

Contents

<i>List of contributors</i>	<i>page</i>	<i>xiii</i>
<i>Preface</i>		xv
Part I Introduction		1
1 Fabless silicon photonics		3
1.1 Introduction		3
1.2 Silicon photonics: the next fabless semiconductor industry		5
1.2.1 Historical context – Photonics		6
1.3 Applications		7
1.3.1 Data communication		8
1.4 Technical challenges and the state of the art		10
1.4.1 Waveguides and passive components		10
1.4.2 Modulators		12
1.4.3 Photodetectors		13
1.4.4 Light sources		14
1.4.5 Approaches to photonic–electronic integration		15
Monolithic integration		15
Multi-chip integration		16
1.5 Opportunities		17
1.5.1 Device engineering		17
1.5.2 Photonic system engineering		17
A transition from devices to systems		18
1.5.3 Tools and support infrastructure		19
Electronic–photonic co-design		19
DFM and yield management		20
1.5.4 Basic science		20
1.5.5 Process standardization and a history of MPW services		20
ePIXfab and Europractice		21
IME		21
OpSIS		21
CMC Microsystems		22
Other organizations		22
References		22

2	Modelling and design approaches	28
2.1	Optical waveguide mode solver	28
2.2	Wave propagation	31
2.2.1	3D FDTD	31
	FDTD modelling procedure	32
2.2.2	2D FDTD	35
2.2.3	Additional propagation methods	36
	2D FDTD with Effective Index Method	36
	Beam Propagation Method (BPM)	37
	Eigenmode Expansion Method (EME)	37
	Coupled Mode Theory (CMT)	38
	Transfer Matrix Method (TMM)	38
2.2.4	Passive optical components	38
2.3	Optoelectronic models	39
2.4	Microwave modelling	39
2.5	Thermal modelling	40
2.6	Photonic circuit modelling	40
2.7	Physical layout	41
2.8	Software tools integration	42
	References	43
Part II	Passive components	47
3	Optical materials and waveguides	49
3.1	Silicon-on-insulator	49
3.1.1	Silicon	49
	Silicon – wavelength dependence	50
	Silicon – temperature dependence	50
3.1.2	Silicon dioxide	51
3.2	Waveguides	51
3.2.1	Waveguide design	53
3.2.2	1D slab waveguide – analytic method	53
3.2.3	Numerical modelling of waveguides	53
3.2.4	1D slab – numerical	54
	Convergence tests	55
	Parameter sweep – slab thickness	57
3.2.5	Effective Index Method	57
3.2.6	Effective Index Method – analytic	59
3.2.7	Waveguide mode profiles – 2D calculations	60
3.2.8	Waveguide width – effective index	63
3.2.9	Wavelength dependence	65

	3.2.10 Compact models for waveguides	66
	3.2.11 Waveguide loss	69
3.3	Bent waveguides	69
	3.3.1 3D FDTD bend simulations	70
	3.3.2 Eigenmode bend simulations	73
3.4	Problems	75
3.5	Code listings	77
	References	89
4	Fundamental building blocks	92
4.1	Directional couplers	92
4.1.1	Waveguide mode solver approach	93
	Coupler-gap dependence	94
	Coupler-length dependence	95
	Wavelength dependence	95
4.1.2	Phase	96
4.1.3	Experimental data	99
4.1.4	FDTD modelling	102
	FDTD versus mode solver	102
4.1.5	Sensitivity to fabrication	103
4.1.6	Strip waveguide directional couplers	105
4.1.7	Parasitic coupling	106
	Delta beta coupling	108
4.2	Y-branch	110
4.3	Mach–Zehnder interferometer	113
4.4	Ring resonators	115
	4.4.1 Optical transfer function	115
	4.4.2 Ring resonator experimental results	117
4.5	Waveguide Bragg grating filters	117
4.5.1	Theory	117
	Grating coupling coefficient	120
4.5.2	Design	120
	Transfer Matrix Method	121
	Grating physical structure design	123
	Modelling gratings using FDTD	125
4.5.3	Experimental Bragg gratings	126
	Strip waveguide gratings	127
	Rib waveguide gratings	128
	Grating period	129
4.5.4	Empirical models for fabricated gratings	130
	Computation lithography models	134
	Additional fabrication considerations	136

4.5.5	Spiral Bragg gratings	137
	Thermal sensitivity	138
4.5.6	Phase-shifted Bragg gratings	138
4.5.7	Multi-period Bragg gratings	140
4.5.8	Grating-assisted contra-directional couplers	141
4.6	Problems	143
4.7	Code listings	144
	References	159
5	Optical I/O	162
5.1	The challenge of optical coupling to silicon photonic chips	162
5.2	Grating coupler	163
5.2.1	Performance	164
5.2.2	Theory	165
5.2.3	Design methodology	168
	Analytic grating coupler design	169
	Design using 2D FDTD simulations	170
	Results	172
	Design parameters	173
	Cladding and buried oxide	177
	Compact design – focusing	179
	Mask layout	180
	3D simulation	181
5.2.4	Experimental results	181
5.3	Edge coupler	182
5.3.1	Nano-taper edge coupler	183
	Mode overlap calculation approach	183
	FDTD approach	187
5.3.2	Edge coupler with overlay waveguide	189
	Eigenmode expansion method	189
5.4	Polarization	190
5.5	Problems	193
5.6	Code listings	193
	References	211
Part III	Active components	215
6	Modulators	217
6.1	Plasma dispersion effect	217
6.1.1	Silicon, carrier density dependence	217
6.2	pn-Junction phase shifter	218
6.2.1	pn-Junction carrier distribution	218
6.2.2	Optical phase response	221

6.2.3	Small-signal response	223
6.2.4	Numerical TCAD modelling of pn-junctions	224
6.3	Micro-ring modulators	226
6.3.1	Ring tuneability	227
6.3.2	Small-signal modulation response	228
6.3.3	Ring modulator design	231
6.4	Forward-biased PIN junction	232
6.4.1	Variable optical attenuator	232
6.5	Active tuning	234
6.5.1	PIN phase shifter	235
6.5.2	Thermal phase shifter	236
6.6	Thermo-optic switch	240
6.7	Problems	241
6.8	Code listings	242
	References	257
7	Detectors	259
7.1	Performance parameters	259
7.1.1	Responsivity	259
7.1.2	Bandwidth	260
	Transit time	260
	RC response	261
	Dark current	262
7.2	Fabrication	264
7.3	Types of detectors	266
7.3.1	Photoconductive detector	266
7.3.2	PIN detector	267
7.3.3	Avalanche detector	268
	Charge region design	270
7.4	Design considerations	271
7.4.1	PIN junction orientation	271
7.4.2	Detector geometry	272
	Detector length	272
	Detector width	272
	Detector height	272
7.4.3	Contacts	273
	Contact material	273
	Contact geometry	274
7.4.4	External load on the detector	275
7.5	Detector modelling	275
7.5.1	3D FDTD optical simulations	276
7.5.2	Electronic simulations	279
7.6	Problems	282

7.7	Code listings	283
	References	292
8	Lasers	295
8.1	External lasers	295
8.2	Laser modelling	296
8.3	Co-packaging	299
8.3.1	Pre-made laser	299
8.3.2	External cavity lasers	300
8.3.3	Etched-pit embedded epitaxy	301
8.4	Hybrid silicon lasers	301
8.5	Monolithic lasers	303
8.5.1	III–V Monolithic growth	303
8.5.2	Germanium lasers	304
8.6	Alternative light sources	306
8.7	Problem	307
	References	307
Part IV	System design	311
9	Photonic circuit modelling	313
9.1	Need for photonic circuit modelling	313
9.2	Components for system design	314
9.3	Compact models	314
9.3.1	Empirical or equivalent circuit models	316
9.3.2	S-parameters	317
9.4	Directional coupler – compact model	318
9.4.1	FDTD simulations	318
9.4.2	FDTD S-parameters	320
	Directional coupler S-parameters	321
9.4.3	Empirical model – polynomial	323
9.4.4	S-parameter model passivity	324
	Passivity assessment	324
	Passivity enforcement	325
9.5	Ring modulator – circuit model	330
9.6	Grating coupler – S-parameters	330
9.6.1	Grating coupler circuits	333
9.7	Code listings	333
	References	348
10	Tools and techniques	349
10.1	Process design kit (PDK)	349

10.1.1	Fabrication process parameters	352
	Silicon thickness and etch	352
	GDS layer map	352
	Design rules	352
10.1.2	Library	352
10.1.3	Schematic capture	353
10.1.4	Circuit export	355
10.1.5	Schematic-driven layout	356
10.1.6	Design rule checking	360
10.1.7	Layout versus schematic	361
10.2	Mask layout	362
10.2.1	Components	362
10.2.2	Layout for electrical and optical testing	362
10.2.3	Approaches for fast GDS layout	364
10.2.4	Approaches for space-efficient GDS layout	364
	References	366
11	Fabrication	368
11.1	Fabrication non-uniformity	368
11.1.1	Lithography process contours	369
11.1.2	Corner analysis	370
11.1.3	On-chip non-uniformity, experimental results	372
	Ring resonators	373
	Grating couplers	377
11.2	Problems	379
	References	380
12	Testing and packaging	381
12.1	Electrical and optical interfacing	381
12.1.1	Optical interfaces	381
	Grating couplers	381
	Edge couplers	382
	Individual fibres	382
	Spot-size converter	383
	Fibre array	384
	Free-space coupling	385
	Fibre taper coupling	386
12.1.2	Electrical interfaces	386
	Bond pads	386
	Probing	387
	Wire bonding	388
	Flip-chip bonding	388
12.2	Automated optical probe stations	389

12.2.1	Parts	391
	Sample stage	391
	Fibre array probe	392
	Electrical probes	393
	Microscopes	393
12.2.2	Software	393
12.2.3	Operation	394
	Loading and aligning a chip/wafer	395
	Aligning the fibre array	395
	Chip registration	396
	Automated device testing	396
12.2.4	Optical test equipment	397
12.3	Design for test	398
	12.3.1 Optical power budgets	400
	12.3.2 Layout considerations	401
	12.3.3 Design review and checklist	402
	References	404
13	Silicon photonic system example	406
13.1	Wavelength division multiplexed transmitter	406
	13.1.1 Ring-based WDM transmitter architectures	406
	13.1.2 Common-bus WDM transmitter	408
	13.1.3 Mod-Mux WDM transmitter	410
	13.1.4 Conclusion	411
	References	412
	<i>Index</i>	414