# Ion Irradiation of Silicon Carbide Schottky diodes


L.Calcagno

F. La Via, G.Litrico, P.Musumeci, M.Mauceri

Physics Department, University of Catania, Catania, Italy
Istitute of Microelectonics and Microsystems (IMM)-CNR, Catania, Italy
Epitaxial Technology Centre


SiCilab –project (device realization) → Physics Department – Catania
IMM-CNR
Epitaxial Technology Centre (ETC - company)

# Summary

- Realization of SiC Schottky diodes

- SiC diodes for MeV ion detection

- Effects of ion irradiation on SiC diodes
  - Low dose regime
  - High dose regime

- SiC detector radiation hardness

- Conclusions

# Physical Properties

| PROPERTY | Si | SiC | Diamond |
|---|---|---|---|
| Band Gap (eV) | 1.12 | 3.3 | 5.5 |
| Electron/hole mobility (@R.T.) | 1350/480 | 800/115 | 1800/1200 |
| Max electric field ($10^6$ V/cm) | 0.3 | 4 | 10 |
| Saturation drift velocity of electrons ($10^7$ cm/s) | 0.8 | 2.0 | 2.2 |
| Average energy for e-h pair (eV) | 3.62 | 7.8 | 13-17 |
| Thermal conductivity (W/cm K) | 1.5 | 4.9 | 20 |
| Relative dielectric constant | 11.9 | 9.7 | 5.7 |
| Atomic displacement energy (eV) | 13 | 40 | 45 |

**Wide Band Gap** → **High Temperature Operation - Low leakage devices**

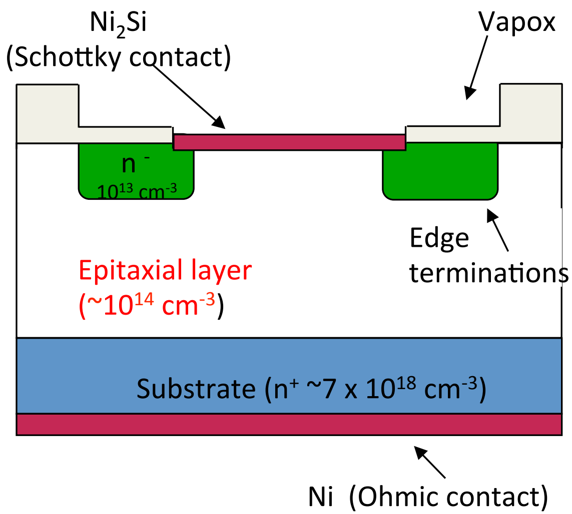
High Saturation Velocity → High frequency/speed devices

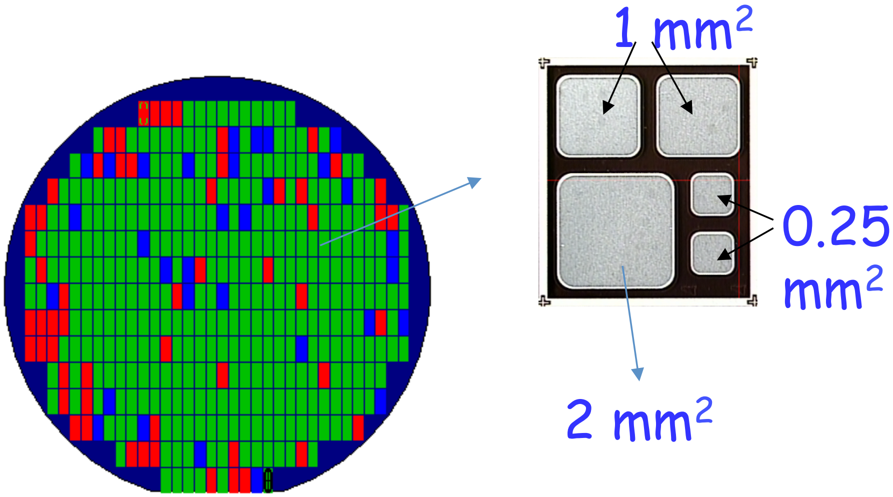
High Thermal Conductivity → High Power devices

High Critical Field → High Voltage devices

**High Displacement Energy** → **High resistance to radiation damage**

# Diode Realization




# Main processes

1) Epilayer growth
- Thick (high energy radiation)
- Low doped (high depletion layer with low voltage )
- Defect free (no carrier trapping)

2) Contact formation:
- Schottky Ni (200 nm) + 950 °C → $Ni_2Si$
- Ohmic contact Ni (200 nm)

# Growth of SiC epilayer


**Gas Precusors:**

silane ($SiH_4$) +ethylene ($C_2H_4$)

“ “ + HCl

**Si/$H_2$ ratio:** 0.02% - 0.6%

**C/Si ratio:** 3 – 0.5

**Temperature:** 1550 – 1650 °C

Optimisation of growth parameters

↓

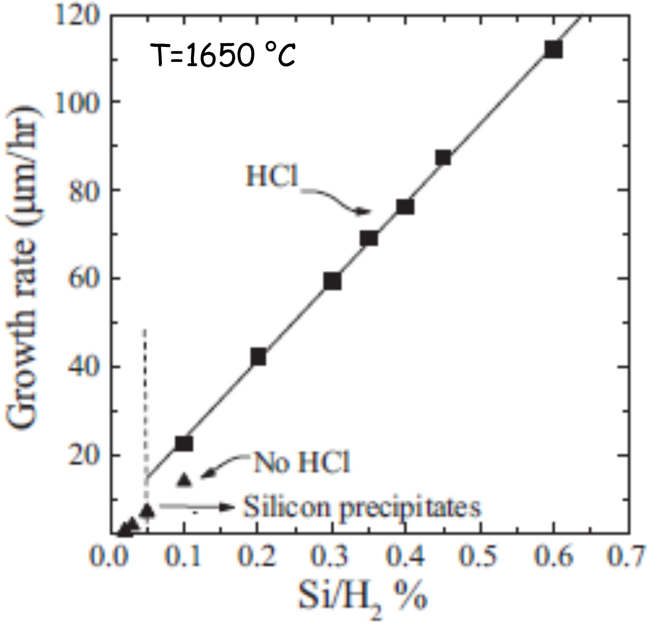
High growth rate
High quality epilayer

## Characterisation techniques

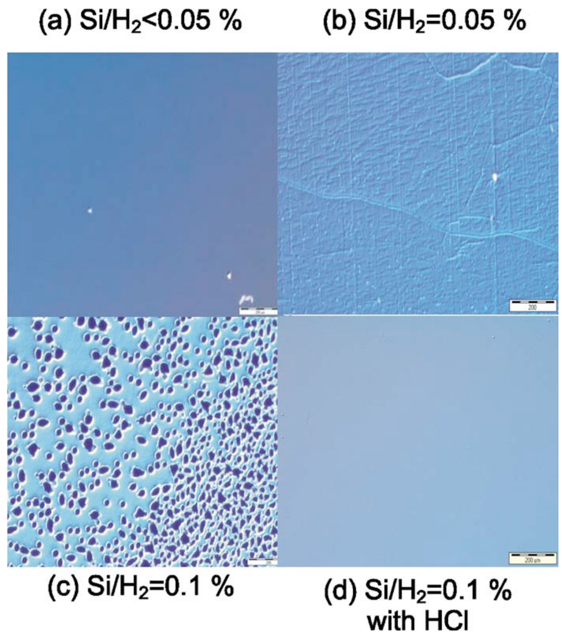
- **LTPL** (low temperature pholuminescence)
- **DLTS** (deep level transient scpectroscopy)
- **TEM** (transmission electron microscopy)
- **Optical microscopy**

# Optimization of growth parameters

## Growth rate and Morphology






$SiH_2$ 0.1 – 0.6 %

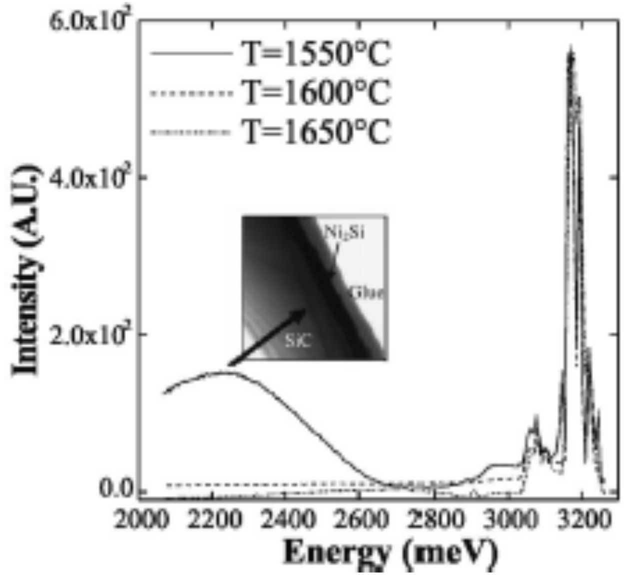
HCl addition

→

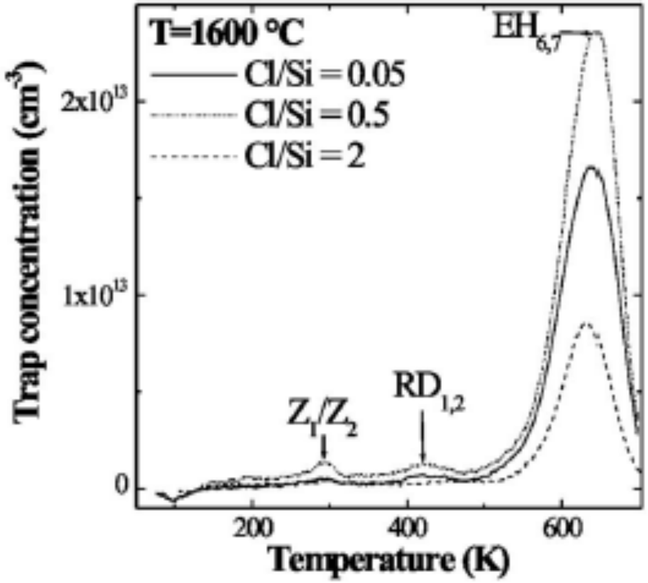
High growth rate (> 100 μm/hr)
Good surface morphology

*La Via et al. Chemical Vapor Deposition 12(2006) 509*

**LTPL**




**DLTS**




T (growth)= 1650 °C

Cl/Si=2.0

$Si/H_2$= 0.3-0.6 %

C/Si=0.4

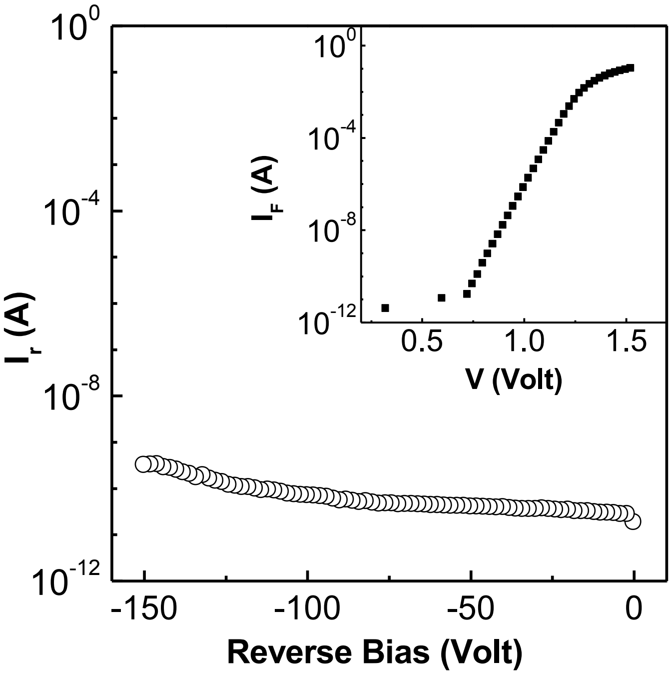
Growth rate > 100 μm/h

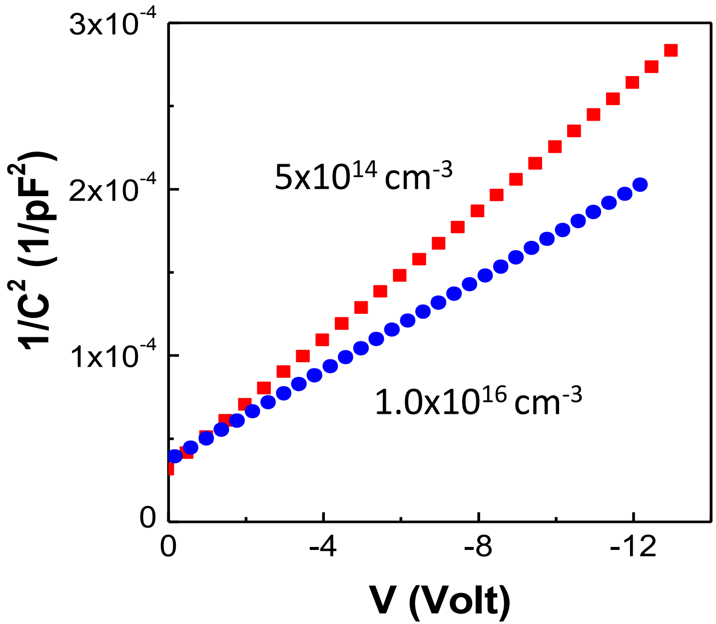
$I_{leakage}$ < $10^{-9}$ A

$N_{defects}$ < $10^{12}$ $cm^{-3}$

$N_{dopant}$ < $10^{14}$ $cm^{-3}$

# Diode electrical characterisation




Schottky Barrier Heigth =1.65 V

Leakage Current $10^{-9}$ A

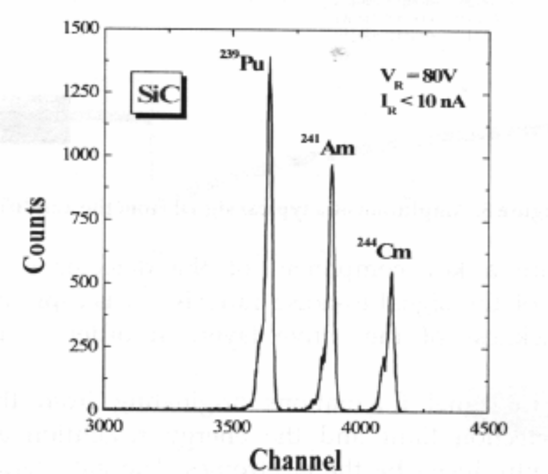
Ideality factor n=1.05

Different dopant concentration

High uniformity

# SiC – Schottky diodes detectors

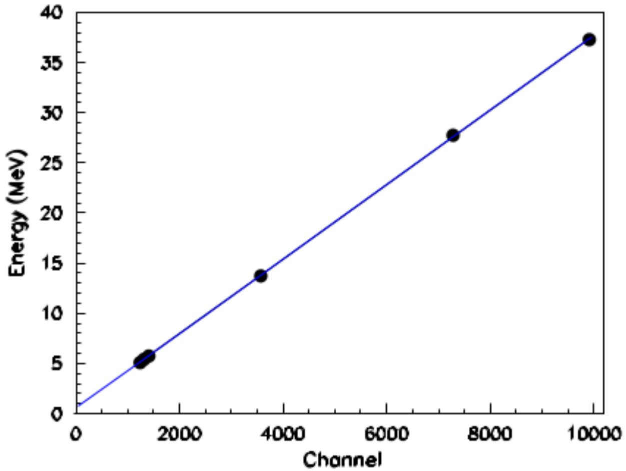
Linearity and resolution

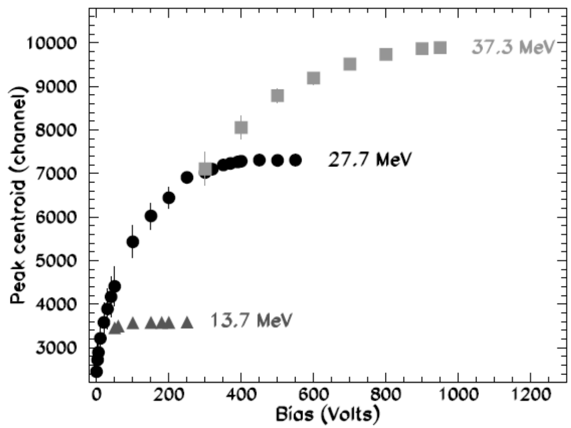



Energy resolution 0.6 % - 0.7 %
D.Puglisi, PHD Thesis (2008)

Literature → [Energy resolution 0.3%
*S.K.Chauddhuri et al NIM A n728 (2013) 97*

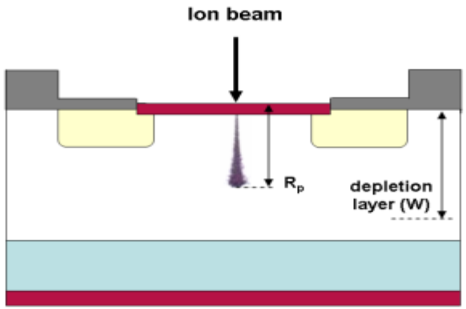
13- 37 MeV $C^+$



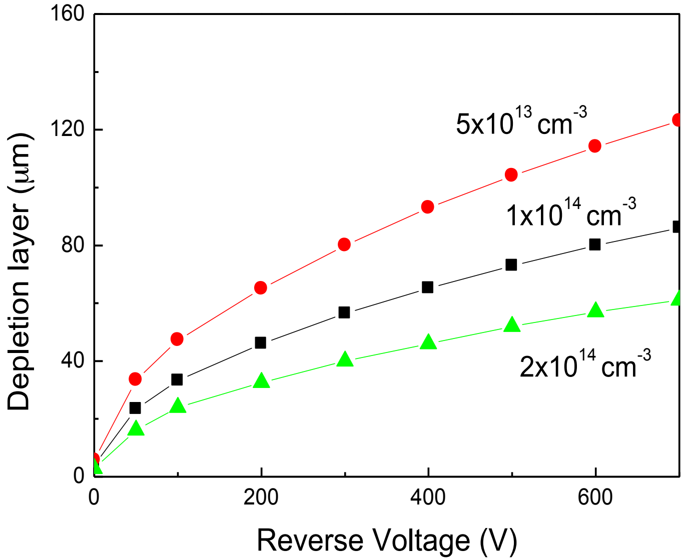

*M.De Napoli Nuc.Instr.Meth. A 600 (2009) 618*

# High energy ion detection

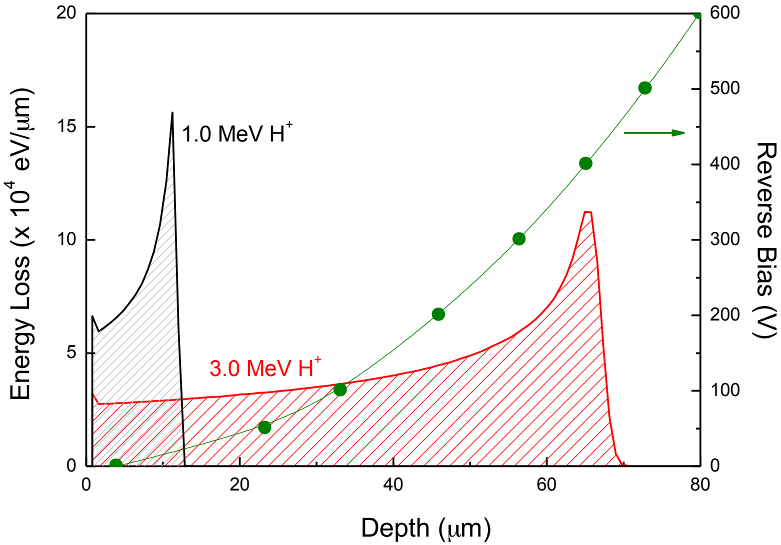



**W > Rp**

High thickness
Low dopant concentration

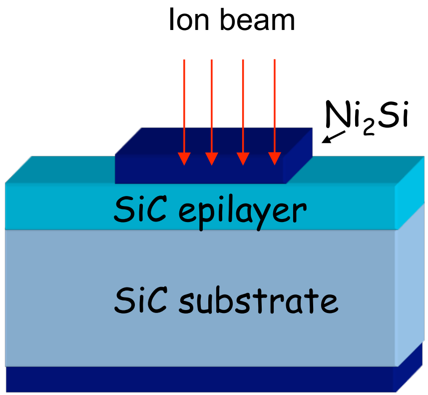


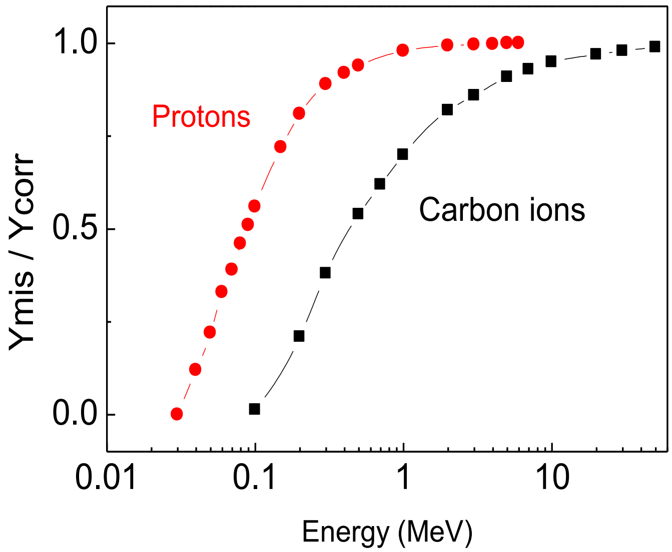

$$w = \sqrt{\frac{2\varepsilon_0\,\varepsilon_r\left|V+\varphi\right|}{qN_d}}$$




$N_d = 10^{14}$ cm$^{-3}$

# Energy loss in the $Ni_2Si$ layer (200 nm)




$H^+$ E > 40 KeV

$C^+$ E> 100 KeV

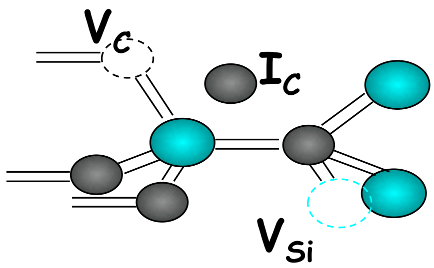
Low energy detection

-thin silicide layer

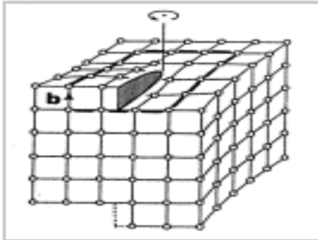
-Interdigitated diodes

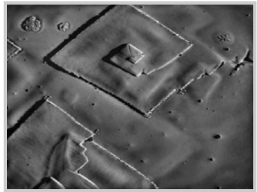
# Effects of ion irradiation

Ion irradiation produces defects in the crystal lattice of the semiconductor

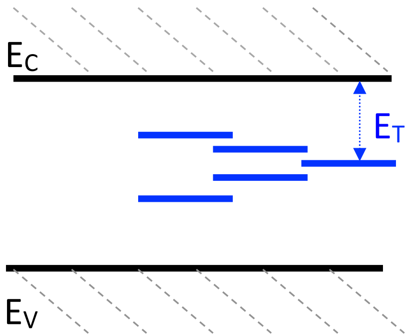



Point defects
(vacancies, interstitial,
antisites, etc…)



Extended defects
(dislocations, clusters,
etc…)

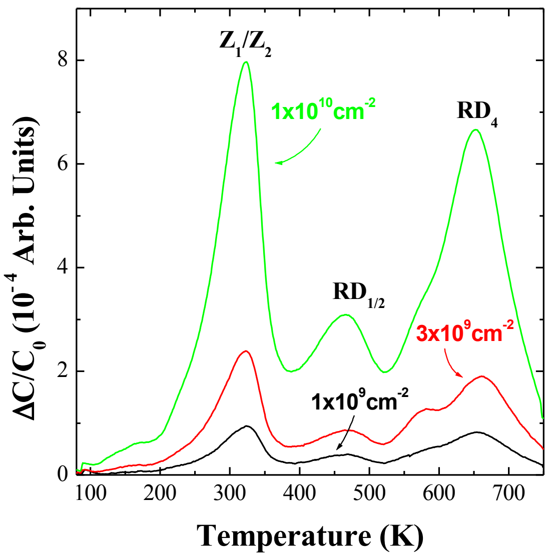



The defects produce some levels
in the band-gap, which deteriorate the
device performances

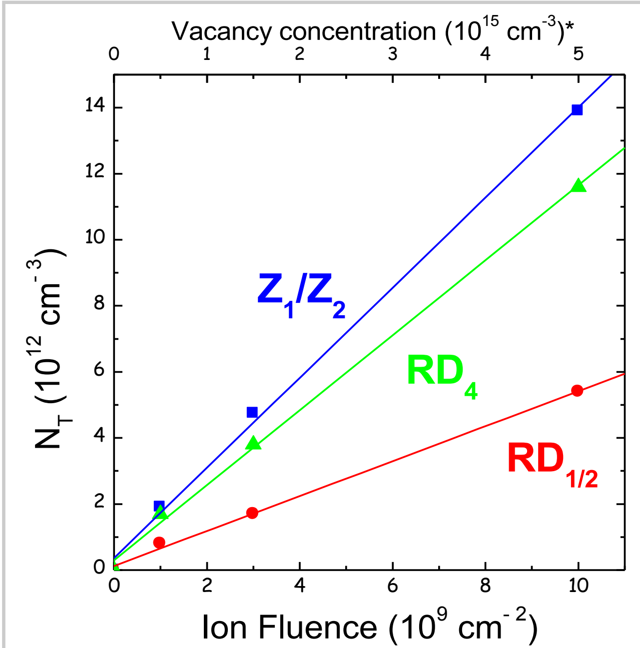
# Defect Analysis

Deep Levels Transient Spectroscopy

## 1) Low fluence ($10^9 - 10^{11}$ ions/cm$^2$)




**7.0 MeV C+**




| | | |
|---|---|---|
| $Z_1/Z_2$ | (0.68 eV) | $V_{Si}$, $Si_C$, $C_{Si}$ (antisites) , .... |
| $RD_{1/2}$ | (0.98 eV) | $V_C$+$V_{Si}$ , ... |
| $RD_4$ | (1.4 eV) | $V_C$, .... |

# Efficiency of point defects production

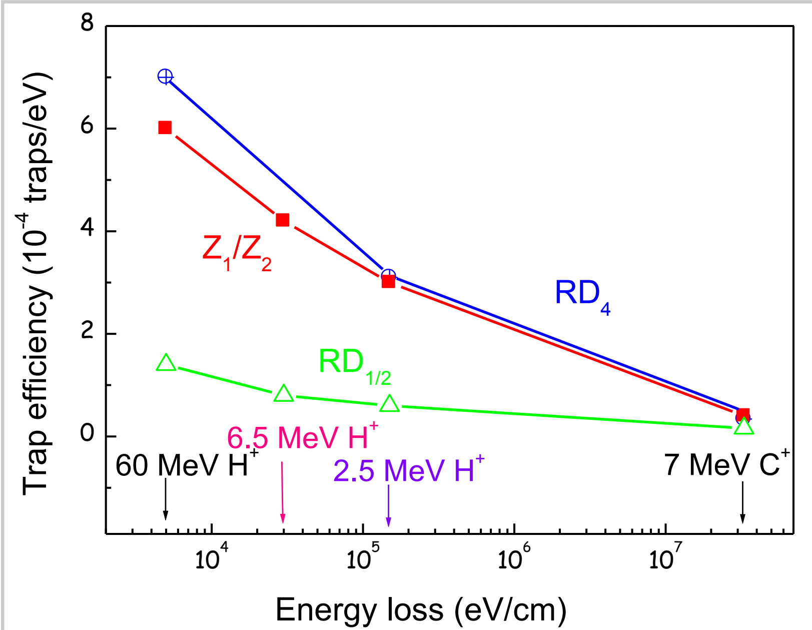
INTRODUCTION RATE $\eta = \dfrac{N_T}{\Phi}$ [traps/cm]

- ion mass
- energy

$\eta\ (Z_1/Z_2)$ { 1363 traps/cm — 7 MeV $C^+$ ; 3 traps/cm — 60 MeV $H^+$ }

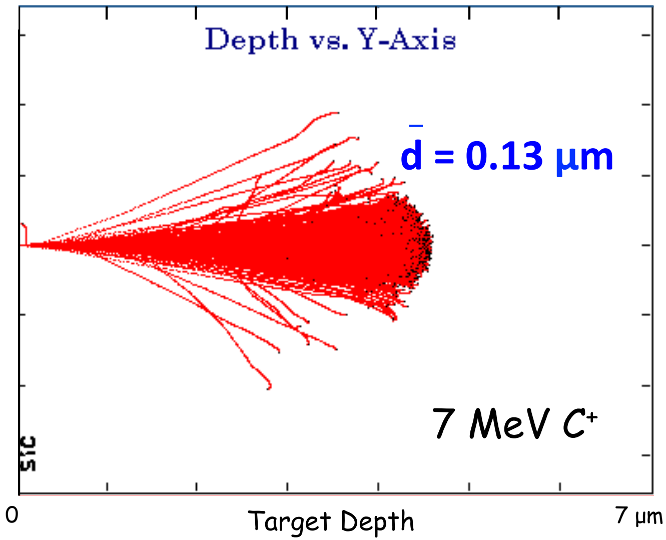
TRAPS PRODUCTION EFFICIENCY

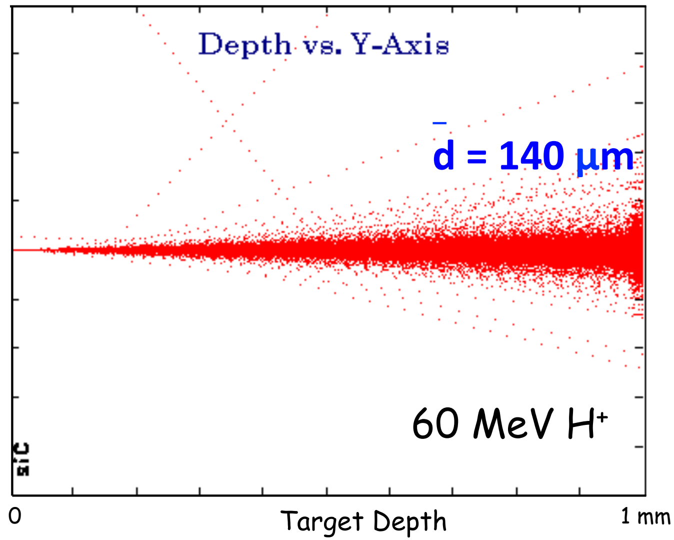
$$\varepsilon = \frac{\eta}{S_n} \quad \text{[traps/eV]}$$




**$S_n$= energy deposited in elastic collisions**

# Ion track effect



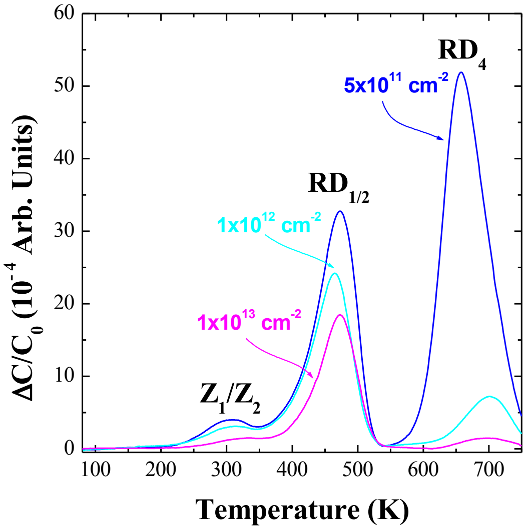

low distance between primary defects

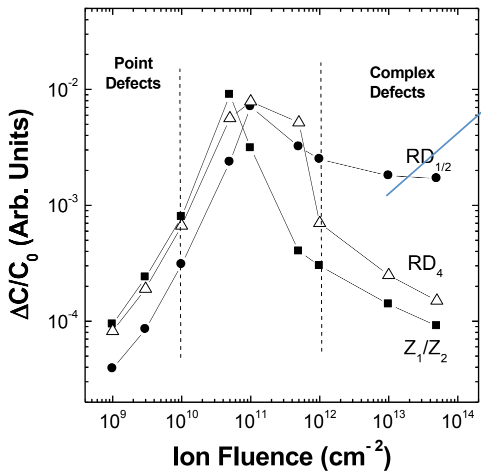
defects recombination
(LOW ε)

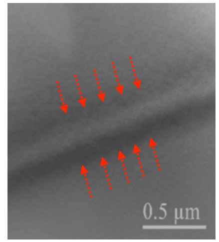
high distance between primary defects

no defects recombination
(HIGH ε)

## 2) High fluence ($10^{12} – 10^{14}$ ions/cm²)




TEM

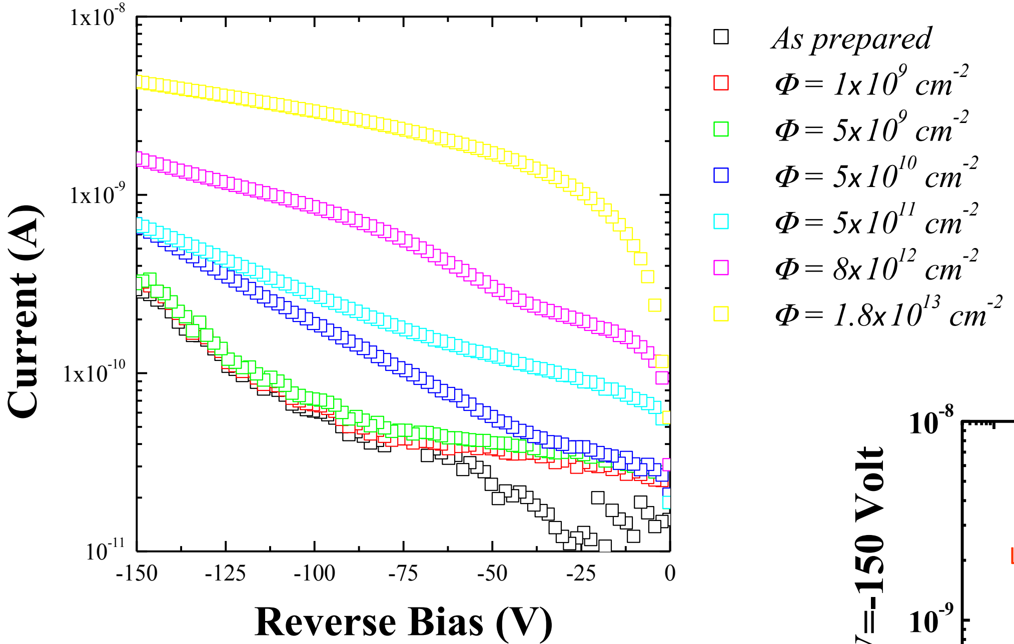
Low fluence: $10^9 – 10^{11}$ ions/cm² point defects

High dose : $10^{12} – 10^{14}$ ions/cm² complex defects → increase of leakage current

*G. Litrico et al. Mater. Sci. For. Vols. 615-617, (2009), pp. 397-400*

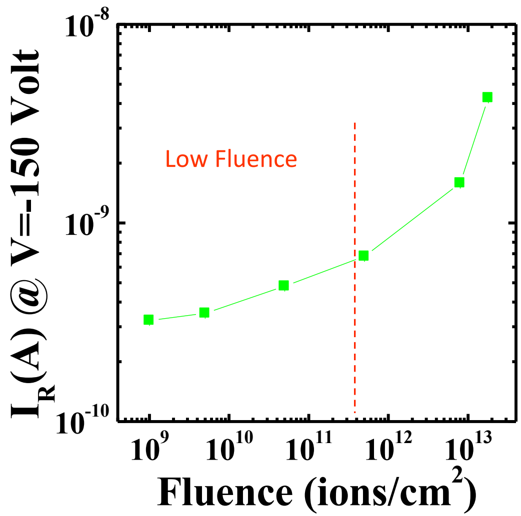
# Effect on I-V (reverse)

1.0 MeV $Si^{+}$




Low fluence

High fluence



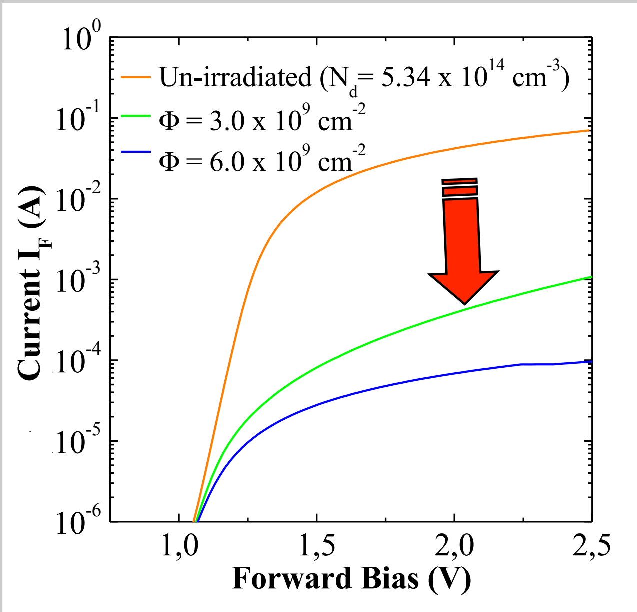

Fluence □= $10^{13}$ ions/$cm^2$

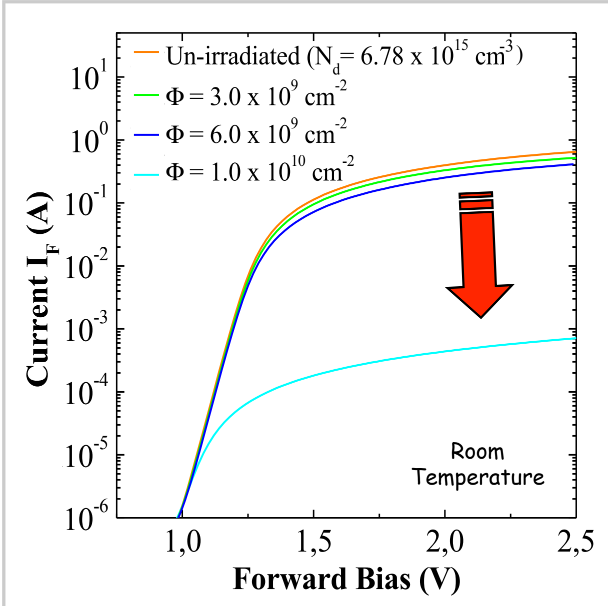
Ion dose □ □ Sn= 2□$10^{22}$ eV/$cm^3$

(1.0 □$10^{6}$ Gy)

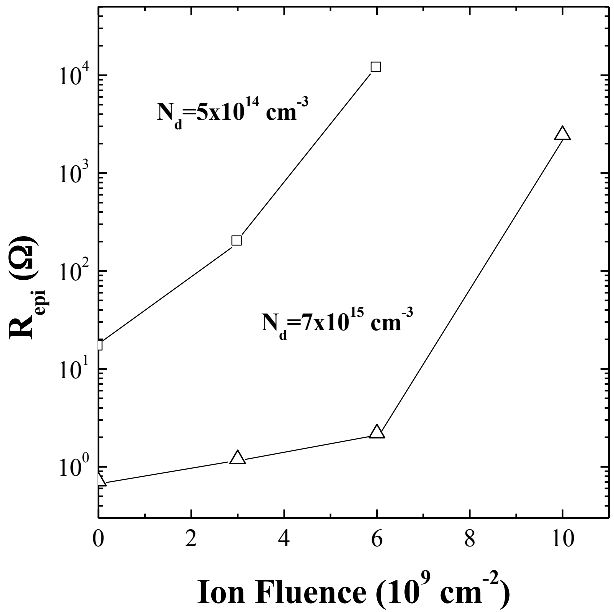
# I-V forward characteristics

7 MeV $C^+$




*The decrease of forward saturation current is related to the increase of epitaxial layer resistance*



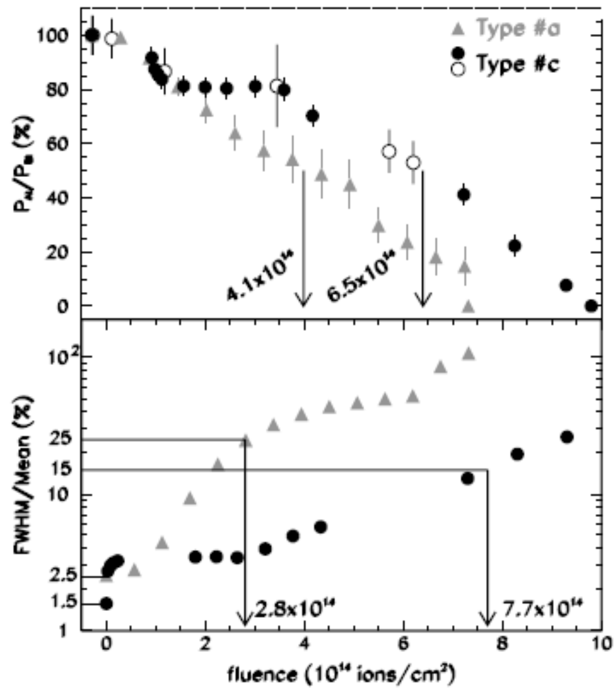

$$R_{epi} = \frac{w}{q \cdot N_d \cdot \mu \cdot A}$$

Decrease of dopant concentration ($N_d$)

*The effect of doping compensation is higher in the low doped epitaxial layer*

# Radiation hardness – detectors

## 35 MeV $O^+$




Increasing the ion fluence (defect density), the characteristics of the detectors deteriorate:

1) Charge Collection Efficiency (CCE) decreases

2) The FWHM increases

Type a $N_d = 7x10^{14}$ $cm^{-3}$
Type c $N_d = 10^{16}$ $cm^{-3}$

**Threshold dose:**

Ion Fluence [illegible]= 5[illegible]$10^{14}$ ion/$cm^2$

Ion dose [illegible][illegible]Sn= $1.0x10^{23}$ eV/$cm^3$

($5$[illegible]$10^6$ Gy)

M. De Napoli et al. Nucl.Phys. B 197 (2009) 198

# CONCLUSIONS

- SiC- Schottky diodes are interesting for high energy ion detectors, showing linearity and high resolution

- The ion irradiation introduces point defects *(low fluence)* or clusters of point defects *(high fluence)*
    - Deactivation of dopant
    - Increase of the leakage current (high fluence)

- The efficiency of point defect introduction depends on the ion energy

- Ion irradiation at high dose (> $5 \times 10^{22}$ eV/cm$^3$) induces a decrease of detection efficiency and a deterioration of detector resolution (FWHM > 10%)