Simulation of LGAD characteristics based on the concept of negative feedback in irradiated Si detectors with carrier impact ionization (part II)

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Goal

How to explain reduction of the gain and collected charge in LGAD: our vision

Outline

- Model of processes in irradiated Si n-on-p strip detectors and LGADs originating internal negative feedback
- Fit of the experimental $Q_c(V)$ data and calculations of $Q_c(F)$ dependencies for LGADs
- $E(x)$ distribution in LGADs
- Signal formation and evolution in LGADs
- Conclusions

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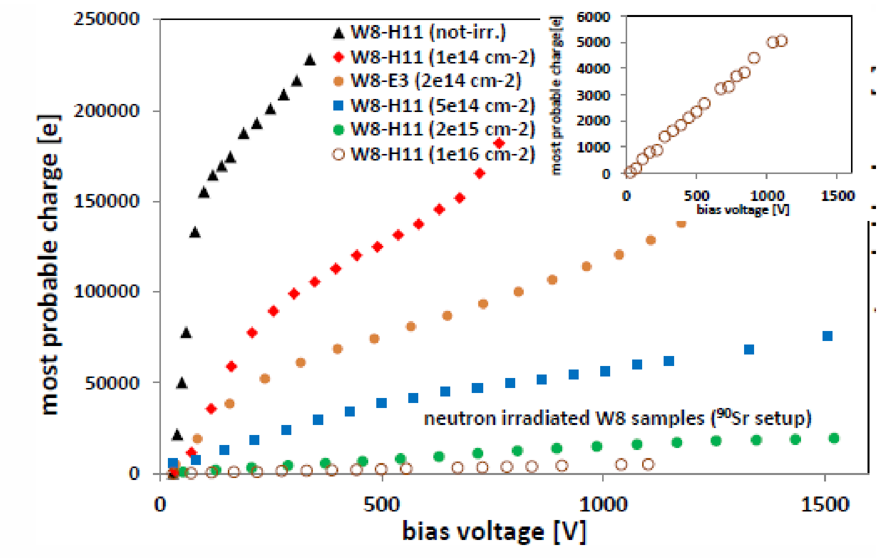
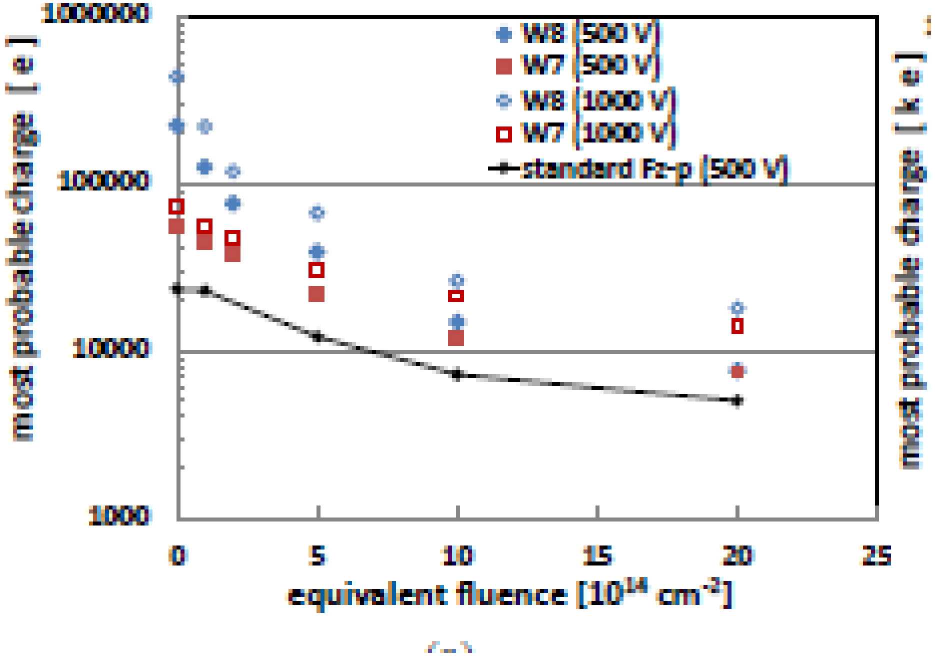
Experimental results of RD50

Experimental data are taken in

1. *G. Pellegrini, et al., NIM A765 (2014) 12*
2. *G. Kramberger, et al.,* 2015 *JINST* 10 P07006.

Neutron irradiation





Gain in nonirradiated LGAD achieves 10-20
and goes down under irradiation being about 1

Negative feedback in irradiated n-on-p strip detectors

High field region: high voltage, electric field focusing by strips

- impact ionization near n^+ strips(e, h)
- hole injection
- hole trapping to DLs

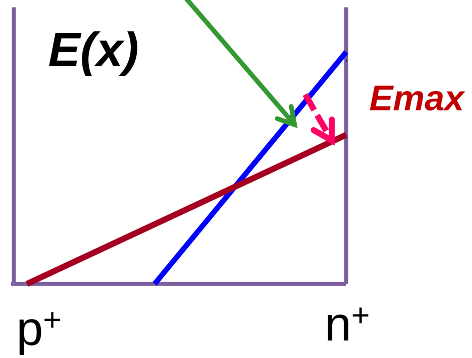
- reduction of $-N_{eff}$
- reduction of dE/dx and stabilization of E_{max} at n^+
- **reduction of $\alpha_{e,h}$**

Trapping-related negative feedback:

- stabilizes avalanche multiplication and total detector performance

BUT

- simultaneously restricts Q_c enhancement



Developed for n-on-p Si strip detectors

V. Eremin, et al., *14 and 15 RD50 workshops, 2009, Freiburg and Geneva*

V. Eremin, et al.,, *NIM A 658 (2011) 145*

E. Verbitskaya, et al., 2012, J. Instrum., v.7, 2, ArtNo: C02061;

E. Verbitskaya, et al., NIM A 730 (2013) 66

Physical background of LGAD simulation

LGADs initially contain high doped built-in layer p_{bi} with E ~ 10^5 V/cm
DLs (traps) are induced by radiation and the processes are the same.

➔ There is no reason to exclude the existence of internal negative feedback in LGAD

The concept of LGAD characteristic simulation is based on:

1) a model of two effective energy levels of radiation-induced defects responsible for the electric field distribution and charge collection in irradiated detectors;

2) a mechanism of internal negative feedback in detectors with impact ionization inside high field region predicting the gain degradation with irradiation

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Algorithm of E(x) and Q_c simulation

Simulation of LGAD characteristics includes two steps:

- formation of a steady-state *E(x)* distribution: equilibrium carriers – thermally generated carriers and carriers arisen via impact ionization in the p_{bi} layer, hole injection from the p_{bi} layer, carrier trapping on radiation-induced DL defects;

- charge collection in the detector bulk with a calculated *E(x)* profile; e and h are generated by MIPss

Procedure and main parameters

♦ **numerical calculation – EXCEL MS Office, p_{bi} layer implemented**

♦ one-dimensional approach for detector geometry with **variable *x* increment**

♦E(x): Poisson equation combined with the continuity equations and SRH theory

♦ Effective deep levels: DA E_c – 0.53 eV; DD E_v + 0.48 eV

♦ Collected charge $Q(x) = Q_o exp(-t(x)/\tau)$

$1/\tau_{e,h} = \beta_{e,h} F_{eq}$; $\beta_e = 3.2\text{x}10^{-16}\ \text{cm}^2\text{ns}^{-1}$, $\beta_h = 3.5\text{x}10^{-16}\ \text{cm}^2\text{ns}^{-1}$

♦ ionization rates $\alpha_{e,h} = A_{e,h} exp(-B_{e,h}/E)$

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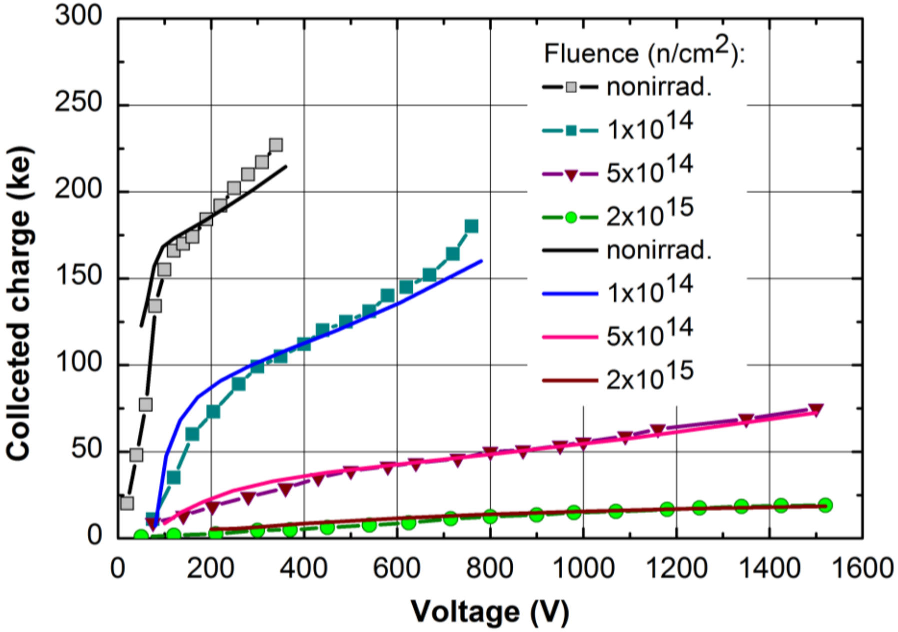
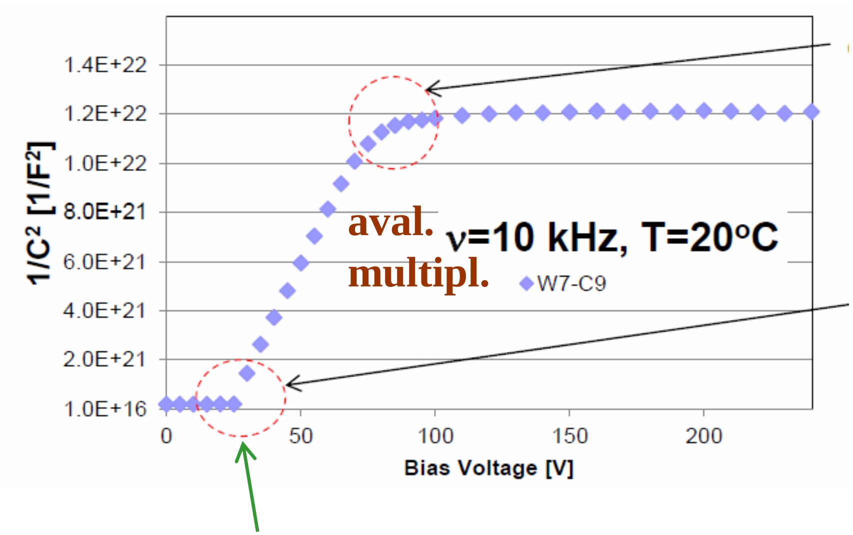
1^{st} step: fitting of $Q_c(V)$ dependencies

- Chosen for fit: LGAD from [1,2] irradiated in steps by 1 MeV neutrons
- Boron profile in the p_{bi} layer is approximated by a triangle





p_{bi} layer depletion

T = -20C

Derived parameters of the p_{bi} layer

D_B: 2.2×10^{12} to 1.7×10^{12} ion/cm^{-2} – *partial boron removal (~25%)*
N_m: $(7\text{-}8)\times10^{15}$ cm^{-3}
w_{pb}: (5.9±0.4) μm – *agrees with published data*

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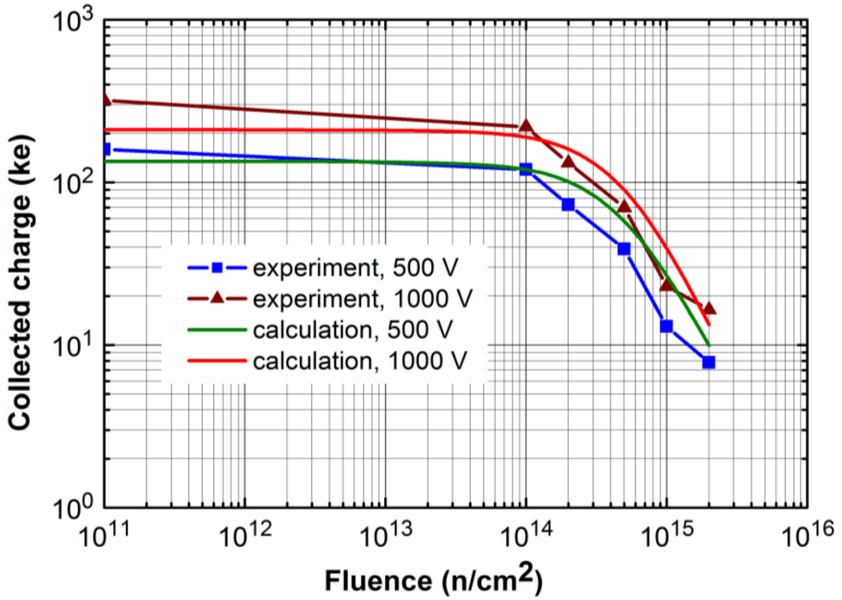
2^{nd} step: calculation of $Q_c(F)$ dependencies



Experiment: data from [2]

Parameters derived from $Q_c(V)$ fits are used

Discrepancies between $Q_c(V)$ fits and experiment are in the transition region from sharp to gradual rise of $Q_c(V)$ curves, presumably due to:

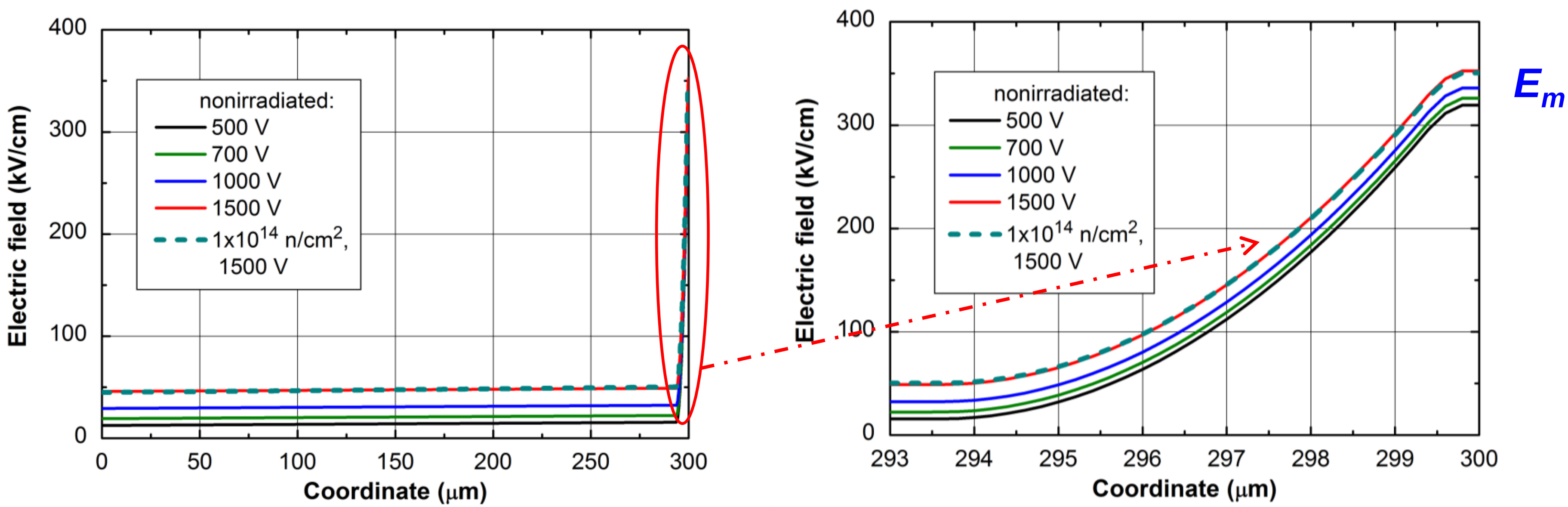
- changes of boron profile because of boron removal,
- smooth boron "tails" extending outside the p_{bi} layer,
- exact position of the n^+-p_{bi} junction is not known.

Reason: various thermal treatments used in the multilayer structure processing

Electric field distribution in LGAD

Calculation: comparison of E(x) profiles in the cases:
impact ionization + hole injection + hole trapping
and “no hole injection” “no hole injection” = “no impact ionization”

Nonirradiated LGAD and F = 1x10^{14} n/cm^2



F = 0: no trapping (no DLs)

F = 1x10^{14} n/cm^2 – the same profiles as at F = 0

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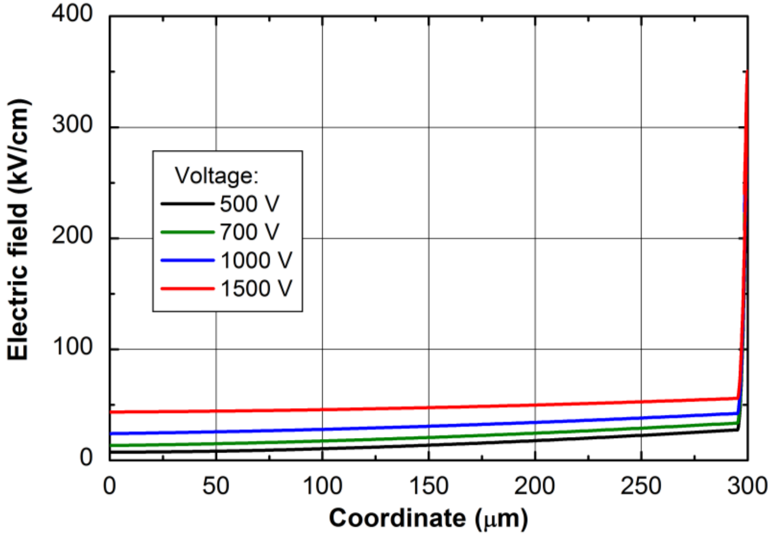
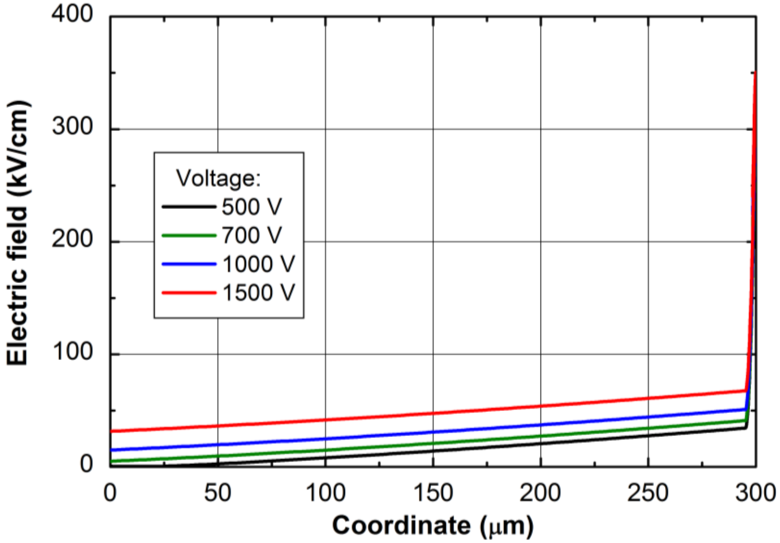
Electric field distribution in irradiated LGAD

F = 5x10^{14} n/cm^2

impact ionization + hole injection + trapping

"no impact ionization"





slight $E(x)$ reduction in the entire detector bulk and a more pronounced one in the p_{bi} layer

reduction of E at the p^+ contact while insignificantly E_m rises.

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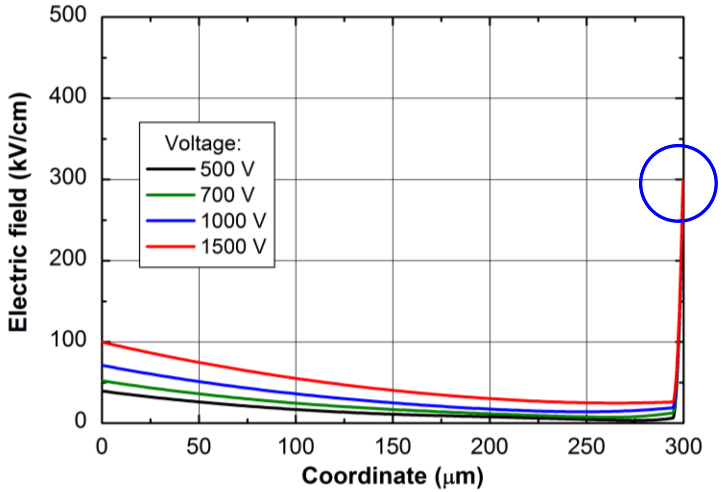
Electric field distribution in irradiated LGAD

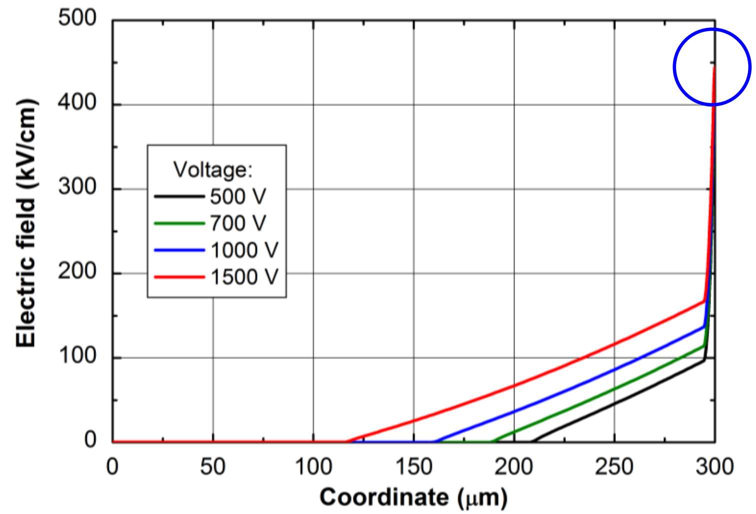
F **= 2x10^{15} n/cm^2 ➔ radical changes**

impact ionization + hole injection + trapping



35% lower

"no impact ionization"



- Second *E(x)* region extending from the p$^+$ contact and the region with a low electric field *in-between*
- Potential redistribution: *V* over p$_{bi}$ layer is few volts only
- **Reduction** of *E* in the p$_{bi}$ layer
- ***E$_m$* reduction is evidence for starting-up of negative feedback**

- *E(x)* region extending from the n$^+$ contact covers only a part of detector
- Region with *E* < 1 kV/cm, active base, covers a significant part of the detector depth (100-200 μm)
- **Significant increase** of *E* in the p$_{bi}$ layer

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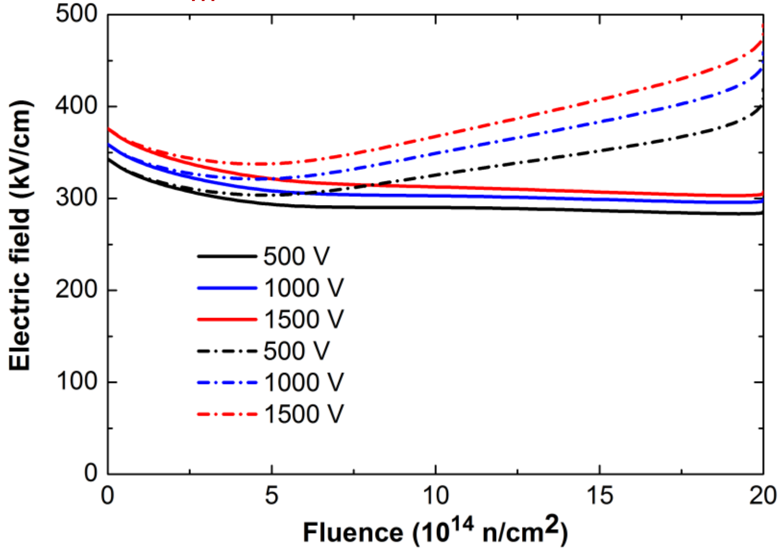
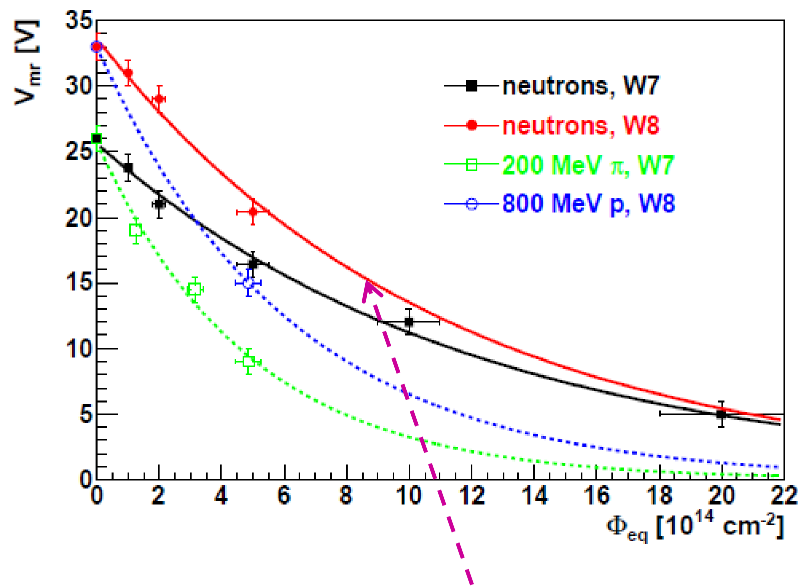
Evolution of electric field distribution under irradiation

E_m in the built-in layer





[2]

- Injection of holes arisen via impact ionization leads **to potential redistribution** and formation of high electric field region near the back contact
- E_m in a built-in layer goes down
- Stabilization of the avalanche multiplication and the total detector performance (e.g. stabilization of noise)

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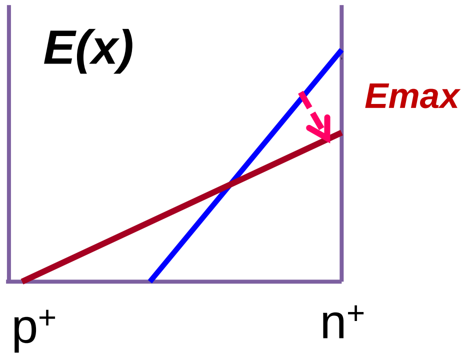
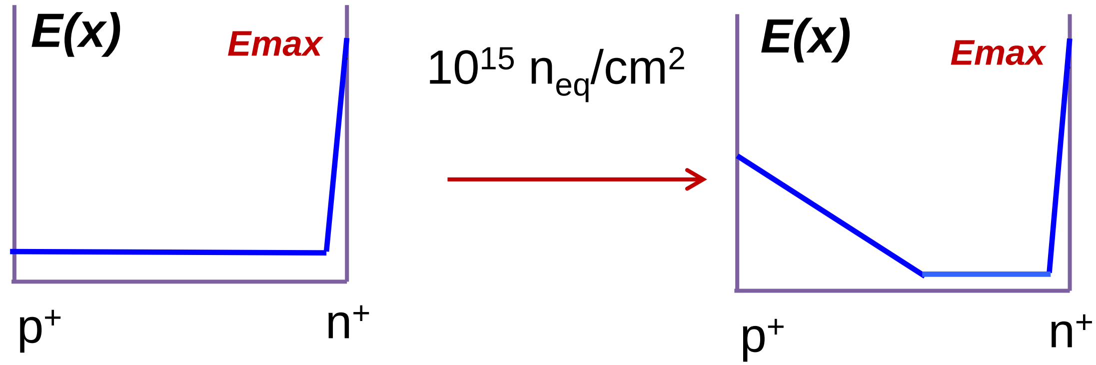
Mechanism of negative feedback in LGAD

strip



LGAD



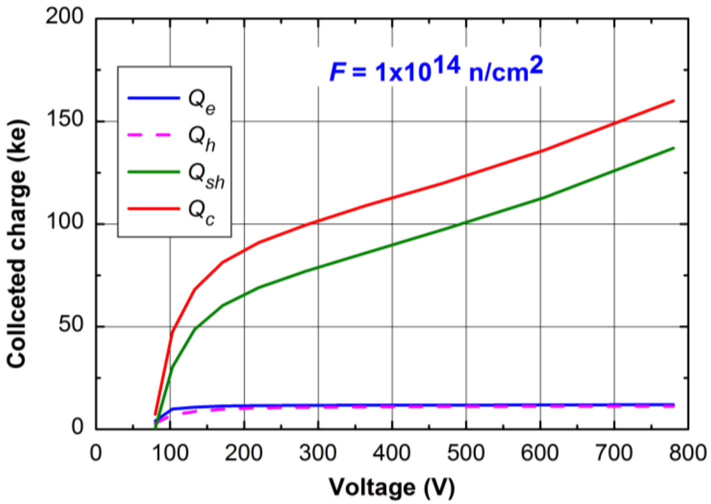
LGAD

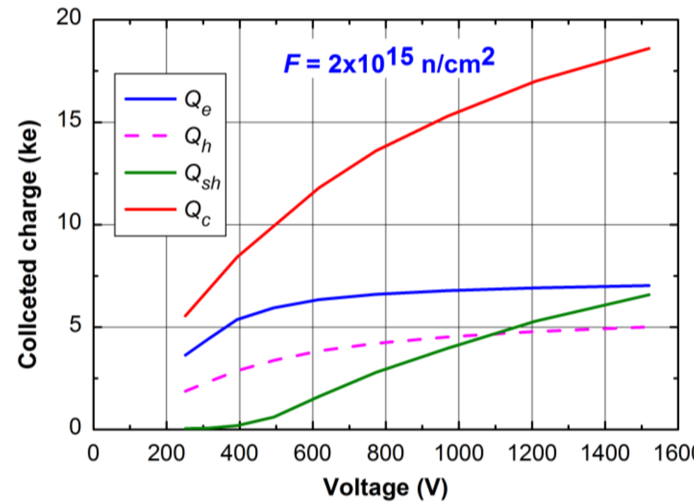
E >1x10^5 V/cm initially arises in LGAD (at *F* = 0) even at low *V*
At *F* ~ 10^{15} n_{eq}/cm^2 high field regions are at both sides and maximal fields can be comparable
→ Impact ionization at the back contact, electrons flow to n^+, impact ionization, and so on
→ self-consistent process which prevents breakdown

Signal formation and evolution in LGADs

Components of Q_c *(nonequilibrium carriers)*

Q_e and Q_h - primary electrons and holes generated from MIPS,
Q_{sh} - secondary holes arisen via impact ionization produced by the primary electrons drifting to the p_{bi} layer





F (n/cm^2)	Q_e	Q_h	Q_{sh}	G_{eff}
0	5.5	5.5	89	30
1×10^{14}	~ as at F = 0			
5×10^{14}	14.5	12.9	73	3
2×10^{15}	37	27	36	0.8

Components in % of Q_c

N.B. Y-axis scales differ in 10 times!

$G_{eff} = Q_{LGAD}/Q_o$

Reduction of G_{eff} is due to significant reduction of Q_{sh} !

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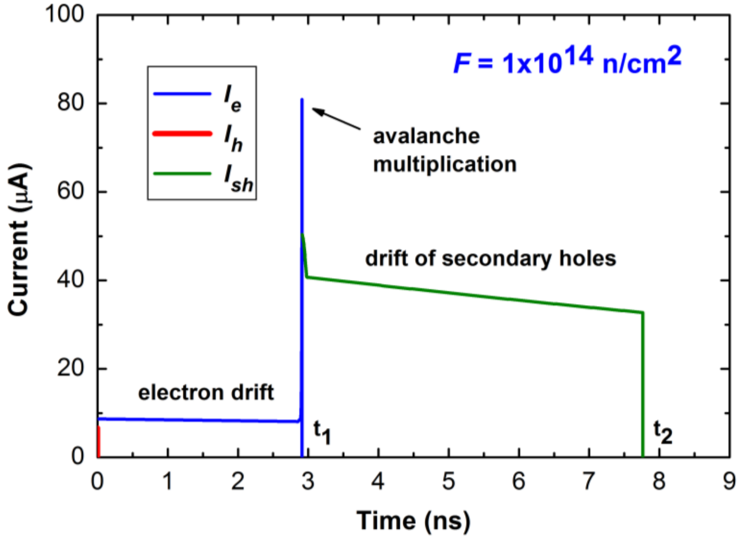
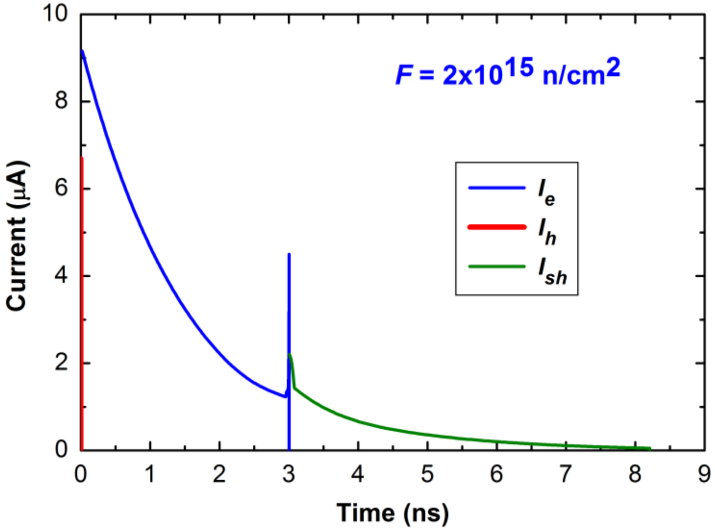
Pulse signal in irradiated LGADs

red laser pulse illuminating the back p^+ contact





***V* = 1000 V**

Y-scales differ in 10 times

primary holes - δ-shape pulse (collection on the p^+ contact), primary electrons drift to the p_{bi} layer

***I(t)* reflect the *E(x)* profiles** (see slides 9 and 11) **and carrier trapping**

1x10^{14} n/cm^2

- *E(x)* ~ uniform,
- L_{de} and L_{dh} ~ 0.3 and 0.2 cm >> *d*, trapping insignificant

$t_1 = d/v_{dr\_e} \sim 3$ *ns*;

$t_2 = d/v_{de} + d/v_{dh}$ ~8 ns

2x10^{15} n/cm^2

- *E(x)* decreases from the p^+ contact
- $\tau_{e,p} \sim F^{-1}$, trapping significant ➔
- significant decrease in the avalanche peak amplitude and I_{sh} – agrees with Q_{sh}↓

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Conclusions

1. The factors which affect reduction of the gain in irradiated LGAD:

♦ Reduction of carrier trapping time constants,

♦ Trapping-related internal negative feedback which leads to:
- redistribution of potential in LGAD bulk

➔ reduction of potential over the p_{bi} layer and formation of high electric field region near the back contact,

➔ reduction of *E* in a built-in p^+ layer.

2. Efficiency of the negative feedback increases with irradiation due to the defect accumulation and the potential redistribution.

3. Two negative effects which cause the gain degradation: the lowering of the electric field in the n^+-p_{bi} region, which reduces the multiplication probability, and the increase of the collection time and trapping-related charge losses.

Acknowledgments

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Thank you for attention!