

**Advanced Silicon and Semiconducting
Silicon-Alloy Based Materials
and Devices**

Edited by
Johan F A Nijs
IMEC, Belgium

Institute of Physics Publishing
Bristol and Philadelphia

Contents

Preface	xv
Introduction	xvii
Figure acknowledgments	xxi
Part One: Single Crystalline Silicon and its Alloys	1
1 Heavy Doping Effects in Silicon	3
<i>P Van Mieghem and R P Mertens</i>	
1.1 Introduction	3
1.2 The physics of heavy doping effects	4
1.2.1 Electron-impurity interactions	5
1.2.2 Electron-electron interactions	5
1.3 Brief review of heavy doping effects	8
1.3.1 Theory	8
1.3.2 Experiments	10
1.4 Theories and models	12
1.4.1 The Fermi level shift due to heavy doping effects: formal description	12
1.4.2 The many body description of a heavily doped semiconductor	14
1.4.3 BGN theories	19
1.4.4 Bandtail theories	25
1.5 Influence of HDE on silicon devices	27
1.5.1 Modification of the minority carrier transport equation	27
1.5.2 Influence of HDE on a bipolar transistor	28
1.5.3 Influence of HDE on a solar cell	29
1.5.4 Influence of HDE on a Si MOSFET	29
1.6 Summary	30
1.7 References	30

2	Defects in Crystalline Silicon	35
	<i>C Claeys and J Vanhellemont</i>	
2.1	Introduction	35
2.2	Structure of lattice defects	35
2.2.1	Semiconductor silicon: crystal structure and physical properties	35
2.2.2	Intrinsic and extrinsic point defects	36
2.2.3	Clustering of point defects: pairing	45
2.2.4	Line defect: dislocation	47
2.2.5	Planar defects: twins and stacking faults	58
2.2.6	Volume defects: precipitates	61
2.3	Electronic properties of defects	65
2.3.1	Donor and acceptor properties	65
2.3.2	Minority carrier lifetime	69
2.3.3	Optical properties	71
2.4	Device processing related defects	75
2.4.1	Grown-in defects	75
2.4.2	Stress-induced defect generation	77
2.5	Metallic contamination and gettering	87
2.6	Impact on device properties	93
2.7	References	97
3	Molecular Beam Epitaxy of Silicon, Silicon Alloys, and Metals	103
	<i>E Kasper and C M Falco</i>	
3.1	Introduction	103
3.2	Electron beam evaporators and metals MBE	103
3.2.1	Recent developments in metals MBE	106
3.2.2	Some prospects for the near future	113
3.3	Silicon molecular beam epitaxy (Si-MBE)	117
3.3.1	Surface cleanliness as key for high quality material	119
3.3.2	The doping problem	126
3.3.3	Differences from III/V MBE	128
3.3.4	Heteroepitaxy	129
3.4	Applications of silicon MBE	132
3.4.1	MBE for clean surface studies	132
3.4.2	Future electronic systems: will MBE be the key technology for realization?	133
3.5	References	134
4	Low Thermal Budget Chemical Vapour Deposition Techniques for Si and SiGe	141
	<i>M R Caymax and W Y Leong</i>	
4.1	Introduction	141

4.2	Prerequisites for low-temperature growth	142
4.3	Growth systems	147
4.3.1	Ultra high vacuum chemical vapour deposition (UHVCVD)	147
4.3.2	Limited reaction processing—rapid thermal CVD	151
4.3.3	Other techniques	155
4.4	Kinetics of CVD growth of Si and SiGe in SiH ₄ /GeH ₄ systems	158
4.4.1	Introduction	158
4.4.2	Kinetics of the silane system	159
4.4.3	Kinetics of the silane germane system	162
4.5	Doping of low temperature Si and Si _{1-x} Ge _x layers	164
4.5.1	p-type doping	164
4.5.2	n-type doping	165
4.6	Selective epitaxial growth (SEG) of Si and SiGe	167
4.6.1	Growth in chlorine-free ambience	168
4.6.2	Growth in chlorine-containing ambience	169
4.7	In-situ and ex-situ characterisation	170
4.7.1	Laser light scattering (LLS)	170
4.7.2	Spectroscopic ellipsometry	172
4.7.3	Modulation spectroscopy (photo-reflectance and electro-reflectance)	173
4.7.4	Photoluminescence	174
	References	177
5	Materials Properties of (Strained) SiGe Layers	185
	<i>J Poortmans, S C Jain, J Nijs and R Van Overstraeten</i>	
5.1	Introduction	185
5.2	Structure and stability	187
5.2.1	Critical layer thickness	187
5.2.2	Equilibrium strain relaxation in thicker layers	191
5.2.3	Strain relaxation in metastable layers	192
5.3	The Si-strained SiGe band alignments	194
5.3.1	Experimental results	194
5.3.2	Theoretical calculations and experimental validation	196
5.3.3	Heavy-doping effects on the band offset's	199
5.4	The indirect bandgap of strained Si _{1-x} Ge _x	201
5.5	Transport properties and effective density of states in strained Si _{1-x} Ge _x layers	203
5.5.1	Changes in the valence band and their influence on hole mobility	204
5.5.2	Changes in the conduction band and its influence on the electron mobility	207
5.6	References	211

6	SiGe Heterojunction Bipolar Applications	215
	<i>J Poortmans, S C Jain and J Nijs</i>	
6.1	Introduction	215
6.2	DC-behaviour of the double heterojunction bipolar transistor	218
6.2.1	Factors determining the enhancement of the injection efficiency in an HBT with strained $\text{Si}_{1-x}\text{Ge}_x$ -base	218
6.2.2	Parasitic barriers and graded-base HBT's	224
6.2.3	Neutral base recombination	228
6.2.4	Early voltage-current gain product of double-barrier HBT's	230
6.3	Frequency and circuit performance of HBT's with strained $\text{Si}_{1-x}\text{Ge}_x$ -base	232
6.3.1	The different contributions to the emitter-collector transit time	232
6.3.2	The strained $\text{Si}_{1-x}\text{Ge}_x$ -base HBT as a switching element	238
6.4	Incorporation of strained $\text{Si}_{1-x}\text{Ge}_x$ -layers in advanced bipolar technologies	240
6.4.1	Introduction	240
6.4.2	Perimeter and surface passivation	241
6.4.3	Emitter formation in strained $\text{Si}_{1-x}\text{Ge}_x$ HBT's	242
6.4.4	HBT's and selective deposition schemes of $\text{Si}_{1-x}\text{Ge}_x$ -alloys	245
6.5	Conclusions	246
6.6	References	247
7	Field-Effect Transistors, Infrared Detectors, and Resonant Tunneling Devices in Silicon/Silicon-Germanium and δ-Doped Silicon	251
	<i>M Willander</i>	
7.1	Introduction	251
7.2	Field-effect transistors	252
7.2.1	Silicon/Silicon-Germanium	252
7.2.2	δ -doped field-effect transistors	259
7.3	Infrared detectors	263
7.3.1	p-i-n detectors	263
7.3.2	Heterojunction internal photoemission detectors	265
7.3.3	Intersubband absorption detectors	269
7.4	Resonant tunneling devices	271
7.4.1	Resonant tunneling diodes	271
7.4.2	Resonant tunneling transistors	279
7.5	Summary	279
	References	280

8	Crystalline Silicon-Carbide and its Applications	283
	<i>T Sugii</i>	
8.1	Introduction	283
8.2	Physical properties	284
8.3	Crystalline SiC growth	286
8.3.1	3C-SiC growth	286
8.3.2	α -SiC growth	297
8.3.3	Polycrystalline SiC growth	300
8.4	Device application	303
8.4.1	3C-SiC/Si heterojunction bipolar transistor (HBT)	303
8.4.2	Pn junctions, Schottky diodes, and FETs	308
8.4.3	Light emitting diodes (LEDs) and detectors	315
8.5	Summary	316
	References	316
 Part Two: Polycrystalline Silicon		 321
9	Large Grain Polysilicon Substrates for Solar Cells	323
	<i>S Martinuzzi and S Pizzini</i>	
9.1	Introduction	323
9.2	Growth of polycrystalline (multicrystalline) silicon	324
9.3	The role of oxygen, carbon and point defects in polycrystalline silicon	332
9.4	Electrical properties of multicrystalline silicon wafers	339
9.4.1	Influence of defects and impurities	339
9.4.2	Improvement techniques	345
9.5	Conclusion	355
9.6	References	357
 10	 Properties, Analysis and Modelling of Polysilicon TFTs	 361
	<i>P Migliorato and M Quinn</i>	
10.1	Introduction	361
10.2	Structural properties and density of states	363
10.3	Effect of the DOS on the I-V characteristics	365
10.4	Current-voltage characteristics	371
10.5	Capacitance voltage characteristics	373
10.6	Electric field at the drain and 'kink' effect	376
10.7	Conclusions	378

10.8	Appendix	379
10.8.1	List of symbols	379
10.8.2	Relationship between ψ_s , F_s , G , V_{GS}	380
10.8.3	Determination of the DOS	383
10.9	References	385
11	Application and Technology of Polysilicon Thin Film Transistors for Liquid Crystal Displays	387
	<i>C Baert</i>	
11.1	Introduction	387
11.2	Applications of polysilicon thin film transistors	388
11.2.1	Principles of TFT-LCD displays	388
11.2.2	Requirement for driver and pixel thin film transistors	390
11.2.3	Direct view and projection displays	391
11.3	Technology of polysilicon thin films	393
11.3.1	Requirements for polysilicon thin films	393
11.3.2	Direct deposition of polysilicon thin films	393
11.3.3	Solid phase crystallisation of polysilicon thin films	395
11.3.4	Laser crystallisation of polysilicon thin films	399
11.3.5	Decrease of polysilicon thin film defect density	402
11.4	Polysilicon TFT device structure	404
11.4.1	Standard coplanar TFT process	404
11.4.2	Low leakage TFT structures	406
11.5	Summary	408
11.6	References	409
12	The Use of Polycrystalline Silicon and its Alloys in VLSI Applications	413
	<i>M Y Ghannam</i>	
12.1	Introduction	413
12.2	Deposition and structural properties of polysilicon	414
12.3	Technological properties of LPCVD polysilicon films	416
12.3.1	Polysilicon doping	416
12.3.2	Polysilicon as a diffusion source	416
12.3.3	Polysilicon oxidation	418
12.3.4	Polysilicon etching	419
12.4	Electrical properties of polysilicon	420
12.4.1	Resistivity of doped polysilicon	420
12.4.2	Minority carrier lifetime and recombination properties	422

12.5	VLSI applications of polysilicon	422
12.5.1	Polysilicon as a material for MOS gate electrodes	422
12.5.2	Polysilicon interconnects	425
12.5.3	Polysilicon in memories	425
12.5.4	Polysilicon diodes	430
12.5.5	Polysilicon thin film resistors	430
12.5.6	Polysilicon in bipolar technology	431
12.5.7	Polysilicon in BiCMOS processes	437
12.5.8	Polysilicon fuses and anti-fuses	437
12.5.9	Polysilicon as a useful material in IC technology	438
12.6	Other applications of polysilicon	438
12.6.1	Polysilicon in power IC's	438
12.6.2	Polysilicon sensors, microstructures and vacuum applications	439
12.7	Semi-insulating polycrystalline silicon (SIPOS)	439
12.8	Polycrystalline silicon/germanium alloys	441
	References	441
	Biographical Details	447
	Keyword Index	457