Table of Contents

Preface i

Resumen v

Resum vii

Abstract ix

Table of Contents xi

Introduction: Challenges and Opportunities for Silicon Photonics xv

1. Physics Background 1

1.1 Fundamentals on Solid State Physics 1

1.1.1 Wigner-Seitz and Brillouin zones 1

1.1.2 Bloch theorem and band structure 3

1.1.3 Doping silicon 6

1.2 pn Junction Theory 8

1.2.1 Forming a pn junction in silicon 8

1.2.2 pn Junction in equilibrium state 8

1.2.3 pn junction under an applied electric field 11

1.2.4 Ideal current-voltage characteristics: Shockley's equation 13

1.2.5 Fabrication process of pn junctions 16

1.3 Fundamentals of Light Propagation in Optical Waveguides 17

1.3.1 Ray optics approach 17

1.3.2 Extension of the ray optics approach 18

1.3.3 Electromagnetic approach 21

1.3.4 Conclusion 22

2. Optical Modulators 23

2.1 What is an Optical Modulator? 23

2.1.1 Introduction and background 23

2.1.2 Amplitude modulator main parameters 25

2.1.3 Amplitude modulator basic parameter calculation 28

2.1.4 Conclusion 33

2.2 Silicon as an Efficient Material for Optical Modulation 34

2.3 Physical Mechanisms for Optical Modulation in Silicon 34

2.3.1 Electro-optic effects 35

2.3.2 Franz-Keldish effect 36

2.3.3 Quantum confined stark effect 37

2.3.4 Thermo-optic effect 38
2.3.5 Plasma dispersion effect 39
2.3.6 Conclusion 42

2.4 Silicon-Based Modulators: The State-of-the-Art 43
2.4.1 Silicon modulators 43
2.4.2 Conclusion and perspectives 51

2.5 Optical Modeling Tools 51
2.5.1 Finite time difference domain (FDTD) 52
2.5.2 Plane wave expansion (PWE) 52
2.5.3 Beam propagation method (BPM) 53

2.6 Electrical Modeling Tools 53
2.6.1 Semiconductor device simulation framework: ATLAS 53

2.7 Electro-Optical Modeling Convergence 54
2.7.1 From ATLAS to BPM 54
2.7.2 From ATLAS to PWE 55
2.7.3 Conclusion 56

2.8 Passive and Active Characterization Setups 57
2.8.1 Introduction 57
2.8.2 Horizontal coupling versus vertical coupling 57
2.8.3 Small signal characterization 59
2.8.4 Data transmission and bit error rate measurements 61

3. Compact Depletion-Based Slow Wave Modulator 63

3.1 Motivation and Background 63

3.2 Target Applications of Slow Wave Structures 65

3.3 Optical Design 67
3.3.1 Slow light propagation background 67
3.3.2 Parity and TE, TM-like modes 69
3.3.3 Slow wave structure choice 70
3.3.4 Slow wave structure overview 77
3.3.5 Parity and TE, TM-like modes in the shallow-etched slow light structure 78
3.3.6 Fabrication constraints drive design 79
3.3.7 Slow wave waveguide modeling 80

3.4 Electrical Design 87
3.4.1 Slow wave phase shifter description 87
3.4.2 DC analysis 90
3.4.3 Transient analysis 99
3.4.4 Analysis of slow light issues 103
3.4.5 Slow light propagation and 3dB roll-off bandwidth limitations 119

3.5 Evolution of the Slow Wave Modulator Electrical Design 121

3.6 Fabrication Process 122
3.6.1 Technology overview 122
3.6.2 Process flow description 123

3.7 Experimental Results 125
3.7.1 Passive characterization overview 125
3.7.2 Passive characterization results 125
3.7.3 Active characterization overview 136
3.7.4 Slow wave modulator overview 136
3.7.5 DC measurements 138
3.7.6 Enhancement versus insertion loss penalty 141
3.7.7 Small signal RF measurements 144
3.7.8 Eye diagrams and bit error rate measurements 151
3.7.9 Conclusion 154

4. Group Index Engineering in Silicon Slow Wave Structures 155

4.1 Motivation and Background 155

4.2 Optical Design 156
4.2.1 Engineered slow wave structure overview 156
4.2.2 Group index engineering guidelines 157
4.2.3 Modeling of the engineered laterally corrugated waveguides 158

4.3 Electrical Design 160
4.3.1 DC analysis of a slow wave phase shifter with broad optical bandwidth 160

4.4 Experimental results 166
4.4.1 Passive characterization results 166
4.4.2 Efficient coupling to the slow light mode 169
4.4.3 Conclusion 170

5. Conclusions and Prospects 173

Appendix A 175

A.1 ATLAS code example 175

A.2 Conversion code from ATLAS to BEAMPROP/BANDSOLVE 176

Appendix B 183

B.1 Modulator masks 183

Appendix C 185

C.1 Publications in peer-reviewed journals 185

C.2 Other contributions in peer-reviewed journals 186

C.3 National and international conferences 186

List of Figures 189

List of Tables 201

Acronyms 203

Bibliography 207