Novel view on extraction of charge carrier transport parameters from the data of classical TCT

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Motivation

TCT is the unique method for investigation of electric field distribution in *heavily irradiated* *p-i-n* structures

TCT goal:

$$i(t) \rightarrow E(x), N_{eff}(x)$$

Ramo's theorem:

$$i(t) = E_w Q(t) v_{dr}(t)$$

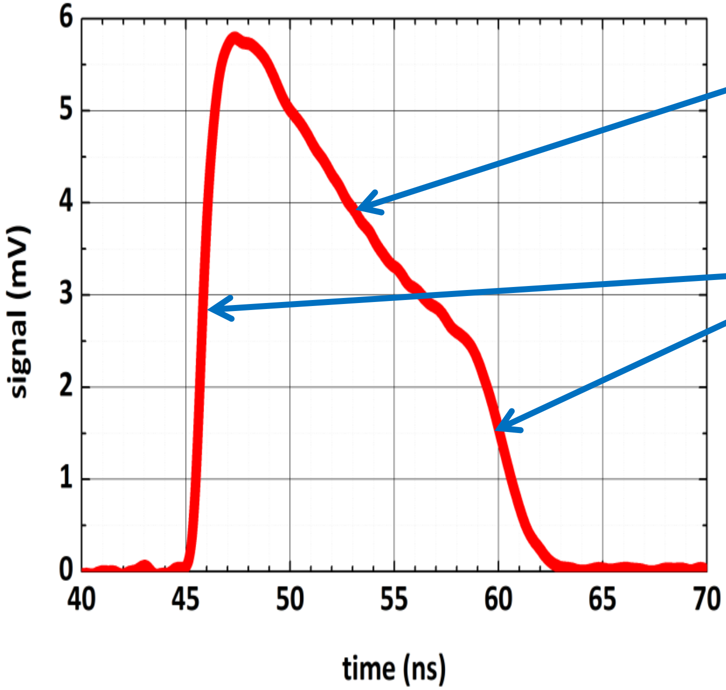
There are some ***problems***:
Pulse shape is determined by a combination of a several factors:

- $E(x), \mu(E(x)) \rightarrow v_{dr} = E\big(x(t)\big) \times \mu[E\big(x(t)\big)]$
  Drift velocity is a function of a several variables
- The charge of drifting carriers is not constant in time $Q = Q(t)$
  Due to the carrier trapping on deep levels (τ_{tr})
- Pulse edges distortions
  Due to the nonuniformity of generated cloud of carriers, diffusion and response of the electric circuit

Outline

- ❖ Motivation
- ❖ Reconstruction of the physical response
- ❖ TCT Signal processing
- ❖ Numerical solution of the system of equations for the electric field
- ❖ Electric field reconstruction in nonirradiated detectors
- ❖ Electric field reconstruction in irradiated detectors
- ❖ Summary

TCT Pulse



Typical TCT pulse of nonirradiated detector

Current induced by electron drift

$$\boldsymbol{i}(t) = \frac{1}{d} \times \boldsymbol{Q}(x(t)) \times \boldsymbol{v_{dr}}(x(t), E(x(t))$$

Distorted **pulse edges**

*in this case, key condition: $\boldsymbol{Q}\big(\boldsymbol{x}(\boldsymbol{t})\big) \equiv \boldsymbol{Q_0}$

We want to obtain the electric field directly from the experimental data without a priori knowledge and any models

Main equations for Electric field reconstruction

The lateral size of the detector's contacts is much bigger than thickness of sensitive area:
1D geometry

Current response

$$i(t) = \frac{Q(t)}{d} v_{dr}(t)$$

Drift velocity

$$v_{dr}(t) = \mu\big(E(t)\big)E(t)$$

Mobility

$$\mu_{eff}(E) = \frac{\partial v_{dr}(E)}{\partial E}$$

Translation to coordinate scale

$$x(t) = \int_0^t v_{dr}(t')dt'$$

Collected charge

$$Q_0 = \int_0^{t_{dr}} i(t)dt$$

$\tau_{tr} \gg t_{dr}$ **only!**

Potential difference

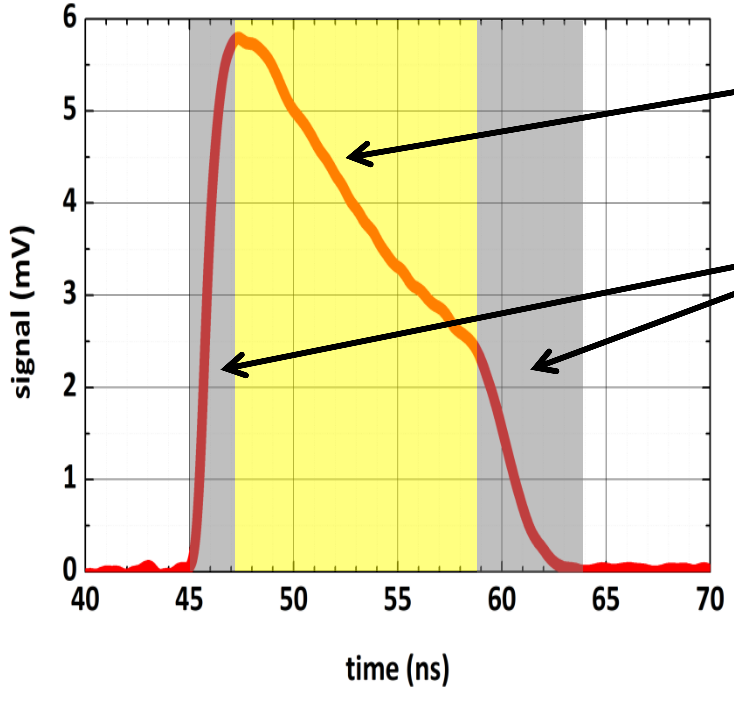
$$\Delta\varphi = \int_0^d E(x)dx = V_{bias}$$

Always!

All we need is solve this system...*but how?*

Simple criteria

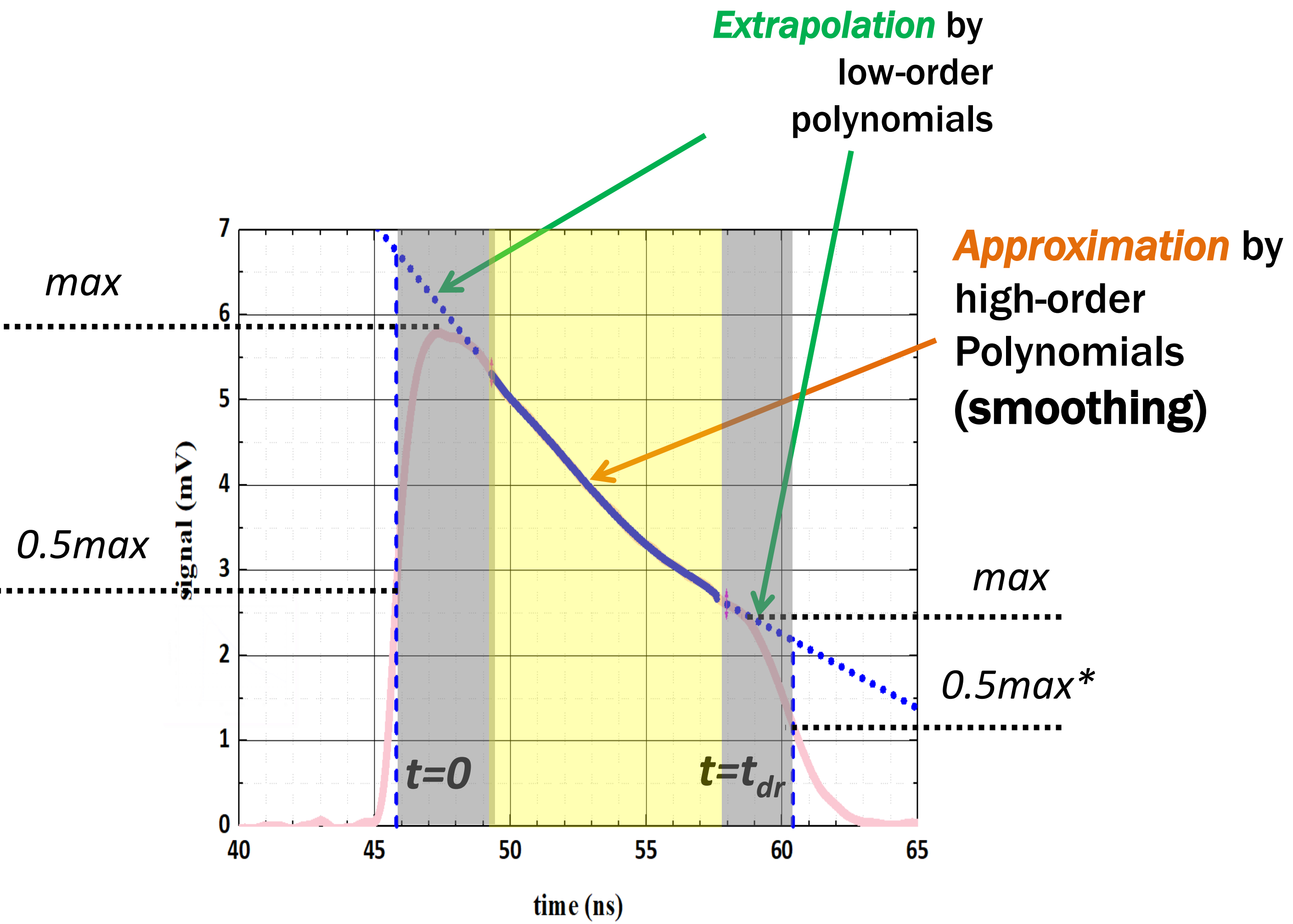
Reconstruction of the E(x) in the assumption of negligible carrier trapping



Current pulse response of the full-depleted detector

$$\tau_{tr} \gg t_{dr}$$

Data processing: reconstruction of physical response



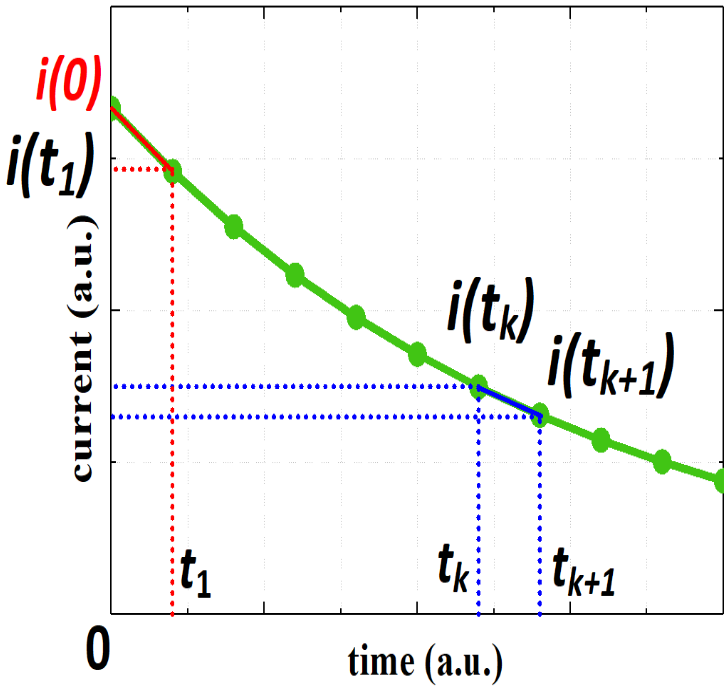
Criterion for the correctness:

$$Q_0^{exp} = Q_0^{phys}$$

In the case of mistake

t_{dr} can be moved

We have the physical response, what's next?



Approach to the reconstruction of the E(x) profile

$$E(0) = \frac{d}{Q_0 \times \mu} \times i(0)$$

Initial condition

$$E_{k+1} = \frac{d}{Q_0}[i(t_{k+1}) - i(t_k)]\mu_{eff}(E_k) + E_k,$$

$$k = 0 \ldots . N-1, \qquad t_N = t_{dr}.$$

$$x_k(t_k) = \int_0^{t_k} v_{dr}(t)dt,$$

N.B. $\mu_{eff} = const$ in the interval $[i_k, i_{k+1})$

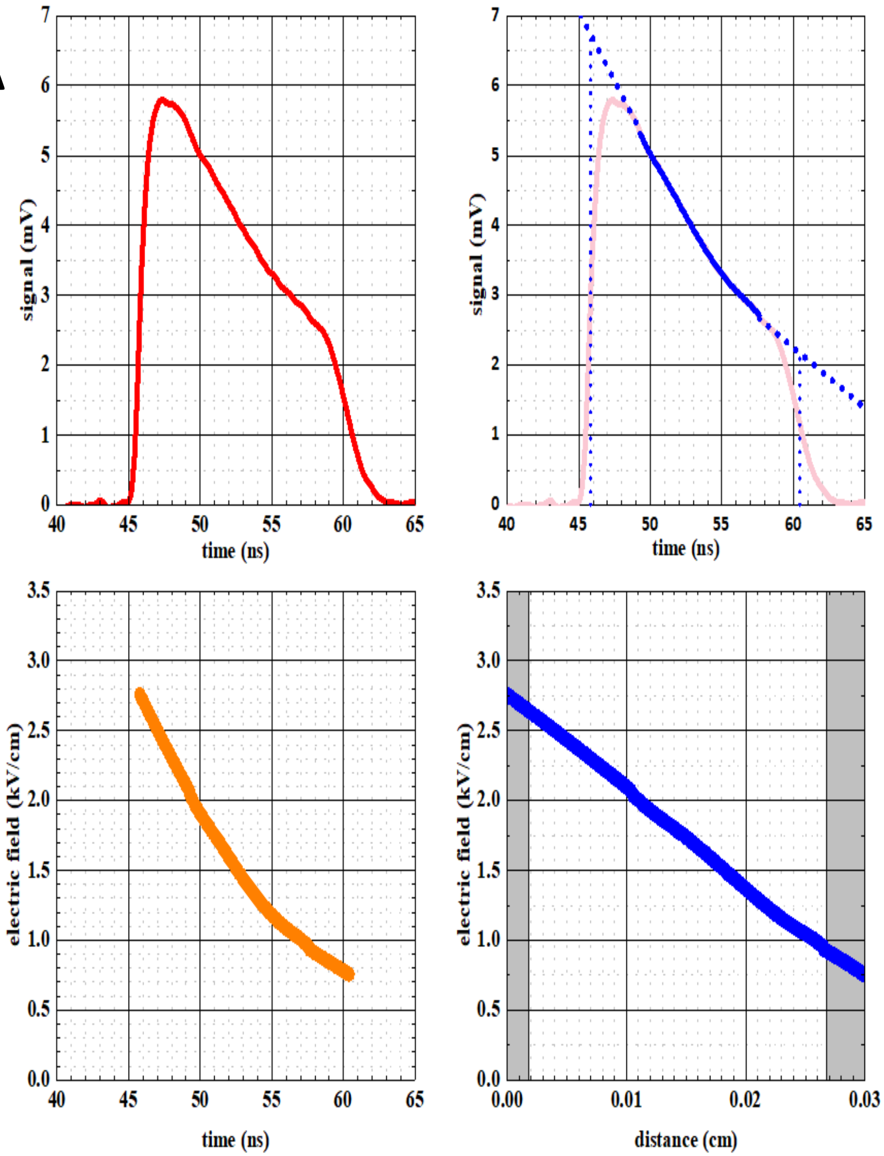
Reconstruction of E(x)

DATA

Physical response

E(t)

E(x)



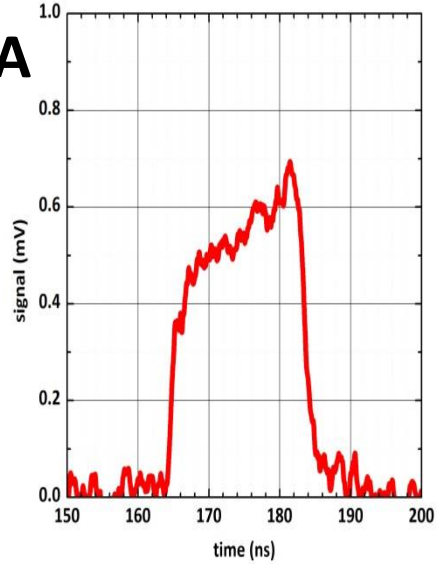
Correctness test:

$$\Delta\varphi = \int_0^d E(x)dx = 52.2\ V$$

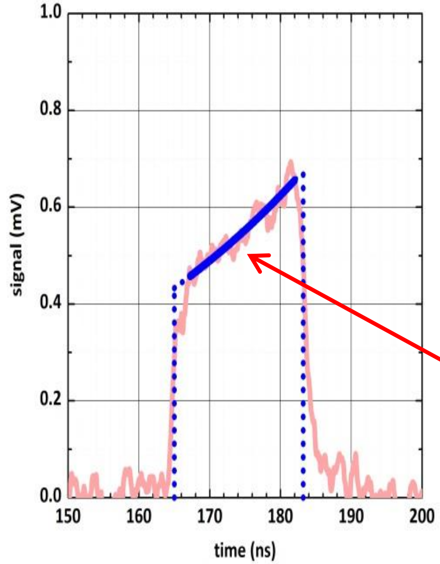
only 4% larger than applied bias of 50 V

Hole current response

DATA

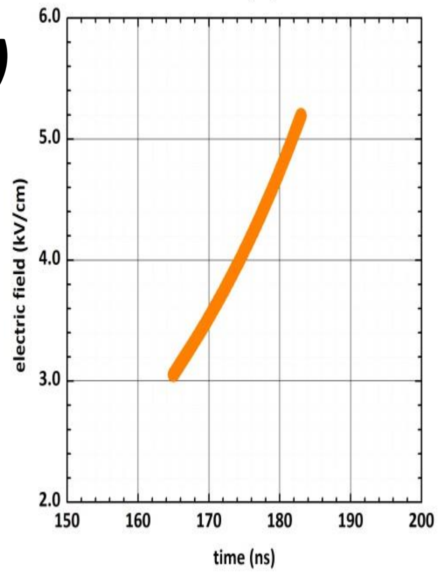


Physical response

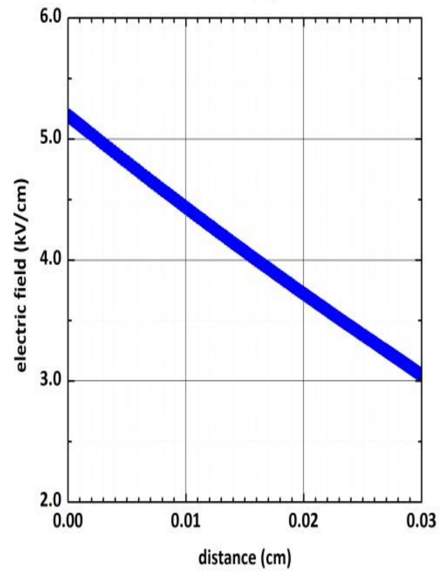


In this case, the correctness of smoothing is ***really important*** ***(suppression of fluctuations produced by noise)***

E(t)



E(x)



Correctness test:

$$\Delta\varphi = \int_0^d E(x)dx = 101.3\ V$$

only 1% larger than applied bias of 100 V

Effective concentration

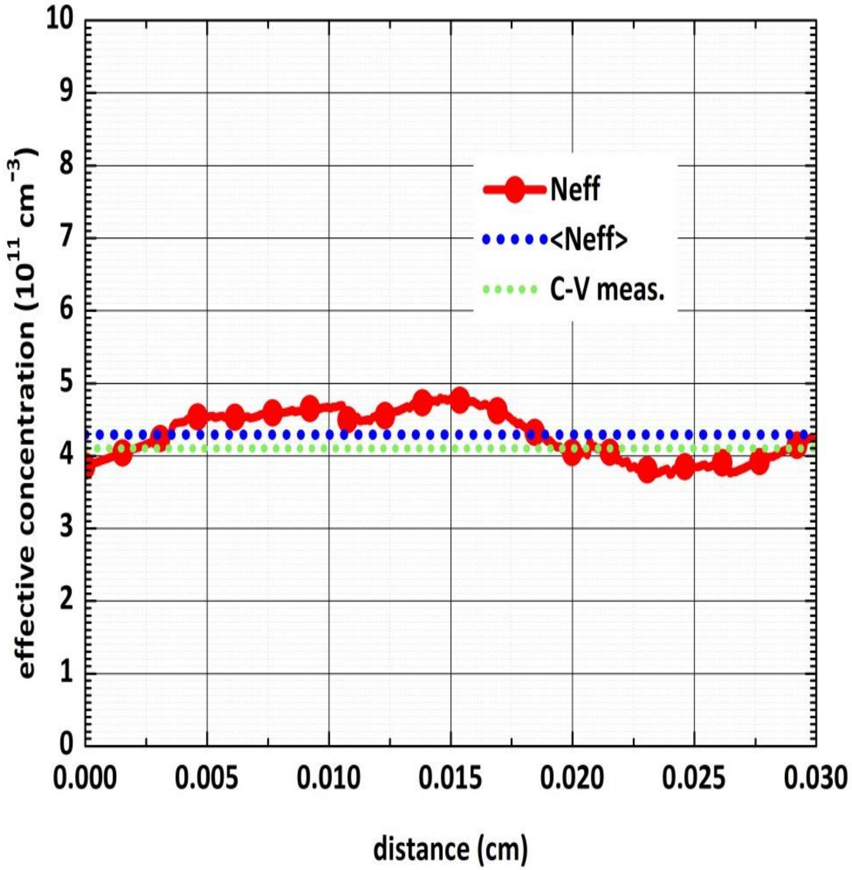
Poisson's eq.

$$E(x) \longrightarrow N_{eff}(x)$$

Method	Electron current response	Hole current response	C-V
N_{eff} (10^{11} см$^{-3}$)	4.3	4.0	4.1

Accuracy: σ = 5%!

The profile of the effective concentration is close to uniform

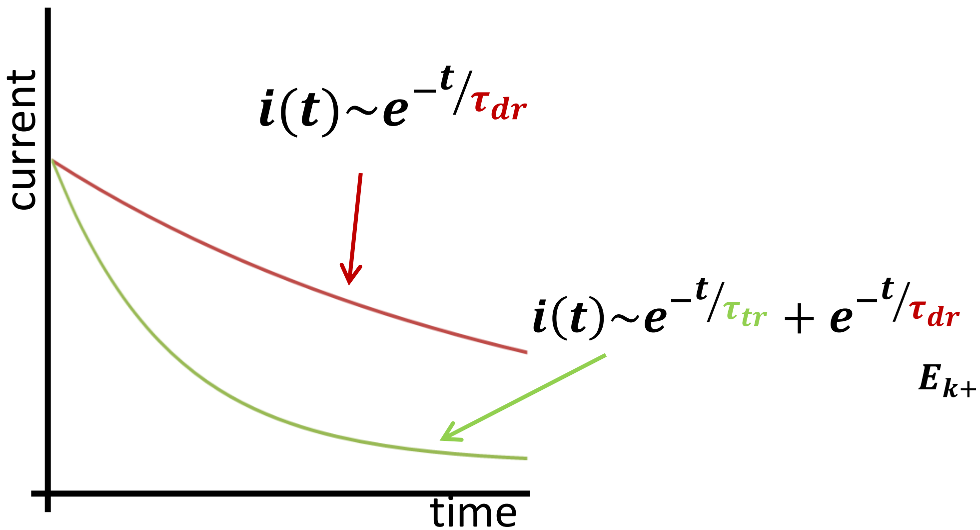


Carrier trapping

In irradiated *Si* detectors, the drifting charge decreases with time due to carrier *trapping* on the deep levels

$$\frac{1}{\tau_{tr}} = \beta \times F$$

Trapping time constant — Proportionality constant — Fluence



However, the same procedure is applicable

TCT signal processing:

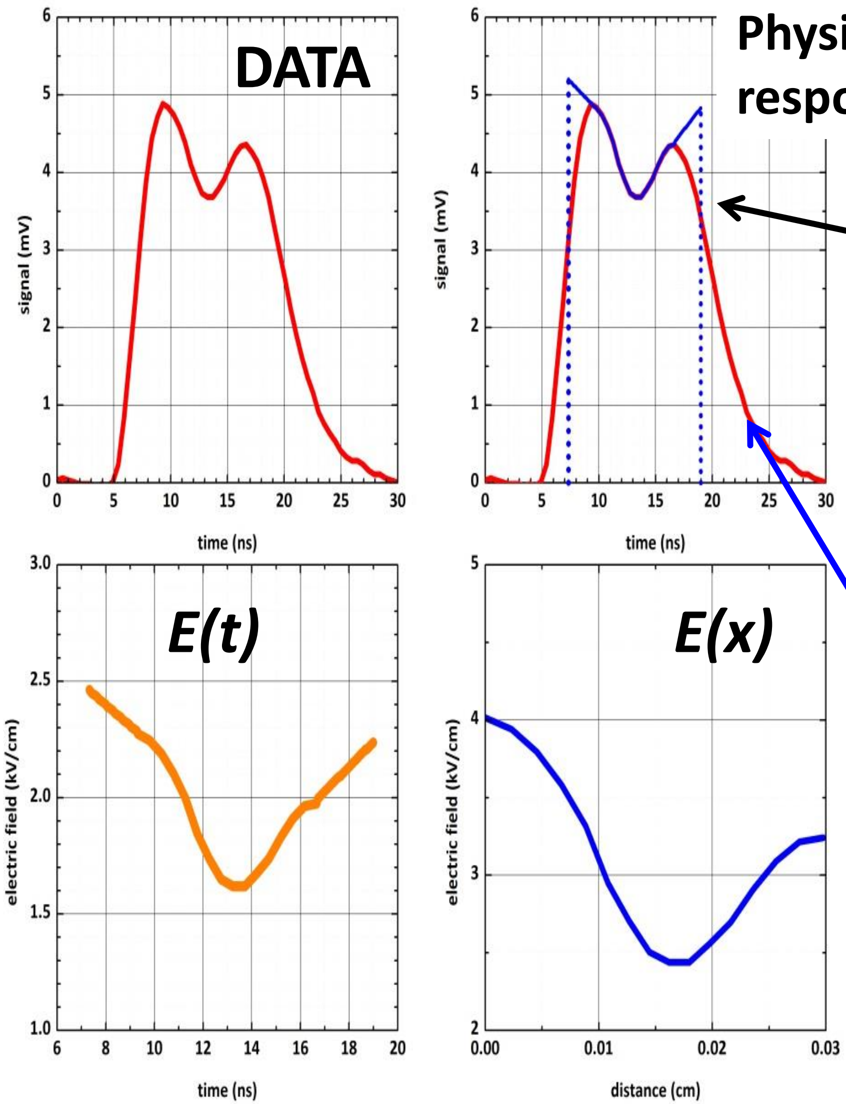
$$E_{k+1} = \frac{d}{Q_0 \exp(-\frac{t_{k+1}}{\tau_{tr}})} [i(t_{k+1}) - i(t_k)] \mu_{eff}(E_k) + E_k,$$

$$k = 0 \dots N-1, \qquad t_N = t_{dr}.$$

N is the number of experimental points

Different processes have a *similar effect* on the pulse shape !

The same steps to the E(x) reconstruction



In this case, ***we can't*** use a criterion of Q_0 and only $\Delta\varphi$ **isn't affected by charge trapping!**

$$\boldsymbol{d = \int_0^{t_{dr}} v_{dr}(t)dt}$$

$$\boldsymbol{\int_0^{\int_0^{t_{dr}} v_{dr}(t)dt} E(x)dx = 80\,V \rightarrow t_{dr} = 12\,ns!}$$

t_{dr} is not on the level of half-amplitude!

The long tail in the response is not connected with the carrier drift and can be explained by the fast trapping/detrapping.
The criterion of potential difference shows it!

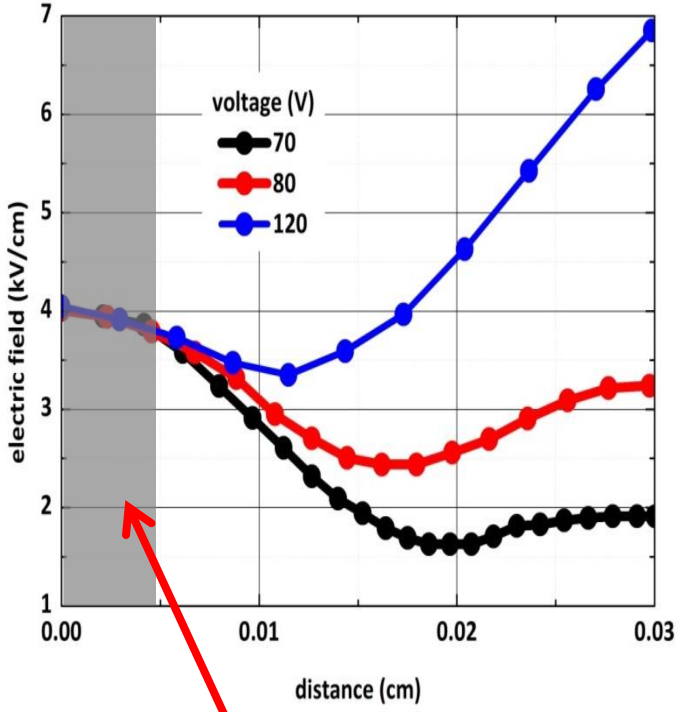
Irradiated Si detector

$p^+/n/n^+$ pad detector
$d = 300\ \mu m$
$N_D = 5 \times 10^{11} cm^{-3}$

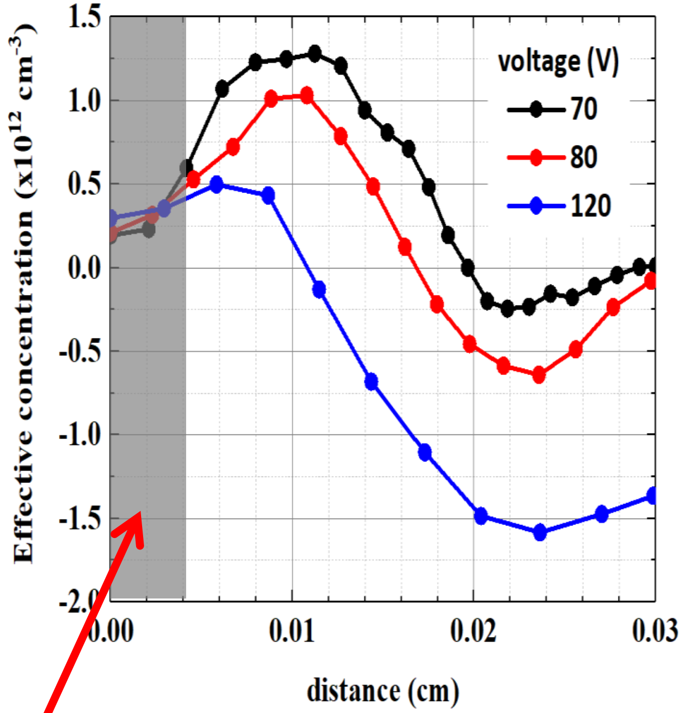
Irradiated by protons
$F = 4 \times 10^{14} cm^{-2}$

The described **algorithm was applied** for the treatment of pulse series recorded for the detector operated at **different bias voltages**

Electric field



Effective concentration



Area of uncertainty (area of extrapolation)

Summary

- The new approach is proposed for obtaining the $E(x)$ and $N_{eff}(x)$ from TCT data. It based on the reconstruction of physical response and numerical solution of the system of transport equations.
- In the case of nonirradiated detector, $E(x)$ and $N_{eff}(x)$ were obtained. They are close to uniform and their mean values equal with 5% accuracy to the results of the C-V measurements.
- The described algorithm was applied to responses of irradiated detectors. In this case, temporal resolution and pulse approximation is critical.

Thank you for attention!