

Contents

Abstract	i
Zusammenfassung	iii
Acknowledgements	vii
List of Symbols	ix
List of Abbreviations	xi
List of Figures	xvii
List of Tables	xxiii
1 Introduction	1
1.1 Nanoelectromechanical systems and nanoresonators	1
1.2 Carbon nanotube mechanical resonators	4
1.3 Clamping in carbon nanotube resonators	8
1.4 Clamping and energy dissipation	12
1.5 Carbon nanotube resonance parameters - literature overview	16
1.6 Thesis motivation and outline	18
2 Carbon Nanotube as a Mechanical Resonator	21
2.1 Dynamics of beam vibrations	21
2.2 Eigenmodes and mode shapes	23
2.2.1 Case of a beam with zero tension	26
2.2.2 Case of a beam with tension : $T = \sigma A_c$	27
2.3 Lumped model of resonating beams	30
2.3.1 Lumped model parameters	31
2.3.2 Electrostatic transduction - actuation force	33
2.4 Beam response	35
2.4.1 Static response	36
2.4.2 Dynamic response	37
2.5 Damping and non-linearity	38
3 Fabrication and Characterization Techniques	41
3.1 MEMS fabrication	41

3.2	Carbon nanotube-growth and assembly	43
3.3	Clamping configurations	43
3.4	Raman spectroscopy for optical pre-characterization	45
3.5	Static electrical measurements	47
3.6	RF characterization for mechanical resonances	49
3.7	Post-characterization and evaluation	52
4	Motional Mechanical Currents and Intermixing	55
4.1	Motional mechanical currents	55
4.1.1	Capacitive modulation current	57
4.1.2	Conductance modulation current	60
4.1.3	Piezoresistive current	62
4.2	Electrical transduction of mechanical motional currents	66
4.2.1	2ω electrical transduction	66
4.2.2	ω electrical transduction	67
4.3	Experiments and results	68
4.3.1	2ω measurements	68
4.3.2	ω measurements	70
4.3.3	Intermixing and separation of motional currents	72
5	Clamping Strength in Carbon Nanotube Resonators	79
5.1	Clamping and surface interactions	79
5.2	Clamping stability	81
5.2.1	Linear versus non-linear regime	83
5.2.2	Motional amplitude and onset of instability	85
5.3	Mechanical stress relaxation	88
5.4	Temperature dependency	95
5.5	Device resistance	97
6	Dissipation and Dephasing Mechanisms	101
6.1	Energy dissipation - intrinsic mechanisms	101
6.2	Energy dissipation - extrinsic mechanisms	103
6.2.1	Fluid damping	103
6.2.2	Clamping losses	104
6.2.3	Clamping and non-linear damping	106
6.3	Dephasing processes - spectral broadening effects	110
6.4	Dephasing processes - frequency fluctuations	113
7	Conclusion and Outlook	117
7.1	Summary and conclusion	117
7.2	Future outlook	119
A	Appendix A - Analytical Models	121
A.1	Effective mode shape dependent actuation force	121
A.2	Effective mode shape dependent capacitance	122
A.3	Thermal mechanical noise	123

A.4	Adsorption-desorption noise	125
A.5	Adsorption-diffusion noise	126
A.6	Temperature fluctuations	127
B	Appendix B - Model Parameters for Simulations	129
B.1	Mechanical resonances and motional currents - model parameters	129
B.2	Q-factors and frequency noise - analytical modeling	130
C	Appendix C - Axial Carbon Nanotube Straining in Integrated CNTFET-MEMS	131
C.1	Integrated MEMS for axial straining	131
C.1.1	Displacement response of thermal beams	133
C.1.2	Mechanical resonance of thermal actuator	134
C.1.3	Thermal and electrical isolation	135
C.2	Fabrication and methods	136
C.3	Experiments and results	138
C.3.1	Measurement setup	138
C.3.2	Thermo-mechanical displacement response	139
C.4	Axial straining of suspended carbon nanotubes	141
D	Appendix D - Measured Devices	145
	Bibliography	149
	Publications	177
	Curriculum Vitae	181