

Charge collection for irradiated p⁺n Si detectors

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Vertex 2000

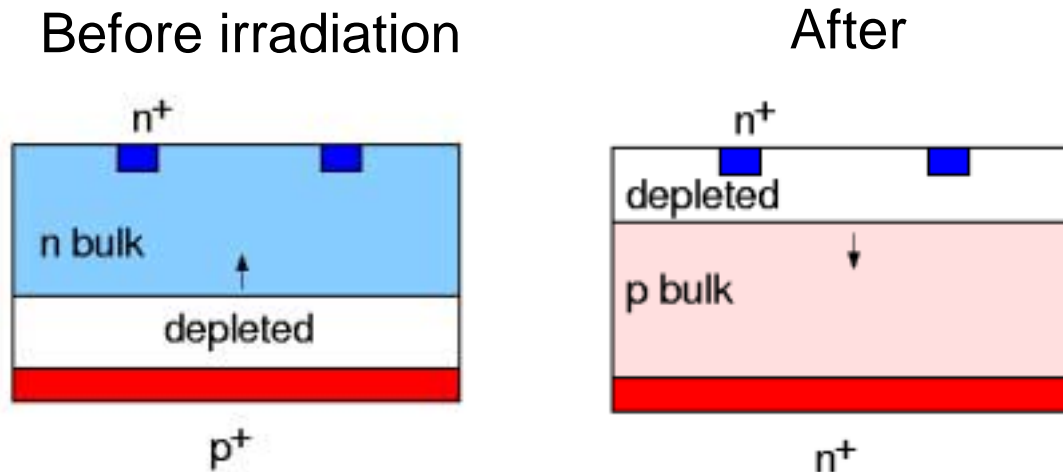
10–15/ September / 2000

Introduction

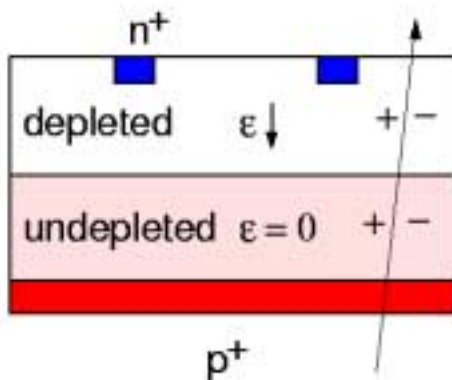
- Radiation damage degrades the performance of silicon sensors as tracking devices
- The main effects of the damages are:
 - change the effective doping concentration
 - electrical properties of the sensor
 - change in V_{dep}
 - bulk type inversion ($n \Rightarrow p$)
 - charge trapping centers
 - signal loss
 - resolution
 - increase of the current
 - heat dissipation
 - noise

Type inversion: n+n

- Growth of the depleted region



- After type inversion n+n detectors can operate partially depleted



Carriers drift due to $\epsilon \Rightarrow$ **signal**

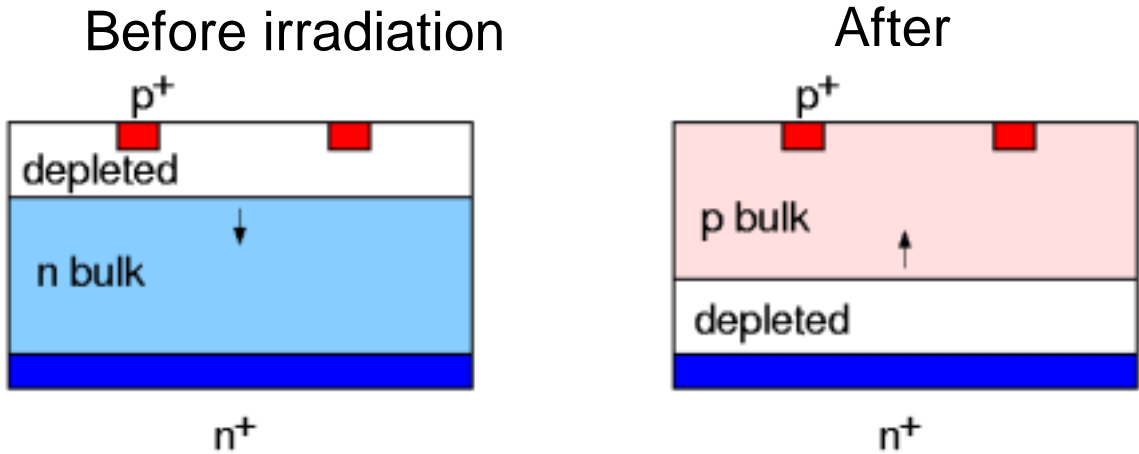
Carriers recombine \Rightarrow **no signal**

- Assuming uniform ionization \Rightarrow the signal is proportional to the width of depleted region

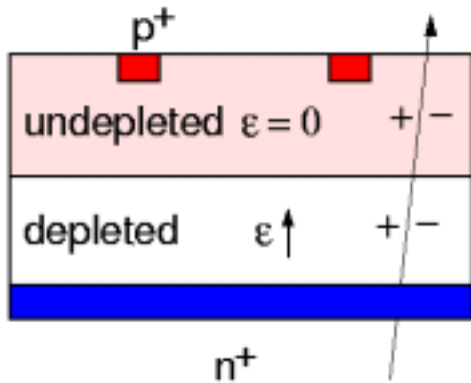
$$V = \frac{e w^2}{2 \epsilon_s} N_{eff}$$

Type inversion: p+n

- Growth of the depleted region

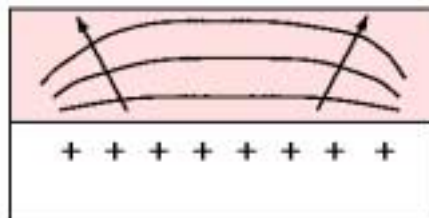


- After type inversion p+n detectors can still operate partially depleted thanks to hole diffusion through the non depleted bulk



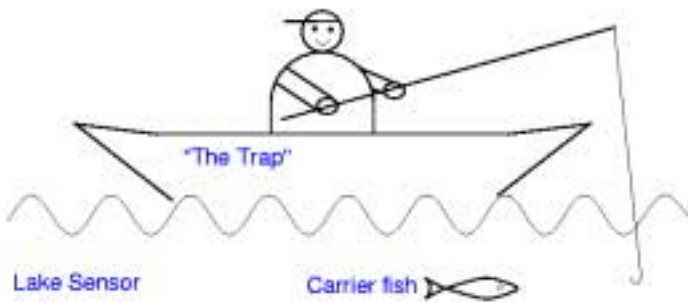
Carriers recombine \Rightarrow **no signal**

Carriers drift due to $\epsilon \Rightarrow$ **signal**



Charge trapping

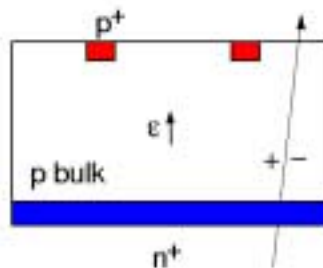
- Radiation induces charge trapping centres
 - carriers not collected in time are effectively lost
- Charge trapping depends on carriers velocity (ultimately ϵ , as $v = \mu\epsilon$)



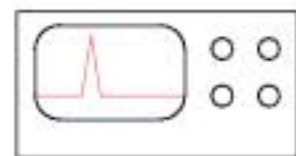
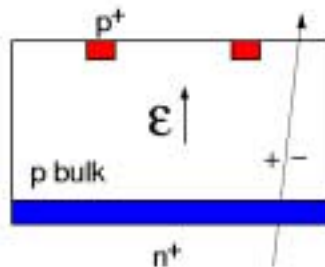
Carriers which spend more time in the vicinity of a trap should have a larger probability of being caught than those moving faster

- Consequence: overdepletion increases the size of the signal

$$V = V_{dep}$$

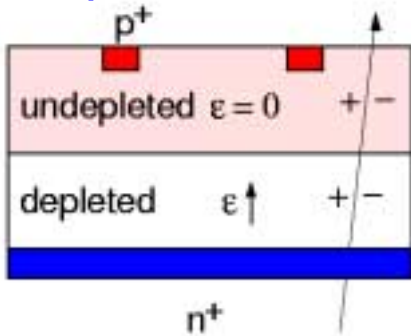


$$V > V_{dep}$$



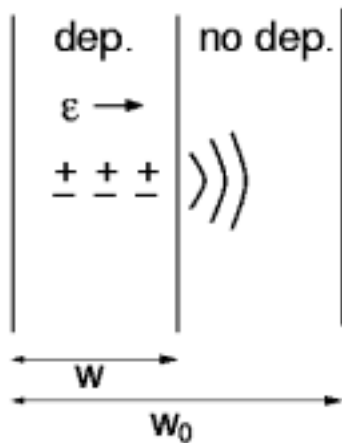
A model for charge collection

- Only that ionization charge produced in the depleted bulk may produce signal



These carriers need to reach the readout strips to produce a signal

- ε drives the carriers to the boundary
 - ↳ charge density gradient
 - ↳ diffusion to the readout channels



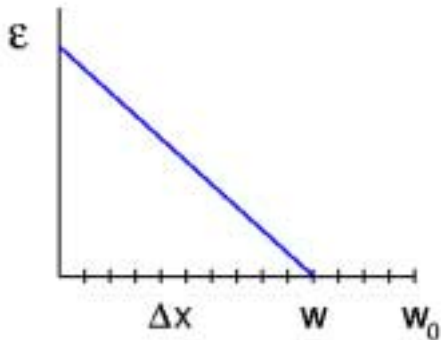
⇒ some carriers are not collected

⇒ remaining: $\propto e^{-(w_0 - w)/\lambda_0}$

λ_0 is the mean free path

↳ detector independent

- Electric field in the depleted region



ε and v varies across the detector \Rightarrow trapping changes

- Mean free path as $\lambda = \lambda(v)$

series expansion:
$$\lambda = \lambda_0 + \lambda_1 \frac{v}{v_s} + \dots$$

being v_s the carriers saturation velocity

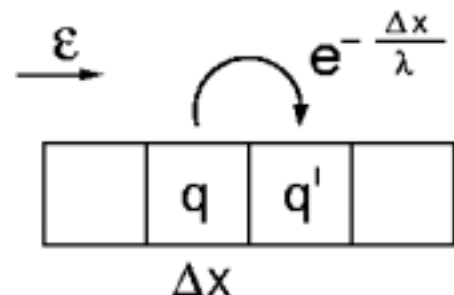
naïve approx.: $v = \mu \varepsilon$

with: $v_s = \mu \varepsilon_s$

$$\lambda(x) = \lambda_0 + \lambda_1 \frac{\varepsilon(x)}{\varepsilon_s}$$

- Transport of carriers:

divide the detector in small cells



- Charge collection for a given bias V

$$q(V) = \frac{Q_0}{w_0} \int_0^w e^{-\frac{x}{\lambda(x)}} dx e^{-\frac{(w_0-w)}{\lambda_0}}$$

- Relationship
depleted region width: $w(V) = \begin{cases} w_0 \sqrt{\frac{V}{V_{dep}}} & V < V_{dep} \\ w_0 & V \geq V_{dep} \end{cases}$

$$\text{carriers mean free path: } \lambda(x) = \begin{cases} \lambda_0 + \lambda_1 \frac{\varepsilon(x)}{\varepsilon_s} & \varepsilon(x) < \varepsilon_s \\ \lambda_0 + \lambda_1 & \varepsilon(x) \geq \varepsilon_s \end{cases}$$

$$\text{electric field } \varepsilon(x) = \frac{1}{w_0} \left(\sqrt{V_{dep} V} - \frac{x}{w_0} V_{dep} \right)$$

- 5-parameter fit:

$$Q_0, V_{dep}, \lambda_0, \lambda_1, \varepsilon_s$$

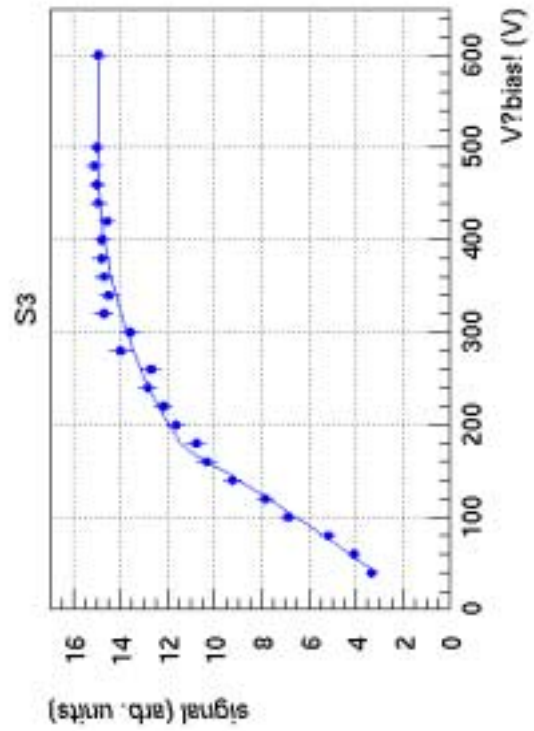
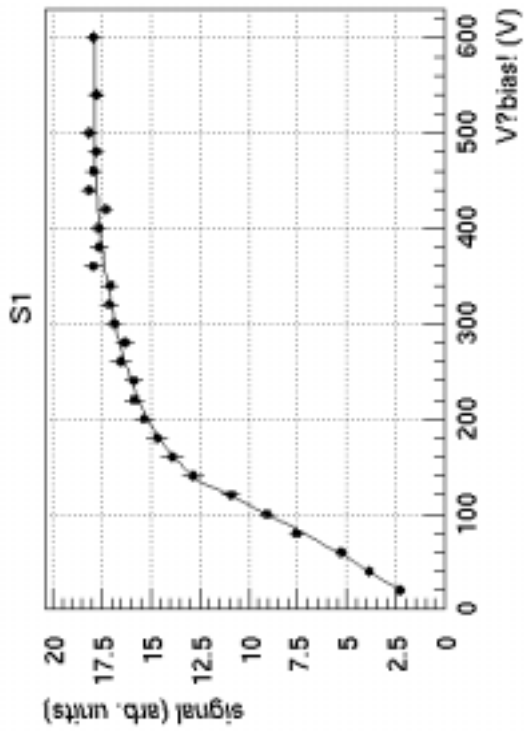
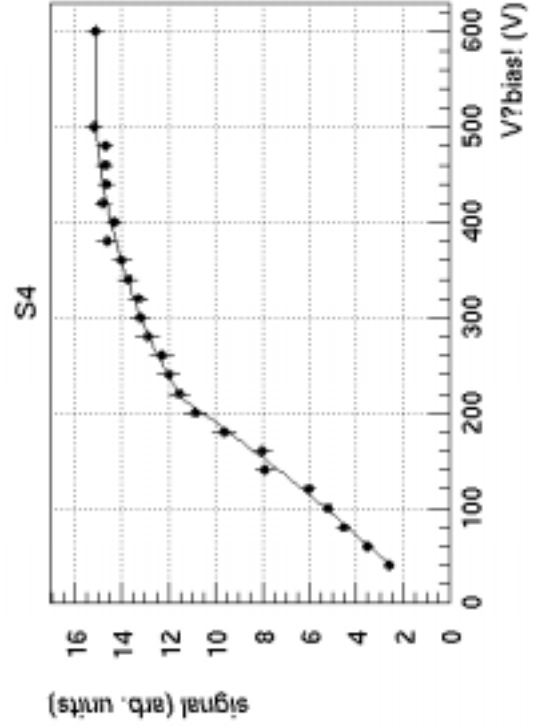
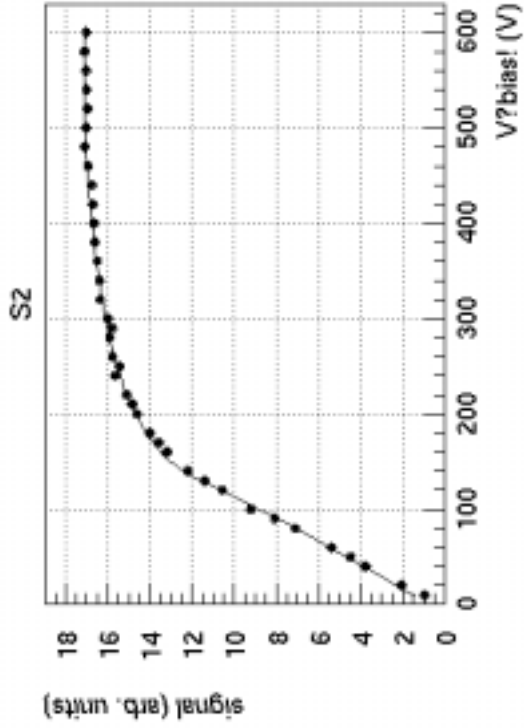
Experimental test

- Test the model over several irradiated p+n sensors

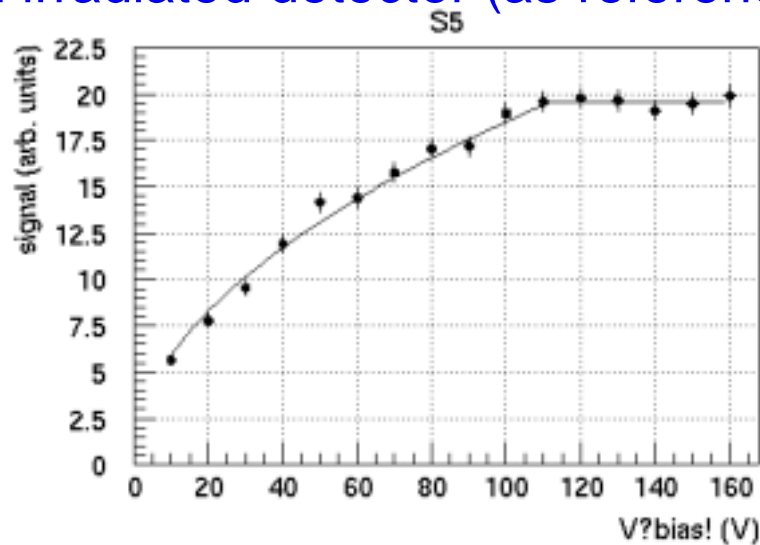
<i>Name</i>	<i>Type</i>	<i>Signal</i>	<i>Dose (p/cm²)</i>	<i>Oxigen</i>
<i>S1</i>	Miniature	Source	3.E+14	Yes
<i>S2</i>	Miniature	Source	3.E+14	
<i>S3</i>	Miniature	Source	4.E+14	Yes
<i>S4</i>	Miniature	Source	4.E+14	No
<i>S5</i>	Miniature	Source		No
<i>W1</i>	Wedge	Source	3.E+14	Yes
<i>W2</i>	Wedge	Source	3.E+14	No
<i>L1</i>	Miniature	Laser	3.E+14	Yes
<i>L2</i>	Miniature	Laser	3.E+14	No
<i>L3</i>	Miniature	Laser	4.E+14	Yes
<i>L4</i>	Miniature	Laser	4.E+14	No

- Use miniature and wedge detectors
- Signals with source (¹⁰⁶Ru) and laser (1064nm)
- Devices with different dose and oxygenation
- Philips Amp. 6594 or SCT128A
- Fit charge collection v bias voltage data using our model and extract the 5 parameters

Source signals



- Non irradiated detector (as reference): S5

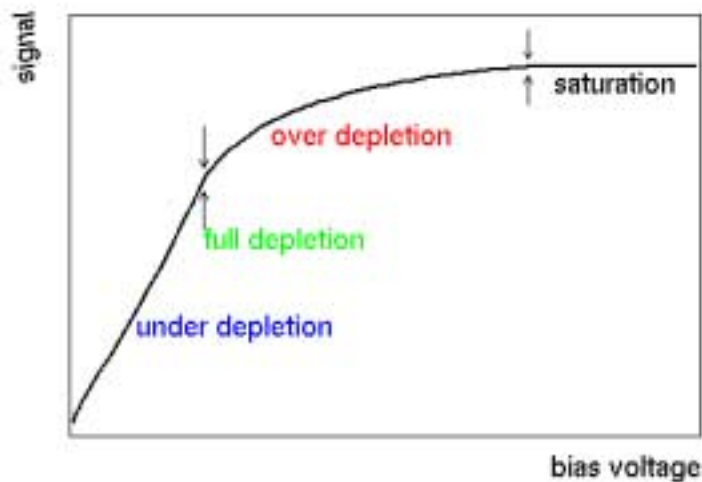


- Fit results

<i>Det.</i>	Q_0	V_{dep}	λ_0	λ_1	ϵ_s
<i>Name</i>	<i>Arb units</i>	<i>Volt</i>	μm	μm	$V/\mu m$
<i>S1</i>	18.5 ± 0.7	135 ± 4	188 ± 6	1180 ± 60	1.2 ± 0.3
<i>S2</i>	19.9 ± 0.9	138 ± 5	206 ± 10	1680 ± 120	1.3 ± 0.1
<i>S3</i>	18.7 ± 0.5	175 ± 11	204 ± 15	440 ± 50	1.1 ± 0.1
<i>S4</i>	19.9 ± 0.8	213 ± 5	184 ± 10	320 ± 90	1.1 ± 0.1
<i>S5</i>	19.6 ± 0.3	112 ± 4			

- Q_0 values are in agreement (with the non irradiated one)
- λ_0 values are compatible (no detector dependence, as expected)

- The model describes well the data

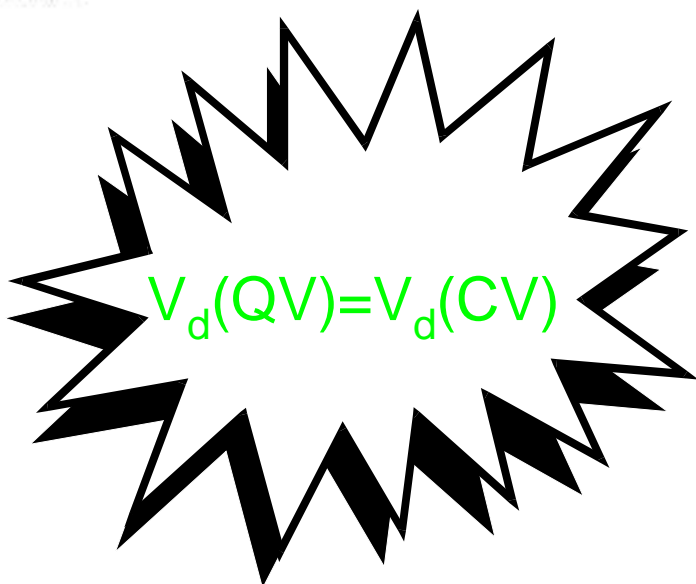


– 3 phases

– signal increases after full depletion

- Depletion voltage:

<i>Det.</i>	$V_{dep} (QV)$	$V_{dep} (CV)$
<i>Name</i>	<i>Volt</i>	<i>Volt</i>
<i>S1</i>	135 ± 4	127 ± 5
<i>S2</i>	138 ± 5	130 ± 4
<i>S3</i>	175 ± 11	183 ± 6
<i>S4</i>	213 ± 5	228 ± 5

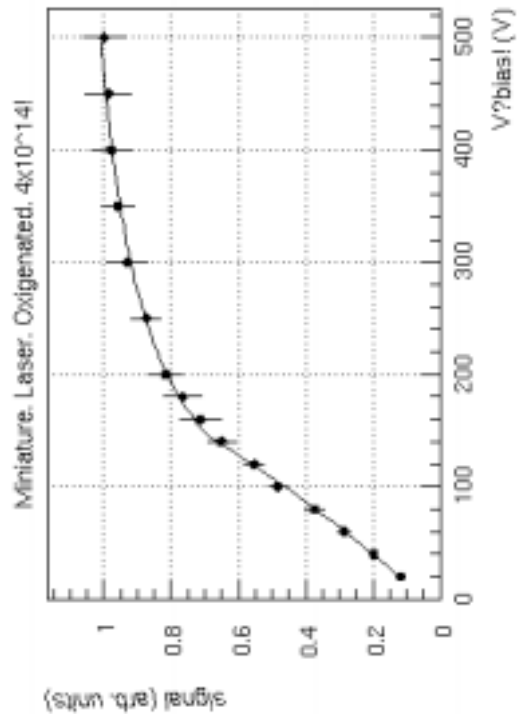
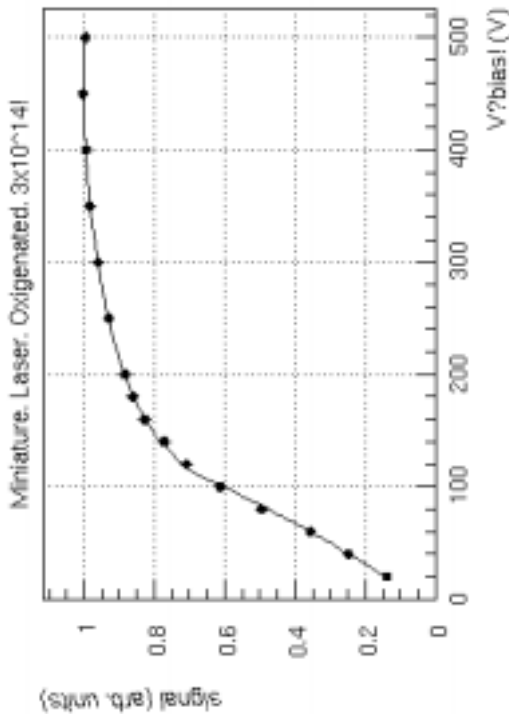
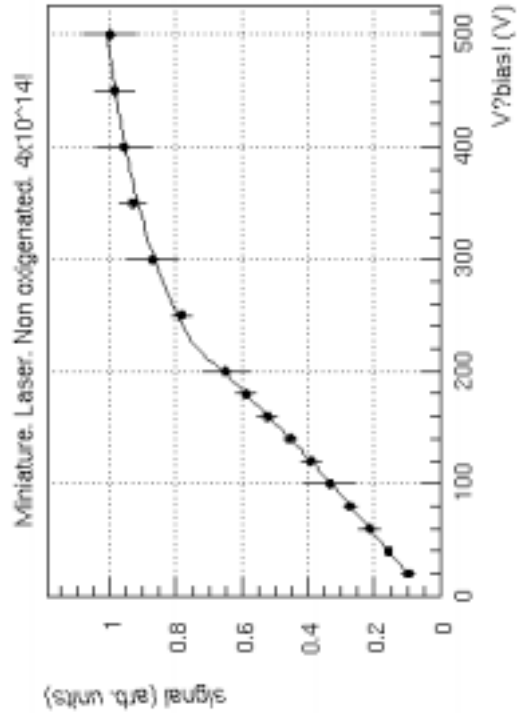
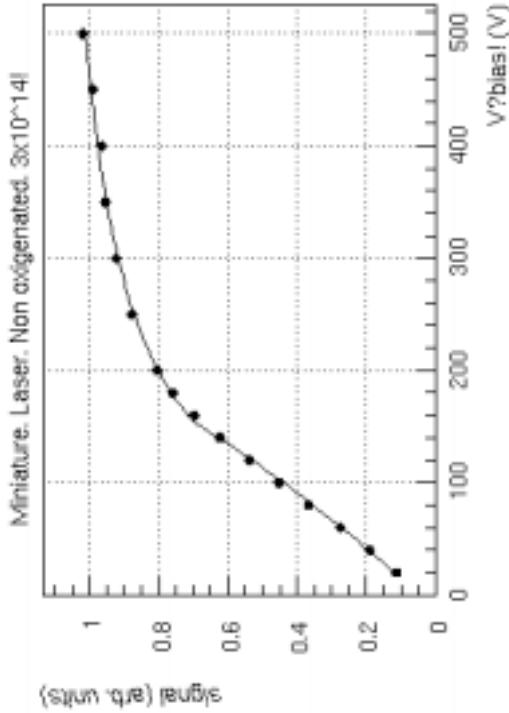


- Charge collection eff.

$CCE @ V_{dep} \sim 0.7 CCE$

<i>Det.</i>	<i>CCE</i>	<i>CCE @ V_{dep}</i>
<i>S1</i>	$91 \pm 4\%$	$\sim 63\%$
<i>S2</i>	$87 \pm 5\%$	$\sim 62\%$
<i>S3</i>	$76 \pm 3\%$	$\sim 57\%$
<i>S4</i>	$77 \pm 4\%$	$\sim 58\%$

Laser signals



- The model also works for laser data

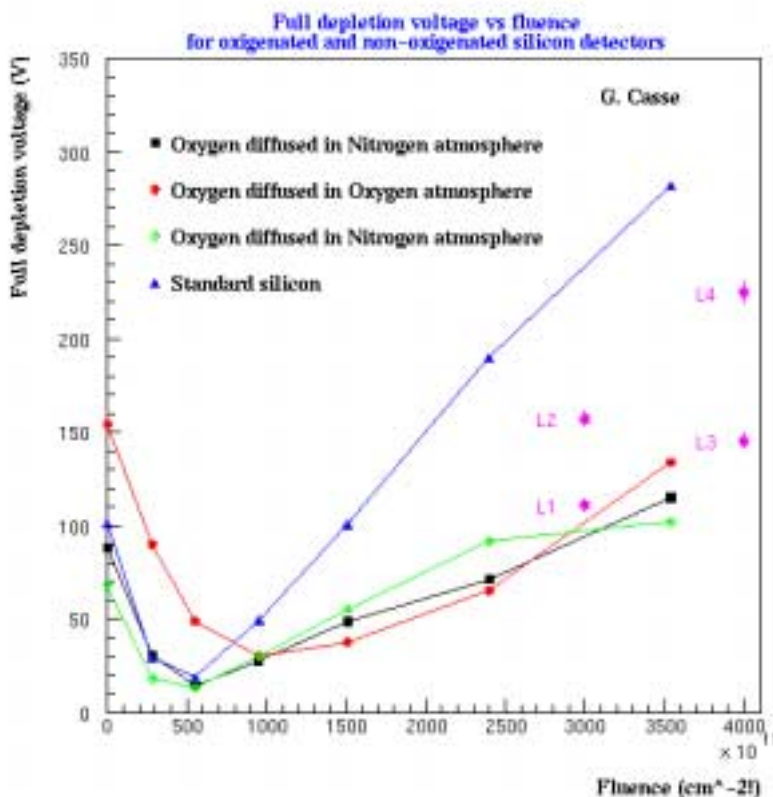
<i>Det.</i>	<i>Q0</i>	<i>Vdep</i>	λ_0	λ_1	ϵ_s
<i>Name</i>	<i>Arb units</i>	<i>Volt</i>	μm	μm	$V/\mu m$
<i>L1</i>	1.11±0.01	111±3	183±4	1170±40	1.08±0.02
<i>L2</i>	1.16±0.01	157±4	188±6	1190±60	1.68±0.10
<i>L3</i>	1.15±0.01	183±4	183±6	1180±30	1.67±0.10
<i>L4</i>	1.24±0.02	223±5	184±4	880±20	1.99±0.10

- Depletion voltage:

Again:

$$V_{dep}(QV) = V_{dep}(CV)$$

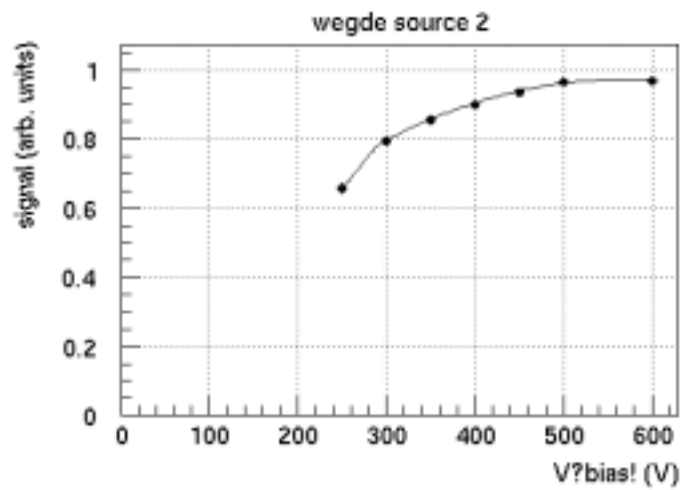
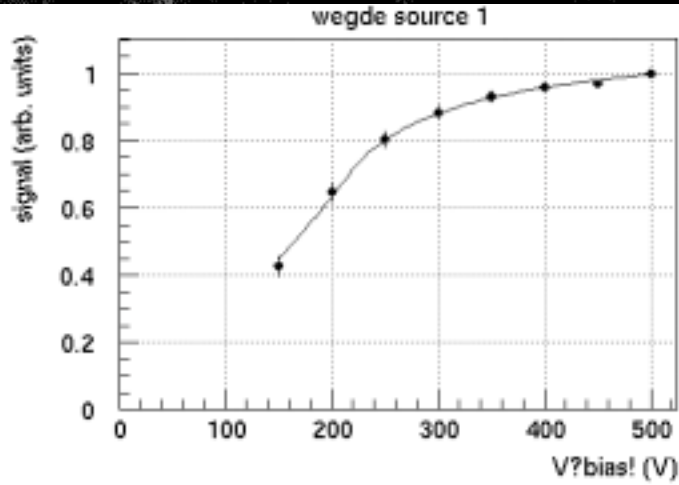
<i>Det.</i>	<i>Vd (QV)</i>	<i>Vd (CV)</i>
<i>Name</i>	<i>Volt</i>	<i>Volt</i>
<i>L1</i>	111±3	N. A.
<i>L2</i>	157±4	N. A.
<i>L3</i>	145±3	133±5
<i>L4</i>	223±5	223±9



Non oxygenated known to show large dispersion

Oxygenated agree well

Wedge detectors with source



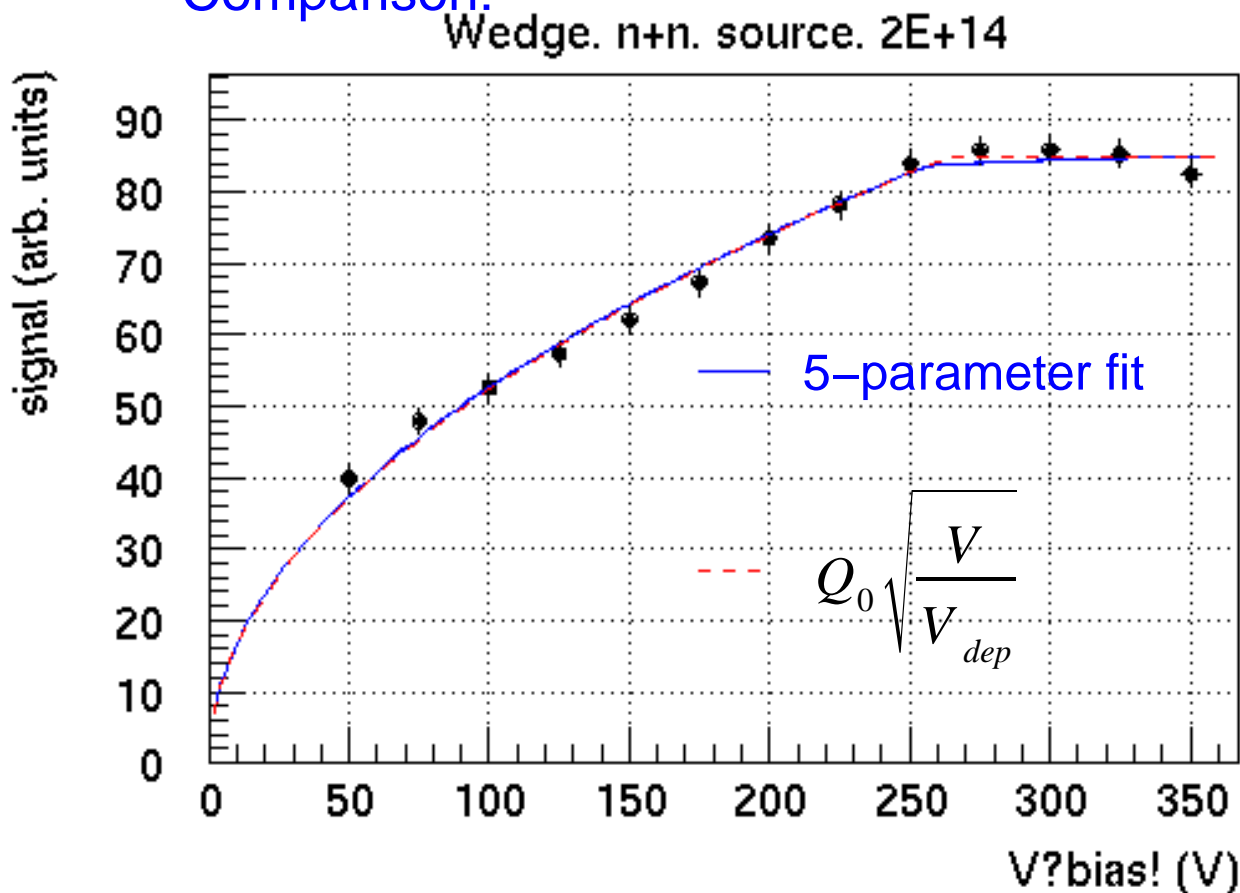
<i>Det.</i>	$Q0$	V_{dep}	λ_0	λ_1	ϵ_s
<i>Name</i>	<i>Arb units</i>	<i>Volt</i>	μm	μm	$V/\mu m$
<i>W1</i>	1.12 ± 0.03	223 ± 3	162 ± 22	1650 ± 120	1.7 ± 0.1
<i>W2</i>	1.48 ± 0.05	290 ± 14	162 ± 17	168 ± 20	0.9 ± 0.1

Irradiated n+n detectors

- Test the model with irradiated n+n detectors
 - mobility is larger for electrons than holes
 - the electric field increases close to the readout strips

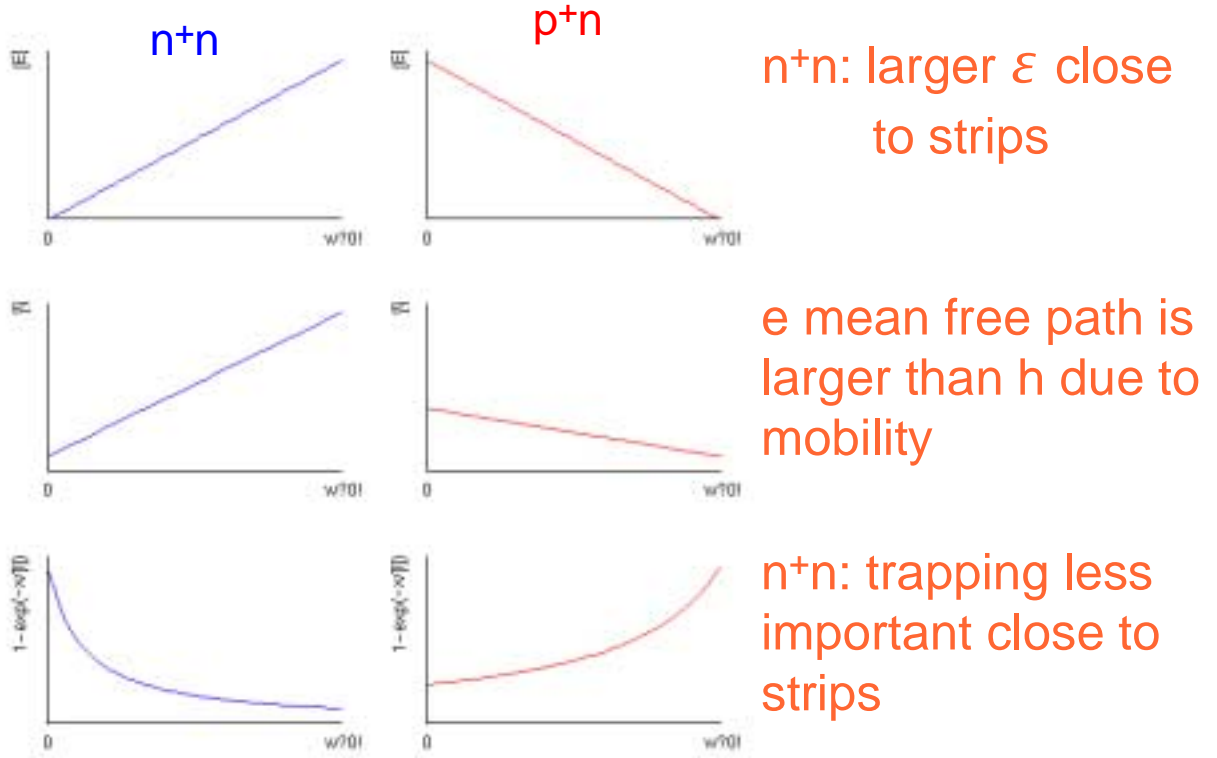
Trapping effects are smaller for electrons

- Comparison:

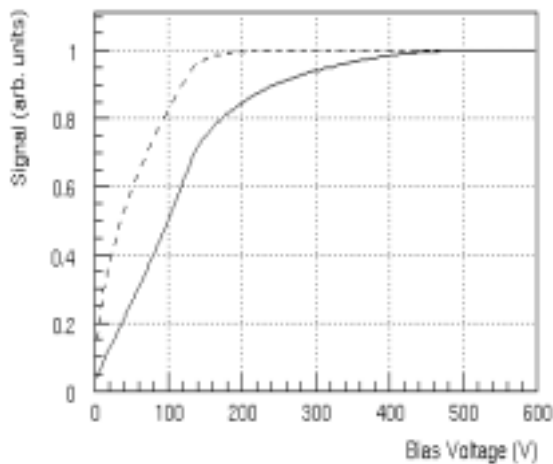


n⁺n vs p⁺n

- Sensor properties:



- Charge collection efficiency vs V_{bias}



Underdepletion:

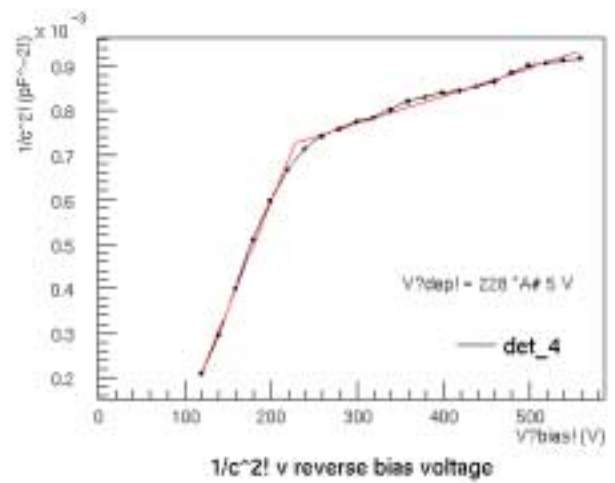
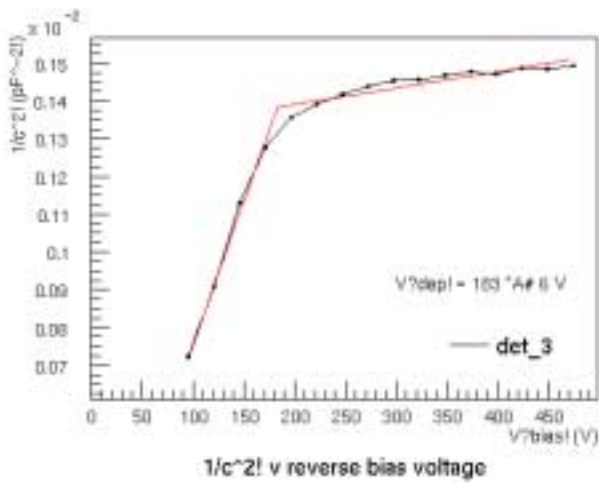
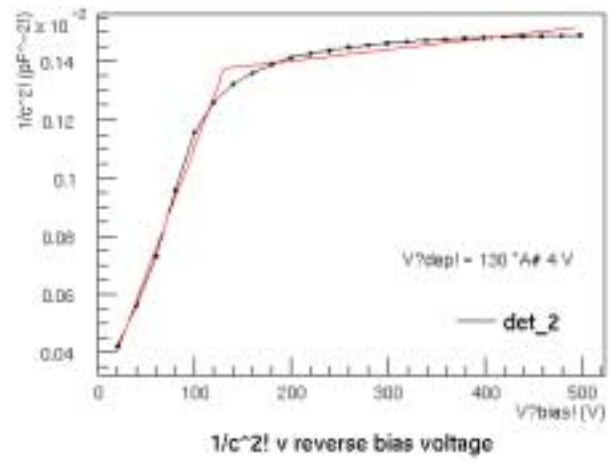
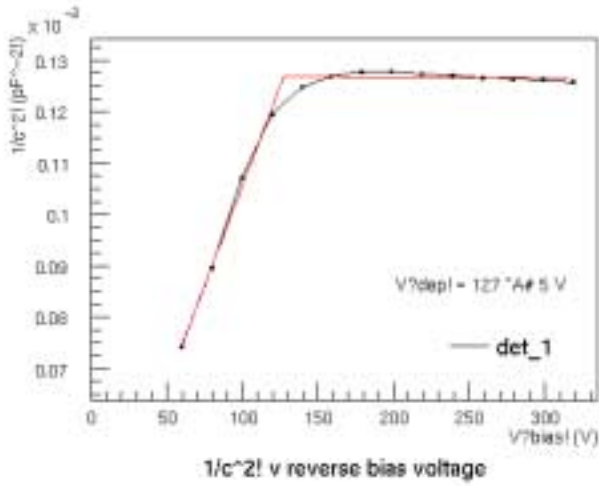
n⁺n detectors perform better

n⁺n seems the natural choice for experiments such as: LHC-b and ATLAS pixels

Summary

- A model to describe the experimental data for charge collection of irradiated silicon (p⁺n and n⁺n) detector has been tested
- The model fits well the data of several irradiated detectors (miniature, wedge; oxygenated, non-oxygenated; source and laser)
- Charge collection of irradiated p⁺n detectors increases after full depletion (well explained by the model)
- The depletion voltage obtained from the fit agrees with that from CV measurements
 - oxygenation improves V_{dep}
 - oxygenation does not improve CCE
- Irradiated n⁺n detectors do perform better than p⁺n for CCE

CV plots



Electric field

