

Contents

1	Basic Principles of a Silicon Detector	1
1.1	Fundamental Silicon Properties.....	1
1.1.1	Just Silicon and Some Impurities	3
1.1.2	The <i>pn</i> -Junction.....	8
1.1.3	SiO ₂	17
1.1.4	Summary of Silicon Properties	20
1.2	Ingredients to Use Silicon as Detector Basis.....	21
1.3	Working Principle of a Silicon Tracking Device	23
1.3.1	Charge Collection – An Illustration.....	25
1.3.2	Signal via Induction – Shockley–Ramo Theorem	27
1.3.3	Signal Charge and Particle Position.....	31
1.3.4	<i>n</i> -Side Isolation of an <i>n</i> -in- <i>n</i> or <i>n</i> -in- <i>p</i> Sensors	35
1.4	Single-Sided – Double-Sided, Double Metal	38
1.5	Noise Contributions	41
1.6	Sensor Parameters.....	44
1.6.1	Global Parameters	45
1.6.2	Bias-, Guard- and Outside Protection Rings	47
1.6.3	Design of Strip Parameters	50
1.7	Practical Aspects of Handling and Testing Silicon Strip Devices.....	60
1.7.1	What Is the Standard/Exhaustive Set of Quality Assurance Tests?.....	61
1.8	R&D Methods and Tools: DLTS, TSC, TCT, Edge TCT, TPA-TCT, SIMS and Simulation	64
1.8.1	Deep Level Transient Spectroscopy – DLTS.....	65
1.8.2	Thermally Stimulated Current – TSC	69
1.8.3	Transient Current Technique – TCT	71
1.8.4	Secondary Ion Mass Spectrometry – SIMS.....	79
1.8.5	Simulation	80



1.9	Production of Silicon Sensors	81
1.9.1	From Pure Sand to Detector Grade Silicon	82
1.9.2	Processing	84
1.9.3	Thinning	93
1.10	Readout Electronics – Strip ASICs	95
1.11	Readout Electronics – Pixel Readout Chips – ROCs	102
1.11.1	Chip Developments for the Future	106
1.12	Other Silicon Detector Types	106
1.12.1	Hybrid Pixels – An Alternative with a High Number of Channels	107
1.12.2	CMOS Detectors – Monolithic Active Pixels – MAPS	107
1.12.3	Silicon on Insulator Detector – SOI	110
1.12.4	HV – CMOS/HR – CMOS	112
1.12.5	Silicon Drift Detector	116
1.12.6	Depleted Field Effect Transistors DEPFET Detectors	117
1.12.7	3D Silicon Detectors	118
1.12.8	Low Gain Avalanche Detectors – LGAD	123
1.12.9	Technology Advantage – Disadvantage – Usage	127
1.13	Some Last Words About the Design of Detectors for High Energy Physics	127
1.14	Some Always Unexpected Problems Along the Way	127
2	Radiation Damage in Silicon Detector Devices	135
2.1	Bulk Damage	135
2.1.1	Damage by Particles	136
2.1.2	Annealing – Diffusion of Defects	143
2.2	Defect Analysis, New Materials and Detector Engineering	148
2.2.1	Study of Microscopic Defects and Their Impact on Macroscopic Parameters	150
2.2.2	Different Materials and Different Radiation Types – NIEL Violation	153
2.2.3	Double Junction	156
2.2.4	Sensors After Very High Radiation Levels	160
2.2.5	Charge Amplification	162
2.3	Surface Damage	164
3	First Steps with Silicon Sensors: NA11 (Proof of Principle)	167
3.1	From Semiconductor Detectors in the 1950s as Spectroscopes to First Tracking Devices in the 1980s	167
3.2	Development of the First Silicon Strip Detector for High Energy Physics NA11 and NA32	168
3.3	Distinguish c Quarks from Others	171

4	The DELPHI Microvertex Detector at LEP	173
4.1	Design and Strategies	173
4.2	The DELPHI Microvertex Detector 1996/1997.	177
4.3	The Silicon Sensors of the DELPHI Microvertex Detector MVD	183
4.4	Implementation of Silicon Labs in Universities to Build a Large Device	188
4.5	Physics with the DELPHI Microvertex Detector.	189
5	CDF: The World's Largest Silicon Detector in the 20th Century; the First Silicon Detector at a Hadron Collider	195
5.1	Historical Evolution of the CDF Vertex Detector.	195
5.2	Design, How to Cover $ \eta \leq 2 $ Without Endcap	200
5.2.1	Tracking System	200
5.3	Six Inch, a New Technology Step for Large Silicon Applications	210
5.4	Lessons Learned from Operation	214
5.5	The t Discovery, CP Violation in the b Quark Sector.	216
6	CMS: Increasing Size by 2 Orders of Magnitude	219
6.1	The CMS Pixel Detector – Phase 0 – 2008 – 2016	222
6.2	The Pixel Phase I Upgrade – Installed February/March 2017.	225
6.3	The CMS Silicon Strip Tracker – SST	231
6.4	Design, How to Survive 10 Years in the Radiation Environment of LHC	239
6.4.1	Electronics – Quarter Micron Technology	239
6.4.2	Silicon Sensors	240
6.5	Construction Issues for Large Detector Systems with Industry Involvement	249
6.5.1	Quality Assurance and Problems During the Process	250
6.5.2	Assembly.	253
6.6	Tracker Operation and Performance	257
6.6.1	Lessons Learned from Operation and Maintenance	257
6.6.2	Signal Processing, Some Key Figures and Tracking with the CMS Tracker.	260
6.7	Physics with the CMS Tracker and High-Level Trigger	282
7	The Design of the CMS Upgrade Tracker and the CMS High Granularity Forward Calorimeter Equipped with Silicon Sensors for the HL-LHC	291
7.1	The CMS Tracker Upgrade for the HL-LHC – Phase II.	293
7.1.1	Sensors for the HL-LHC CMS Tracker.	307
7.2	The CMS Endcap Calorimeter Upgrade for the HL-LHC.	319

8 Continuing the Story: Detectors for a Future Linear Collider ILC or a Future Circular Collider FCC	331
8.1 A Silicon Tracker for the International Linear Collider – ILC ...	333
8.2 The Next Big Future Circular Collider – FCC	337
9 Conclusion and Outlook	341
Appendix A: Glossary	343
Appendix B: Some Additional Figures	349
References	357
Index	371