

Contents

Abstract	iii
Zusammenfassung	v
Acknowledgement	vii
List of Abbreviations	xiv
List of Figures	xix
List of Tables	xxvii
1 Introduction	1
1.1 Impact of global air quality on human health	1
1.1.1 Recommended limit values for air pollutants	2
1.1.2 WHO air quality guidelines	4
1.2 SoA on smart gas sensing technology	6
1.2.1 Solid-state gas sensing elements	6
1.2.2 Hybrid sensing technologies	11
1.2.3 Other sensing technologies	12
1.2.4 SoA preliminary conclusions	14
1.3 MOS-FET and CNT-FET devices	15
1.3.1 MOS-FET as circuit building device	16
1.3.2 Carbon Nanotube FET	16
1.3.3 CNT-FET device architecture	20
1.4 Gas sensors: development and market trends	24
1.4.1 Smart gas-sensing systems for environmental monitoring	25
1.4.2 NO ₂ CNT sensors - research prototypes	25
1.4.3 Commercial solutions	26
1.4.4 Start-up companies based on CNT sensors	26
1.4.5 CMOS low-power interfaces for CNT sensors	27
1.5 Chapter summary	28
1.6 Thesis organization	30
2 Embedded Sensing Platform	33
2.1 Conceptual design	33
2.2 CNT-FET(s) drain bias	35

2.3	CNT-FET(s) gate bias	35
2.4	CNT-FET(s) sensor signal acquisition	37
2.4.1	Current-to-digital converter (CDC)	38
2.4.2	DDC114 CDC operation principle	39
2.5	Embedded programming	45
2.5.1	Hardware described v.s. the software described FSMs	46
2.5.2	Interruption-based v.s. input-pulling execution	47
2.5.3	Implementation of FSM for measuring NO ₂ gas concentration	49
2.5.4	SD card data file system	50
2.6	Physical design	52
2.7	Power consumption	53
2.8	Further development	56
2.8.1	Power consumption optimisation	56
2.8.2	Relative humidity and temperature sensors	56
2.8.3	NO ₂ reference sensor	58
2.9	Chapter summary	59
3	Dynamic Signal Acquisition ASIC	63
3.1	General design considerations	63
3.2	Proposed IC front-end architecture	64
3.3	Drain bias for CNT-FET nanosensor	65
3.3.1	Voltage regulator and current mirror	66
3.3.2	Matrix resistive DAC	67
3.4	CNT-FET nanosensor signal-path	69
3.4.1	Transimpedance amplifier	69
3.4.2	Successive approximation register ADC	92
3.5	System evaluation	111
3.5.1	Relative measurement error	111
3.5.2	Power consumption	112
3.6	Further development	113
3.6.1	Gate bias sub-block	113
3.6.2	Measurement results	117
3.7	Chapter summary	119
4	System Measurement Results	123
4.1	CNT-FET nanosensor fabrication	123
4.2	CNT-FET nanosensor gas kinetics	124
4.3	Lab gas characterization setup	126
4.4	Embedded platform NO ₂ measurement results	126
4.4.1	KTDS15 CNT-FET nanosensor characterization	127
4.4.2	Experimental determination of bias voltages for KTDS 15 device sensing and reset	129
4.4.3	Experimental determination of reset time for KTDS 15 device	131

4.4.4	Experimental results with NO ₂ exposure of KTDS15 device	132
4.4.5	Relative humidity cross-sensitivity	133
4.5	ASIC NO ₂ measurement results	134
4.5.1	KTDS19 CNT-FET nanosensor characterization	134
4.5.2	Experimental results with NO ₂ exposure of KTDS 22-23 device	135
4.6	Power consumption	136
4.7	Chapter summary	137
5	CNT-FET Nanosensor Signal Evaluation	139
5.1	CNT-FET sensing regimes	139
5.1.1	CNT-FET NO ₂ quasi-steady-state response	140
5.1.2	CNT-FET NO ₂ transient response	140
5.2	Experimental determination of LOD and R ²	141
5.2.1	Limit of detection (LOD)	141
5.2.2	Coefficient of determination: R ²	141
5.3	Sensor signal evaluation acquired with the embedded platform	142
5.3.1	Transient slope detection SD signal response	142
5.3.2	Quasi-steady-state QSS signal response	144
5.3.3	CNT-FET LOD and R ² bias dependency	145
5.4	Sensor signal evaluation acquired with the ASIC	146
5.4.1	CNT-FET LOD and R ² bias dependency	146
5.5	Chapter Summary	147
5.5.1	CNT-FET nanosensor and the embedded sensing platform	147
5.5.2	CNT-FET nanosensor and the dynamic signal acquisition ASIC	148
5.6	Preliminary design conclusions	148
6	Sensor Node Demonstrator with the CNT-FET and ASIC	151
6.1	Conceptual design	151
6.2	Daughterboard	152
6.3	Adafruit Feather nRF 52	154
6.4	LIR1025 battery and USB power	155
6.5	Voltage LDO	155
6.6	Charge-pumps	157
6.7	ADC control signals	157
6.8	Slope detection algorithm	159
6.9	Physical design	160
6.10	Android App design	160
6.11	Power consumption	162
6.12	Chapter summary	163

7 Conclusions and Future Work	165
7.1 Embedded sensing platform	165
7.2 Dynamic signal acquisition ASIC	166
7.3 Sensor node demonstrator employing the CNT-FET and ASIC	167
A Appendix	169
A.1 DDC114	169
A.2 DDC114	169
A.3 Signal Path	170
A.3.1 Input Impedance	170
A.3.2 TIA	171
A.3.3 Schematic of the flip-flop data registers of the SAR ADC	178
A.3.4 FFT spectral analysis technique for calculating ENOB of the designed SAR ADC	180
A.4 ASIC V1 Tape-out	181
A.4.1 ASIC V1 silicon die photo	181
A.4.2 ASIC V1 pin-out	182
A.5 ASIC V2 tape-out	183
A.5.1 ASIC V2 silicon die photo	183
A.5.2 ASIC V2 pin-out	184
A.6 ASIC V3 tape-out	185
A.6.1 ASIC V3 silicon die photo	185
A.6.2 ASIC V3 pin-out	186
A.7 Algorithm for computation of NO_2 gas concentration with slope detection	188
Bibliography	189
Student Projects	229
Publications	231
Resume	233