Current generation in heavily irradiated Si detectors: mechanisms of the current saturation at HL-LHC fluences

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Motivation

Were simulated

- $E(x)$, $N_{eff}(x)$, V_{fd}
- $n(x)$, $p(x)$
- Detector signal (current response, collected charge)
- Impact ionization/signal multiplication
- Detector current?

Experiment: $I/\mathbf{Vol} = \alpha\Phi_{eq}$ $\Phi \leq 10^{15}\ n_{eq}/cm^2$

Speaks in favor of thermal generation

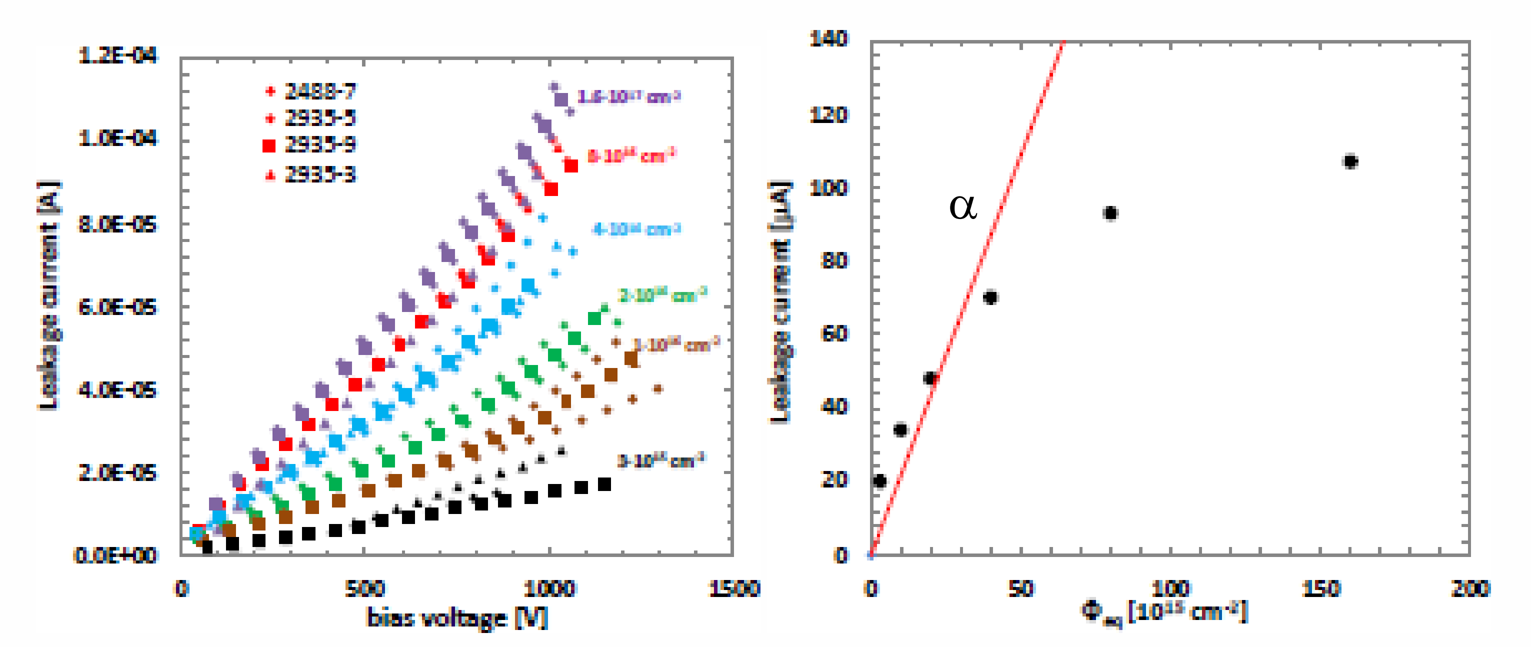
What we know about the detector current at very high Φ?

When $E(x)$ is vastly nonuniform

Recent experimental results of RD50

Experimental data
G. Kramberger, et al., 2013 JINST 8 P08004

Si n-on-p “spaghetti” detectors
V = 1000 V; T = -23°C
Neutron irradiation up to $\underline{1.6\times10^{17}}$ n/cm^2



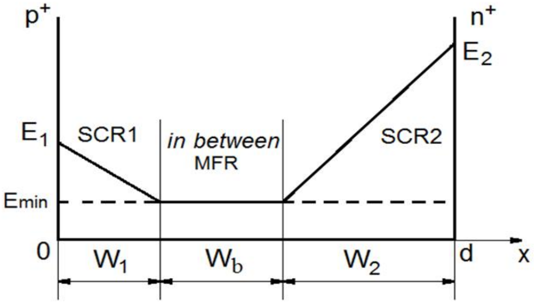
Tendency to saturation of the current!

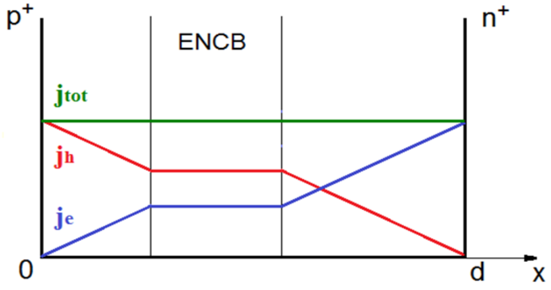
E. Verbitskaya, et al., 31 RD50 Workshop, CERN, Geneva, Nov 20-22, 2017

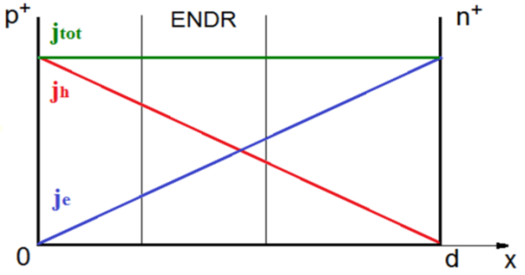
Double Peak E(x) distribution

Si p-on-n detectors,
Φ beyond SCSI

V. Eremin, et al., NIM A 476 (2002) 556







DP E(x) profile; In-between region with low E: terms

- E. Verbitskaya, et al., NIM A 624 (2010) 419 - **active base,** impact of neutral base region on the collected charge;
- G. Kramberger, 2014 JINST 9 P10016: **electrically neutral bulk ENB, depth**

In this study: new term:

MFR – Minimum Field Region: it can be

Electrically Neutral Conductive Base (ENCB),

or

Electrically Neutral Depleted Region (ENDR) with a zero N_{eff}

- **Different mechanisms and contribution to the total detector current?**

Goal

- ✓ **To find impact of the active base region on the current of heavily irradiated Si detectors**
- ✓ **Explain reduction of the current rise at $\Phi > 10^{15}\ n_{eq}/cm^2$**

Results are published in:

V. Eremin, N. Fadeeva, E. Verbitskaya, The impact of active base on the bulk current in silicon heavily irradiated detectors, 2017 *JINST* **12** P09005

Physical background for simulation

Evolution of: **E(x) distribution vs. Φ (was earlier)** **+** **Current densities j_e, j_h, j_{tot} vs. Φ (new)**

- ✓ Poisson equation: E(x)
- ✓ Continuity equations: profiles of current density j_e, j_h, j_{tot} vs. x
- ✓ Current: thermal generation + diffusion + ionization
- ✓ j_{gen}: Shockley-Read-Hall theory
- ✓ Radiation damage: described via two effective energy levels of radiation-induced defects:
  DD E_v + 0.47 eV, DA E_c - 0.52 eV
- ✓ Impact ionization at n-n^+ junction:
  ionization rates $\alpha_{e,h} = A_{e,h} exp(-B_{e,h}/E)$

Detector bulk current density

$$j_{tot} = \frac{qn_iW}{\tau_{gen}} + \frac{qD_hp_n}{L_h}$$

High V: $j_{gen} + j_{dif} + j_{ion}$

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Detector structure and simulation

p-on-n pad detector; resistivity $\rho = 2$ kΩcm
thickness 300 μm
T = -10 °C

Irradiation: 1 MeV neutrons, $\Phi \leq 5\times10^{16}$ cm^{-2}

Simulation is built on:

♦ numerical schemes to solve the drift-diffusion equations,

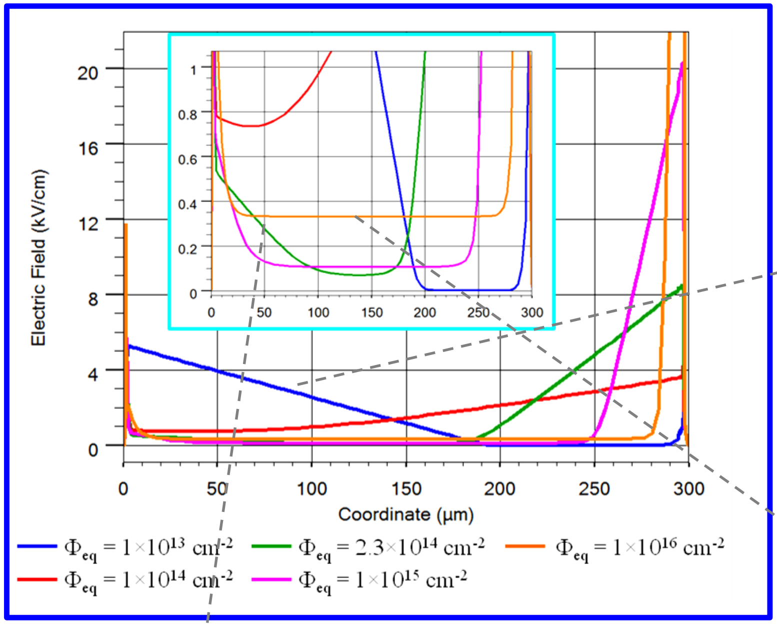
♦ basic equations implemented and solved via iteration procedure

♦ Selberherr model of impact ionization

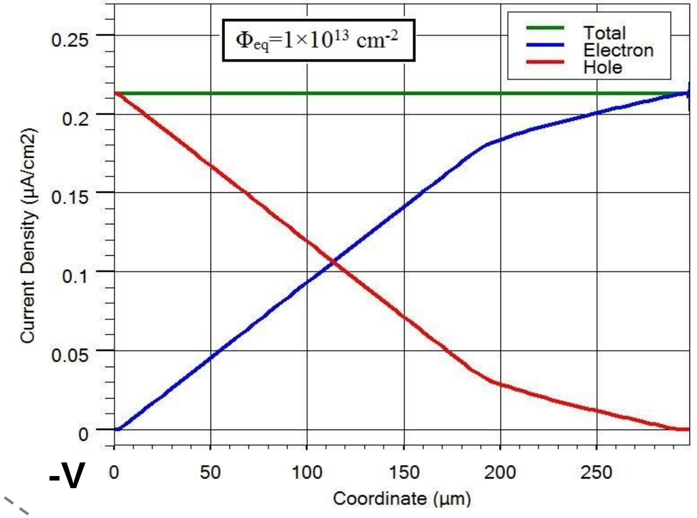
♦ simulation program in the C++ language

Evolution of E(x) and j(x) profiles vs. F

V = 50 V



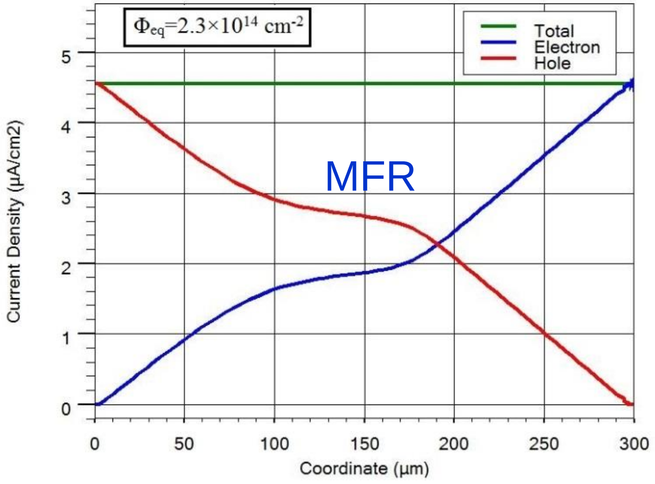
Φ_1



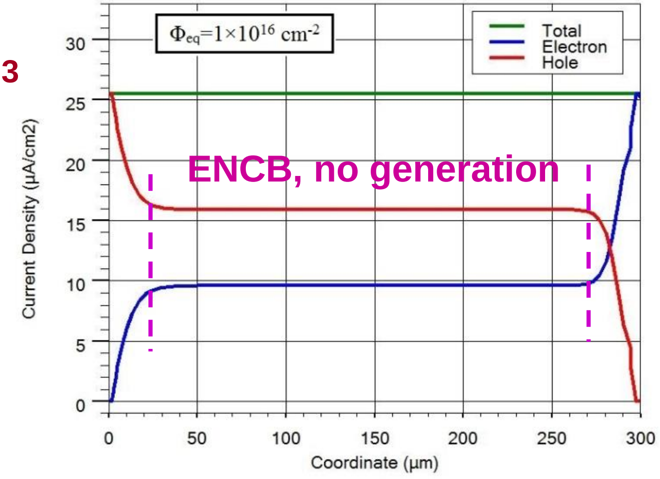
At $\Phi\uparrow$

j_{dif} at the border of SCRs and MFR

Φ_2



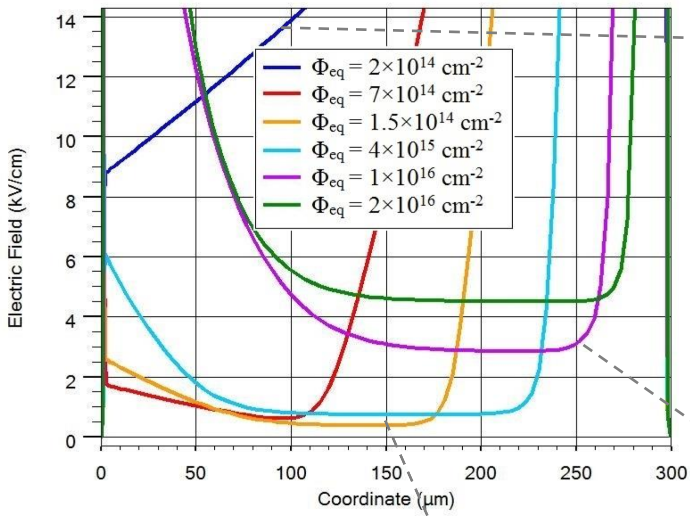
Φ_3

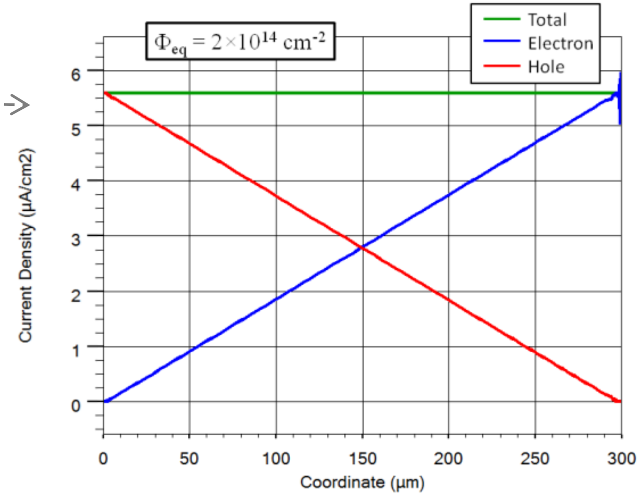


Evolution of E(x) and j(x) profiles vs. F

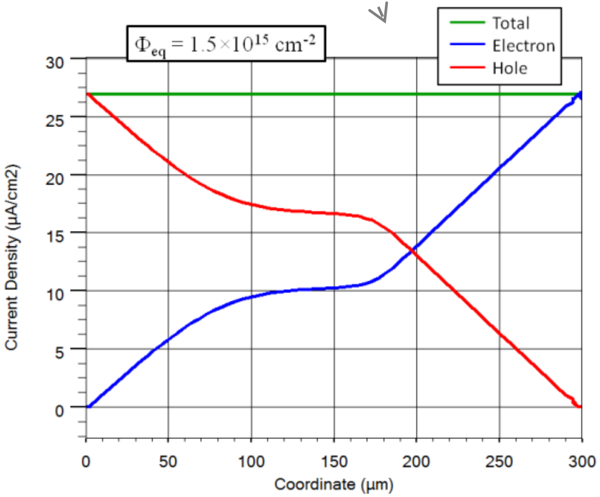
V = 500 V

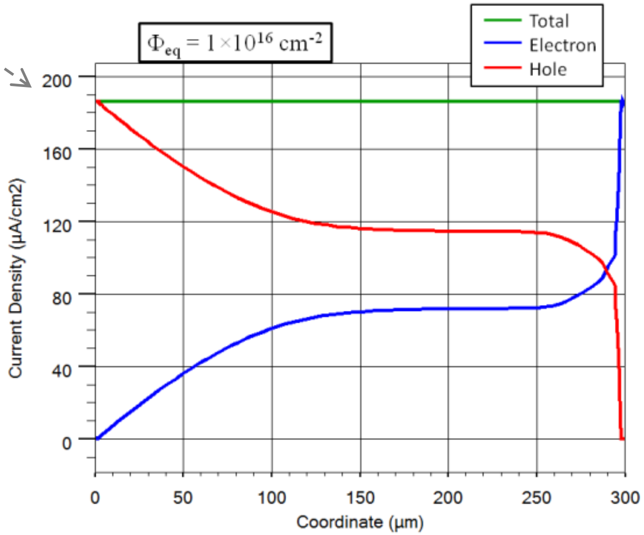
Fragment, E(x) in MFR





E$_{min}$ changes nonmonotonically

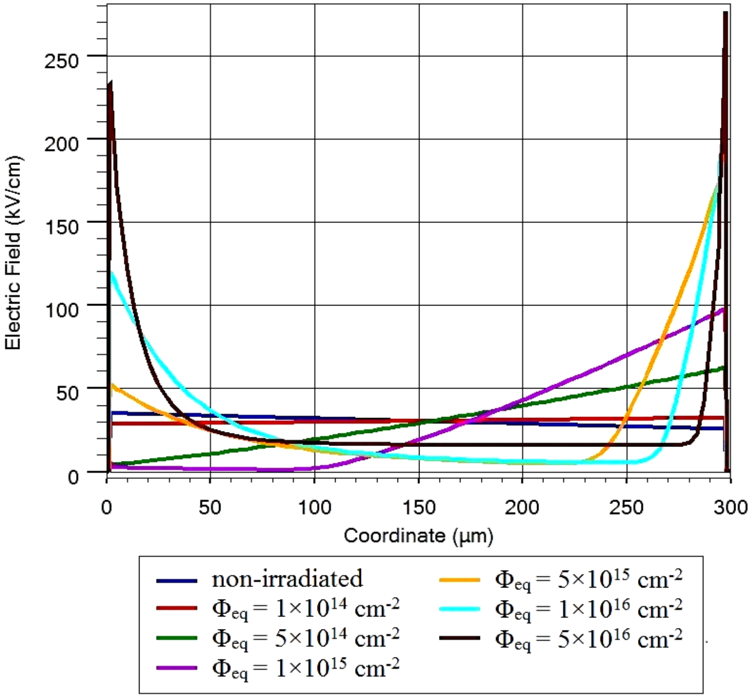




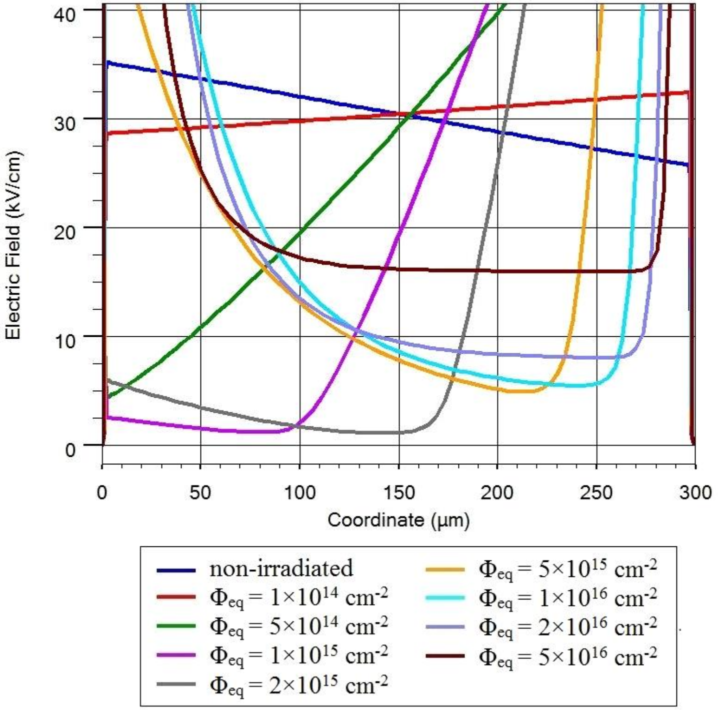
Φ = 4×1015: MFR converts to ENCB and keeps this type up to 2×10^{16}

Evolution of E(x) vs. F

V = 900 V



Fragment, E(x) in MFR

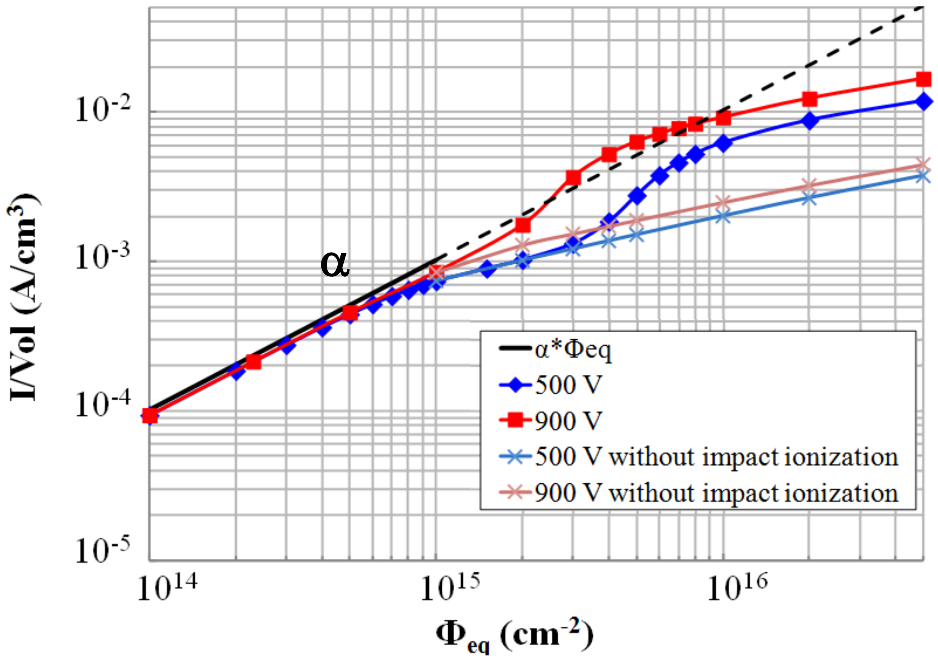


~1×10^{14} cm^{-2} – SCSI
(purple curve)

1×10^{15} cm^{-2} - DP E(x)
(violet curve)

At fixed Φ ENCB width goes down
with the bias increase
while at fixed V its width increases with Φ

Dependence of the bulk current on fluence



$\Phi \leq 1\times10^{15}\ n_{eq}/cm^2$

$$\frac{I}{Vol} = \alpha \cdot \Phi_{eq}$$

$\alpha = 1.03\times10^{-18}$ A/cm (-10°C) (black)

- ✓ Agreement with α:
  500 V: $\leq 6\times10^{14}$
  900 V: $\leq 1\times10^{15}$
- ✓ At higher Φ – appearance of ENCB
- ✓ Step – impact ionization

At high Φ even with impact ionization the rate of the current rise is lower than α

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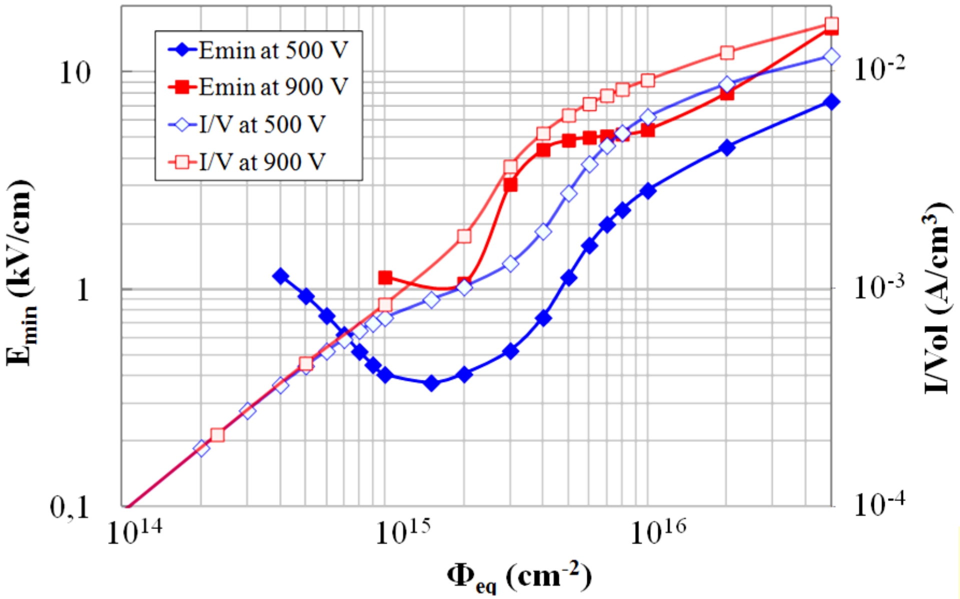
Correlation between the detector current and electric field E_{min} in MFR



500 V: $E_{min}(F)$ dependence is strongly nonmonotonic:
In DP E(x) non-zero MFR appears at 4×10^{14} cm^{-2}; then E_{min} ↓ and ↑ as evolution of MFR → transformation from ENDR into ENCB

900 V: monotonic dependence:
In DP E(x) MFR arises at 1×10^{15} cm^{-2} and increases;
$(4\text{-}10)\times10^{15}$ cm^{-2} – dE/dx reduction (impact ionization), E_{min} rises slowlier:
$\Phi > 1\times10^{16}$ cm^{-2} - E_{min} rises

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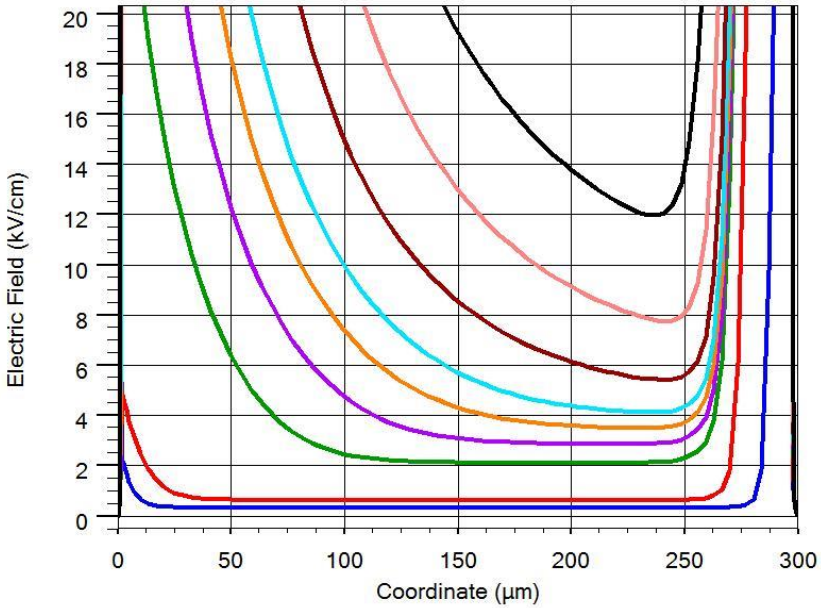
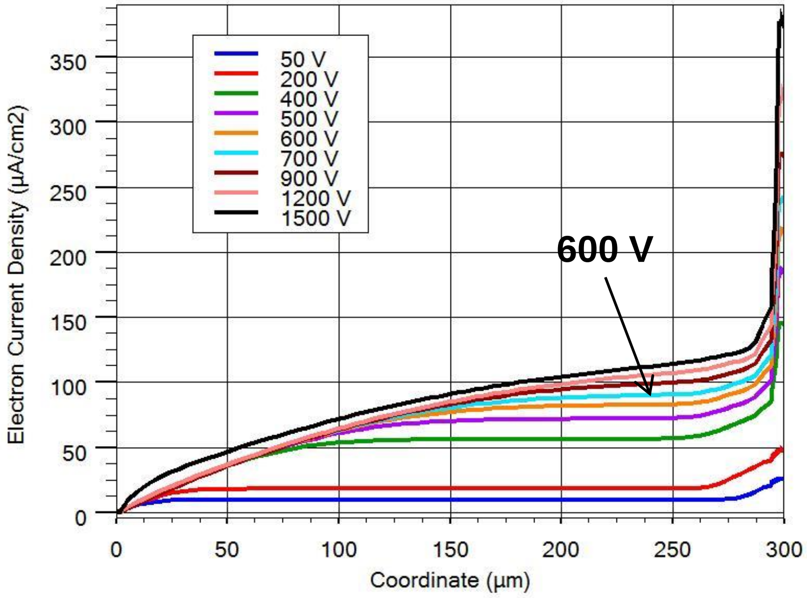
Evolution of profiles of E(x) in MFR and $j_e(x)$ vs. V at $F = 1\times10^{16}$ cm^{-2}



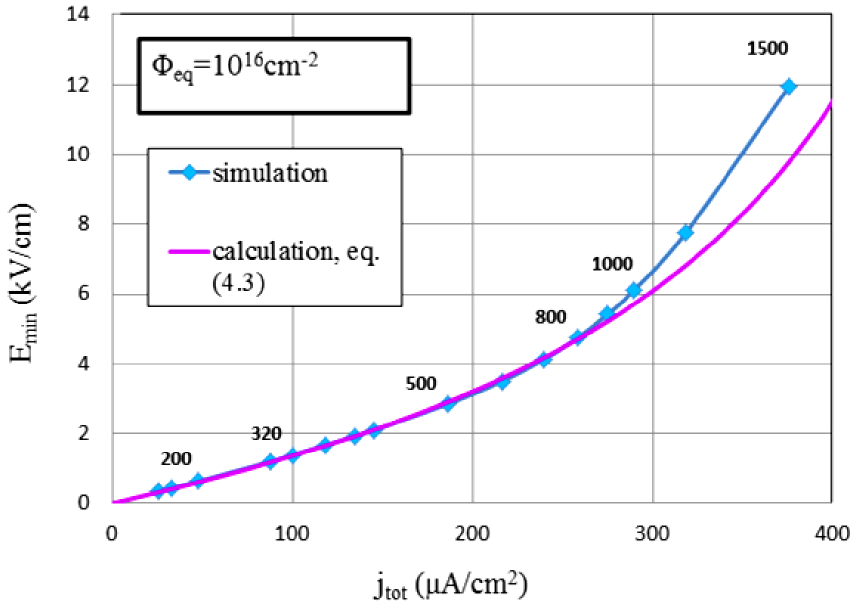


Colors in E(x) curves are the same as in j_e(x)

$j_{tot} = j_e$ at x = 300 µm

- ✓ Extended ENCB at 50-600 V;
- ✓ Violation at 600 V, j_e increases with coordinate: part of ENCB → transforms to ENDR;
- ✓ At V ↑ - collapse of base region, j_{tot} increases

Dependence of E_{min} on j_{tot}: 1×10^{16} cm^{-2}



Red curve: calculation

$E_{min} = \rho \times j_{tot}$ **Ohm's law**

$$\rho = \frac{1}{q(\mu_e + \mu_h)n_i}$$

Blue curve: E_{min} at V = 50-1500 V (along the curve) derived from the simulated profiles (slide 13) vs. simulated values of the total current density

Good agreement with Ohm's law at $V \leq 600$ V, MFR does not contribute to j_{tot}

Rather good agreement: 600-900 V where MFR gradually transforms from ENCB to ENDR

V → 1500 V: superlinear increase of E_{min} after a total collapse of the active base at $V > 900$ V, at the same j_{tot} simulated E_{min} are higher → change of the mechanism responsible for E(x) from Ohm's law to the mechanism described by the electrostatic equations

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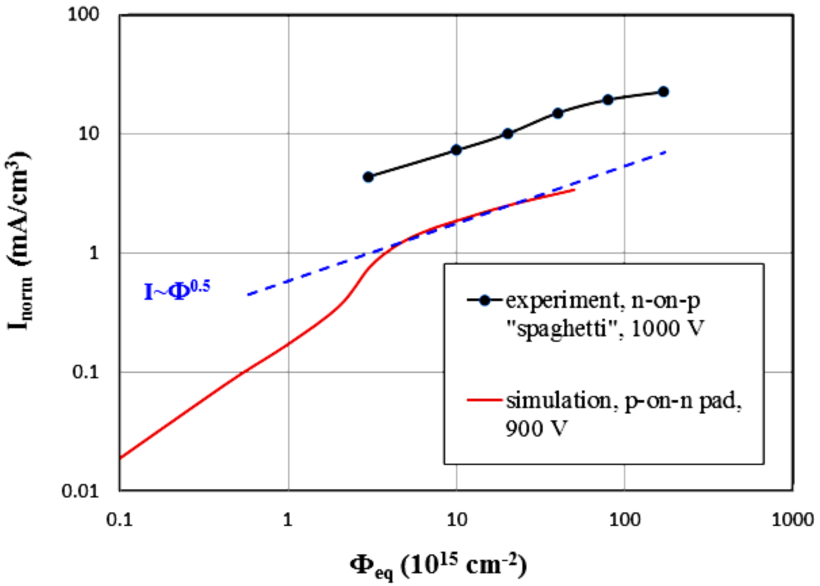
Comparison between simulated and experimental detector current: new dependence on Φ

Data on normalized current recalculated to -23°C



Similar shape while the experimental values are about four times larger – different topology

At $F > 2\times10^{15}$ cm^{-2} both curves show

$$I_{norm} = \beta\Phi^{0.5}$$

This conversion takes place when impact ionization starts to evolve; nevertheless total current drops below the generation current

Mechanisms which can restrict the current rise with fluence:

- ✓ operation of MFR as ENCB;
- ✓ recombination lifetime drop to less than a ns;
- ✓ negative feedback leading to redistribution of potential and E(x) in the bulk relevant to heavily irradiated detectors operated with impact ionization

Summary

1. Minimum Field Region can act as ENCB whose contribution to the detector current is governed by diffusion, and/or ENDR contributing to the current via carrier thermal generation.

2. MFR type depends on the applied bias voltage and irradiation fluence.

3**. At F ≥2×10^{15} cm^{-2} the linear dependence of the current on fluence converts to the square-root dependence restricting the current.**

4. Tendency to current saturation at very high fluences is caused by:
  - functioning of MFR as ENCB,
  - extremely low carrier lifetime,
  - stabilization of E_{max} via negative feedback, which takes place despite the fluence rise and irrespective of the detector type and geometry.

5. In practice, a sublinear current increase is advantageous for the silicon detector operation at very high fluences since it restricts the current and power dissipation and improves signal to noise ratio.

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Acknowledgments

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Thank you for attention!