Evidence of multistage charge collection in Si irradiated detectors operated as monitors of intensive fragmented proton beams

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Outline

- Motivation
- Experiment and experimental results
- Multistage process with avalanche multiplication
- Data treatment and simulations
- Third stage of charge collection
- Electric field profile
- Internal charge gain and hole trapping time constant degradation rate
- Conclusions

Motivation

Motivation of semiconductor detector application for monitoring of proton beam loss in LHC machine:

- installation of compact detectors in the vicinity of superconductive magnets, increase in sensitivity of monitoring the particle loss of proton beam, **initiated by CERN BE-BI** (Beam Div., Beam Instrumentation)

The goal of the presented study:

- further analysis of the results of the unique *in situ* irradiation test of Si detectors;
- new findings in detector and radiation physics at low T

Experiment

In situ **irradiation tests (the only method of experimental study at 1.9 K)**

2012 – *in situ* irradiation test 1 at 1.9K, 6 weeks of operation:

Si p^+-n-n^+ detectors; ρ ~ 10-15 kΩ, 300 µm; processed in Russia

Irradiation:
23 GeV protons beam fragmented into 400 ms spills

Beam intensity 1.3×10^{11} p/cm^2 per 400 ms spill (~10^{10} p/s on detectors)
- ♦ Fluence to 1×10^{15} -1×10^{16} p/cm^2
- ♦ Beam position monitoring (BPM + Si beam telescopes)

- ♦ Current pulse response, **TCT**, LeCroy WavePro,

3 GHz bandwidth, 630 nm laser, width 45 ps

Laser illumination of the n^+ contact

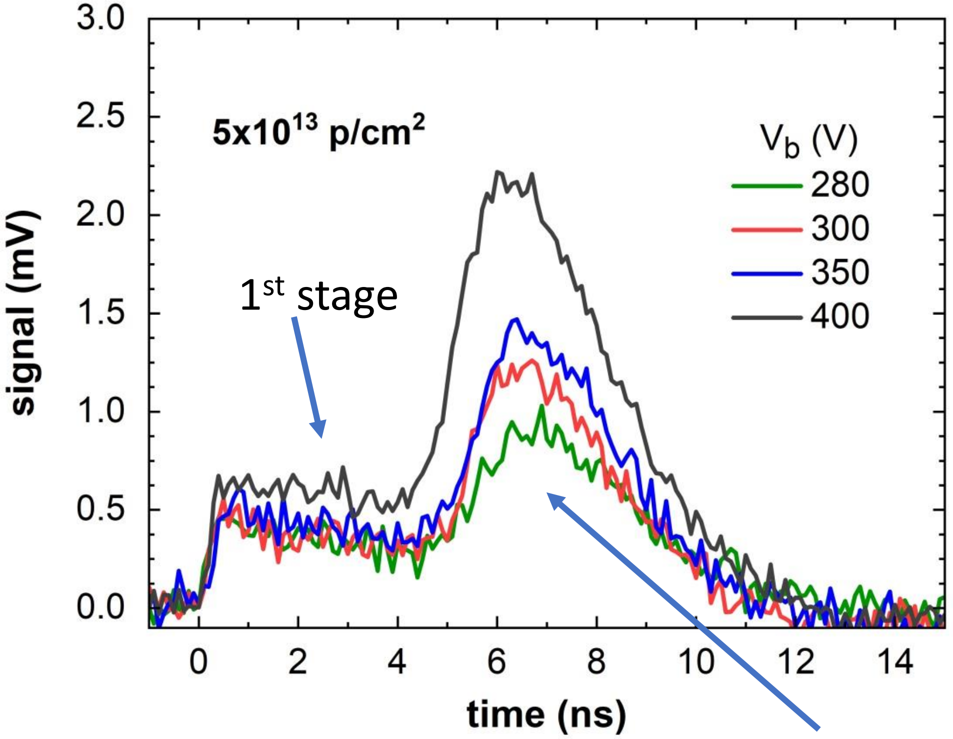
Experimental results

No reflection as seen at lower F
At higher F – details of fine structure

irradiation dose

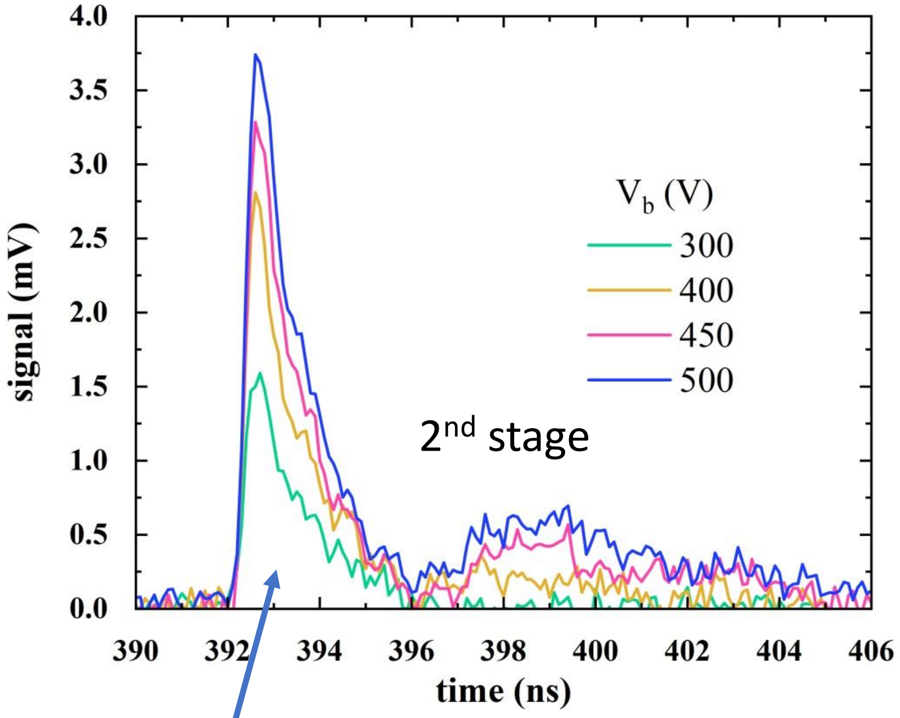
$5x10^{13}$ p/cm^2

$2.7x10^{14}$ p/cm^2



1st stage

2nd stage

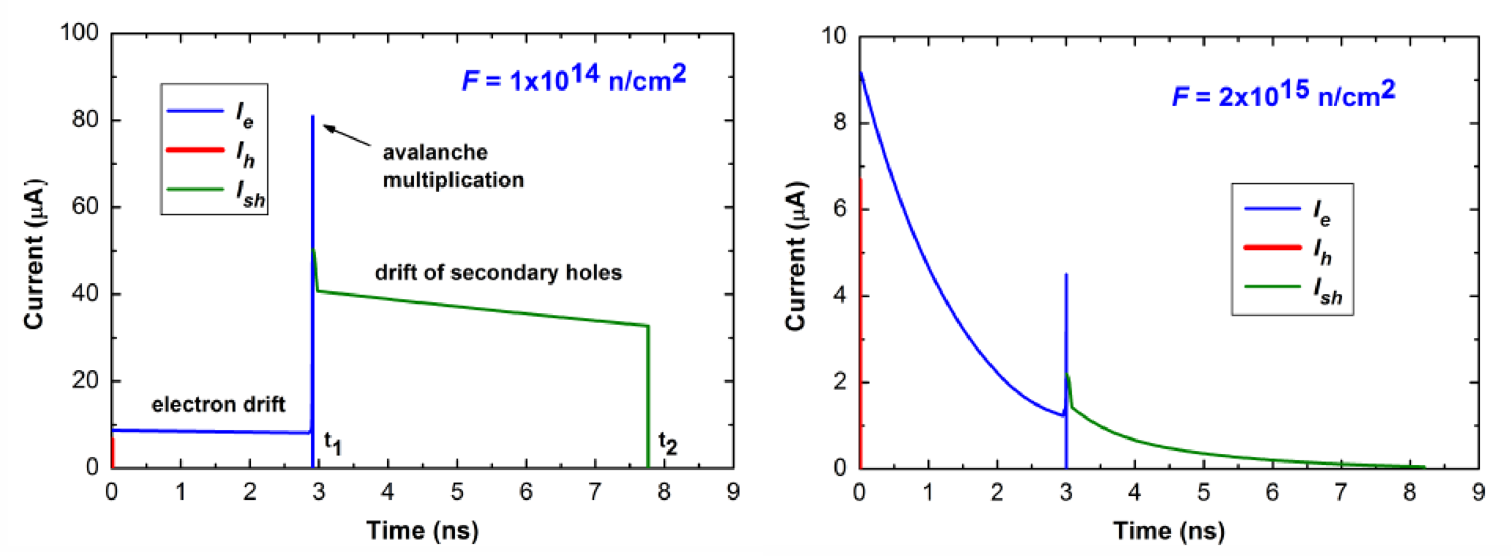


2nd stage

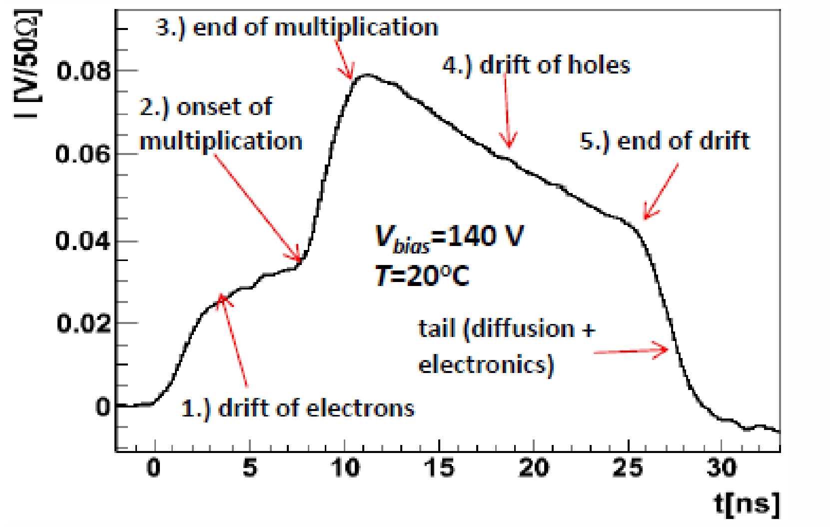
1st stage

Motivation to consider multistage process with avalanche multiplication

Simulation: irradiated LGAD



Experiment: nonirradiated LGAD

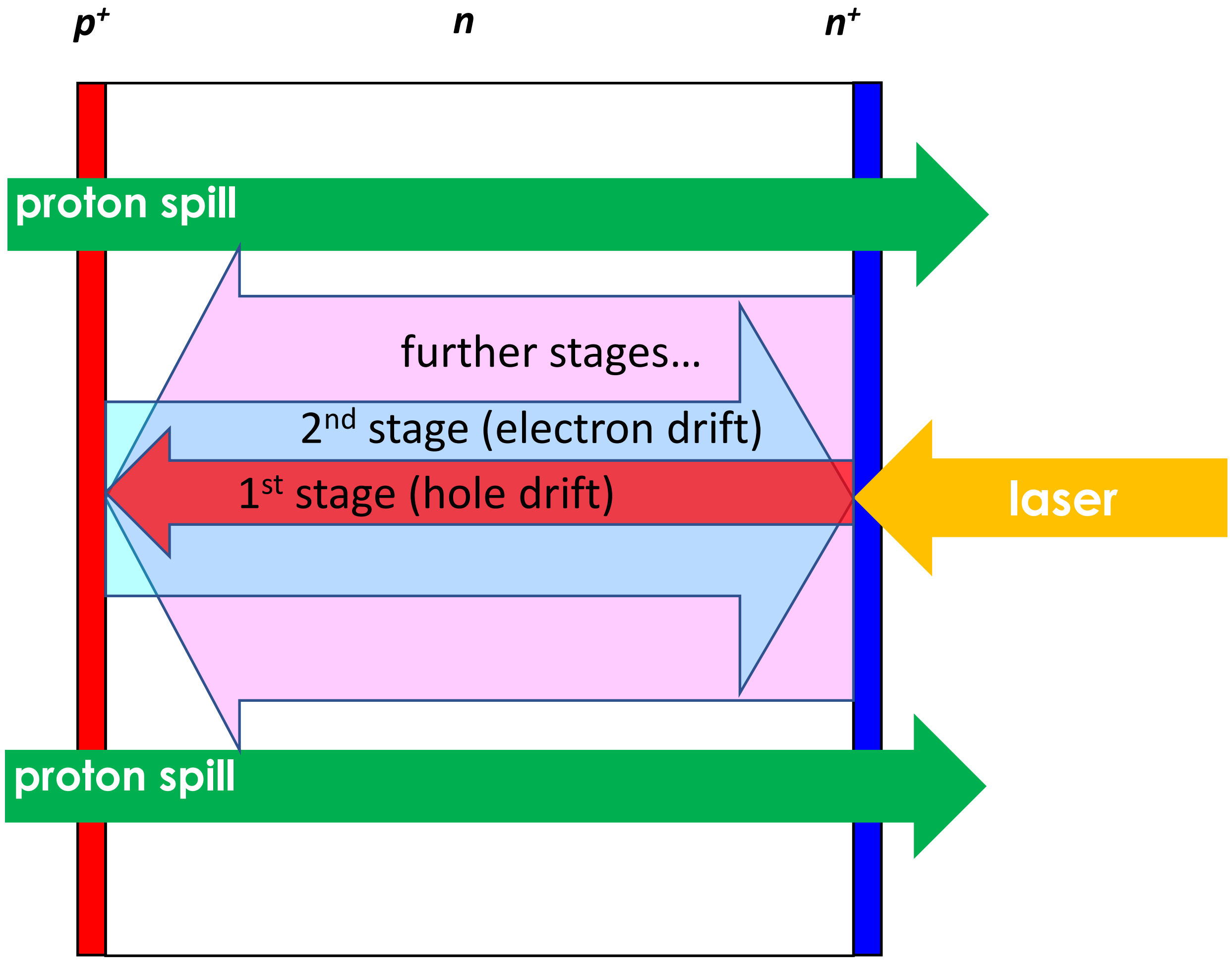


G. Kramberger, et al., 2015 JINST 10 P07006

E. Verbitskaya, et al.,
2016 JINST 11 P12012

Charge multiplication in structure **without** built-in layer

Multistage process of charge collection



Two stages of drift:

1st stage

- initial hole drift from n^+ to p^+
- impact ionization and charge multiplication initiated by holes at p^+

2nd stage

- electron drift from p^+ to n^+

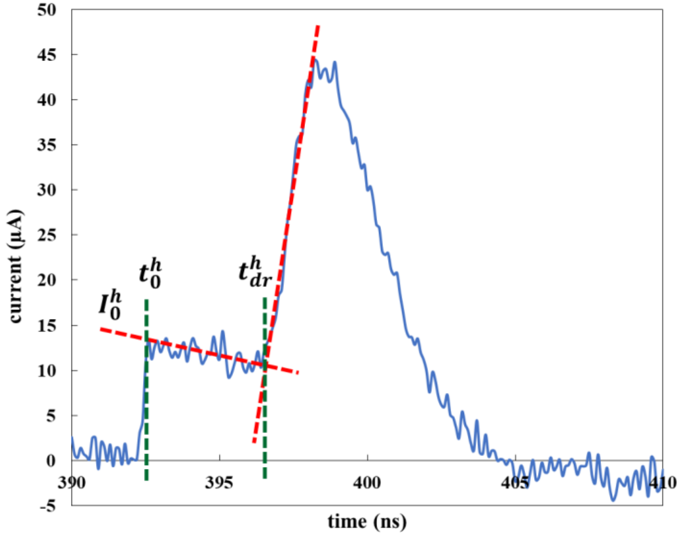
If electric field near n^+ contact is **high**: electrons initiate multiplication and **3rd stage** of charge collection (hole drift again)

Data treatment and simulations

LOWER DOSE: 5×10^{13} p/cm^2

HIGHER DOSE: 2.7×10^{14} p/cm^2

1st stage approximation

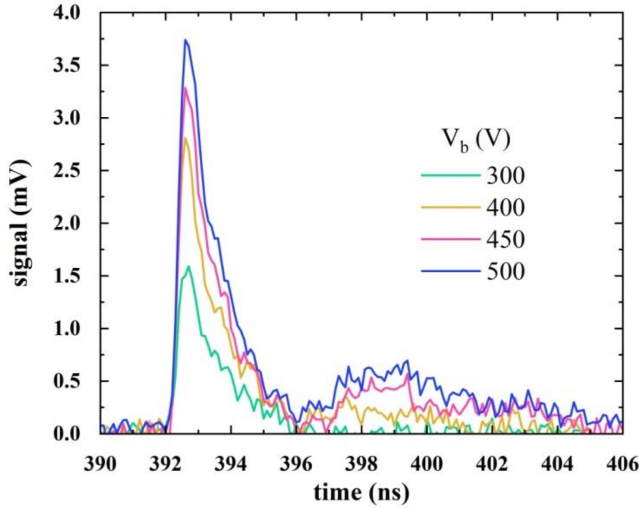


$$Q_c^h = \int_{t_0^h}^{t_{dr}^h} Q_0 \frac{v_s}{d} exp\left(-\frac{t}{\tau_{tr}^h}\right) dt = I_0^h \tau_{tr}^h \left[1 - exp\left(-\frac{t_{dr}^h}{\tau_{tr}^h}\right)\right]$$

difficult to perform exp. fit

Signal construction

$$s(t) = \begin{cases} I_0^h \exp\left(-\frac{t}{\tau_{tr}^h}\right), & 0 < t < t_{dr}^h \\ \ldots & \ldots \end{cases}$$



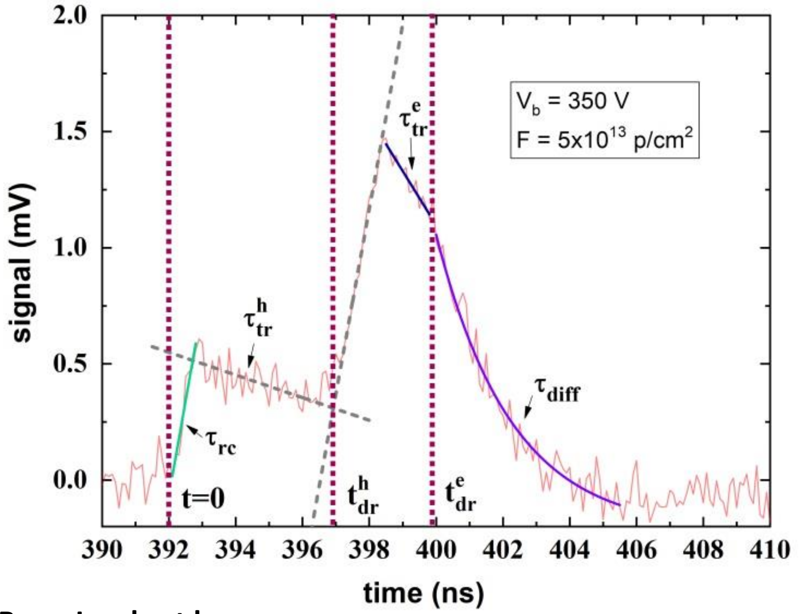
ONLY 1st stage approximation

+ accurate exp. fit
(direct τ_{tr}^h extraction)

Data treatment and simulations

2^{nd} stage and pulse tail

complicated because of carrier cloud size



Beer–Lambert law

$$p(x,0) = p_0 e^{-\alpha x}$$

Hole distribution during drift

$$p(x,t) = \frac{1}{2} p_0 \exp\left(\frac{\alpha^2\sigma^2}{2} - \alpha x\right) \operatorname{erfc}\left(\frac{\alpha\sigma^2 - 2x}{2\sigma}\right)$$

$$\sigma = \sqrt{2Dt}$$

Signal construction

$$s(t) = \begin{cases} I_0^h e^{-\frac{t}{\tau_{tr}^h}}, & 0 < t \le t_{dr}^h \\ s(t = t_{dr}^h)[1 + G_Q f(t)] e^{-\frac{t - t_{dr}^h}{\tau_{tr}^e}}, & t_{dr}^h < t \le t_{dr}^e \\ s(t = t_{dr}^e) e^{-\frac{t - t_{dr}^e}{\tau_{diff}}}, & t > t_{dr}^e \end{cases}$$

f(t) - the function defined by the change of charge in the detector determined by integration of *p(x, t)*

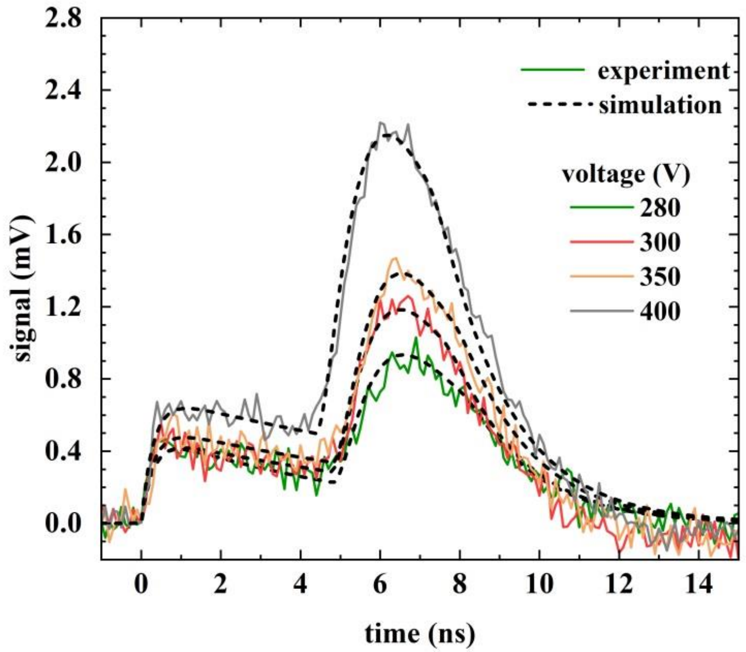
+ RC distortion

$$y(t) = \int_0^t s(t') h(t - t') dt'$$

taking into account

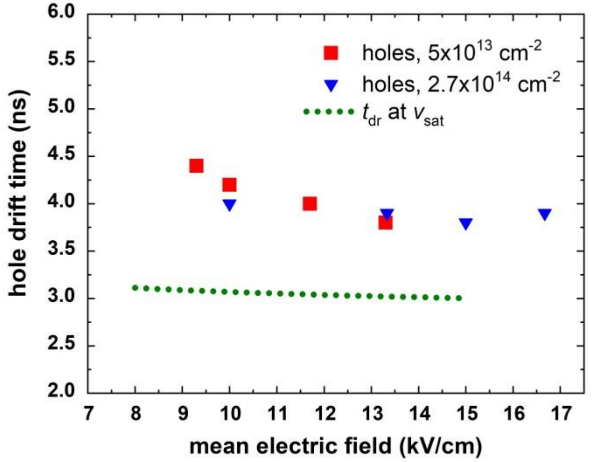
- initial nonuniformity
- diffusion spreading

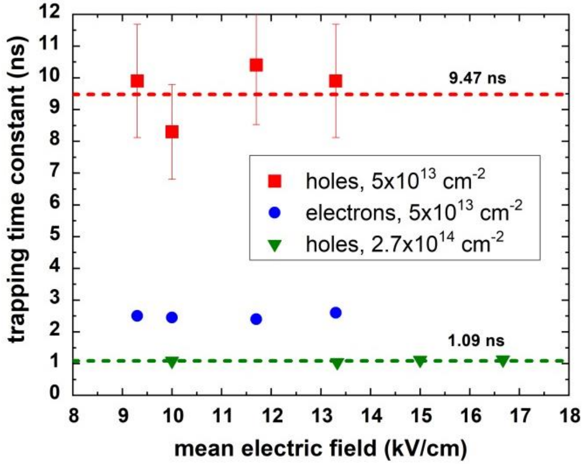
dash lines: simulated current responses



Carrier transport characteristics

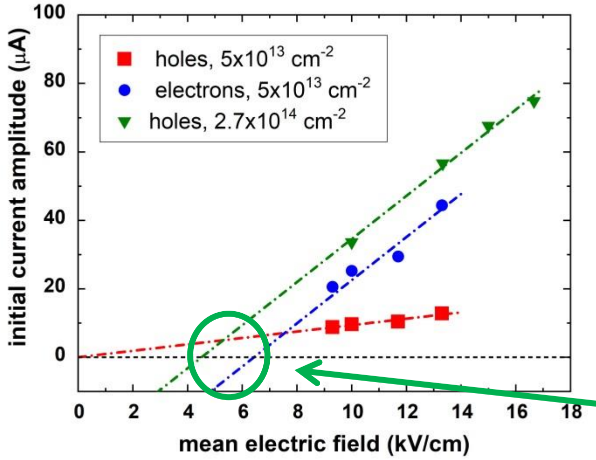
bias voltage → mean electric field $<E> = \frac{V_b}{d}$



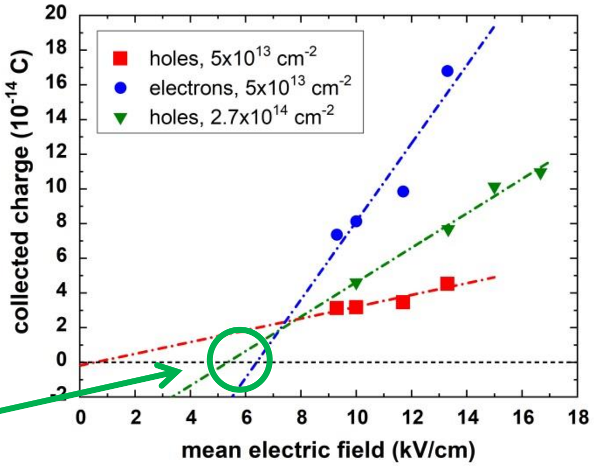


more accurate for higher dose because of exp. fit

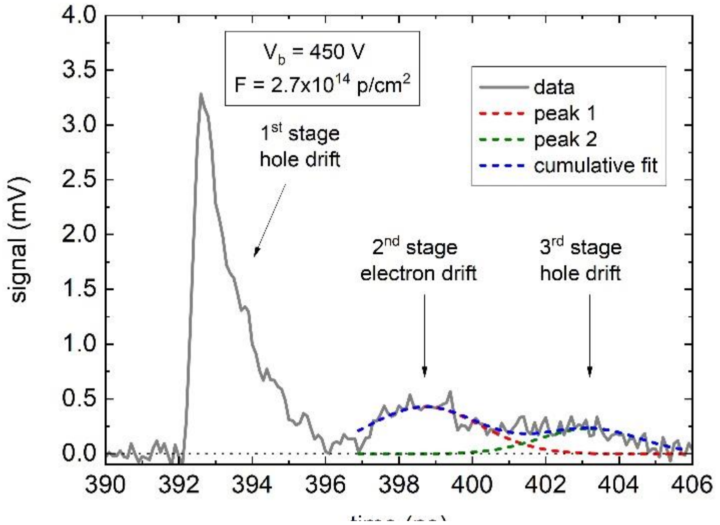
hole parameters at
$F = 5\times10^{13}$ p/cm^2
cross (0, 0)



threshold



Third stage of charge collection



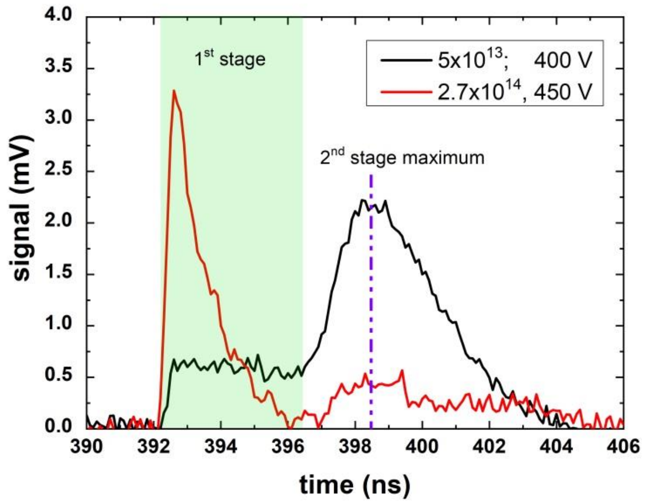
3rd stage is the **drift of holes** after impact ionization produced by electrons near n$^+$ contact

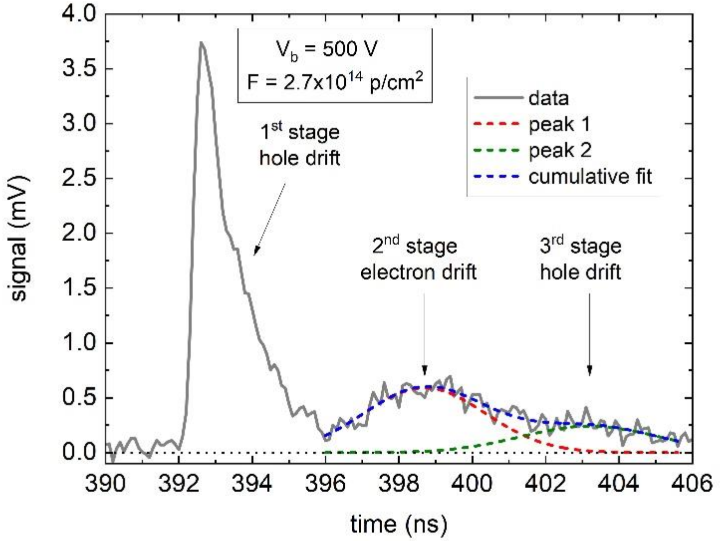
Sum of Gaussian fit

$$y(t) = y_0 + \frac{A}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(t-t_m)^2}{2\sigma^2}\right)$$

the result of the fit

Dose comparison



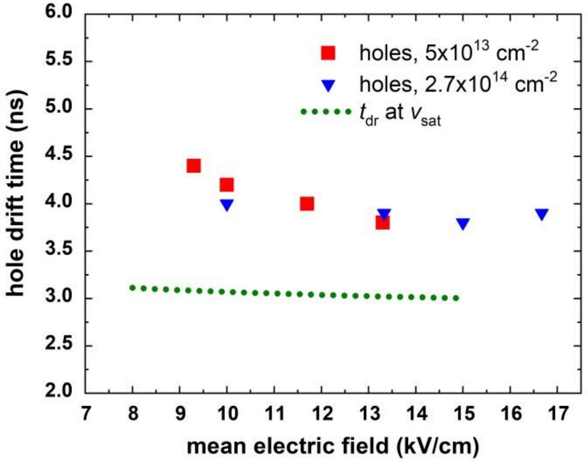


Parameter	450 V		500 V	
	S2	S3	S2	S3
t_m (ns)	**398.7**	**403.2**	**398.7**	**403.2**
σ (ns)	3.0 ± 0.2	2.9 ± 0.3	3.3 ± 0.1	3.4 ± 0.4
A (10^{-14} C)	3.3 ± 0.2	1.6 ± 0.1	5.0 ± 0.1	2.2 ± 0.2

The time between maxima **correlates** with t_{dr} with drift **velocity below saturated,** but the **current maximum** is determined by **charge** drifting inside the detector

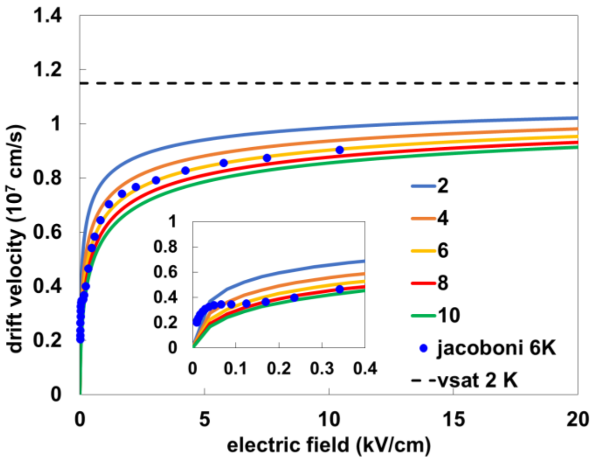
Electric field profile: low field

result for hole drift time

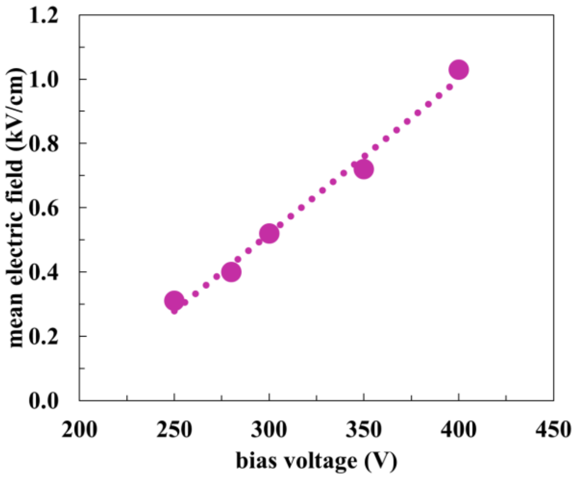


$$< v_{dr} >= \frac{d}{t_{dr}^{h}}$$

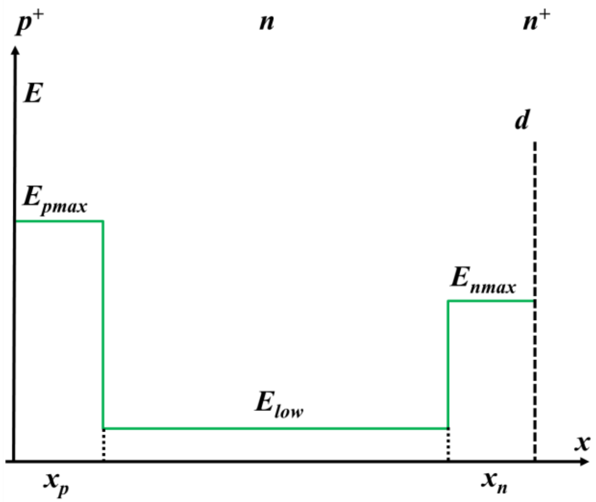
drift velocity vs electric field



low electric field *in between*



electric field distribution



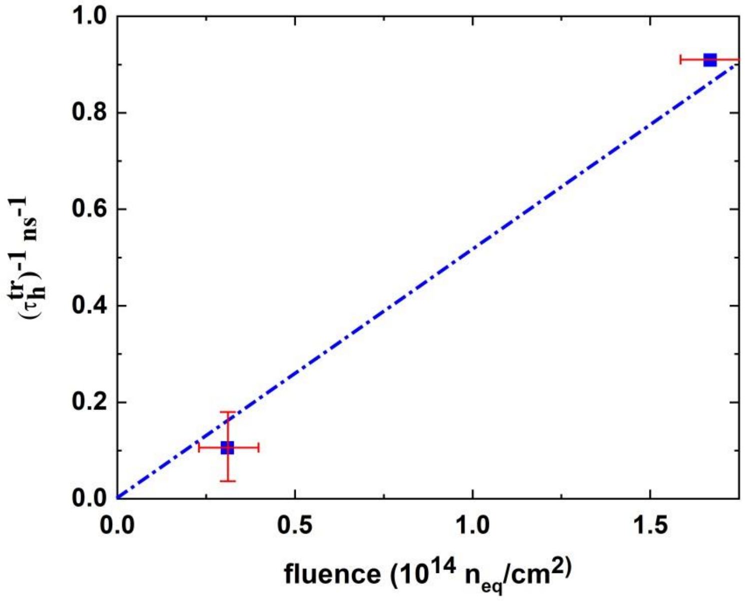
x_p and x_n are thin ($\leq 10\ \mu$m)

1st stage decay **controlled by hole trapping**

$E_{pmax} > E_{nmax}$

Internal charge gain and τ_h degradation rate

trapping time constant vs eq. fluence



$$\frac{1}{\tau_h} = \beta_h F$$

1.9 K:

$\beta_h = 3.65 \times 10^{-15}$ **cm²/ns**

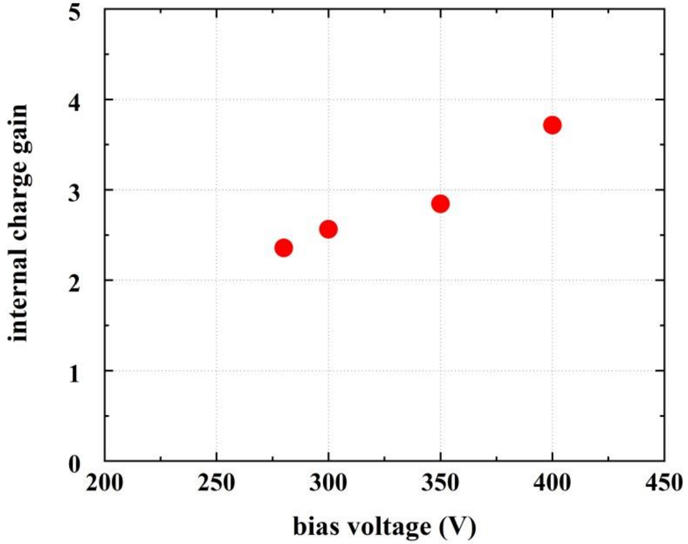
at -10° C:

$\beta_h = 7.7 \times 10^{-16}$ **cm²/ns**

(NIM A 481 (2002) 297)

Internal charge gain

$$G_Q = \frac{Q_{col}^e + Q_{col}^h}{Q_0}$$



negative feedback due to carrier trapping

Conclusions

- In the unique experiment at 1.9 K, Si $p^+/n/n^+$ detector maintains operation as a regular diode structure with highly doped contacts.
- The effect of sequential stages of charge multiplication was found. The third stage of charge collection was observed.
- The developed procedure of TCT data treatment for irradiated Si detectors with avalanche multiplication allowed extraction of full set of carrier transport parameters and internal charge gain.
- Comparison of the trapping time constant degradation rate at 1.9 K and room temperature showed fivefold increase of β_h at 1.9 K.

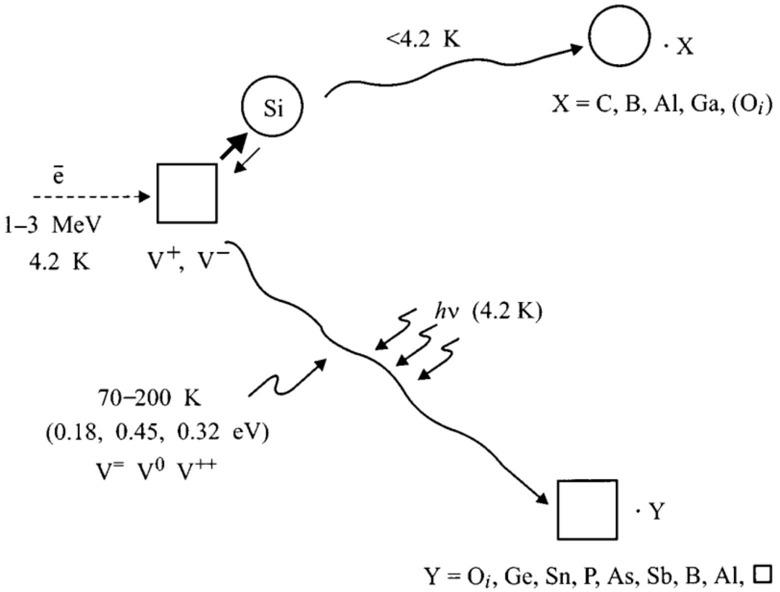
New questions have arisen:

❖ conservation of the low-field region after polarization,

❖ relaxation of current response after spill escape.

Thank you for your attention!

Why $E_{pmax} > E_{nmax}$?



J.D. Watkins

At such a low temperature defect formation is not a well-known mechanism
There is J.D. Watkins hypothesis that mobility of initial defects is different and at T < 4.2 K more donors (hole traps) are forming, while at a RT more acceptors (electron traps) are forming.