

# Contents

<b>Acknowledgments</b>	<b>xv</b>
<b>Introduction</b>	<b>1</b>
<b>1 CMOS-sensor applications</b>	<b>5</b>
1.1 High-energy physics experiments . . . . .	5
1.1.1 Understanding of the requirements - the CBM experiment as an example	5
1.1.2 Upgrade of the STAR experiment. . . . .	10
1.1.3 The International Linear Collider. . . . .	11
1.2 Beam telescopes . . . . .	12
1.2.1 TAPI: Télescope À Pixels de l'IPHC. . . . .	13
1.2.2 The EUDET telescope . . . . .	14
1.3 Conclusions and summary . . . . .	15
<b>2 Particle interactions with matter and radiation damage</b>	<b>17</b>
2.1 Heavy charged particle interactions with matter . . . . .	17
2.1.1 Energy-loss distribution for charged particles . . . . .	19
2.1.2 Energy loss of electrons and positrons . . . . .	20
2.2 Interactions of photons . . . . .	21
2.3 Neutron interactions with matter . . . . .	23
2.4 Principles of particle detection with semiconductor detectors . . . . .	23
2.4.1 Signal formation in silicon detectors . . . . .	25
2.4.2 Radiation damage in silicon detectors . . . . .	25
2.4.2.1 Ionizing damage . . . . .	25
2.4.2.2 Non-ionizing damage . . . . .	27
2.5 Conclusions and summary . . . . .	31
<b>3 Position sensitive particle detectors</b>	<b>33</b>
3.1 Strip detectors . . . . .	33
3.2 Hybrid Active Pixel Sensors . . . . .	35
3.2.1 The classical approach . . . . .	35
3.2.2 Hybrid sensors with transversal charge collection ("3D sensors") . . . . .	37
3.2.3 Diamond-based hybrid sensors . . . . .	39

3.3	Classical Charge-Coupled Devices . . . . .	40
3.4	In-Situ storage Image Sensors . . . . .	42
3.5	DEPFET sensors . . . . .	44
3.6	Silicon On Insulator sensors . . . . .	46
3.7	Conclusions and summary . . . . .	47
<b>4</b>	<b>CMOS pixel sensors and status of their radiation hardness</b>	<b>51</b>
4.1	CMOS pixel sensor – the device . . . . .	51
4.1.1	Principle of operation . . . . .	51
4.1.2	Pros and cons of CMOS pixel sensors . . . . .	53
4.1.3	Basic in-pixel architectures implemented in CMOS pixel sensors . . . . .	54
4.1.4	Noise and its sources in CMOS pixel sensors . . . . .	58
4.1.4.1	Temporal noise . . . . .	58
4.1.4.2	Fixed Pattern Noise (FPN) . . . . .	60
4.1.4.3	Random Telegraph Signal (RTS) . . . . .	60
4.2	Tools and measurement methods . . . . .	62
4.2.1	Correlated Double Sampling . . . . .	62
4.2.2	Measurements – sensor readout and setup . . . . .	65
4.2.2.1	Basic readout architecture . . . . .	65
4.2.2.2	Measurement setup . . . . .	67
4.2.2.3	The dark chamber . . . . .	69
4.2.2.4	System automation . . . . .	69
4.2.3	Observables measured in the laboratory conditions . . . . .	70
4.2.3.1	Sensor calibration with an $^{55}\text{Fe}$ source . . . . .	70
4.2.3.2	Charge Collection Efficiency . . . . .	73
4.2.3.3	Pixel capacitance measurements . . . . .	73
4.2.3.4	Leakage current and noise calculations . . . . .	75
4.2.4	Observables measured with Minimum Ionizing Particles . . . . .	79
4.2.4.1	Detection efficiency – $\epsilon_{det}$ . . . . .	79
4.2.4.2	Spatial resolution – $\sigma_{res}$ . . . . .	79
4.2.4.3	The average fake hit rate – $\text{FH}_{rate}$ . . . . .	80
4.2.4.4	Adequacy of a $^{106}\text{Ru}$ source for the sensor characterization . . . . .	80
4.2.5	Sensor irradiation facilities used for this work . . . . .	82
4.2.5.1	Ionizing radiation source used in this work . . . . .	82
4.2.5.2	Non-ionizing radiation sources used in this work . . . . .	84
4.3	Radiation effects in CMOS pixel sensors and current radiation tolerance status . . . . .	86
4.3.1	Ionizing radiation effects in CMOS pixel sensors . . . . .	86
4.3.1.1	Parasitic path creation . . . . .	86
4.3.1.2	Increase in the sensing-diode leakage current . . . . .	87

4.3.1.3	Noise increase . . . . .	89
4.3.2	Ionizing-radiation-tolerance status of CMOS sensors developed at the IPHC-Strasbourg (2007) . . . . .	90
4.3.3	Non-ionizing radiation effects . . . . .	92
4.4	Conclusions and summary . . . . .	93
<b>5</b>	<b>Radiation tolerance of CMOS pixel sensors with a column-parallel readout</b>	<b>97</b>
5.1	The need for the column-parallel architecture . . . . .	97
5.2	Towards a fast column-parallel architecture with FPN noise removal and in-pixel signal processing . . . . .	98
5.2.1	The first prototype of the CMOS sensor with the column-parallel architecture – MIMOSA-6 . . . . .	99
5.2.2	The architecture towards FPN noise reduction – MIMOSA-8 prototype . . . . .	101
5.2.3	Improvement of the charge collection efficiency - MIMOSA-16 . . . . .	102
5.3	First radiation-tolerance assessment for a large-scale CMOS sensor with in-pixel signal processing . . . . .	104
5.3.1	Performance tests of the in-pixel amplifier architectures . . . . .	104
5.3.2	Ionizing-radiation tolerance of MIMOSA-22 – laboratory tests and results . . . . .	106
5.3.3	Ionizing-radiation tolerance of MIMOSA-22 – beam test results . . . . .	107
5.4	Improvement in the radiation hardness of an in-pixel amplifier with a negative feedback loop – MIMOSA-22bis . . . . .	110
5.4.1	Tested subarrays – MIMOSA-22bis . . . . .	111
5.4.2	Beam-test results of improved in-pixel amplifier architectures – larger diodes . . . . .	111
5.4.3	Motivation for extended tests . . . . .	116
5.4.4	MIMOSA-22bis — laboratory test results — the influence of the feedback-transistor type on the radiation tolerance . . . . .	117
5.4.5	Tests on subarrays with smaller diodes - tests of the influence of feedback-transistor type and geometry on the noise performance . . . . .	121
5.4.6	The influence of the input-transistor and load-transistor geometry on the in-pixel amplifier performance after irradiation . . . . .	121
5.4.7	Further improvements towards a better ionizing radiation tolerance – MIMOSA-22ter . . . . .	123
5.5	First large-scale chip with a column-parallel architecture and data sparsification – MIMOSA-26 . . . . .	128
5.6	Conclusions and summary . . . . .	130
<b>6</b>	<b>Radiation-tolerance assessment of the different CMOS processes</b>	<b>133</b>
6.1	Radiation tolerance of the 0.25- $\mu\text{m}$ BiCMOS process with a graded EPI layer . . . . .	136
6.1.1	The sensor prototype based on a graded EPI layer – MIMOSA-21bis . . . . .	137

6.1.2	Sensor calibration with an $^{55}\text{Fe}$ source . . . . .	139
6.1.3	Ionizing radiation tolerance . . . . .	140
6.1.4	The charge collection properties after neutron irradiation . . . . .	143
6.1.5	Conclusions . . . . .	146
6.2	Performance of sensors based on a high-resistivity epitaxial layer – MIMOSA-25	146
6.2.1	Substrate properties . . . . .	147
6.2.2	Design of the MIMOSA-25 prototype based on the XFAB 0.6- $\mu\text{m}$ high-resistivity EPI layer . . . . .	148
6.2.3	Non-ionizing radiation tolerance assessment of MIMOSA-25 . . . . .	149
6.2.3.1	Temporal noise before and after neutron irradiation . . . . .	149
6.2.3.2	Charge collection properties of the high-resistivity EPI layer studied in the laboratory. . . . .	151
6.2.3.3	Charge collection properties of a high-resistivity EPI layer measured with high-energy pion beam. . . . .	153
6.2.4	MIMOSA-25 ionizing radiation tolerance – laboratory tests and results . .	155
6.2.4.1	Leakage current measurements . . . . .	156
6.2.4.2	Temporal noise measurements . . . . .	156
6.2.5	Conclusions . . . . .	157
6.3	Radiation-tolerance of the XFAB 0.35- $\mu\text{m}$ process with a standard EPI layer . . .	158
6.3.1	The first prototype in the XFAB 0.35- $\mu\text{m}$ technology – MIMOSA-24 . . . .	159
6.3.2	Sensor gain calibration and pixel capacitance measurements . . . . .	163
6.3.3	Leakage current and temporal noise measurements before irradiation . .	163
6.3.4	Charge collection performance observed before irradiation . . . . .	165
6.3.5	Ionizing radiation tolerance . . . . .	167
6.3.5.1	Leakage-current measurements after irradiation. . . . .	168
6.3.5.2	Temporal-noise measurement after irradiation . . . . .	169
6.3.6	Non-ionizing-radiation-tolerance assessment . . . . .	170
6.3.7	Conclusions on the XFAB 0.35- $\mu\text{m}$ process . . . . .	172
6.4	Conclusions and summary . . . . .	173

**7 Modeling of the radiation effects in the Charge-Coupled Devices 175**

7.1	Confrontation of the CCD performance with the ILC experiment requirements .	175
7.2	Charge transfer losses in 2-phase CCD devices . . . . .	178
7.2.1	Insufficient gate voltage . . . . .	178
7.2.2	Bulk radiation damage . . . . .	178
7.3	Simulation model . . . . .	179
7.3.1	Device specification in ISE-TCAD . . . . .	179
7.3.2	CTI and its extraction from ISE-TCAD simulation . . . . .	181
7.3.3	Estimation of the trap density in the CCD channel . . . . .	183

7.4	Influence of the clock amplitude and frequency on the charge transfer . . . . .	184
7.5	Dependence of the CTI on the temperature and readout-clock frequency – TCAD simulations . . . . .	186
7.5.1	Model parameters . . . . .	186
7.5.2	Simulation results . . . . .	188
7.6	Summary and conclusions . . . . .	191
<b>Summary</b>		<b>193</b>
<b>A Appendices</b>		<b>199</b>
A.1	Readout scheme of CMOS sensors with column-parallel architecture. . . . .	199
A.2	Test matrices implemented in the MIMOSA-22ter prototype . . . . .	203
A.3	MOS capacitor . . . . .	204
A.4	MIMOSA-25 readout scheme . . . . .	206
<b>Bibliography</b>		<b>207</b>

# List of Figures

1.1	The CBM experiment . . . . .	6
1.2	The principle of the track reconstruction of the short-lived particles with vertex detector . . . . .	7
1.3	The influence of the impact parameter required on the sensor performance . . . . .	8
1.4	The STAR detector . . . . .	10
1.5	The two concepts of the ILD vertex detector developed for the ILC . . . . .	12
1.6	Beam telescope based on Monolithic Active Pixel Sensors . . . . .	13
1.7	Plane configurations of the EUDET telescope . . . . .	14
2.1	Average energy loss per unit of path length as function of the particle momentum	19
2.2	Passage of particles through matter — energy-loss distribution in a thin absorber	19
2.3	Average energy loss in silicon per unit of path length as a function of the muon kinetic energy . . . . .	20
2.4	Interactions between photons and bound electrons . . . . .	22
2.5	Probability for the interaction between a photon and a 300 $\mu\text{m}$ thick silicon detector as function of the photon energy . . . . .	22
2.6	Consequences of particle interactions with a detector material . . . . .	24
2.7	Creation of ionizing damage in a Metal-Oxide-Semiconductor structure . . . . .	26
2.8	Creation of unstable and stable defects in silicon . . . . .	27
2.9	Emission and capture processes through intermediate states induced by non-ionizing radiation . . . . .	28
2.10	Displacement damage as a function of energy of different particles plotted relatively to 1 MeV neutrons . . . . .	30
3.1	Concept of a double-sided strip sensor . . . . .	34
3.2	Pattern ambiguities in 2D strip sensors . . . . .	35
3.3	Hybrid pixel sensor – ATLAS pixel module . . . . .	36
3.4	Charge collection in planar and 3D sensor . . . . .	38
3.5	Simplified view of pixels implemented in the sensitive volume with transversal charge collection . . . . .	39
3.6	Charge-Coupled Devices – cross-sectional view and readout scheme . . . . .	41
3.7	In-Situ Charge Storage Sensor – cross-sectional view of the first prototype . . . . .	43
3.8	DEPFET pixel cell – principle of operation . . . . .	44

3.9	Major steps for SOI process and cross-sectional view of the simplified pixel cell made in SOI sensor technology . . . . .	47
4.1	Cross-sectional view of a Monolithic Active Pixel Sensor . . . . .	52
4.2	The "three transistor" pixel – architecture and time diagrams . . . . .	55
4.3	"Self-biased" pixel – architecture and time diagrams . . . . .	56
4.4	Illustration of standard and RTS pixels . . . . .	61
4.5	Correlated Double Sampling operation – 3T pixel example . . . . .	63
4.6	Correlated Double Sampling operation – "self-biased" pixel example . . . . .	65
4.7	CMOS pixel sensor: concept of the sequential readout . . . . .	66
4.8	A typical setup configuration used for CMOS-sensor performance assessment . . . . .	68
4.9	A typical $^{55}\text{Fe}$ spectrum observed with a CMOS pixel sensor . . . . .	71
4.10	Re-binning method for fitting the $^{55}\text{Fe}$ $K_{\alpha}$ peak . . . . .	72
4.11	Readout channel gain measurements . . . . .	74
4.12	Calculations of the average leakage current . . . . .	76
4.13	Calculations of the temporal noise . . . . .	78
4.14	Spectrum of the electrons emitted by a $^{106}\text{Ru}$ source . . . . .	81
4.15	Dose spectrums of the X-Rays from the Seifert Rp149 facility used for the sensor irradiation . . . . .	83
4.16	Energy spectrum of the neutron sources used for sensor irradiation . . . . .	85
4.17	Consequences of the ionizing damage in MOS transistor . . . . .	87
4.18	Radiation-tolerant transistor: transistor with enclosed-layout geometry . . . . .	88
4.19	Ionizing radiation effects in CMOS sensors . . . . .	89
4.20	The leakage current of the radiation-tolerant diodes implemented in the MIMOSA-15 prototype as a function of temperature . . . . .	90
4.21	Ionizing radiation effects – temporal noise as a function of the temperature and integrated dose observed for MIMOSA-11 . . . . .	91
4.22	Impact of the pixel pitch and the thickness of the EPI layer on the tolerance of CMOS sensors to non-ionizing radiation . . . . .	93
4.23	Non-ionizing radiation effects: radiation tolerance as a function of pixel pitch . . . . .	93
5.1	Schematic view of the sensor equipped with a column-parallel readout and data sparsification . . . . .	98
5.2	Simplified schematic of the first sensor prototype – MIMOSA-6 – with the column-parallel architecture . . . . .	100
5.3	Simplified schematic of the improved column-parallel architecture implemented in MIMOSA-8 . . . . .	102
5.4	The detection efficiency assessed with the digital part of the MIMOSA-16 prototype as a function of the discriminator threshold voltage . . . . .	103
5.5	Simplified sensor architecture of the MIMOSA-22 prototype . . . . .	105

5.6	The three in-pixel amplifier architectures studied with MIMOSA-22 . . . . .	105
5.7	The temporal noise and the FPN as functions of ionizing dose measured for MIMOSA-22 featuring in-pixel architectures with and without a feedback loop . . . . .	107
5.8	The results from the studies of MIMOSA-22 with the 120 GeV/c pion beam . . . . .	108
5.9	The performance of MIMOSA-22 subarray S6 as a function of the discriminator threshold voltage. The parameters were assessed with a high-energy particle beam for sensors before and after irradiation to 300 krad . . . . .	109
5.10	Layouts of MIMOSA-22bis – illustration of the main in-pixel architecture modifications . . . . .	112
5.11	Layouts of MIMOSA-22bis pixels with different feedback transistor types and geometry . . . . .	113
5.12	Degradation of the performance after irradiation for MIMOSA-22bis architectures with standard-transistor and ELT in the feedback loop . . . . .	115
5.13	Temporal noise of MIMOSA-22bis (subarrays S4 and S5) each as functions of ionizing dose for different feedback transistors type: standard and ELT . . . . .	117
5.14	MIMOSA-22bis – variation of the temporal noise with temperature after irradiation to 1 Mrad. Temporal noise as a function of the integrated dose, observed at a constant temperature of -10 °C . . . . .	118
5.15	Temporal noise as a function of integration time for standard and enclosed-layout feedback transistors . . . . .	120
5.16	Temporal noise as a function of ionizing dose for the three investigated feedback transistors: "weak", "strong", and ELT . . . . .	121
5.17	Influence of input-transistor and load-transistor transconductance on the amplifier performance after irradiation to 1 Mrad . . . . .	124
5.18	Diagram of the in-pixel elements investigated with the MIMOSA-22ter prototype . . . . .	124
5.19	Pixel layouts of the MIMOSA-22ter prototype . . . . .	126
5.20	Two possible implementations of the SB pixel . . . . .	127
5.21	1/f-noise frequency spectrum before and after irradiation compared with the frequency response of the CDS, acting as a high-pass filter . . . . .	128
5.22	Simplified illustration of the data sparsification implemented in MIMOSA-26 . . . . .	129
6.1	Cross-sectional view of the BiCMOS process . . . . .	137
6.2	Three pixels implemented in MIMOSA-21bis A in order to explore the influence of a p-type-buried silicon layer surrounding the sensing diodes . . . . .	138
6.3	MIMOSA-21bis A: leakage current and temporal noise as a function of temperature after sensor irradiation up to 500 krad . . . . .	141
6.4	MIMOSA-21bis B: Leakage current and temporal noise as a function of temperature after sensor irradiation of up to 500 krad . . . . .	142



- 6.5 Vertical cut of the MIMOSA-21bis A prototype illustrating the influence of the p-type-buried-layer exclusion on the charge collection . . . . . 145
- 6.6 Doping profile and electric potential distribution of the CMOS sensor based on low-resistivity EPI layer . . . . . 147
- 6.7 Potential distribution in a pixel cell of the CMOS sensor based on a high-resistivity EPI layer . . . . . 148
- 6.8 The two versions of MIMOSA-25 . . . . . 150
- 6.9 Sketch view of standard and radiation-tolerant diodes implemented in MIMOSA-25 . . . . . 151
- 6.10 The distribution of the signal charge from a <sup>106</sup>Ru source collected by the seed pixel of MIMOSA-25<sub>RadTol</sub> for three investigated matrices . . . . . 152
- 6.11 Comparison of the collected charge as a function of the cluster size for MIMOSA-25 and for older devices based on standard EPI layer – MIMOSA-9 and MIMOSA-18 . . . . . 153
- 6.12 Comparison of SNR as a function of non-ionizing radiation fluence for sensors based on high-resistivity EPI layer – MIMOSA-25 – and those based on standard EPI layer – MIMOSA-15 and MIMOSA-18 . . . . . 155
- 6.13 Leakage current of different MIMOSA-25 diodes as a function of ionizing dose . 156
- 6.14 The temporal noise measured for the different sensing diodes implemented in the MIMOSA-25 sensors . . . . . 157
- 6.15 Standard and “test” pixel cell implemented in MIMOSA-24 . . . . . 160
- 6.16 MIMOSA-24 – subarray implementation . . . . . 161
- 6.17 Cross-sectional view of the radiation-tolerant diode design implemented in the AMS technology . . . . . 161
- 6.18 Cross-sectional view of the different sensing diodes implemented in the MIMOSA-24 prototype . . . . . 162
- 6.19 MIMOSA-24-sensor leakage current before irradiation as a function of the temperature . . . . . 164
- 6.20 Temporal noise as a function of temperature for the MIMOSA-24 sensor before irradiation . . . . . 165
- 6.21 Signal and SNR distributions observed for the MIMOSA-24 prototype before irradiation . . . . . 166
- 6.22 Leakage current as a function of temperature for MIMOSA-24 sensors exposed up to 1 Mrad. Leakage current as a function of integrated dose, measured at constant temperature of +20 °C . . . . . 169
- 6.23 Temporal noise as a function of temperature for MIMOSA-24 sensors irradiated up to 1 Mrad. Temporal noise as a function of integrated dose at a constant temperature of +20 °C . . . . . 170
- 7.1 Readout organization of Charge-Coupled Devices . . . . . 176

7.2	Implementation of the 3-phase and 2-phase CCD . . . . .	177
7.3	Simplified 2D TCAD model of the 2-phase CP-CCD used in simulations . . . . .	180
7.4	Main properties of the simplified 2D simulation model of the CCD pixel . . . . .	181
7.5	Simulation of the charge transfer along the CCD channel . . . . .	182
7.6	Simulation of the charge transfer through an irradiated 2-phase CCD . . . . .	183
7.7	CTI as a function of clock amplitude . . . . .	185
7.8	CTI as a function of clock amplitude for different p+ implant doping concentrations, and for various n-channel doping concentrations . . . . .	186
7.9	The CTI simulation flow in TCAD . . . . .	187
7.10	Simulation of an influence of previous charge transfer on the CTI . . . . .	188
7.11	The simulated CTI as a function of temperature and readout clock frequency . . . . .	189
7.12	Simulated CTI as a function of trap concentration . . . . .	190
8.1	Charge collected by the seed pixels measured for MIMOSA-18 AHR fabricated with a high-resistivity EPI layer . . . . .	197
A.1	Readout scheme of the column-parallel CMOS sensor: time diagram . . . . .	199
A.2	Readout scheme of the column-parallel CMOS sensor . . . . .	201
A.3	Readout scheme of the column-parallel CMOS sensor: integration time . . . . .	202
A.4	MOS capacitor . . . . .	204
A.5	Readout scheme of the MIMOSA-25 sensor prototype . . . . .	206

# List of Tables

1.1	Performance requirements for the sensors composing the CBM Micro Vertex Detector . . . . .	10
1.2	Specification of the CMOS sensors equipping the STAR pixel detector . . . . .	11
1.3	The requirements of the ILC experiment regarding pixel sensors equipping the innermost layer of the vertex detector . . . . .	12
1.4	The main characteristics of the CMOS sensors with digital and sparsified output used for EUDET telescope . . . . .	14
4.1	Comparison of the MPV of the charge collected by the seed pixel, assessed with the $^{106}\text{Ru}$ source and high-energy pions . . . . .	81
5.1	Main features of the column-parallel CMOS sensors developed at IPHC-Strasbourg	100
5.2	The most probable values of the SNR for the three amplifier architectures studied with MIMOSA-22 before irradiation . . . . .	107
5.3	Test results with a high-energy pion beam for the S6 subarray of MIMOSA-22 . .	109
5.4	Feedback transistors used in the test architectures implemented in MIMOSA-22bis	112
5.5	Results from the tests with a high-energy pion beam for the two investigated subarrays of MIMOSA-22bis: standard (S5) and ELT (S4) . . . . .	114
5.6	The input, load, and feedback transistors transconductance modification . . . . .	122
5.7	Performance of MIMOSA-26 . . . . .	130
6.1	The three CMOS processes investigated in order to improve the radiation hardness	136
6.2	Description of pixels implemented in the A and B versions of MIMOSA-21bis . .	139
6.3	Parasitic capacitances of sensing diodes, temporal noise, and leakage current measured with MIMOSA-21bis A and B prototypes before irradiation . . . . .	140
6.4	Estimation of the charge expected in the seed pixel for the MIMOSA-21bis A prototype . . . . .	144
6.5	Temporal noise of MIMOSA-25 <sub>RadTol</sub> before and after neutron irradiation, measured at a temperature of +20 °C . . . . .	150
6.6	The MPV of the charge collected by the seed pixel assessed with MIMOSA-25 <sub>RadTol</sub> before irradiation . . . . .	152
6.7	The MPV of charge collected by the seed pixel as measured with MIMOSA-25 <sub>RadTol</sub> , MIMOSA-15, and MIMOSA-18, before and after irradiation	154

- 6.8 The MPV of the SNR measured with high-energy pion beam with MIMOSA-25<sub>RadTol</sub> before and after irradiation . . . . . 155
- 6.9 Comparison of the most relevant XFAB and AMS-OPTO-0.35- $\mu\text{m}$  process parameters . . . . . 159
- 6.10 MIMOSA-24 – description of implemented subarrays . . . . . 160
- 6.11 MIMOSA-24 – measured pixel capacitances . . . . . 163
- 6.12 Comparison of the leakage currents measured at a temperature of +20 °C with sensing diodes implemented in the AMS (MIMOSA-15) and the XFAB (MIMOSA-24) 0.35- $\mu\text{m}$  processes . . . . . 164
- 6.13 Comparison of the CCE observed with pixels before irradiation from different MIMOSA prototypes, based on either the AMS or the XFAB technologies . . . . . 166
- 6.14 Parameters measured during tests with high-energy pion beam: MPV of the charge collected by the seed pixel, corresponding SNR (MPV), and detection efficiency . . . . . 167
- 6.15 Comparison of the leakage currents measured at 20 °C with sensing diodes implemented in the AMS (MIMOSA-15) and the XFAB (MIMOSA-24) 0.35- $\mu\text{m}$  processes . . . . . 168
- 6.16 Comparison of the CCE after irradiation to  $3 \cdot 10^{12} \text{ n}_{\text{eq}}/\text{cm}^2$  of sensors manufactured in the 0.35- $\mu\text{m}$  AMS-OPTO and XFAB processes . . . . . 171
- 6.17 The MPV of the collected charge in the seed pixel and the corresponding SNR. . . 172
  
- 7.1 Simulated background results for three different detector concepts . . . . . 183
- 7.2 Trap concentrations and electron capture cross-sections used in the TCAD simulations . . . . . 184
- 8.1 The performance achieved with the column-parallel CMOS sensor (MIMOSA-26) based on a high-resistivity EPI layer . . . . . 196
  
- A.1 MIMOSA-22ter test sub-matrices . . . . . 203