Effects of Irradiation on Silicon Carbide Radiation Detectors

Francesco Moscatelli

IMM-CNR Bologna, Bologna, Italy

Outline

- Introduction
- Irradiation with electrons
- Irradiations with protons and neutrons
- Annealing effects
- New silicon detectors for HL-LHC
- Conclusions

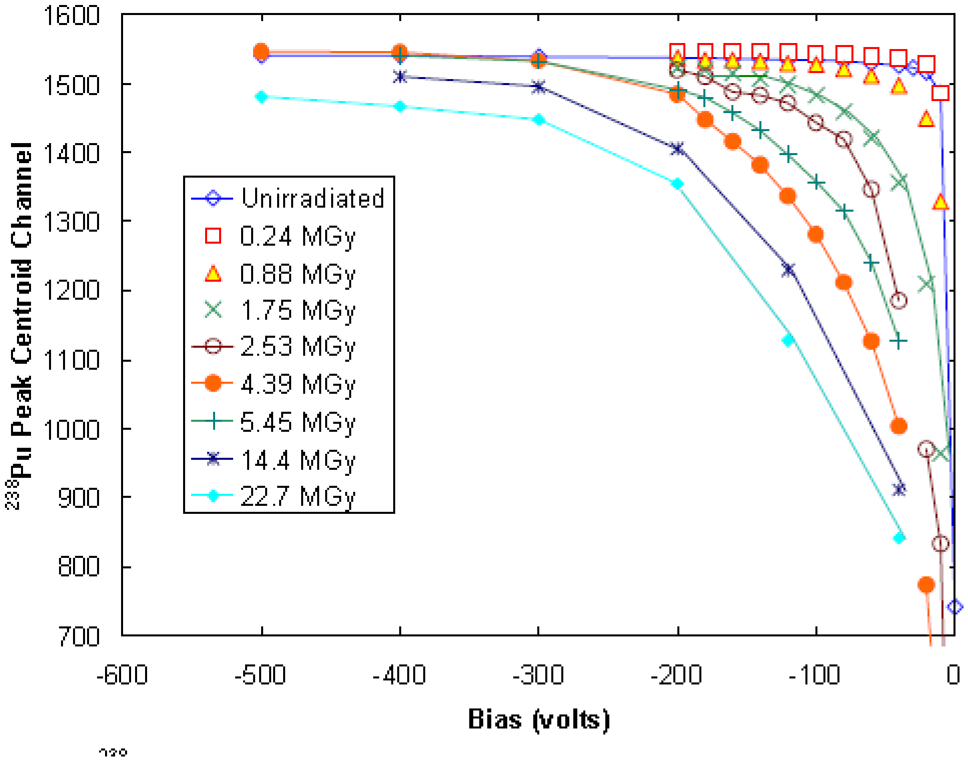
Introduction

- Energetic particles can cause two types of damage:
- Bulk damage
  - Variation of effective doping concentration
  - Variation of the leakage current
  - Trapping
- Surface damage: accumulation of oxide and interface charge in the oxide

Threshold displacement energy E_d

- The radiation resistance is typically higher for semiconductor or semi-insulating materials with a higher threshold displacement energy, E_d.
- The value of E_d for 4H–SiC is 20-35 eV larger than those for Si, GaAs and CdTe by a factor of 1.5 or more and is smaller than that for diamond by a factor of 2.
- This theoretical prediction has promoted research in the world on the radiation resistance of SiC

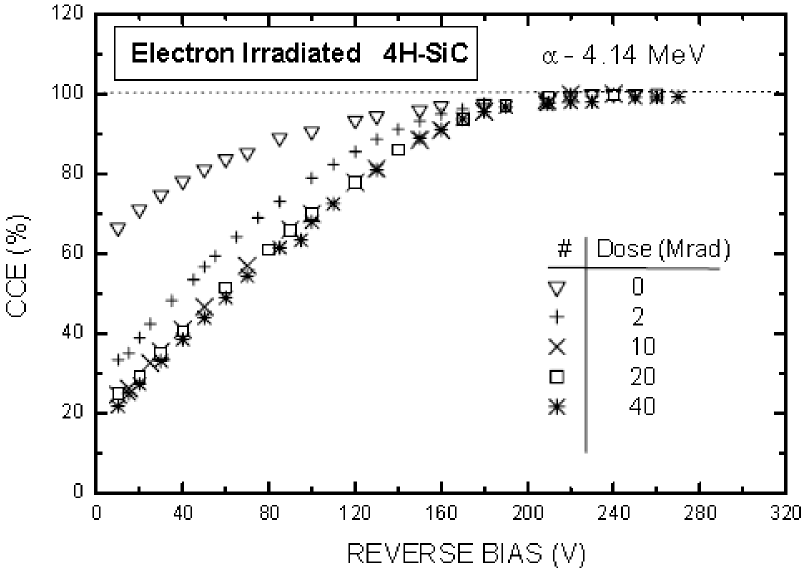
Gamma rays

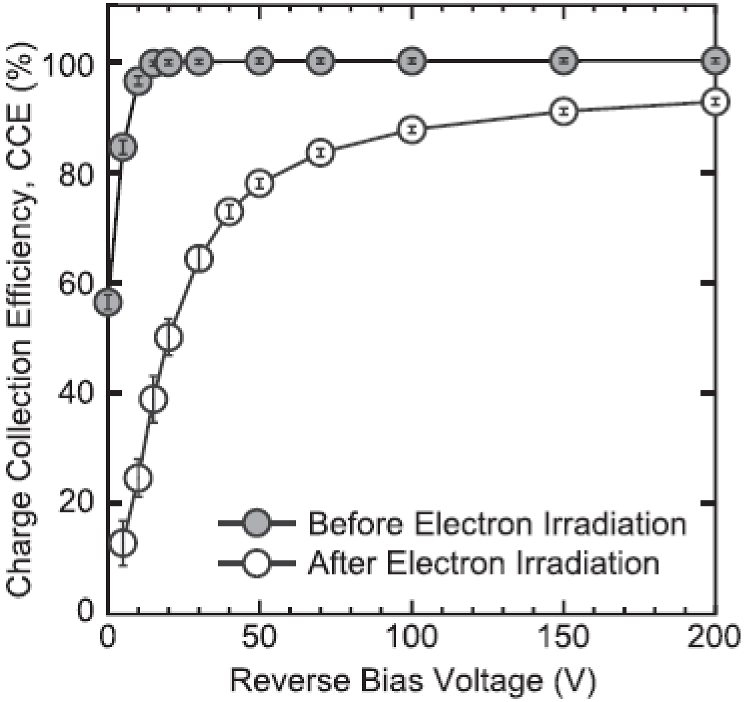


CCE= 84% after extreme cumulative gamma-ray dose of 22.7 MGy

F. H. Ruddy and J. G. Siedel, Effects of Gamma Irradiation on Silicon Carbide Semiconductor Radiation Detectors, Nucl. Scie. Symp. Conf. Records, 583-587, 2006.

Irradiation with electrons





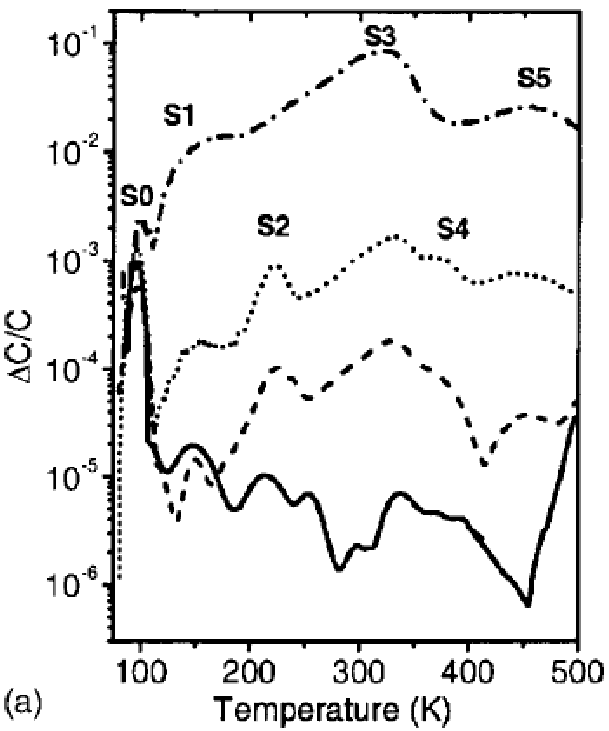
100 % after 40 Mrad
electrons 8.2 MeV

90% after 1 MeV electrons fluence
1x10^{15} cm^{-2} (alpha particle)

- F. Nava, E. Vittone, P. Vanni, P. G. Fuochi, and C. Lanzieri, Nucl. Instrum. Methods Phys. Res. A **505**, 645 (2003).

- N. Iwamoto et al, “Defect-induced performance degradation of 4H-SiC Schottky barrier diode particle detectors,” Journal of Applied Physics 113, 143714 (2013).

DLTS: protons and electrons

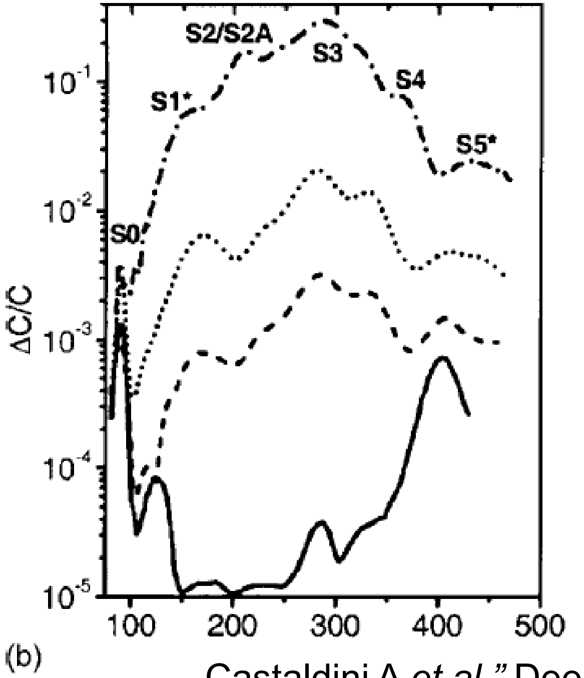


Protons 6.5 MeV

Trap label	E_T (eV)	N_T(cm^{-3})	σ_{inter}(cm^2)	η_T(cm^{-1})	Comparison with published data Deep level	 Attribution
S0	0.18	1.0×10^{13}	2×10^{-14}	~0	Ti,[a] P_1/P_2[b]	Ti impurity[a,c] primary defects[b]
S1	0.20	6.3×10^{13}	7×10^{-18}	3.2	…	…
S2	0.40	1.3×10^{14}	1×10^{-15}	4.1	EH1[d]	…
S3	0.72	3.5×10^{14}	2×10^{-14}	11.0	Z_1/Z_2,[a,b] EH2[d]	$N+I_C$[e]
S4	0.76	1.1×10^{14}	1×10^{-14}	3.5	EH3[d]	…
S5	1.09	7.7×10^{13}	5×10^{-13}	2.4	RD1/2,[a] EH5[d]	V_C+V_{Si}[b]

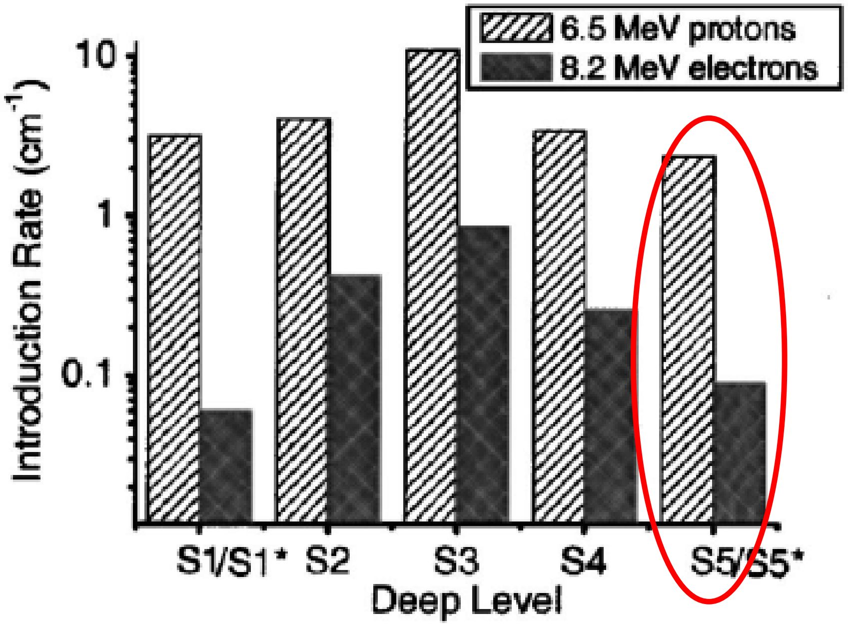
Electrons 8.2 MeV

Trap label	E_T (eV)	N_T(cm^{-3})	σ_{inter}(cm^2)	η_T(cm^{-1})	Comparison with published data Deep level	 Attribution
S0	0.15	1.4×10^{13}	6×10^{-16}	~0	Ti,[a] P_1/P_2[b]	Ti impurity[a,c] primary defects[b]
S1*	0.23	5.5×10^{13}	9×10^{-16}	0.06	…	…
S2A	0.33	6.9×10^{14}	7×10^{-16}	0.73	…	I_C[d]
S2	0.39	4.0×10^{14}	2×10^{-15}	0.42	EH1[e]	…
S3	0.65/0.50	$4.2/5.4\times10^{14}$	$10^{-16}/10^{-14}$	0.44	Z_1/Z_2,[a,b] EH2[e]	$N+I_C$[f]
S4	0.75	2.6×10^{14}	6×10^{-15}	0.27	EH3[e]	…
S5*	0.89	4.6×10^{13}	7×10^{-15}	0.09	RD1/2,[a] EH5[e]	V_C+V_{Si}[b]



Castaldini A *et al,"* Deep levels by proton and electron-irradiation in 4H silicon carbide," *J. Appl. Phys.* **98** 53706 (2005).

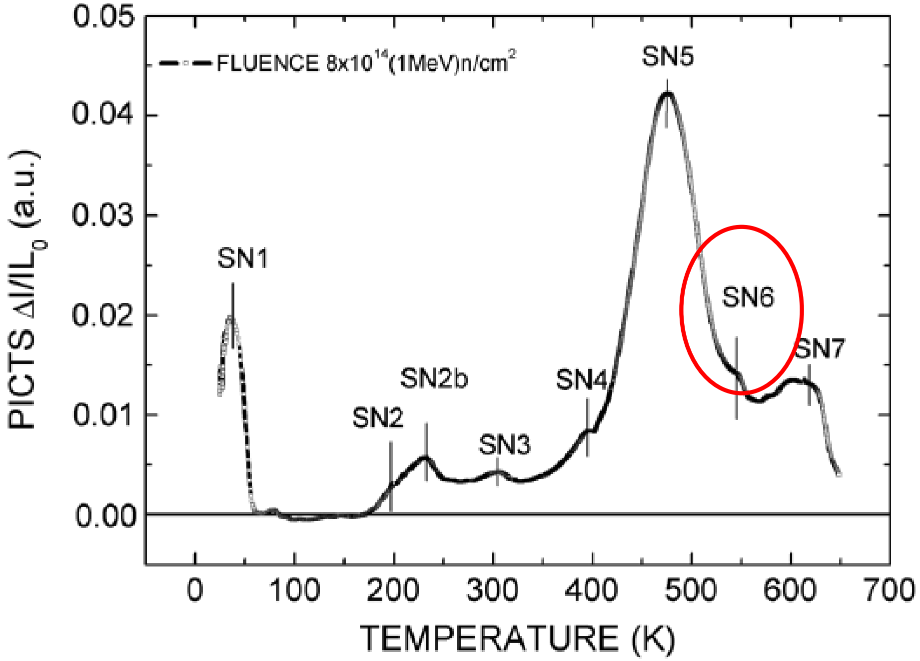
Defects: protons and electrons



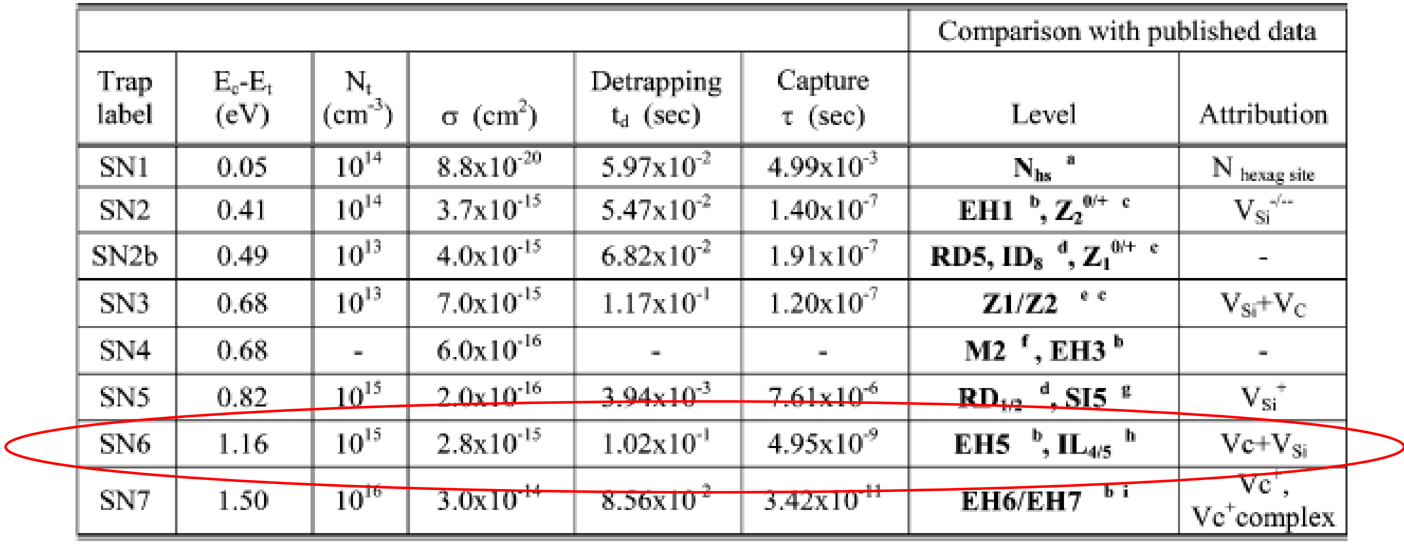
The ratio of the introduction rates between proton- and electron irradiated samples is about 30

Castaldini A *et al,"* Deep levels by proton and electron-irradiation in 4H silicon carbide," *J. Appl. Phys.* **98** 53706 (2005).

DLTS neutrons



F. Nava et al, “Silicon carbide and its use as a radiation detector material,” Meas. Sci. Technol. 19 102001 (2008)



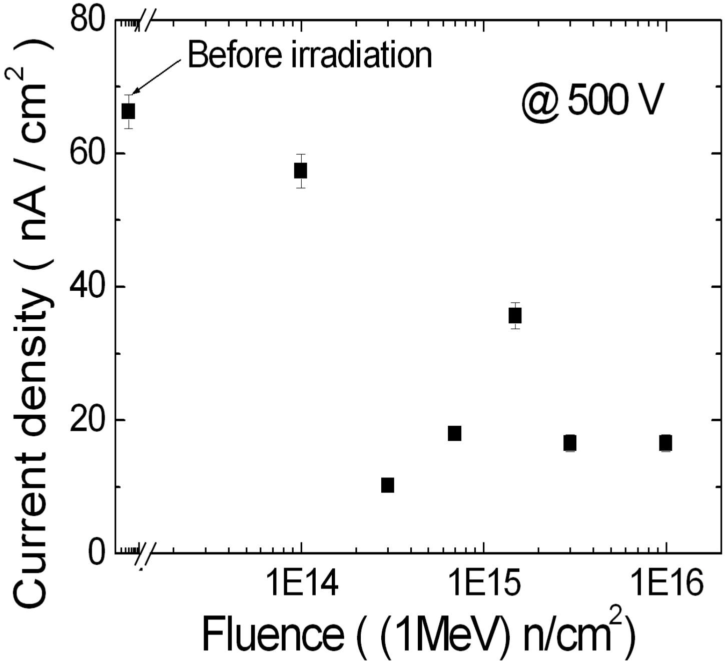
						Comparison with published data	
Trap label	E_c-E_t (eV)	N_t (cm^{-3})	σ (cm^2)	Detrapping t_d (sec)	Capture τ (sec)	Level	Attribution
SN1	0.05	10^{14}	$8.8x10^{-20}$	$5.97x10^{-2}$	$4.99x10^{-3}$	**N_{hs}** [a]	$N_{hexag\ site}$
SN2	0.41	10^{14}	$3.7x10^{-15}$	$5.47x10^{-2}$	$1.40x10^{-7}$	**EH1** [b], **$Z_2^{0/+}$** [c]	$V_{Si}^{-/--}$
SN2b	0.49	10^{13}	$4.0x10^{-15}$	$6.82x10^{-2}$	$1.91x10^{-7}$	**RD5, ID_8** [d], **$Z_1^{0/+}$** [c]	-
SN3	0.68	10^{13}	$7.0x10^{-15}$	$1.17x10^{-1}$	$1.20x10^{-7}$	**Z1/Z2** [e] [c]	V_{Si}+V_C
SN4	0.68	-	$6.0x10^{-16}$	-	-	**M2** [f], **EH3** [b]	-
SN5	0.82	10^{15}	$2.0x10^{-16}$	$3.94x10^{-3}$	$7.61x10^{-6}$	**$RD_{1/2}$** [d], **SI5** [g]	V_{Si}^+
SN6	1.16	10^{15}	$2.8x10^{-15}$	$1.02x10^{-1}$	$4.95x10^{-9}$	**EH5** [b], **$IL_{4/5}$** [h]	Vc+V_{Si}
SN7	1.50	10^{16}	$3.0x10^{-14}$	$8.56x10^{-2}$	$3.42x10^{-11}$	**EH6/EH7** [b] [i]	Vc^+, Vc^+complex

Protons 8 MeV and 1 GeV

- Analysis with protons of 8 MeV and 1 GeV
- The number of primary vacancies for proton energies of 8 MeV and 1 GeV equal 110 : 1, due to a decrease in the cross section for proton scattering by Si and C atoms as the proton energy increases.
- Experimentally, concentrations of the V_C+V_{Si} in the two above cases are related as 400 to 1.
- In the case of irradiation with high-energy protons, more compact Frenkel pairs are formed; recombination of vacancies and interstitial atoms occurs more efficiently for these pairs. Accordingly, a lesser number of vacancies is transferred from the tracks of recoil atoms to the film bulk with subsequent formation of the V_C+V_{Si} centers.

Lebedev A A, Ivanov A M and Strokan N B,"Radiation resistance of SiC and nuclear radiation detectors based on SiC films," *Semiconductor* **38** 125–47 2004

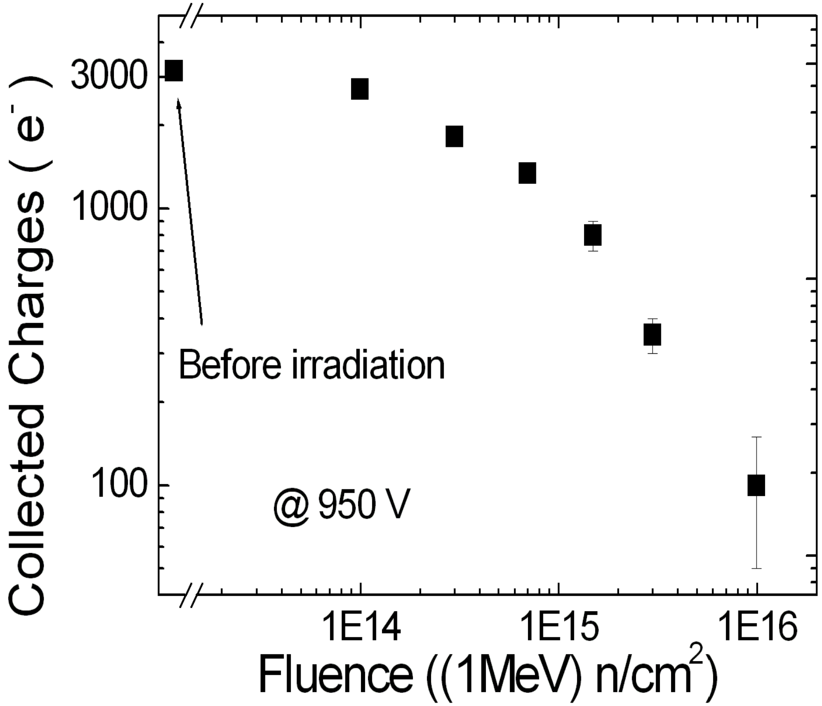
1 MeV Neutrons: I- V after irradiation



Reverse current density decreases after irradiation

F. Moscatelli, et al, "Radiation Hardness after Very High Neutron Irradiation of Minimum Ionizing Particle Detectors Based on 4H-SiC p+n Junctions", Nuclear Science, IEEE Transactions on , Volume: 53, n. 3 , June 2006 Page(s): 1557 –1563.

1 MeV neutrons CC vs fluence



55 μm thick n-epi

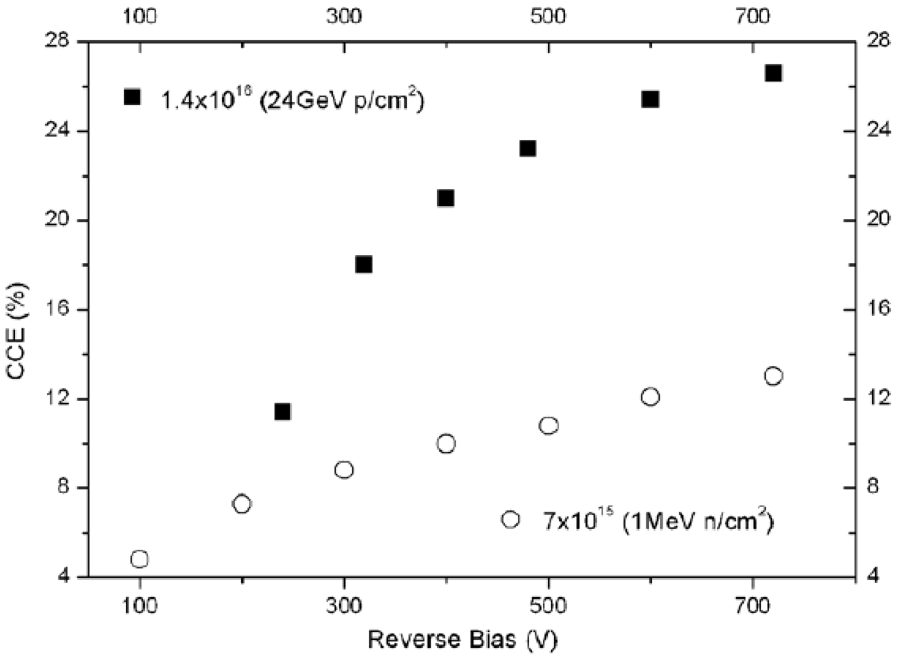
CC is high until some 10^{14} n/cm^2

CC decreases sharply after 10^{15} n/cm^2. Only 130 e$^-$ after 10^{16} n/cm^2

Minimum Ionized Particles (MIPs) of ^{90} Sr beta particle source 55 e/h pairs per μm

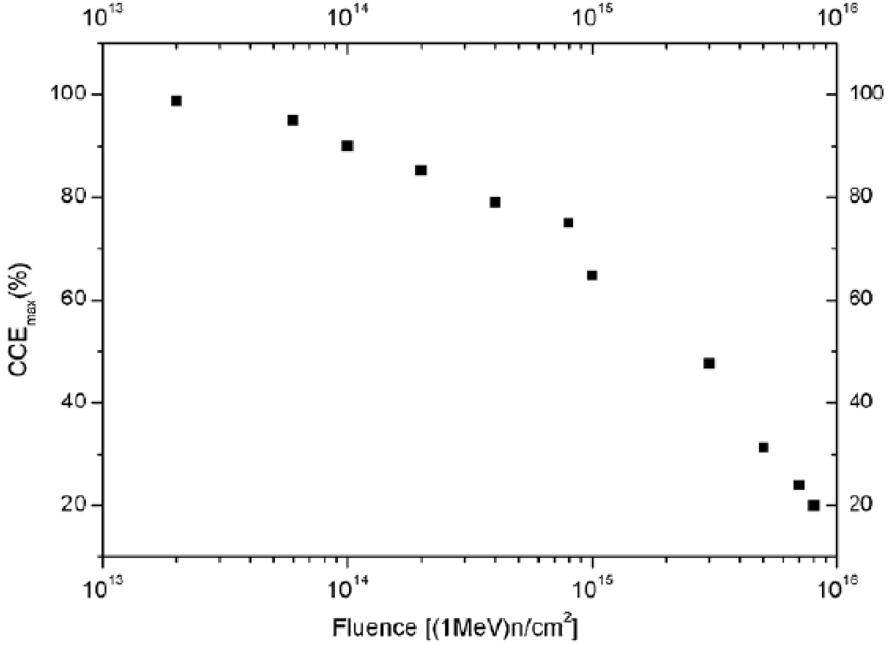
F. Moscatelli, et al, "Radiation Hardness after Very High Neutron Irradiation of Minimum Ionizing Particle Detectors Based on 4H-SiC p+n Junctions", Nuclear Science, IEEE Transactions on , Volume: 53, n. 3 , June 2006 Page(s): 1557 –1563.

CC protons and neutrons



Minimum Ionized Particles (MIPs) of ^{90} Sr beta particle source

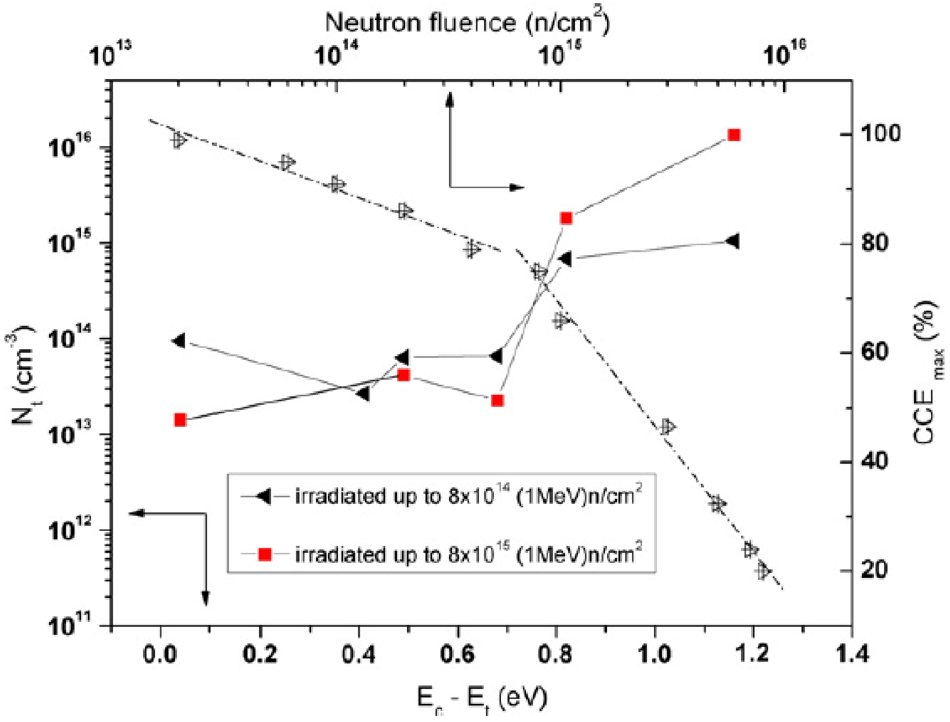
- S. Sciortino et. al.,"Effect of heavy proton and neutron irradiations on epitaxial 4H-SiC Schottky diodes," *Nucl. Instrum. Meth. Phys. Res. A* 552, 138-145, 2005.



5.48 MeV alpha particles

- F. Nava et al., "Minimum ionizing and alpha particle detectors based on epitaxial semiconductor silicon carbide," *IEEE Trans. Nucl.Sci.*, vol. 51, pp. 238–244, 2004.

Importance of $V_C + V_{Si}$ defect

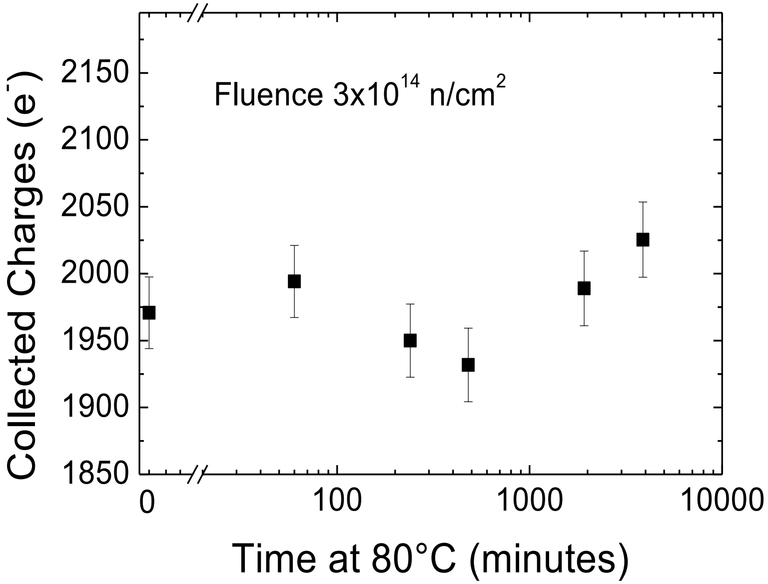


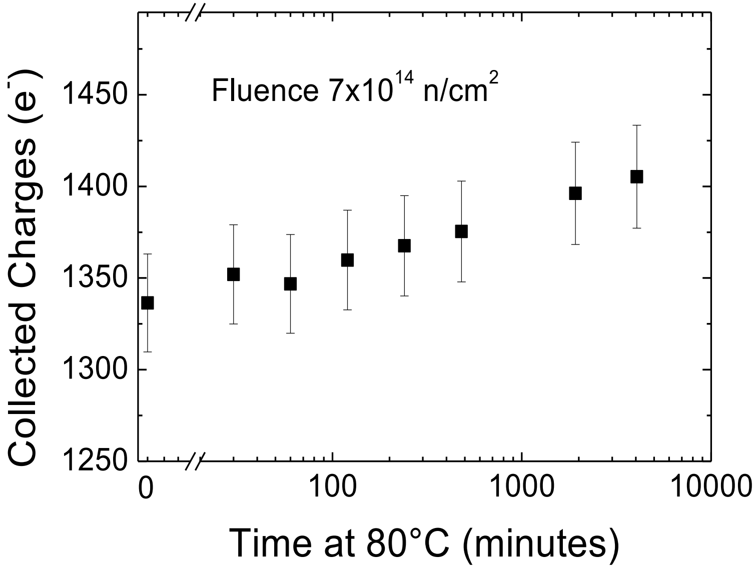
F. Nava et al, “Silicon carbide and its use as a radiation detector material,” Meas. Sci. Technol. 19 102001 (2008)

- At $\Phi > 3 \times 10^{15}$ n cm^{-2}, $E = E_C - 1.16$ eV dominant (concentration and capture cross section).
- It acts as an electron trapping centre
- Electron lifetime τ_e is comparable to the transit time of the electrons in the detector active (drift) region
- a detrapping time, t_d = 0.1 s, >> the typical time constants (τ_{sh} = 0.5–10 μs) of the signal-processing electronics.

This centre was related to vacancies, namely ($V_C + V_{Si}$).

CC measurements after 80°C annealing



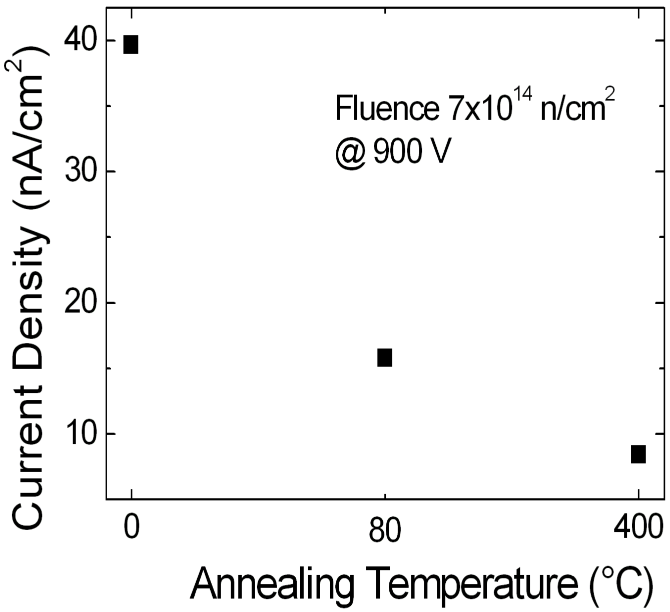


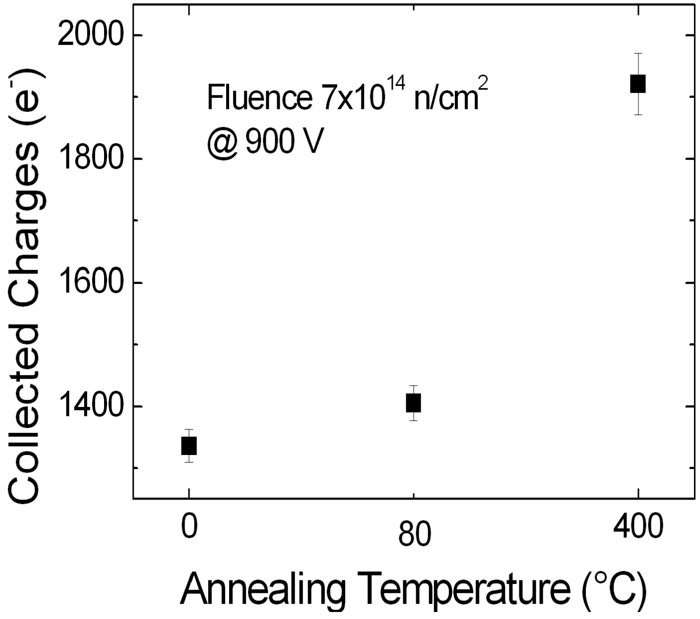
Minimum Ionized Particles (MIPs) of ^{90} Sr beta particle source

After annealing at 80°C we observe a slight increase of the collected charge, in the range of the experimental error.

Moscatelli F, “)“Silicon Carbide for UV, alpha, beta and X-ray Detectors: Results and Perspectives”, NIMA 583 (1): 157-161 (2007)

I-V and CC after annealing at 400°C



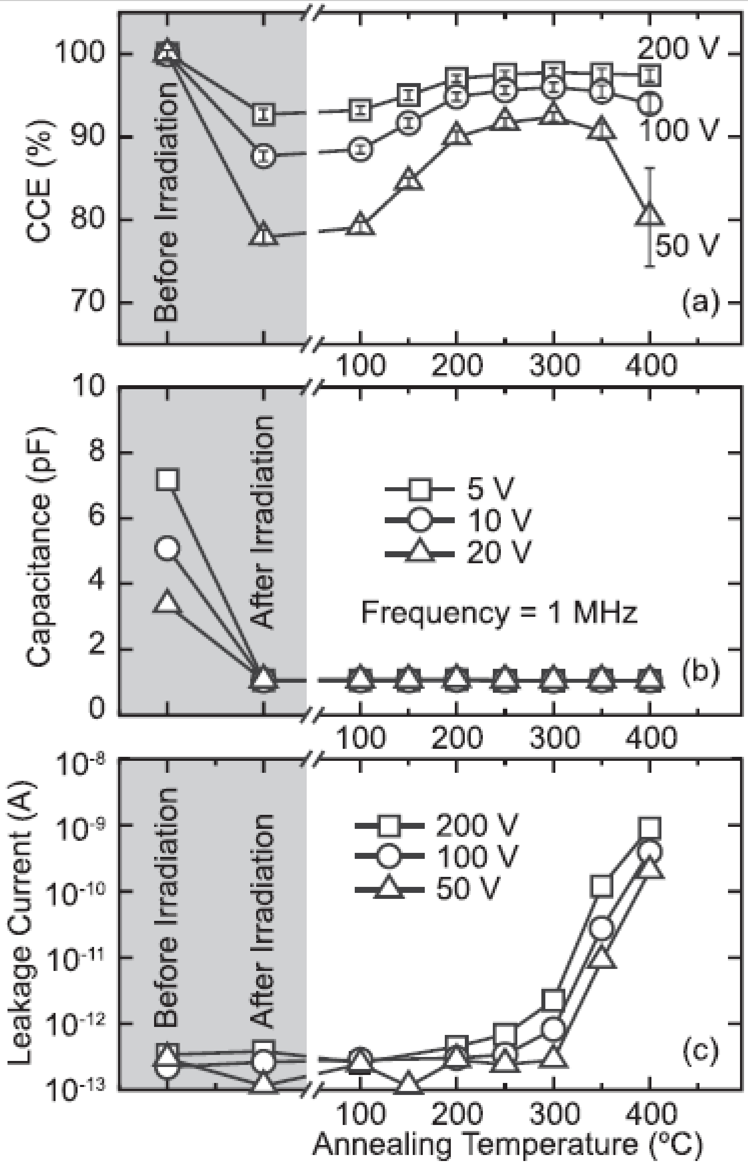


Minimum Ionized Particles (MIPs) of ^{90} Sr beta particle source

After 30 min at 400°C the current furtherly decreases and the CC increases of the 40% (from 1400 e^- to 1900 e^-)

Moscatelli F, ")"Silicon Carbide for UV, alpha, beta and X-ray Detectors: Results and Perspectives", NIMA 583 (1): 157-161 (2007)

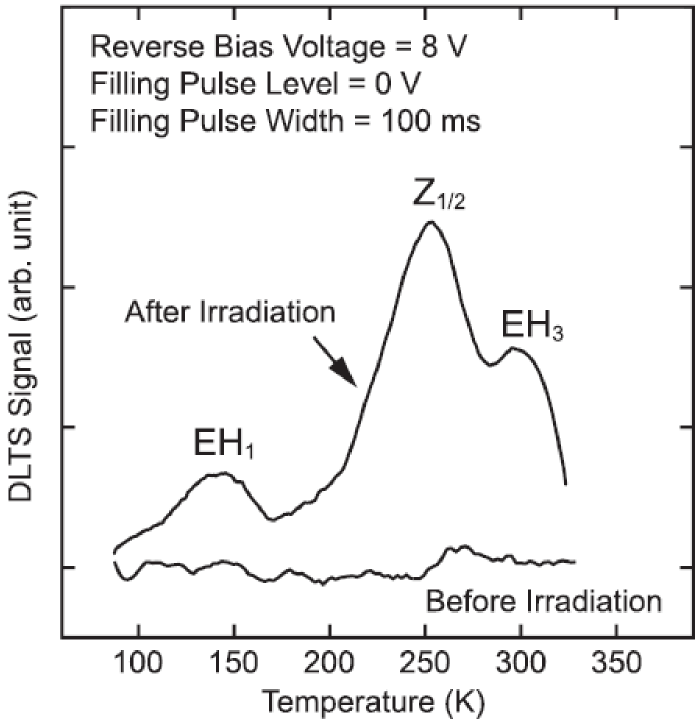
Annealing electron irradiation

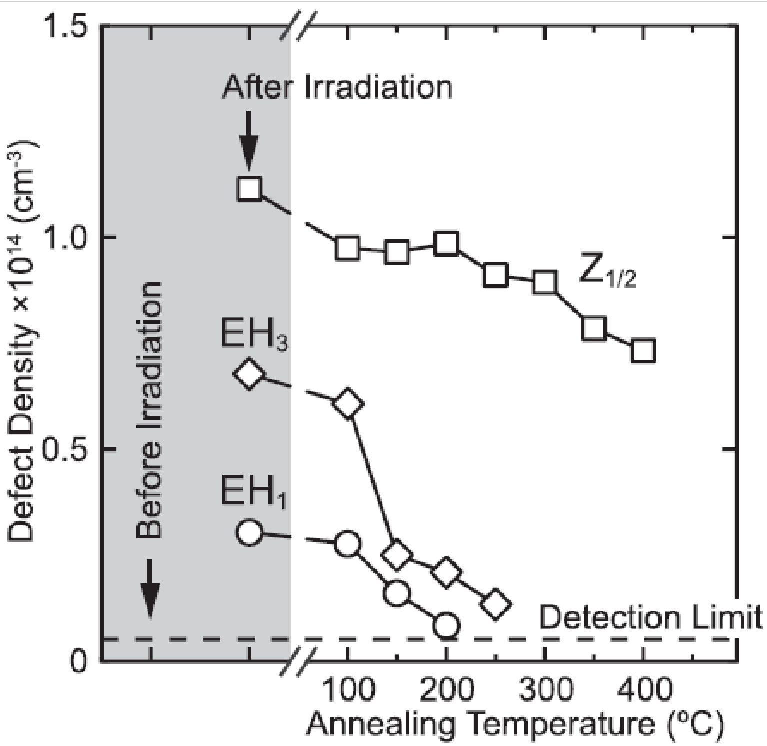


- As the annealing temperature increases up to 300° C, the CCE at all bias voltages recovers.
- No annealing effect on the capacitance
- Up to 300°C no annealing effect on the leakage current

- N. Iwamoto et al, "Defect-induced performance degradation of 4H-SiC Schottky barrier diode particle detectors," Journal of Applied Physics 113, 143714 (2013).

Annealing electron irradiation: DLTS

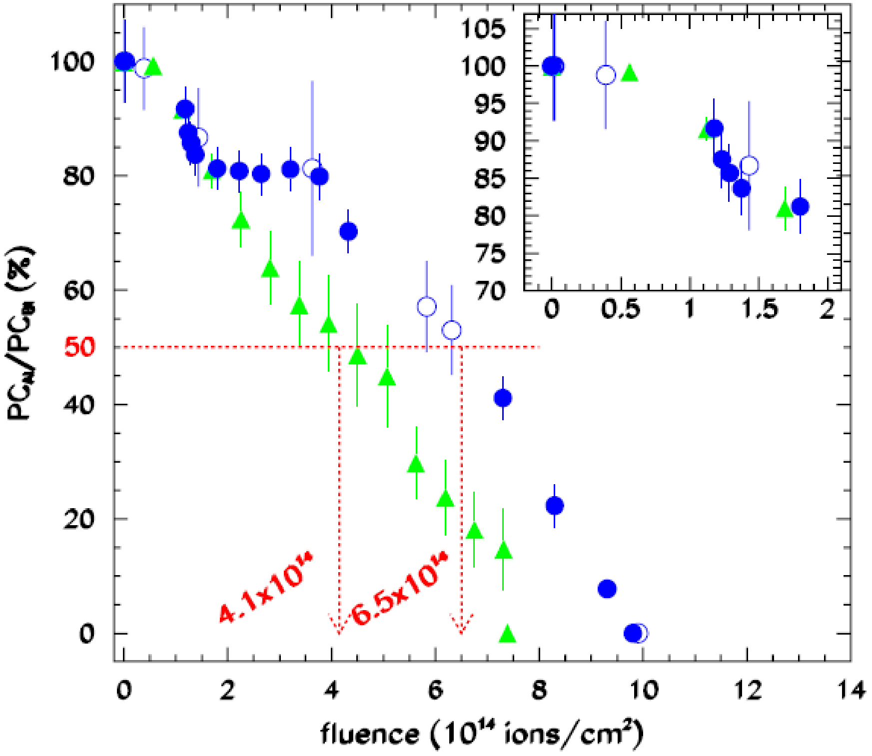


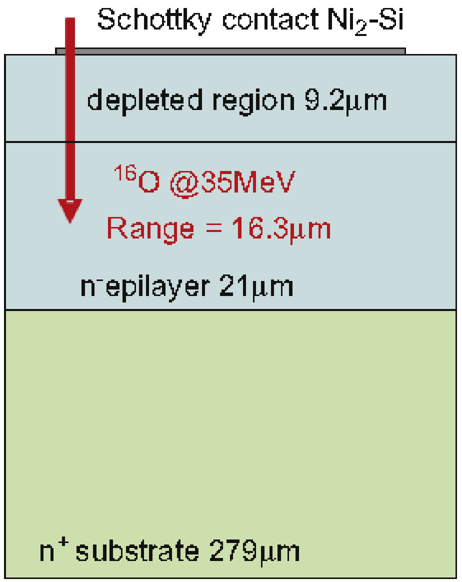


- Analysis limited at 330 K- Decreases of Z1/2, EH1 and EH3 with increasing annealing temperature.
- No analysis of deepest defects

- N. Iwamoto et al, “Defect-induced performance degradation of 4H-SiC Schottky barrier diode particle detectors,” Journal of Applied Physics 113, 143714 (2013).

Light ions





Schottky contact Ni_2-Si

depleted region 9.2µm

^{16}O @35MeV

Range = 16.3µm

n^-epilayer 21µm

n^+ substrate 279µm

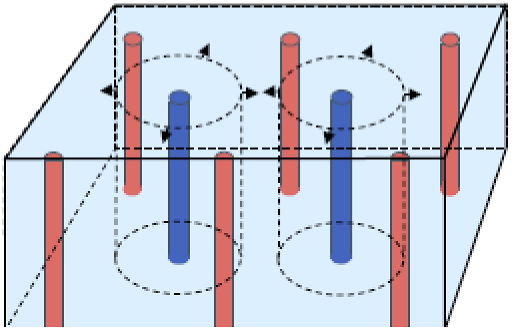
Ratio of the peak centroid of the ^{16} O energy spectrum after (PC_{AI}) and before irradiation (PC_{BI}) for two different SiC samples as a function of the fluence

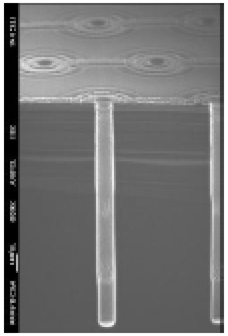
- Sample a (green) $N=6\times10^{14}$ cm^{-3}, V=600 V, W=32.7 µm
- Sample c (blue) $N=5\times10^{15}$ cm^{-3}, V=400 V, W=9.2 µm

M. De Napoli et al,”Dopant concentration dependance of the response of SiC Schottky diodes to light ions, NIMA, 600, pp. 618-623, 2009.

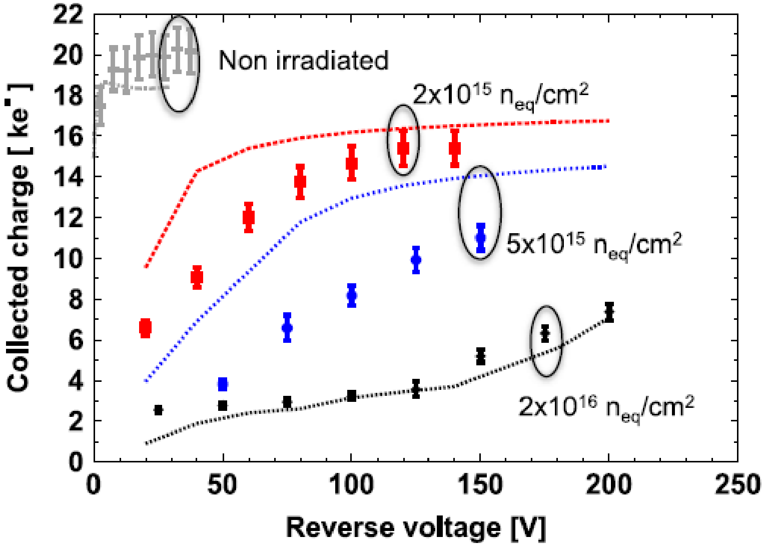
New Silicon Detectors for HL-LHC

Si detectors: 3D

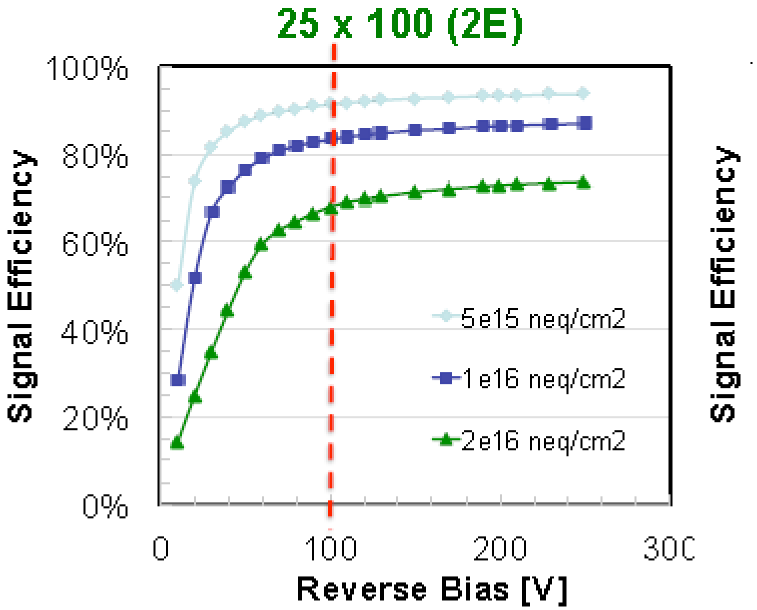




- 7 ke$^-$ @ 200 V after 2x10^{16} n/cm^2
- New design with increased CCE

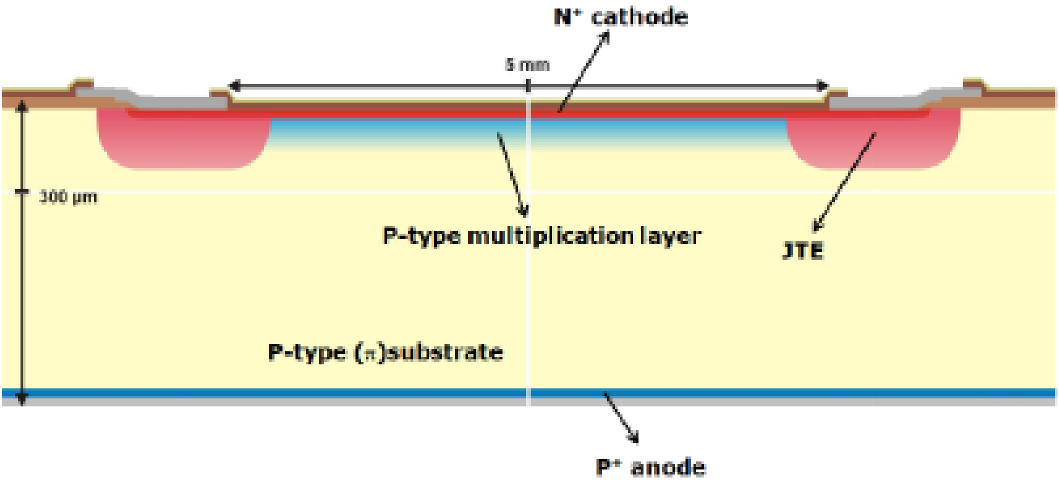


G.-F. Dalla Betta et al., “Radiation hardness tests of double-sided 3D strip sensors with passing-through columns ,” NIMA, 675, pp165-170, 2014

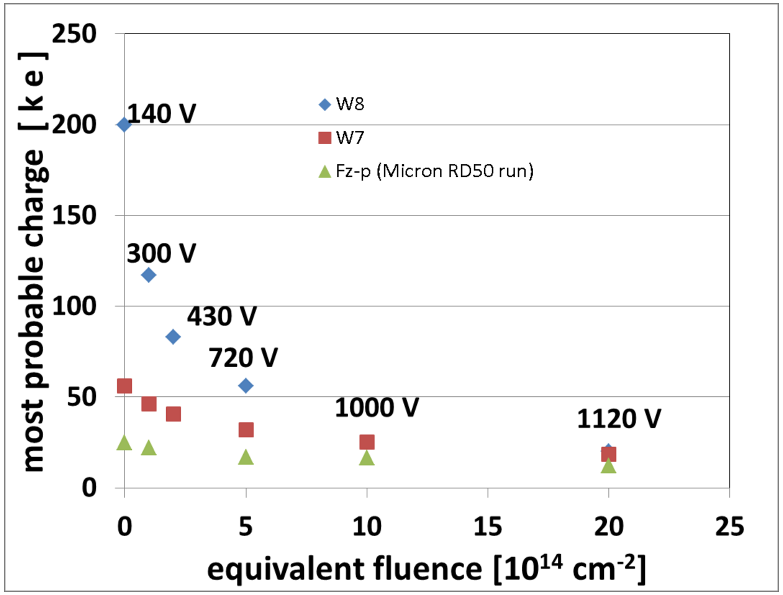

25 x 100 (2E)

Simulations using radiation damage model of Perugia (D. Passeri et al. (doi:10.1016/j.nima.2015.08.039))

Si detectors: LGAD



G.-F. Dalla Betta, IFD2105, Dec.16, 2015



G. Kramberger et al, 24th RD50 meeting

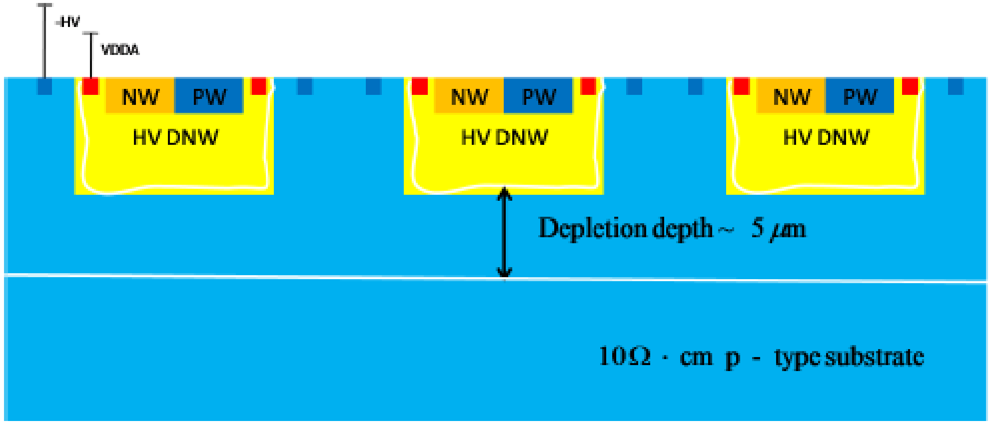
p-type multiplication layer

High sensitivity to the implant dose of the multiplication layer

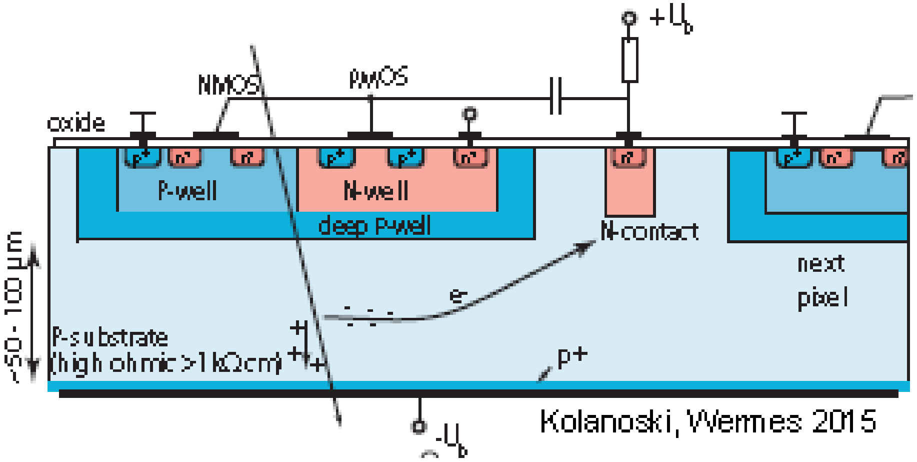
Gain vs breakdown voltage trade-off

Gain decreses with radiation

HV-CMOS and HR-CMOS



J. Liu et al,"HV/HR-CMOS sensors for the ATLAS upgrade concepts and test chip results," JINST 10, C03033, 2015



Kolanoski, Wermes 2015

Mattiazzo S, et al, NIMA 718, pp 288-291 (2013)

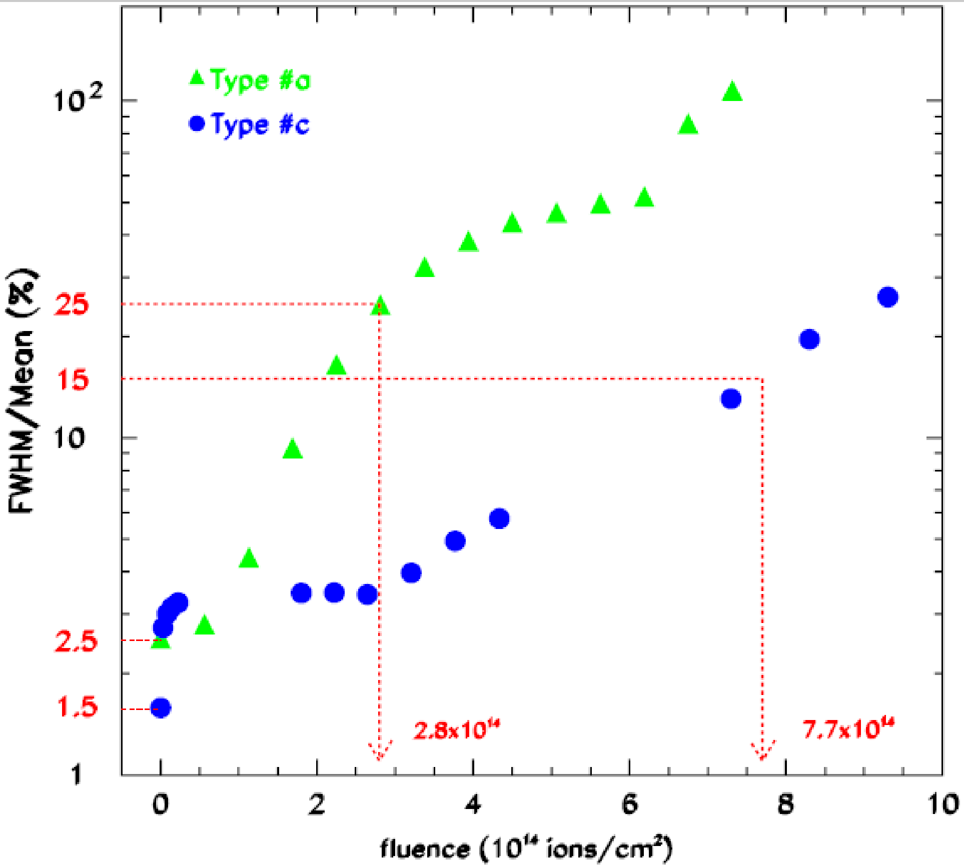
- Lightly doped deep n-well (DNW) in p-type substrate is used as charge collecting electrode.
- The entire CMOS electronics is implemented in the DNW.
- The electron-hole pairs generated by ionization are separated and quickly collected by drift (instead of diffusion) towards the electrodes due to the electric field in the space charge regions.

HR-CMOS has an high resistivity substrate to increase the depleted region

Conclusions

- The parameters of the radiation defects, such as ionization energy, capture cross section and structure, are similar for different irradiations
- No significant degradation of the CCE was observed after irradiation with alphas, electrons and gamma rays even at very high doses
- CCE of 95% with 8 MeV protons and 1 MeV neutrons at fluences lower than 3×10^{14} p cm^{-2} and 5×10^{13} n cm^{-2}, respectively.
- For 1 MeV neutron fluences above 8×10^{14} n cm^{-2} $V_C + V_{Si}$ defect plays an important role. Evaluate how to avoid its formation
- CCE recovery after annealing at high temperature (200-400°C)

Light ions (2)



Relative Energy resolution for two types of Schottky SiC detectors with different dopant concentration

Sample a (green) $N=6\times10^{14}$ cm^{-3}
Sample c (blue) $N=5\times10^{15}$ cm^{-3}

M. De Napoli et al,"Dopant concentration dependance of the response of SiC Schottky diodes to light ions, NIMA, 600, pp. 618-623, 2009.