

Table of Contents

1	Introduction.....	1
1.1	Optoelectronic devices for data- and telecommunications.....	1
1.2	Optoelectronic Modulators.....	3
1.3	Graphene as a novel material for electronic and optoelectronic devices.....	5
1.4	Graphene-based electro-optical modulators.....	6
1.5	Scope of this work.....	9
2	Solid state physics of graphene.....	11
2.1	Crystal structure and electronic properties of graphene.....	11
	Carbon allotropes and graphene lattice.....	11
	Hamiltonian and electronic band structure.....	12
	Dispersion relation around the K point and Dirac fermions.....	15
	Limitations of the approximated model.....	15
2.2	Graphene-light interaction.....	16
	Optical conductivity.....	16
	Dielectric function.....	17
	Refractive index and absorption coefficient.....	18
	Chemical potential and optical properties.....	18
	Influence of intraband scattering rate and temperature.....	21
	Spectral dependence of refractive index and absorption.....	22
2.3	Tuning of the chemical potential.....	25
	Tuning via doping and adsorbates.....	25
	Tuning via external electric field.....	26
	Chemical potential in graphene.....	27
2.4	Summary.....	28
3	Design and simulation of graphene-polymer modulators.....	29
3.1	Active area and tuning mechanism.....	29
	Graphene-capacitor active area.....	29
	Voltage-induced tuning of the chemical potential.....	30
3.2	Design of the electro-optically active GP-EAM section.....	32
	Models used in optical simulations.....	34
	Methods for optical simulations of GP-EAMs.....	35
	Chemical potential and voltage-tuning implementation.....	36
	Simulation and design of the EOA section.....	38
3.3	Influence of graphene parameters on GP-EAM characteristics.....	43
	Scattering time and wavelength.....	43
	Graphene doping.....	45
3.4	RF design and electro-optical bandwidth.....	49
	Design of the electrical device layout.....	50

	Estimation of the electro-optical bandwidth	51
3.5	Design considerations and summary	55
4	Development of the graphene-polymer modulator fabrication process.....	57
4.1	Methods of graphene synthesis	57
	Exfoliation – “Scotch tape” method	57
	Epitaxial growth on crystalline substrates	58
	Chemical vapor deposition on metals	58
	Suitability of graphene fabrication methods for this work	59
4.2	Clean room processes for graphene-polymer devices	60
	Spin-coating of polymers and photoresists	60
	Plasma-enhanced chemical vapor deposition	60
	Metal deposition.....	60
	Photolithography	61
	Dry-etching of graphene, polymers and silicon nitride	61
	Wet-etching of metals and silicon nitride.....	61
4.3	Graphene transfer process and fabrication of devices.....	62
	Process A – PMMA-assisted transfer	62
	Process B – Gold-assisted transfer	65
4.4	Graphene characterization	67
	Contact and sheet resistance	67
	Charge carrier mobility and doping quantification	73
4.5	Summary and further optimization potential	80
5	Characterization of graphene-polymer modulators	81
5.1	Static measurements.....	81
	Setup for static optical measurements	81
	Influence of metal contact proximity.....	82
	Tuning curves of graphene-polymer modulators	83
	Comparison with simulations.....	85
	Wavelength-dependence of graphene-polymer modulators	88
	Polarization, optical power, and DC power consumption	90
	On-wafer device statistics	93
5.2	RF measurements.....	95
	Setup for electro-optic modulation experiments	95
	Extinction ratio, bandwidth, and SNR.....	97
	Wavelength-dependence of RF modulation	99
	Comparison with bandwidth model	100
5.3	Summary and further optimization potential	101
6	Conclusion and outlook	103
7	References	107