Trapping-related negative feedback as the reason for collected charge restriction in heavily irradiated Si detectors operating with avalanche multiplication

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Outline

◆ Motivation

◆ PTI model of Q_c enhancement in irradiated Si detectors

◆ Restriction on collected charge arisen from negative feedback in irradiated Si detectors: comparison with “Quasi-APD”

◆ Stabilization of $E(x)$ in irradiated Si n-on-p strip detectors

◆ Gain in Q_c in detectors with various thickness

◆ Comparison with experimental data

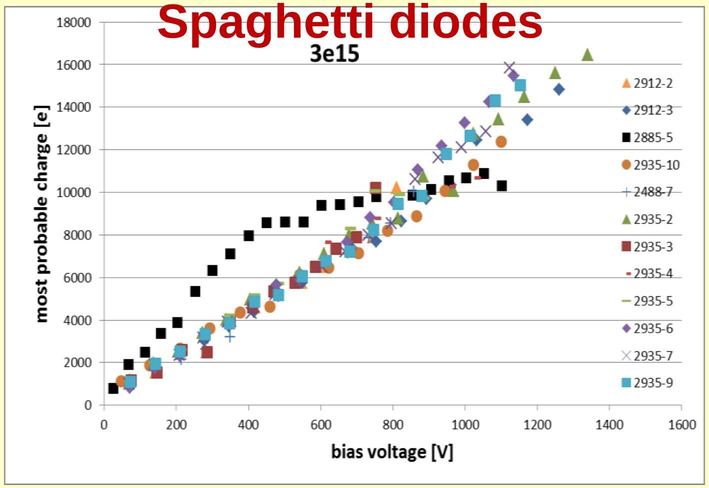
Conclusions

Motivation

Experimental results of RD50

Detector design:

strip n-on-p **Q_{cmax}/Q_{mip} 1.5 – 1.8;**
pad (Epi p-on-n) **6-9**
(e-h near the surface)


Spaghetti diodes

Almost no difference in charge collection efficiency for different implants

Extended fluence range

- up to 10^{17} n_{eq}/cm^2 (2013)
- stable operation

Our calculation

n-on-p, strip
Q_{cmax}/Q_{mip} 1.5 – 1.9
- as in the experiments

Relatively low!

Avalanche PhotoDiodes (APD)
High electric field + impact ionization -
E – hundreds kV/cm, **internal gain ~200**
(Hamamatzu) and even more

What is the origin of restriction on Q_c gain in heavily irradiated Si n-on-p strip detectors?

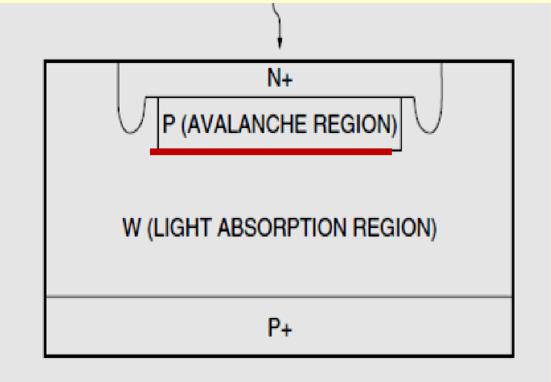
Origin of Q_c restriction: comparison with imaginary "APD"

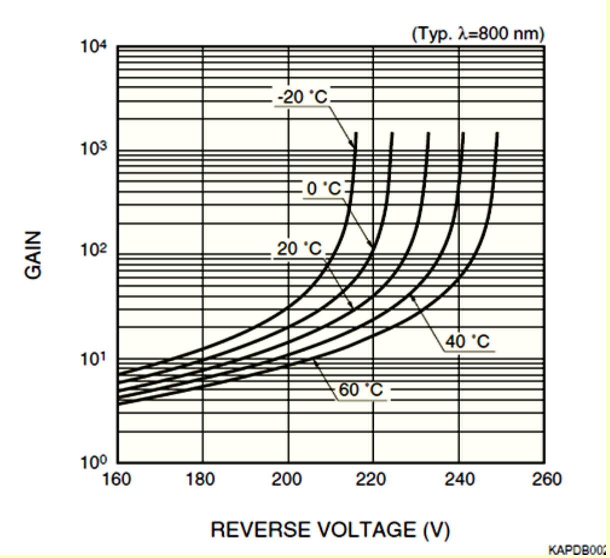
Hamamatsu APD

Read structures

I ~ 20 pA (∅ 1.5 mm)

E – hundreds kV/cm





Irradiated detector is compared with imaginary structure - "Quasi-APD":

- n-on-p strip diode
- *E*(*x*) as in heavily irradiated detector (high *V*)
- carrier avalanche multiplication

but

- no injection and trapping of holes
- τ_{tr} = 1 ms (no trapping of nonequilibrium carriers)

Q_c enhancement:

$K_{enh} = Q_{cmax}/Q_{mip}$

In n-on-p strip detectors **K_{enh} = 1.5-1.9** -

our calculation and experiment

Internal gain

$G = Q_{am}/Q_o$

Q_o - signal induced on the strip, calculated without avalanche multiplication

Q_{am} - signal measured or calculated in the same detector with avalanche multiplication

Goal

- Finding the **origin of restriction** on the collected charge enhancement (gain in collected charge) in heavily irradiated Si n-on-p strip detectors

by simulation *E(x)* and Q_c and comparison with Quasi-APD

- structure different from classic APD and LGAD

Results are published in:
E. Verbitskaya, et al., NIM A 730 (2013) 66

PTI model of Q_c enhancement due to avalanche multiplication in heavily irradiated n-on-p Si strip detectors

The PTI model considers:

- formation of Double Peak (DP) electric field profile – DP *E(x)*;
- focusing of the electric field and current near the collecting n^+ strips;
- avalanche hole generation near the n^+ strips, hole injection into the detector bulk, and hole trapping to radiation-induced deep levels defects

➔ give rise to the **negative feedback** which stabilizes the avalanche multiplication and total detector performance

V. Eremin, et al., *14 and 15 RD50 workshops, 2009, Freiburg and Geneva*
V. Eremin, E. Verbitskaya, A. Zabrodskii, Z. Li, J. Härkönen, *NIM A 658 (2011) 145*
E. Verbitskaya, V. Eremin, A. Zabrodskii, 2012, J. Instrum., v.7, 2, ArtNo: C02061;
doi: 10.1088/1748-0221/7/02/C02061
E. Verbitskaya, et al., NIM A 730 (2013) 66

PTI model of Q_c enhancement via avalanche multiplication and negative feedback

Equilibrium carriers			High bias voltage			Nonequilibrium carriers		
source/ origin	process	characteristic /result		process	characteristic /result	source/ origin	process	characteristic /result
Bulk generation current	**Trapping to DLs**	I_{bgen}; **steady-state DP $E(x)$**	Junction region with high E; focusing	Impact **ionization,** carrier **injection** into the bulk, **trapping** to DLs	I_{bgen} increase; Change of steady-state DP $E(x) \rightarrow$ ***E* reduction** near the junction	Generated by particles	**Trapping to DLs during drift in $E(x)$**	$\tau_{tr}(F)$; pulse response, Q_c **(CCE)**
				Trapping – related negative feedback				

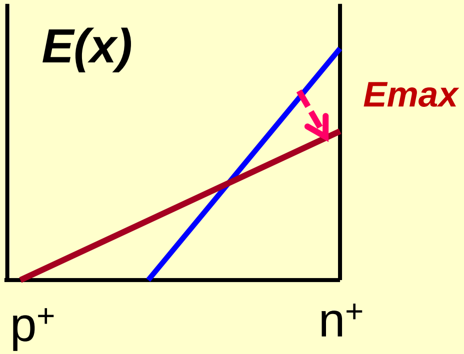
E. Verbitskaya,, et al., 23 RD50 workshop, Nov 13-15, 2013, CERN

E(x) changes via trapping-related negative feedback

Negative feedback in n-on-p detectors:

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

- reduction of $-N_{eff}$
- reduction of dE/dx and 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

Trapping-related or Space Charge Limited Current negative feedback

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Algorithm of E(x) and Q_c simulation

Processes considered:

- ✓ formation of a steady-state *E(x)* distribution:
  equilibrium carriers (bulk generation current) and avalanche generated carriers near n^+ strips, their trapping on radiation-induced DL defects;
- ✓ charge collection in the detector bulk with a calculated *E(x)* profile;
- ✓ e and h are generated by MIPs

Procedure and main parameters

- ♦ Poisson equation combined with the rate equation
- ♦ one-dimensional approach for detector geometry
- ♦ Effective deep levels: DA $E_c - 0.53$ eV; DD $E_v + 0.48$ eV
- ♦ $1/\tau_{e,h} = \beta_{e,h} F_{eq}$; $\beta_e = 3.2\text{x}10^{-16}$ cm^{2}ns^{-1}, $\beta_h = 3.5\text{x}10^{-16}$ cm^{2}ns^{-1}
- ♦ ionization rates $\alpha_{e,h} = A_{e,h} \exp(-B_{e,h}/E)$

  (*A* and *B* from *B. J. Baliga, Modern Power Devices, Hoboken, NJ; Wiley, 1987)*
- ♦ **numerical calculation**

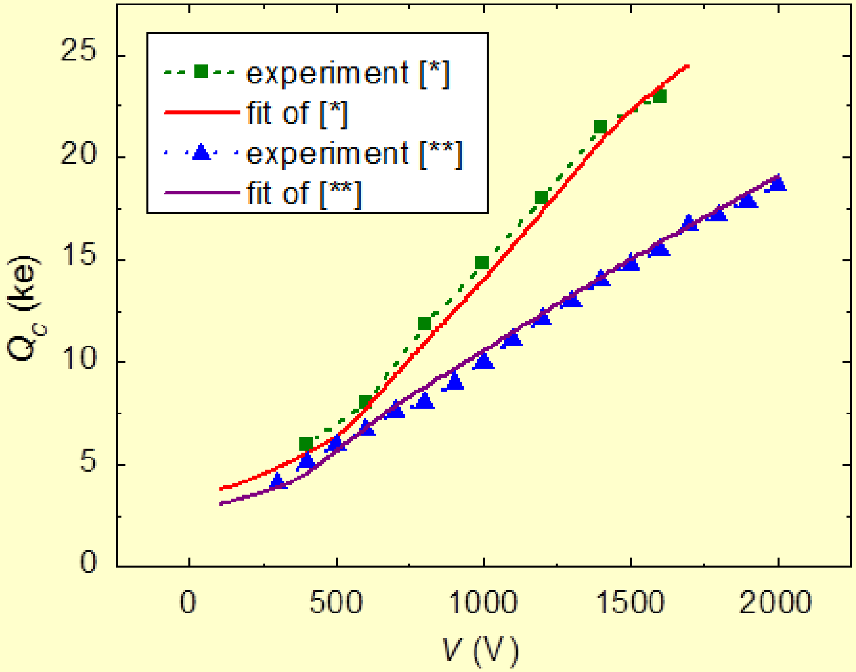
Simulation of Q_c enhancement

Variable parameters

♦ detector bias voltage ***V***,
♦ temperature ***T*** in the LHC range,
♦ irradiation fluence ***F***,
♦ strip detector **geometry** (strip width, detector thickness)

Starting point for simulation –

fit to the curve [*] with maximal Q_c:
$F = 3\text{x}10^{15}\ n_{eq}/\text{cm}^2$, T = -20C



* *I. Mandić, et al., NIM A 612 (2010) 474)*
** *G. Casse, Recent developments in silicon detectors, 13th VCI, Feb 11-15, 2013 Vienna; http:// vci.hephy.at*

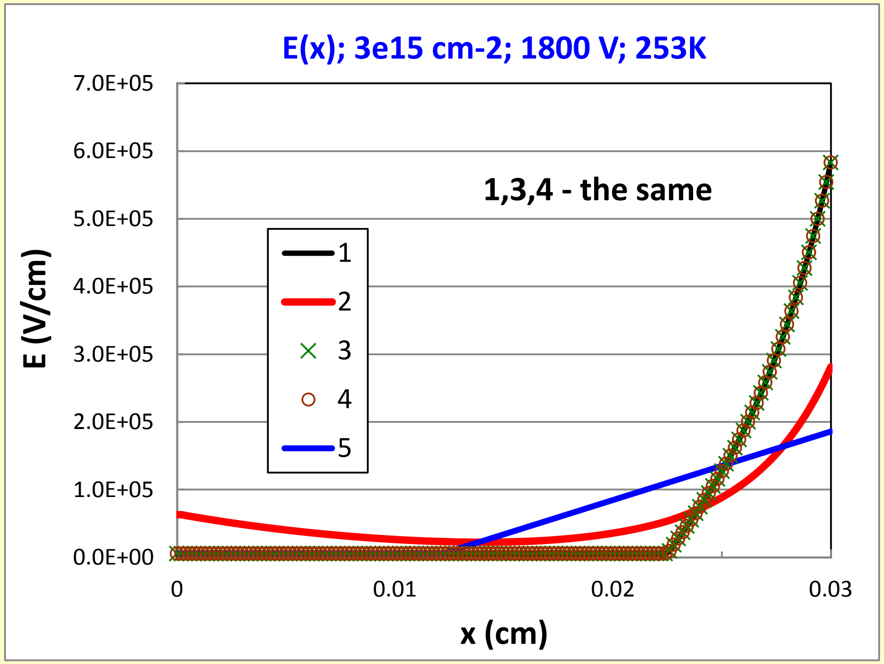
Options for E(x) and Q_c simulations

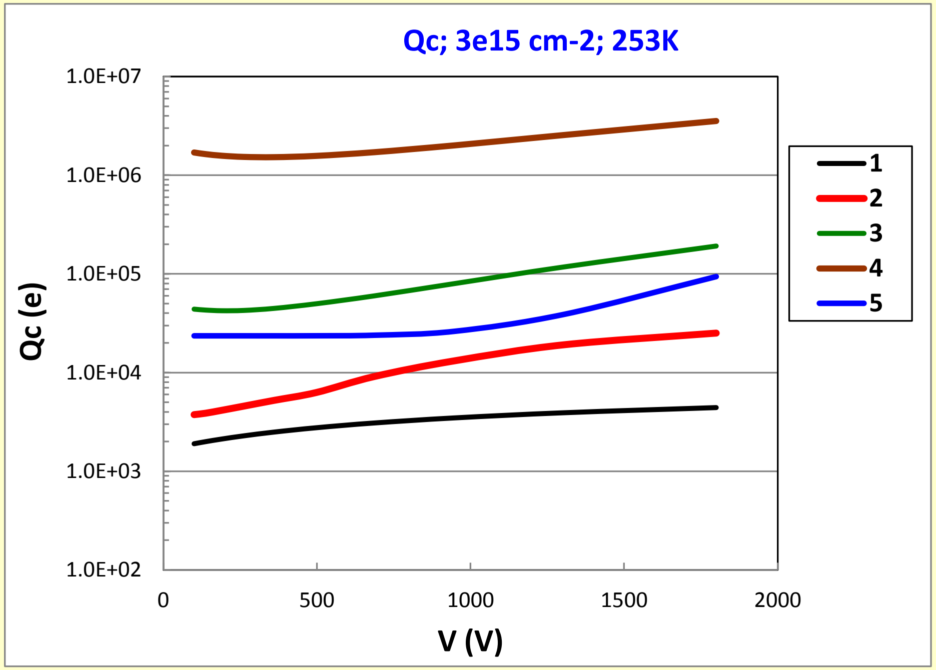
		K_{aval}	K_{inj}	m_j	τ_{tr}
#	**Possible values**	**1/0**	**1/0**	**$1/1\text{x}10^{-4}$**	**$\tau_{tr}(F)$/1 ms**
1	**Detector, no multiplication**	**0**	**1/0**	**1**	**$\tau_{tr}(F)$**
2	**Detector, with multiplication**	**1**	**1**	**1**	**$\tau_{tr}(F)$**
3	**Detector, with multiplication, NO feedback**	**1**	**0**	**1**	**$\tau_{tr}(F)$**
4	**Quasi-APD 1**	**1**	**0**	**1**	**1 ms**
5	**Quasi-APD 2**	**1**	**0**	**$1\text{x}10^{-4}$**	**1 ms**

K_{aval} – avalanche multiplication
K_{inj} - injection of avalanche generated holes
m_j - current generation rate

Allows differentiation between impact of different factors - *E(x)* profile, current generation rate, trapping

Comparative results on E(x), Q_c and G





		Gain at 1800 V
1	**Detector, no multiplication**	**1**
2	**Detector, with multiplication**	**5.7**
3	**Detector, with multiplication,** **no feedback**	**43**
4	**Quasi-APD 1**	**800**
5	**Quasi-APD 2**	**21**

n-on-p strip detector; *d* = 300 μm; pitch/strip width 80/20 (μm)
F **= 3x10^{15} n$_{eq}$/cm^2**

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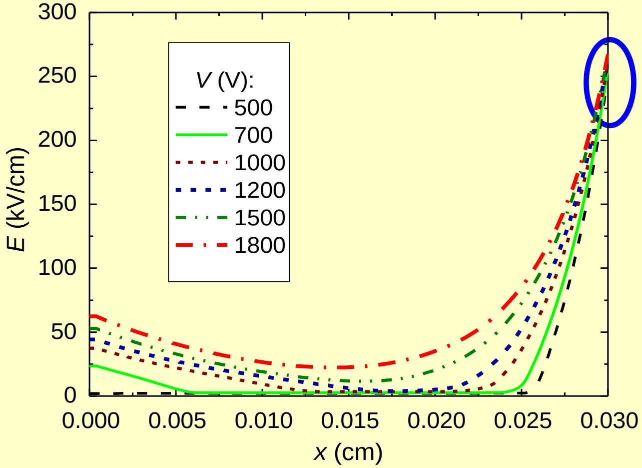
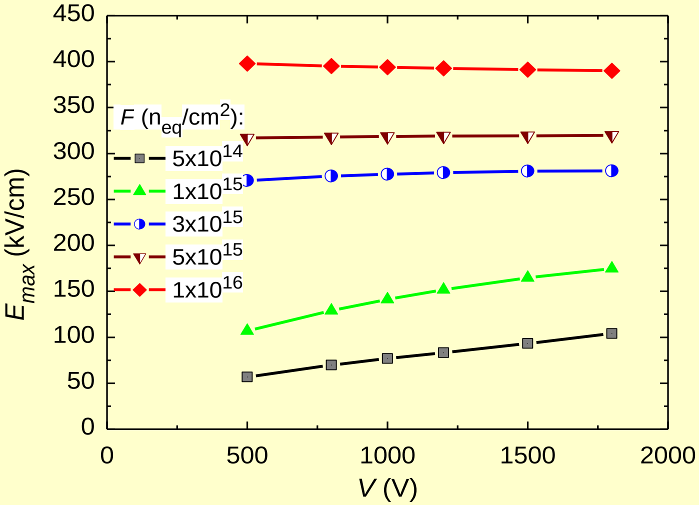
E(x) stabilization at different V and F due to negative feedback

$F = 3x10^{15}\ n_{eq}/cm^2$

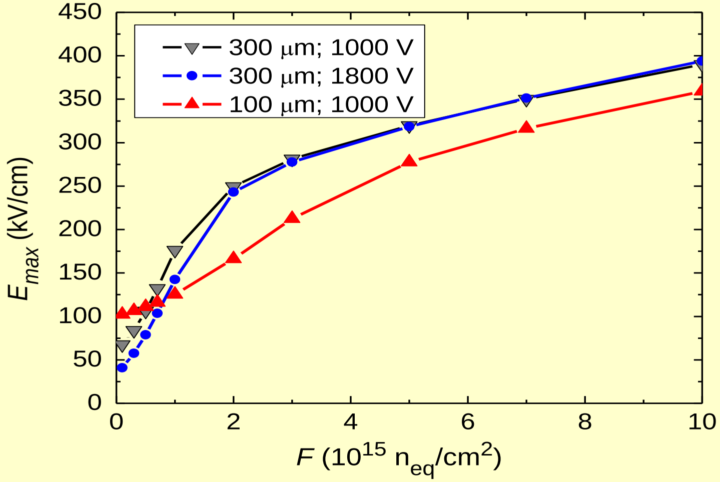


- DP *E(x)* in avalanche multiplication mode
- E_{max} at n^+ strip is stable
- E_{max} stability reduces sensitivity of Q_c to the design of the region with high *E (shown in the experiments e.g. with spaghetti diodes).*

Stabilization of E_{max} at n^+ strips



At $F > 1x10^{15}\ cm^{-2}$ E_{max} is insensitive to *V*



At $F > 5x10^{15}\ cm^{-2}$ the difference in E_{max} in 300 μm and 100 μm detectors is not essential at fixed *V*

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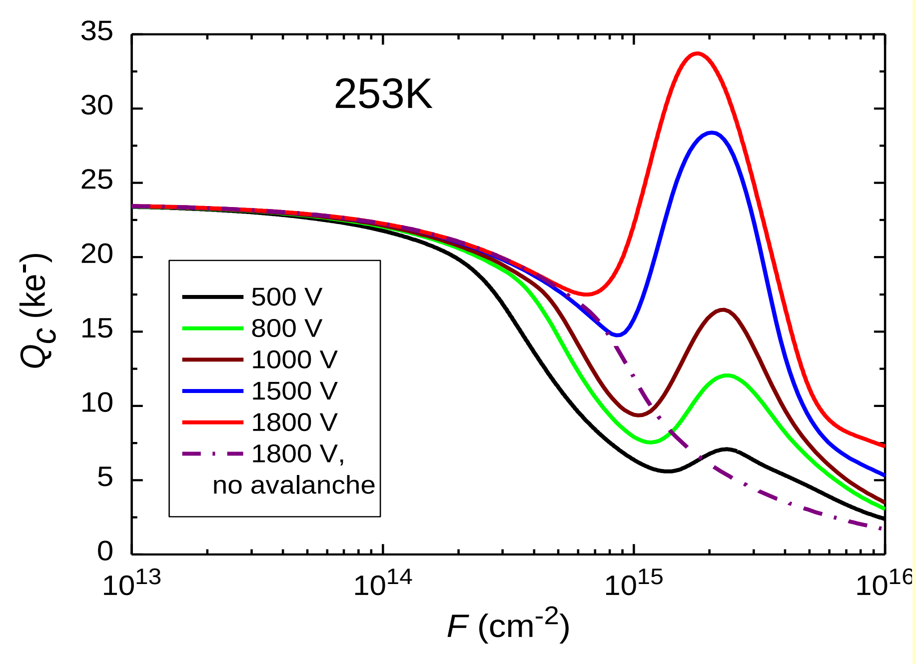
$Q_c(F)$ dependence in n-on-p strip detectors



E. Verbitskaya, et al.,, 2012, J. Instrum., v.7, 2 # C02061

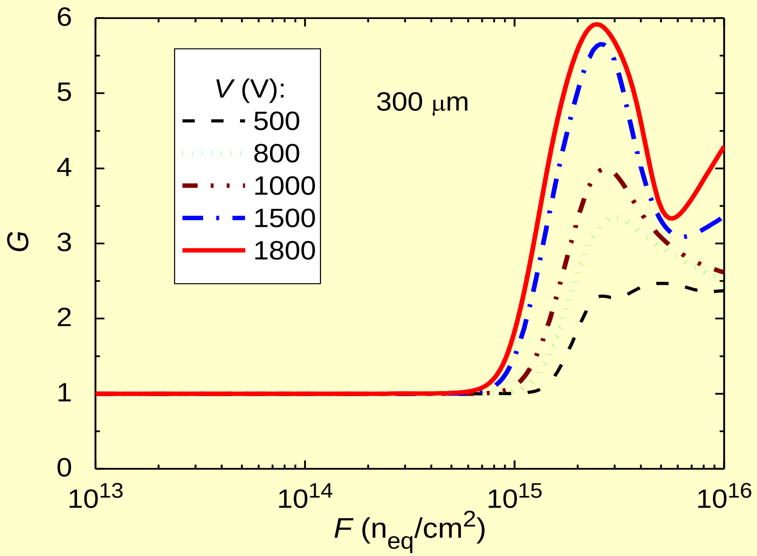
- Q_c enhancement starts at ~500 V - DP $E(x)$ (d = 300 μm)
- $Q_c(F)$ is nonmonotonous and shows a **bump**
- Q_c in bump is larger than Q_{mip}

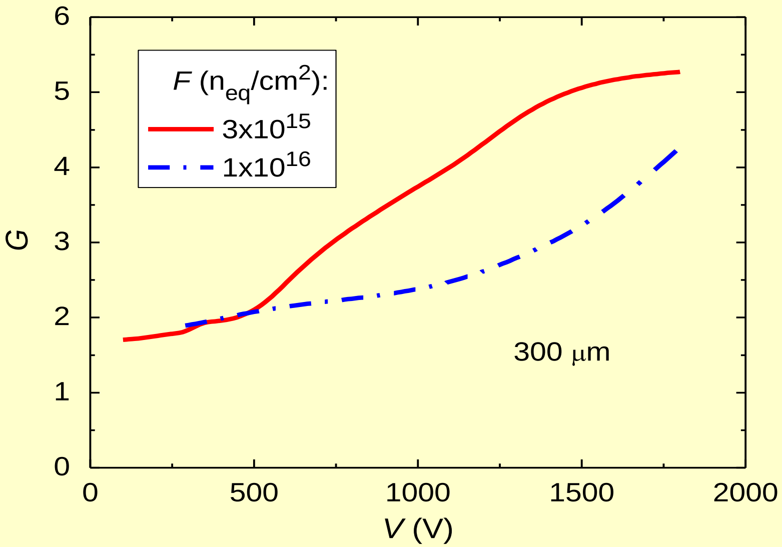
$K_{enh} = Q_{cmax}/Q_{mip}$

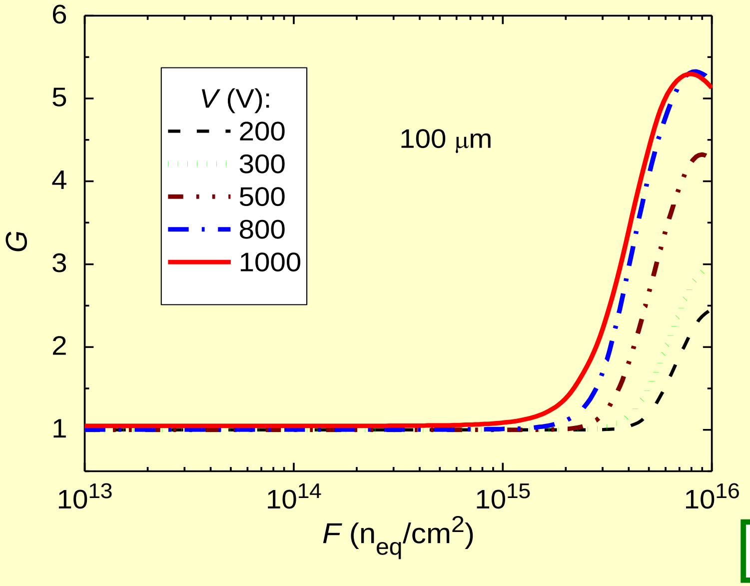
= **1.4** - 300 μm
1.9 - 100 μm

- agrees with experiment

Gain in strip detectors with various thickness







- Similar *G* in 300 μm and 100 μm detectors at highest *V*
- Maximum *G* is shifted to higher *F* in 100 μm detectors

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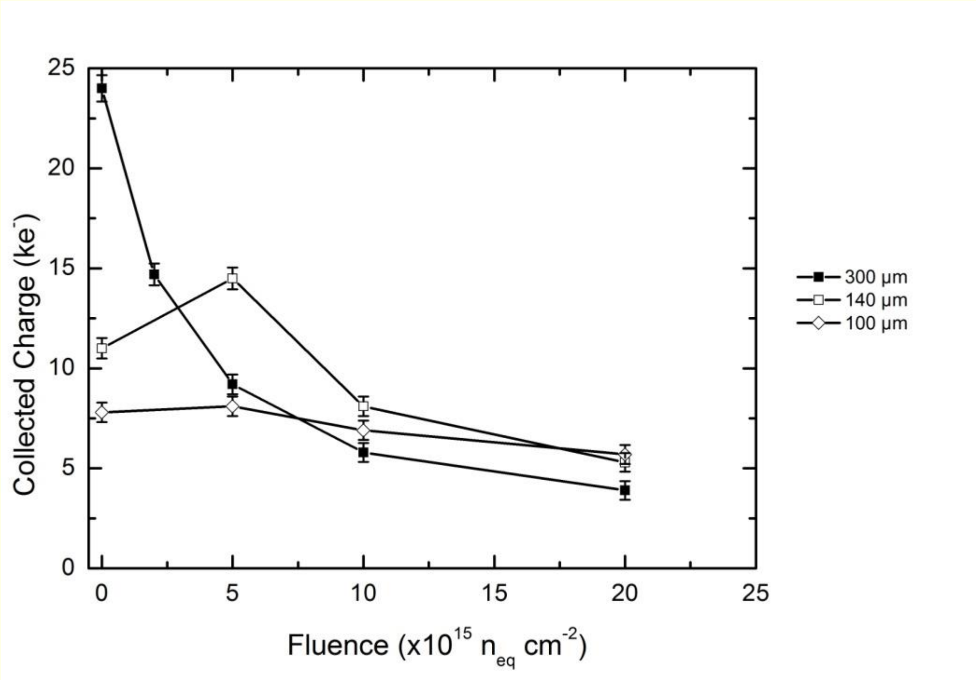
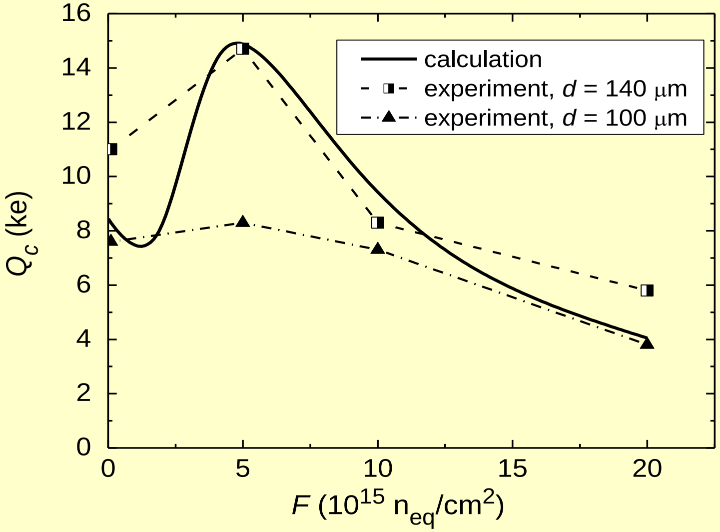
Comparison with experimental results



G. Casse,20th RD50 Workshop, Bari, 31/05-02/06 2012

Calculated $Q_c(F)$ with a bump correlates to the experiment for thin detectors



E. Verbitskaya,, et al., 23 RD50 workshop, Nov 13-15, 2013, CERN

Conclusions

- Internal gain in collected charge due to avalanche multiplication is strongly suppressed and simultaneously stabilized by the trapping-related negative feedback which is a specific of detectors with high concentration of deep levels.
- The gain is in the range 1-6 for both standard and thin detectors, which defines the limit for the signal enhancement and operational fluence range.
- Trapping-related negative feedback makes the gain practically insensitive to the design of the detector high field region

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Thank you for attention!