
	13.5 Thermomigration in Pb-free flip-chip solder joints	303
	13.6 Thermomigration and creep in Pb-free flip-chip solder joints	304
	References	306
	Problems	307
14	Stress migration in thin films	309
	14.1 Introduction	309
	14.2 Chemical potential in a stressed solid	311
	14.3 Diffusional creep (Nabarro–Herring equation)	313
	14.4 Void growth in Al interconnects driven by tensile stress	317
	14.5 Whisker growth in Sn/Cu thin films driven by compressive stress	319
	14.5.1 Morphology of spontaneous Sn whisker growth	319
	14.5.2 Stress generation (driving force) in Sn whisker growth	323
	14.5.3 Effect of surface Sn oxide on stress-gradient generation	325
	14.5.4 Measurement of stress distribution by synchrotron radiation micro-diffraction	328
	14.5.5 Stress relaxation by creep: broken oxide model in Sn whisker growth	332
	References	334
	Problems	335
15	Reliability science and analysis	336
	15.1 Introduction	336
	15.2 Constant volume and non-constant volume processes	337
	15.3 Effect of lattice shift on divergence of mass flux in irreversible processes	338
	15.3.1 Initial distribution of current density, temperature, and chemical potential in a device structure before operation	338
	15.3.2 Change of the distributions during device operation	340
	15.3.3 Effect of lattice shift on divergence of mass flux	341
	15.4 Physical analysis of electromigration failure in flip-chip solder joints	341
	15.4.1 Distribution of current density in a pair of joints	342
	15.4.2 Distribution of temperature in a pair of joints	343
	15.4.3 Effect of current crowding on pancake-type void growth	346
	15.5 Statistical analysis of electromigration failure in flip-chip solder joints	350
	15.5.1 Time-to-failure and Weibull distribution	353
	15.5.2 To calculate the parameters in Black's MTTF equation	355
	15.5.3 Modification of Black's equation for flip-chip solder joints	357
	15.5.4 Weibull distribution function and JMA theory of phase transformations	359

Contents

xiii

15.5.5 Physical analysis of statistical distribution of failure	360
15.6 Simulation	361
References	361
Problems	362
<i>Appendix A: A brief review of thermodynamic functions</i>	363
<i>Appendix B: Defect concentration in solids</i>	366
<i>Appendix C: Derivation of Huntington's electron wind force</i>	368
<i>Appendix D: Elastic constants tables and conversions</i>	373
<i>Appendix E: Terrace size distribution in Si MBE</i>	380
<i>Appendix F: Interdiffusion coefficient</i>	385
<i>Appendix G: Tables of physical properties</i>	388
<i>Index</i>	392