UNIVERSITE JOSEPH FOURIER-GRENOBLE 1

SCIENCES ET GEOGRAPHIE

THESE

pour obtenir le grade de

DOCTEUR DE L'UNIVERSITE JOSEPH FOURIER

Discipline: Physique

Présentée et soutenue publiquement

Par

CASSE Gianluigi

23 september 1998

The effect of hadron irradiation on the electrical properties of particle detectors made from various silicon materials

Directeur de thèse

V. Comparat

COMPOSITION DU JURY:

D. Bisello - Rapporteur

P. Boyer - Président

V. Comparat

F. Lemeilleur

C. Leroy - Rapporteur

S. Pospišil

Remerciements

Cette thèse résume mon travail de recherche dans le laboratoire CERN/EP/MIC/SD, auquel je suis arrivé grâce à Paolo Giubellino qui a proposé ma candidature à *l'Associazione per lo Sviluppo Scientifico e Tecnologico del Piemonte* (ASP) pour une bourse de deux ans au CERN, et à l 'ASP, qui m'a accepté et financé.
Je tiens à remercier Vincent Comparat, qui a accepté d'être mon directeur de thèse et qui m'a aussi beaucoup aidé dans toutes les démarches administratives.
Le laboratoire du CERN dans lequel j'ai été accueilli et où il s'est déroulé mon travail de recherche est dirigé par François Lemeilleur, avec la précieuse collaboration de Maurice Glaser. Je leur suis reconnaissant pour la masse de connaissances scientifiques et techniques qu'ils m'ont transmises. Plus importants de ça sont les relations humaines qui se définissent pendant des années de travail commun. Avec eux, j'ai trouvé assez agréable le temps passé dans le laboratoire ou autrement ensemble, comme à l'occasion de voyages de travail.
Je remercie Claude Leroy, pour les discussions scientifiques et les nombreux précieux conseils pendant la thèse. J'ai cherché d'apprendre beaucoup de son expérience et de ses connaissances.
Je tiens à remercier les membres de la *Czech Technical University* de Prague, Prof. Stanislav Pospišil et Prof. Bruno Sopko pour les conseils en matière de spectroscopie et de physique du solide, et pour avoir accepté que je fasse partie de leur groupe pendant ces six derniers mois de travail. M. Pospišil nous a aussi conseillé l'utilisation de l'accélérateur Van de Graaf de la Charles University de Prague, dont je remercie toute l'équipe pour son assistance pendant les mesures.
Je remercie les membres de l'*Insitut Jozef Stefan* de Ljubljana, et particulièrement Marko Mikuz et Vladimir Cindro, pour nous avoir mis à disposition le réacteur nucléaire de recherche pour les irradiations en neutrons et pour nous avoir aidé sur place. Merci également a tout le staff du réacteur.
Je remercie Karl Zankel, pour beaucoup de conseils et discussions à propos de mon travail.
Je remercie Dario Bisello, pour avoir accepté de faire partie du jury et M. Pierre Boyer pour avoir accepté de le présider.
Je remercie Eugene Grigoriev, qui a participer, a la prise de centaines de données de collection de charge et avec qui ont a commencer l'étude des détecteurs irradiés avec une LED pulsée.
Plusieurs collègues ont travaillé avec moi, en moment et pour de périodes différentes, et je les remercie tous pour leur collaboration pendant les irradiations et les mesures, comme je remercie tous les membres de la collaboration ROSE, en particulier Steve Watts, avec qui j'ai discuté les résultats et par qui j'ai appris beaucoup en ce qui concerne le dommage de radiation dans les détecteurs au silicium.
Je suis reconnaissant à tous les membres des compagnies qui ont collaboré au projet ROSE et qui ont fourni matériel et compétence pour les essais. En particulier, des nombreuses mesures de caractérisation ont été demandé à ITME, spécialement à Elzbieta Nossarzewska, qui a toujours collaboré avec enthousiasme. Merci encore à ITE pour avoir accepté de participer aux expériences de diffusion de l'oxygène à haute température et à DIOTEC (grâce à l'intéressement de B. Sopko), pour avoir fabriqué des centaines de diodes *mesa.*

Contents

List of figures …….. 7

List of tables …… 16

Introduction …….. 19

Chapter 1 – Motivation and framework

1.1 The Large Hadron Collider (LHC) …….. 21

1.2 Physics at LHC …… 22

1.2.1 The ATLAS and CMS experiments …… 24

1.2.2 The radiation environment……26

1.3 The ROSE (CERN-R&D 48) collaboration ……27

Chapter 2 – Basic Features of Silicon Detectors

2.1 General principles of semiconductor physics …… 30

2.2 The p-n junction…… 33

2.3 Silicon mono-crystal fabrication and detector manufacturing …….. 40

2.3.1 Crystal growth methods …….. 41

2.3.2 Detector manufacturing ……... 44

2.4 Operation of silicon detectors …….. 48

2.4.1 Biasing features ……..….. 48

2.4.2 Particle detection ……. 51

Chapter 3 – Radiation damage effects

3.1 The radiation damage mechanism ……54

3.2 Changes in detectors properties ……... 59

3.2.1 Reverse Current ……... 61

3.2.2 Effective doping concentration (N_{eff}) ……...65

3.2.3 Charge Collection Efficiency ……...69

Chapter 4 – Experimental methods

4.1 C-V measurements ……...73

4.2 I-V measurements …… 79

4.3 Charge Collection Measurements …… 82

4.3.1 β particles …… 86
4.3.2 Low range particles: α particles and low energy protons …… 89
4.3.3 Red light ……..…… 91
4.4 Carrier lifetime measurement ……...93
4.5 Irradiation facilities ……... 95
4.4.1 Proton Irradiation Facility ……95
4.4.2 Neutron Irradiation Facility ……. 98

Chapter 5 – Materials

5.1 Impurities ……. 99
5.1.1 Measurement techniques of the impurity concentration ……..100
5.1.2 Introduction of impurities in the silicon ingot …….. 101
5.1.3 The impurity diffusion experiment ……...… 102
5.1.4 Neutron transmutation doping of silicon ……. 108
5.2 Overview of the materials …… 109
5.3 Devices ……..… 111

Chapter 6 – Experimental results

6.1 Diodes before irradiation ……..114
6.2 Proton irradiations ……116
6.2.1 N_{eff} as a function of the fluence …… 116
6.2.2 N_{eff} as a function of the time after irradiation …….. 120
6.2.3 Reverse current as a function of the fluence ……122
6.3 Neutron irradiations ……. 124
6.3.1 N_{eff} as a function of the fluence …… 127
6.3.2 N_{eff} as a function of the time after irradiation ……... 131
6.3.3 Reverse current as a function of the fluence ……132
6.4 Charge collection efficiency as a function of the fluence ……. 134
6.5 Discussion …… 135

Chapter 7 – Evolution of the active volume in irradiated detectors

7.1 Charge collection from low range particle illumination …… 142

7.2 Charge collection from red LED light illumination …….. 147

7.3 Discussion …… 162

Conclusion ……... 165

APPENDIX A - Experimental set-ups ……167

APPENDIX B - The diffusion theory in silicon ……... 171

References 174

List of figures

Chapter 1

Fig. 1 *The LEP/LHC tunnel map and (b) the CERN accelerator system.*…… 20

Fig. 1.1 *Cross section of the LHC/LEP tunnel. LEP magnet is hosted above the double-coil LHC magnet*……. 21

Fig. 1.2 *Cross section for various processes expected in proton-proton interactions as a function of the centre-of-mass energy* $\sqrt{s}$ …….…… 23

Fig. 1.3 (a) *The CMS detector (b) The ATLAS detector.* ……..…….. 25

Fig. 1.4 *(a) The CMS and (b) ATLAS inner trackers with Si pixels, SemiConductor (Si) Tracker, and TRT (Transition Radiation Tracker).* ……..…. 26

Fig. 1.5 - *Neutron and charged fluxes per year at different radii in the CMS tracking cavity*……27

Chapter 2

Fig. 2.1 *Schematic band diagram for (a) n-type and (b) p-type semiconductor.* E_D *= energy level of the donor impurity;* E_A *= energy level of the acceptor impurity*……... 32

Fig. 2.2 *Band diagram of (a) uniformly doped p-type and n-type silicon (b) after the junction formation*…… 33

Fig. 2.3 *Schematic energy band diagram of a p-n junction under external bias (a) forward bias (b) reverse bias.* ……..…… 36

Fig. 2.4 Ideal I-V characteristic of a silicon diode. ……..... 37

Fig. 2.5 Processes at an intermediate defect level: (a) generation (b) recombination (c) trapping (d) compensation. ……..... 37

Fig. 2.6 *The capacitance-voltage characteristic of a* p^+*-n junction.* ……. 39

Fig. 2.7 *Depletion region of a* p^+*-n junction: (a)* $V_1 < V_{FD}$ *, (b)* $V_2 \geq V_{FD}$…… 40

Fig. 2.8 *CERN2 mask for planar device production. This mask is adapted to process 3" or 4" wafers (internal and external circles respectively).* ……. 45

Fig. 2.9 *Basic steps for the planar fabrication of a p^+-n-n^+ detector.* …….…….…….. 46
Fig. 2.10 *Basic steps for the mesa fabrication of diodes.* …….…….…… 47
Fig. 2.11 *Effect of the guard ring (G-R) contacting on the delimitation on the electric field region (a) G-R floating (b) G-R biased.*..…….…….…….. 49
Fig. 2.12 *C-V characteristic of an irradiated planar diode. The decrease of the capacitance above full depletion is due to the lateral extension of the depleted volume*…… 50

Chapter 3

Fig. 3.1 *Diagram of some defects in the silicon crystal lattice due to point defect complexes.* …….…….…….…….…….…….…… 55
Fig. 3.2 *Picture of a typical recoil-atom track with formation of final highly damaged regions (clusters) as a consequence of heavy-particle irradiation* [3.2]…… 56
Fig. 3.3 *Displacement damage cross section as a function of energy for various particle in silicon* [3.15]. ……..…….……..…….……..…….……... 58
Fig. 3.4 *The current characteristic as function of the square root of the reverse bias. The reverse current is proportional to the depleted volume until full depletion*…… 62
Fig. 3.5 *Radiation damage constant, α, as a function of time after irradiation for silicon detectors irradiated and stored at various temperatures* [3.20] ……63
Fig. 3.6 *N_{eff} (V_{FD}) as a function of pion fluence* [3.28]. …….……. 66
Fig. 3.7 *Resistivity as a function of fluence (1 MeV neutrons)* [3.32]. …….……... 67
Fig. 3.8 *Depletion voltage (normalised to 300 μm thickness) versus time after irradiation at room temperature for various high resistivity silicon detectors* [2.6]…… 68
Fig. 3.9 *Charge collection efficiency as a function of 24 GeV/c proton fluence* [3.20]….. 70
Fig. 3.10 *V_{FD} changes as a function of 24 GeV/c proton fluence for detector irradiated at various temperatures* [3.20]…….…….…….. 71

Chapter 4

Fig. 4.1 (a) *$1/C^2$ vs bias for a 200 μm thick non-irradiated diode. N_{eff}, calculated from*

V_{FD}, is $7.5 \cdot 10^{12}$ cm^{-3} (b) *N_{eff} profile vs depth.* 73

Fig. 4.2 (a) *$1/C^2$ vs bias for a 300 μm thick non-irradiated low resistivity (180 Ω cm) diode. The detector breakes down before full depletion. (b) N_{eff} profile vs depth. The average value of N_{eff} corresponds to the nominal resistivity. The calculated V_{FD} is ≈ 1900 V*..... 75

Fig. 4.3 *Typical C-V characteristics with the frequency as a parameter for (a) non-irradiated and (b) irradiated diodes* [4.5]. 76

Fig. 4.4 (a) *C-V characteristic of an irradiated type-inverted diode.* (b) *N_{eff} profile versus depth*..... 77

Fig. 4.5 *Leakage current as a function of the reverse bias for variously irradiated silicon diodes with floating and biased guard ring. The reverse current for the non irradiated diode is the same with and without G-R.* 81

Fig. 4.6 *The volume reverse current as a function of fluence measured with and without bias on the G-R.* 82

Fig. 4.7 *Generation of carriers along the path of particle tracks and electric field distribution in the silicon diode*..... 83

Fig. 4.8 *Ideal pulse shape for (a) electron injection (junction side) and (b) hole injection (ohmic side) of an n-type silicon detector. $V_{FD} \geq V_1 \geq V_2$.* 86

Fig. 4.9 *CC curve as a function of the square root of bias in the case of β particle Illumination*..... 87

Fig. 4.10 *Landau distribution of the energy loss of a MIP in a 300 μm thick silicon detector. The most probable value is ≈ 80 keV*.. 88

Fig. 4.11 *Averaged signal pulse shape and integral of the signal induced by β particles in a 307 μm thick silicon detector*..... 88

Fig. 4.12 *Energy loss of 1.7 MeV protons in silicon as a function of the path (Bragg's curve) and integrated energy loss as a function of the depletion depth in case of (a) front injection and (b) rear injection*..... 89

Fig. 4.13 *Simulated charge collection for front (a) and rear (b) illumination with 1.7 MeV protons in a silicon detector with V_{FD} = 120 volts.* 90

Fig. 4.14 *Example of (a) energy loss spectrum and (b) signal pulse shape and integral of the*

signal of an α particle in a fully depleted silicon diode. …….. 91
Fig. 4.15 *Ionisation as a function of depth for red (670 nm) light in silicon*……. 92
Fig. 4.16 *Comparison between the V_{FD} measurements obtained with the C-V and the β charge collection (C.C.) methods on the same diode irradiated with 24 GeV/c protons…* 93
Fig 4.17 *(a) Reverse recovery circuit schematic (b) current and (c) voltage waveforms. At t = 0, ΔV_d is due to the drop on the resistance R: $\Delta V_d = RI_r$.* ……..…. 94
Fig. 4.18 *Reverse recovery signal for a non-irradiated planar diode. The minority carrier lifetime is 70 μs.*……..……... 95
Fig. 4.19 *Beam relative intensity profile (a) front view (b) 3-d view. X is the horizontal co-ordinate and Y is the vertical co-ordinate.* …… 96
Fig. 4.20 *Sketch of the detector alignment in the proton beam.* …… 97
Fig. 4.21 *Fluence (24GeV/c protons) versus Secondary Emission Chamber (SEC) counts...* 97

Chapter 5

Fig. 5.1 *Calculated diffusion profile of P and B for diffusion during 3h at 1200°C*…….... 102
Fig. 5.2 *Boron and phosphorus concentrations versus depth in a mesa diode, measured by the spreading resistance method.* ……... 104
Fig. 5.3 *Phosphorus and boron profiles obtained by SIMS from a mesa sample: (a) junction (p^+) side (b) ohmic (n^+) side.* …… 104
Fig. 5.4 *Resistivity profile of a mesa diode before and after two successive annealing steps of 1 h at 800 °C in H_2 and normal atmosphere. Measurements performed by ITME.*……... 105
Fig. 5.5 *Oxygen and carbon SIMS profiles in a mesa diode.* ……... 105
Fig. 5.6 *Calculated concentration profiles for (a) C and (b) Sn in silicon for different temperatures and times.* ……... 106
Fig. 5.7 *Oxygen profile in (a) a mesa detector (3h at 1200 °C) and (b) a sample diffused at Technion (20h at 1150 °C).*…… 107
Fig. 5.8 *Calculated oxygen profile for different diffusion time at 1150 °C.* …… 107
Fig. 5.9 *SIMS profile of (a) O and (b) C concentration in O-diffused wafers #8 and #10..* 109

Fig. 5.10 *Oxygen and carbon concentration profiles measured by SIMS for material #14*... 110
Fig. 5.11 *Oxygen and carbon concentration profiles measured by SIMS for various ITME epitaxial materials*..... 111
Fig. 5.12 *Simulated distribution of the implanted (a) P and (b) B ions for the ohmic and junction side formation in the planar process*..... 112

Chapter 6

Fig. 6.1 *Energy spectra, recorded by an ADC, of β^- particles from ^{106}Ru in overdepleted (a) mesa and (b) planar diodes*..... 114
Fig. 6.2 *Energy of impinging protons versus ADC channel for mesa and planar non irradiated diodes*..... 115
Fig. 6.3 *N_{eff} versus fluence for standard (#5) and weakly oxygenated (#6) diodes processed by SINTEF.* 117
Fig. 6.4 *N_{eff} versus fluence for standard (#4, #5) and weakly oxygenated (#6) diodes. #4 is processed by ITE,* #5 and #6 by SINTEF. 117
Fig. 6.5 *N_{eff} versus fluence for standard diodes with a different starting resistivity*..... 118
Fig. 6.6 *N_{eff} versus fluence for epitaxial planar n-type diodes (#17, #18, #19)*..... 118
Fig. 6.7 *N_{eff} versus fluence for mesa standard (#5) and weakly oxygenated diodes (#6)*.... 119
Fig. 6.8 *N_{eff} versus fluence for mesa epitaxial (a) n-type and (b) p-type diodes*..... 119
Fig. 6.9 *Comparison of N_{eff} versus fluence between planar and mesa diodes: (a) standard FZ and (b) epitaxial diodes.* 120
Fig. 6.10 N_{eff} *versus annealing time (room temperature equivalent) for planar and mesa diodes made from materials #5 and #6 and for two different final fluences: (a) $1.1 \cdot 10^{14}$ cm^{-2}, (b) $1.9 \cdot 10^{14}$ cm^{-2}. Picture (c) is the same as (b)but plotted in logarithmic scale to evidence the beneficial annealing (irradiation April '97)*..... 121
Fig. 6.11 N_{eff} *versus annealing time (room temperature equivalent) for planar and mesa diodes made from materials #5 and #6. The final fluence is $1.4 \cdot 10^{14}$ cm^{-2}. The plot (b) in logarithmic scale evidences the beneficial annealing (irradiation June '97)*..... 121

Fig. 6.12 *N_{eff} versus annealing time (20 °C equivalent) for planar and mesa diodes made from epitaxial materials (#17 to #19). The final fluence is $1.8 \cdot 10^{14}$ cm^{-2}. The plot (b) in logarithmic scale evidences the beneficial annealing (irradiation August '97)….* 122

Fig. 6.13 *Reverse leakage current versus fluence for planar diodes made from standard materials with different resistivities (#1 and #2).……..……* 123

Fig. 6.14 *I_{vol} versus fluence for planar diodes* m*ade from FZ materials #4, #5 and #6…….* 124

Fig. 6.15 *I_{vol} versus fluence for planar diodes* m*ade from epitaxial materials #17, #18 and #19. ……..……..……..……..……..* 124

Fig. 6.16 *I_{vol} versus fluence for mesa diodes from the same standard silicon wafer (#5) and from a weakly oxygenated wafer (#6).……..……..……* 124

Fig. 6.17 *V_{FD} versus time at 80 °C for non-inverted standard (#3) and jet oxygenated (#11) diodes after irradiation. ……..……..……..……...* 125

Fig.6.18 C*omparison between V_{FD} measured after a fluence of $1 \cdot 10^{14}$ cm^{-2} for three pairs of diodes either submitted successively to 7 irradiations and annealing steps (circled points) or irradiated directly to the final fluence and annealed in one step only. Each annealing step is 4 min. at 80 °C. ……..……..……* 126

Fig. 6.19 *Comparison between V_{FD} as a function of the fluence measured ≈ 30 min. after irradiation and at the end of the beneficial annealing for two similar detectors…* 126

Fig. 6.20 *N_{eff} versus fluence for planar diodes made from standard (#5) and O-diffused (#8,#9 and #10) silicon. The diffusion time of oxygen at 1150 °C is indicated in the pictures. ……..……..……..……..……* 127

Fig. 6.21 *N_{eff} versus fluence for planar diodes* m*ade from epitaxial materials (#15)……...* 128

Fig. 6.22 Comparison of *N_{eff} versus fluence for planar diodes made from O diffused FZ (#9) and epitaxial materials (#15)…..……..……* 128

Fig 6.23 *Comparison of N_{eff} versus fluence between standard (#5) and NTD diodes (#23 #24). ……...* 128

Fig. 6.24 *N_{eff} versus fluence for planar diodes made from FZ low resistivity standard (#3) and jet oxygenated (#11) silicon. ……...* 129

Fig 6.25 *N_{eff} versus fluence for planar diodes made standard low resistivity silicon #3 and tin enriched low resistivity silicon #13. ……* 129

Fig. 6.26 *N_{eff} as a function of the fluence for planar diodes made from standard (#5), carbonated (#7) and jet-oxygenated (#12) silicon.* …… 130

Fig. 6.27 *N_{eff} versus fluence for planar diodes made from MACOM 100 μm epitaxial silicon #14 (a) 5x5 mm^2 square diode (b) 1.36 cm^2 round device.* …… 130

Fig. 6.28 *N_{eff} as a function of the annealing time at 60 °C for planar diode made from standard (#5) and O-diffused (#8, #9 and #10) silicon. Irradiation fluence: $1.5 \cdot 10^{14}$ cm^{-2}.* …… 131

Fig. 6.29 *N_{eff} as a function of the time after irradiation for planar and mesa diode made from standard material (#5) and planar diodes made from jet-oxygenated silicon (#11): (a) full scale (b) limited scale to evidence the beneficial annealing.* ……. 131

Fig. 6.30 *I_{vol} as a function of fluence for planar diodes made from standard (#5) and oxygen diffused (#9) wafers.* …… 132

Fig. 6.31 *I_{vol} as a function of fluence for planar diodes made from similar epitaxial wafers* (#15). …… ……. 133

Fig. 6.32 *I_{vol} as a function of fluence for planar diodes made from low resistivity (a) tin enriched (#13) and (b) standard (#3) FZ wafers. The reverse current has been annealed to 10 days equivalent at room temperature.* ……... 133

Fig. 6.33 *I_{vol} as a function of fluence for planar diodes made from standard (#5), jet-oxygenated (#12) and carbonated (#7) materials.* ……. 134

Fig. 6.34 *I_{vol} as a function of fluence for planar diodes made from similar epitaxial wafers* (#14). …….. 134

Fig. 6.35 *Charge collection efficiency versus proton fluence for planar diodes made from Standard (#2, #5) and weakly oxygenated (#6) materials.* ……. 135

Fig. 6.36 *Comparison between (a)β values, (b) $\Phi_{inv}/N_{eff}(0)$ and (c) g_y for various sets of mesa and planar diodes made from a similar material and irradiated with protons (labels # refer to Table 6.1).* …….. 137

Fig. 6.37 *Comparison between β values for neutron irradiated diodes made from various materials. Measurements performed (a) after 30-60 minutes irradiation and (b) after an annealing step of 4' at 80 °C. The labels # refer to Table 6.2*…….. 139

Fig. 6.38 *β versus resistivity for neutron irradiated diodes made from various materials.* 140

Chapter 7

Fig. 7.1 *Simulated specific energy loss of low-range protons in silicon.* …… 142

Fig. 7.2 *Charge collection versus $V^{1/2}$, recorded by an ADC, for (a) front and (b) rear illumination of a non-irradiated silicon detector with protons of different energies.* ……..142

Fig. 7.3 *CCE as a function of $V^{1/2}$ for diodes of different thicknesses irradiated by protons to ≈ 7.5 10^{13} cm^{-2}. The α source was positioned on the rear side. Diode thicknesses: (a) 147μm, (b) 303μm, (c) 503μm*…….. 143

Fig. 7.4 *Charge collection (CC) versus $V^{1/2}$ for variously irradiated diodes illuminated by protons of different energies from a Van de Graaf accelerator [6.1]. The CC is recorded by an ADC in the case of front injection (column (a)) and rear injection (column (b))*….. …….. 145

Fig. 7.5 *V_{80} as a function of fluence for front and rear injection of low range protons: (a) 1 MeV (b) 2.5 MeV protons.* ……. 146

Fig. 7.6 *Shape of the LED pulse measured with a PM.* ……...… 148

Fig 7.7 *CCE as a function of $V^{1/2}$ for front and rear illumination of non-irradiated (a) n-type and (b) p-type diodes.* …….. 149

Fig. 7.8 *Signal pulse shape in a non-irradiated n-type diode. (a) Front illumination (b) Rear illumination from 80 to 95 volts (c) Rear illumination from 95 to 150 volts. V_{FD} = 105 volts.* …….. 149

Fig. 7.9 *Peaking time versus $V^{1/2}$ for a non-irradiated and irradiated (low fluences) diodes for front LED illumination.* …… 150

Fig. 7.10 *Peaking time (t_p) versus $(V/V_{FD})^{1/2}$ for rear injection in (a) n-type and (b) p-type non irradiated diodes.* …… 151

Fig. 7.11 *CCE versus $V^{1/2}$ for front and rear illumination of n-type irradiated (non-inverted) diodes: (a) $\Phi = 1.0 \cdot 10^{12}$ cm^{-2} ($\Phi < \Phi_{inv}$), (b) $\Phi = 1.5 \cdot 10^{13}$ cm^{-2} ($\Phi < \Phi_{inv}$).* ……. 151

Fig.7.12 *CCE versus $V^{1/2}$ for an n-type diode irradiated up to $\Phi = 1.0 \cdot 10^{14}$ cm^{-2} ($\Phi > \Phi_{inv}$). (a) rear illumination (b) front illumination.* …….. 152

Fig. 7.13 *CCE versus $V^{1/2}$ for an n-type diode irradiated up to $\Phi = 1.7 \cdot 10^{14}$ cm^{-2} ($\Phi > \Phi_{in}$). (a) rear illumination (b) front illumination.* 152

Fig. 7.14 *CCE versus $V^{1/2}$ for an n-type diode irradiated up to $\Phi = 2.9 \cdot 10^{14}$ cm^{-2} ($\Phi > \Phi_{inv}$). (a) rear illumination (b) front illumination.* 152

Fig. 7.15 *Signal pulses for $1 \cdot 10^{14}$ cm^{-2} irradiated diode illuminated by red LED light. (a) Front illumination: 10-40 V (b) Front illumination: 45-75 V (c) Front illumination: 80-180 V (d) Rear illumination 5-150 V. V_{FD} = 70 volts*... 153

Fig. 7.16 *Signal pulses for $1.7 \cdot 10^{14}$ cm^{-2} irradiated diode illuminated by red LED light. (a) Front illumination: 2.5-65 V, (b) Front illumination: 70-105 V, (c) Front illumination: 110-170 V (d) Rear illumination 5-140 V. V_{FD} = 115 volts*..... 154

Fig. 7.17 *Signal pulses for $2.9 \cdot 10^{14}$ cm^{-2} irradiated diode illuminated by red LED light. (a) Front illumination: 10-100 V (b) Front illumination: 110-180 V, (c) Front illumination: 200-250 V, (d) Rear illumination 10-250 V. V_{FD} = 225 volts*..... 155

Fig. 7.18 *Height of the signal pulse as a function of $V^{1/2}$ for diodes irradiated up to: (a) $1.1 \cdot 10^{14}$ (b) $1.7 \cdot 10^{14}$ and (c) $2.9 \cdot 10^{14}$ cm^{-2}.* 155

Fig. 7.19 *Qualitative electric field distribution in a detector irradiated above type inversion [7.3].* 157

Fig. 7.20 *Peaking time of the second peak (t_{pf}) as a function of $V^{1/2}$ for front illumination of three heavily irradiated diodes.* 158

Fig. 7.21 *Peaking time of the second peak (t_{pf}) as a function of $(V/V_{FD})^{1/2}$ for front illumination of three heavily irradiated diodes: (a) $1.1 10^{14}$ cm^{-2} (b)$1.7 10^{14}$ cm^{-2} (c) $2.9 10^{14}$ cm^{-2}.* 158

Fig. 7.22 *Signal pulses for front illumination of a $5.3 \cdot 10^{13}$ cm^{-2} irradiated diodes ($\approx \Phi_{inv}$): (a)5-15 V, (b) 17-30 V and (c) 36-120 V.* 159

Fig. 7.23 *Signal pulses for rear illumination of a $5.3 \cdot 10^{13}$ cm^{-2} irradiated diodes ($\approx \Phi_{inv}$): (a)5-15 V, (b) 18-45 V and (c) 55-160 V.* 160

Fig. 7.24 *Peaking time of the second peak (t_{pf}) as a function of $(V/V_{FD})^{1/2}$ for front and rear Illumination of a diode irradiated up to $5.2 10^{13}$ cm^{-2}.* 160

Fig. 7.25 *Simulated [7.7] electric field irradiated detectors at different values of the applied bias.* 162

Fig. 7.26 *Concentration of free majority carriers (holes) as a function of depth for heavily irradiated detectors at different values of the applied bias.* …….. 162
Fig. 7.27 *Simulated values [7.6] of the electric field at 100, 150 and 200 μm depths as a function of* $V^{1/2}$. ……... 163

List of tables

Chapter 1

Table 1.1 *Annual fluxes expected in silicon due to various damaging particles, expressed as the 1 MeV Equivalent neutron flux as a function of radial position for the ATLAS inner tracker. Flux units of the damaging particles are* 10^{13} *(1 MeV) neutrons* cm^{-2} yr^{-1}. …… 28

Chapter 2

Table 2.1 *Difference between the bottom of the conduction band (*E_C*), the top of the valence band (*E_V*) and the impurity level (*E_L*) for the most important donors and acceptor in silicon.* …….. 32

Chapter 3

Table 3.1 *Hardness factor for the normalisation to the 1MeV neutron fluence for the two facilities used for the irradiation.* …….. 59
Table 3.2 *A few defect reactions in silicon. The subscript i stands for interstitial, s for substitutional, I for Si interstitial, V for vacancy, C for carbon, O for Oxygen and P for phosphorus.* ……... 61
Table 3.3 *Identified defect states with their energy levels in eV.* ……... 61
Table 3.4 *Fitting parameters for the annealing at room temperature of the reverse current*

of detectors made from standard silicon. ……..……...…….……. 64

Chapter 4

Table 4.1 *Different components of the reverse current.* ……. 80

Chapter 5

Table 5.1 *Diffusion parameters for boron and phosphorus in silicon found by different workers* [5.13]. ……..……..……..……..……..103

Table 5.2 *Diffusion parameters and solubility for O, C and Sn in silicon* [5.13]…….. 106

Table 5.3 *Tested silicon materials. Labels* (*) *indicate the analysis method used for the impurity concentrations:* [(a)] *Fourier Transform Infrared Spectroscopy (FTIR) at room temperature,* [(b)] *FTIR at 5K,* [(c)] *Secondary Ion Mass Spectrometry (SIMS) profiling and* [(d)] *SIMS bulk measurement.* …….. 113

Chapter 6

Table 6.1 *Radiation hardness parameters extracted from the proton irradiation data*…….. 136

Table 6.2 *Radiation hardness parameters extracted from the neutron irradiation data: measurements performed (a) 30-60' after irradiation and (b) after 4' at 80 °C*… 138

Chapter 7

Table 7.1 *Detectors used for the LED charge collection study. The detectors are 280 µm thick silicon diodes made from standard FZ silicon and irradiated with 24 GeV/c protons. All the diodes are n-type, unless otherwise indicated*……..148

Table 7.2 *Values of the velocity and of the electric field in the quasi-neutral bulk (QNB) bulk*…….. 156
Table 7.3 *Values of the v_M and E_M for three heavily irradiated diodes*……...157
Table 7.4 *Comparison between N_{eff} for three heavily irradiated diodes calculated using the C-V and the CCE methods*. …… 162