Analysis of I-V characteristics as a method in the study of radiation degradation of Si detectors

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Radiation field expected for Si detectors in HL-LHC

ATLAS inner tracker at HL-LHC: $F_{max} = 2\times10^{16}\ n_{eq}/cm^2$

Radiation-induced defects: point and clusters

In degradation of Si detectors placed close to the interaction points (pixels, short strips)
contribution of defect clusters will dominate !!

Object: local heavily damaged region induced by short-range ions

→ dominating of clusters in the local region with known depth

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Goal

- analysis of I-V characteristics to obtain parameters control the bulk generation current

Will be presented**:**

- the algorithm of I-V characteristic analysis,
- the profile of the current generation rate and related parameters

Experimental

Samples

- Pad **p^+-n-n^+**
- n-type CZ Si, ρ ~**60 Ωcm,** 300 μm thick, S = 0.23 cm^{-2}

Irradiation:

- Ioffe Institute cyclotron
- 53.4 MeV **^{40}Ar** ions, RT
- Ion range 15 μm
- fluence: F1=1×10^9, F2=2×10^9, F3=4×10^9 ion/cm^2
- dose rate 2×10^7 $cm^{-2}s^{-1}$

Measurements:

- I-V characteristics
- C-V characteristics

Simulation:

TRIM

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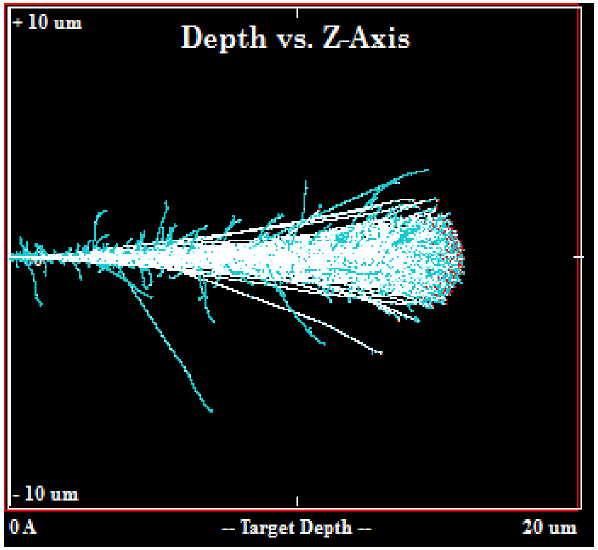
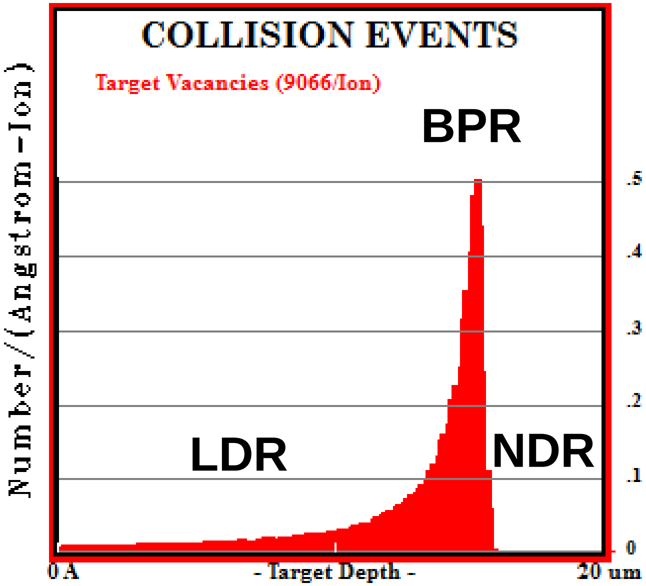
Simulations of collision events induced by ^{40}Ar ion irradiation



5000 ^{40}Ar ions
range 15 μm



Collision cascade

Profile of primary defect (vacancies) concentration $N_v(x)$ along the track

- $N_v(x)$ has a shape with a Bragg peak at the track end
- N_v maximum is at x = 15.2 μm, FWHM ~1 μm independent on F
- Within the BP (*x* = 13-15 μm), $N_v(x)$ is up to 100 times higher than at the beginning of the track

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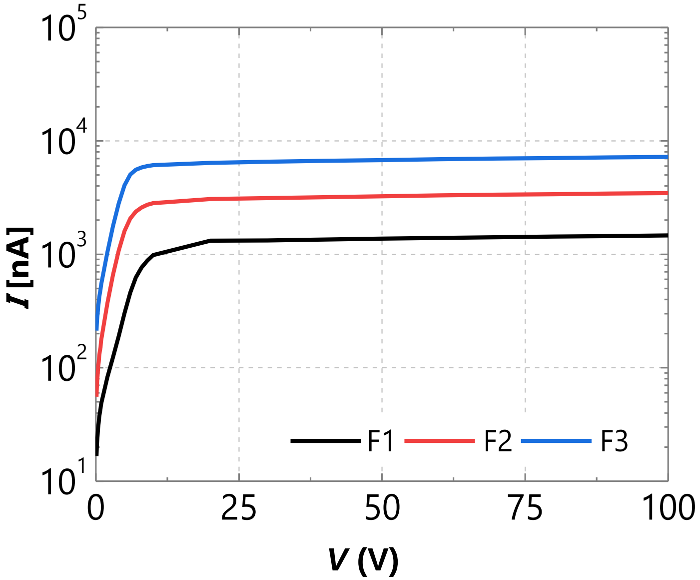
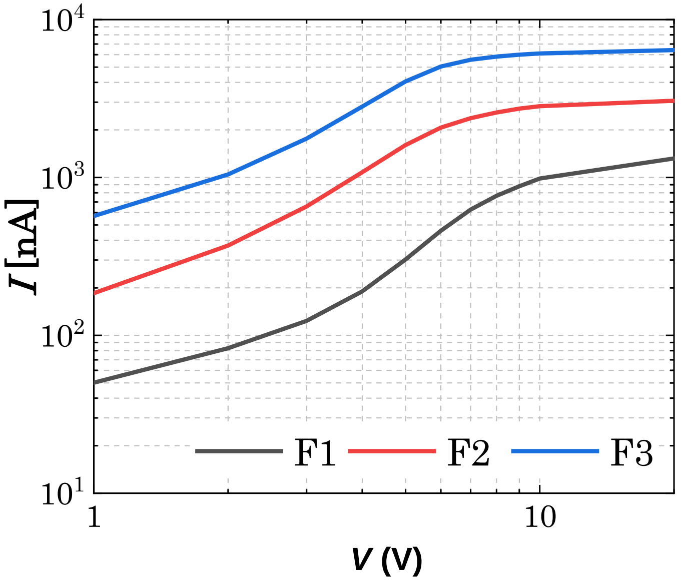
Experimental results: I-V characteristics





Fragment: V = 0-20 V

Three regions:

- ✓ a moderate rate of current rise (~0-3 V), Low Damaged Region (**LDR**)
- ✓ a higher rate, Bragg Peak Region (**BPR**) **- ??**
- ✓ slow rise, Non-Damaged Region (**NDR**), insignificant current increase (random leakage?)

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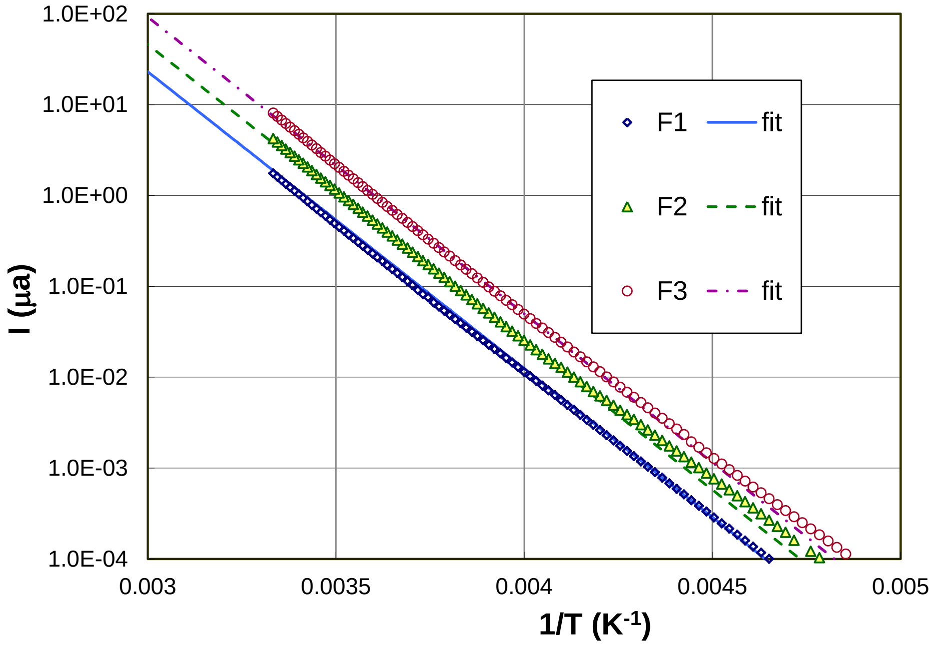
Experimental results:
I-T characteristics



Shockley-Read-Hall statistics

Carrier generation rate

$$U = \frac{n_i}{\tau_h exp\left(\frac{E_i - E_t}{kT}\right) + \tau_e exp\left(\frac{E_t - E_i}{kT}\right)}$$

$$\tau_{e,h} = (\sigma_{e,h} v_{th} N_t)^{-1}$$

Linear fit "Single level"

$$I_{gen} = eUWS = \frac{ev_{th}\sigma N_t WS\sqrt{N_c N_v}}{exp(E_{gen}/kT)}$$

Linear fit gives:

E_{gen} = 0.65 eV > Eg/2 = 0.56eV

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Algorithm of I-V characteristic analysis

1. Calculation of space charge region (SCR) width **W** from C-V characteristics
2. Transition from I-V characteristics to **I-W** characteristics
3. Calculation of the current generation rate profile

   $\mathbf{G(x=W) = dI_{gen}/dW}$
4. Calculation of I-V characteristics using TRIM data and their comparison with experimental I-V curves
5. Estimation of related parameters

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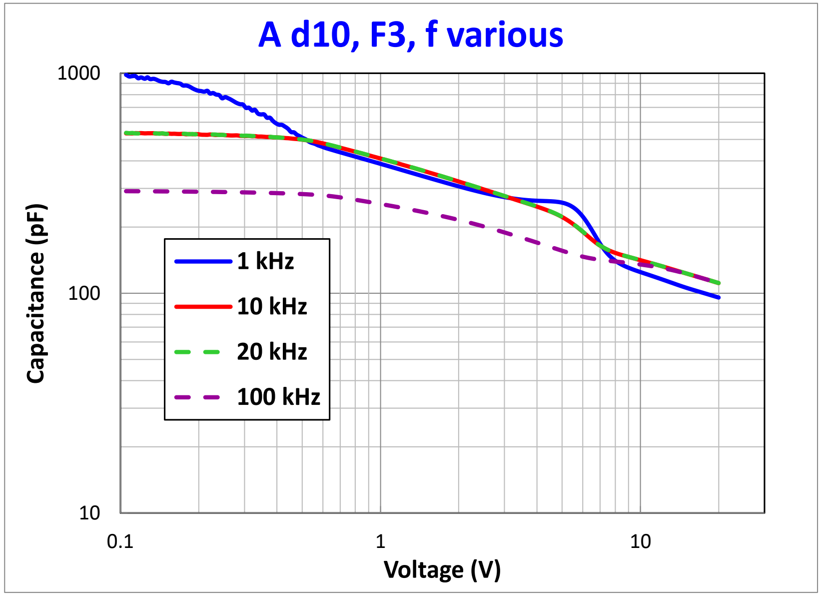
1. Determination of SCR width W from C-V characteristics

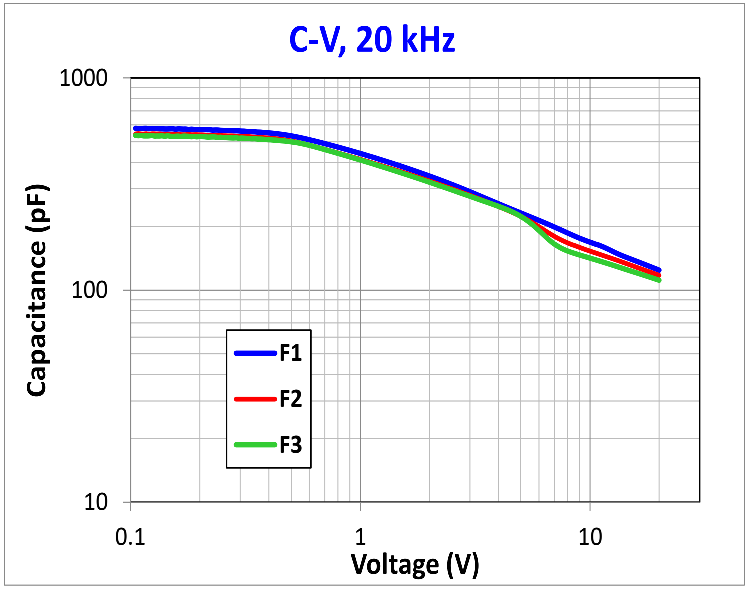
N_{eff} is nonuniform and unknown

$$C = \frac{\varepsilon\varepsilon_0 S}{W}$$

In irradiated Si P-n junctions capacitance depends on the frequency f

Z. Li and H.W. Kraner, IEEE Trans. Nucl.Sci. 38 (1991) 244
E. Borchi, et al., Solid-State Electron. 42 (1998) 2093

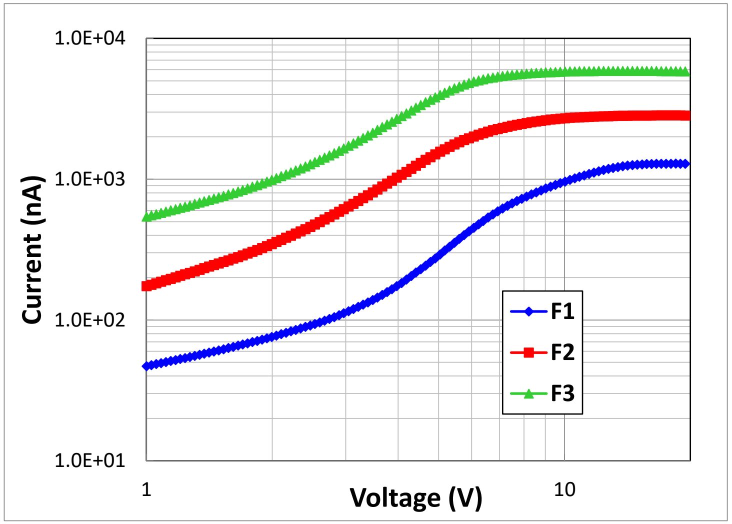




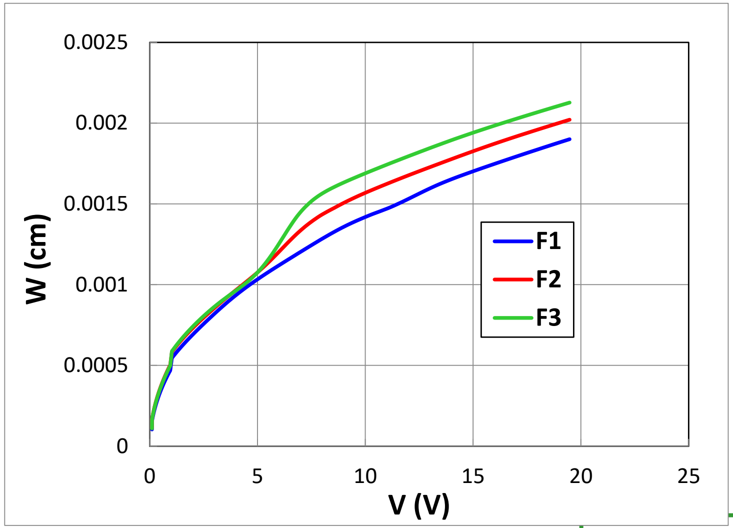
C-V data at f = **20 kHz** are used

2. Transition from I-V characteristics to I-W characteristics

1

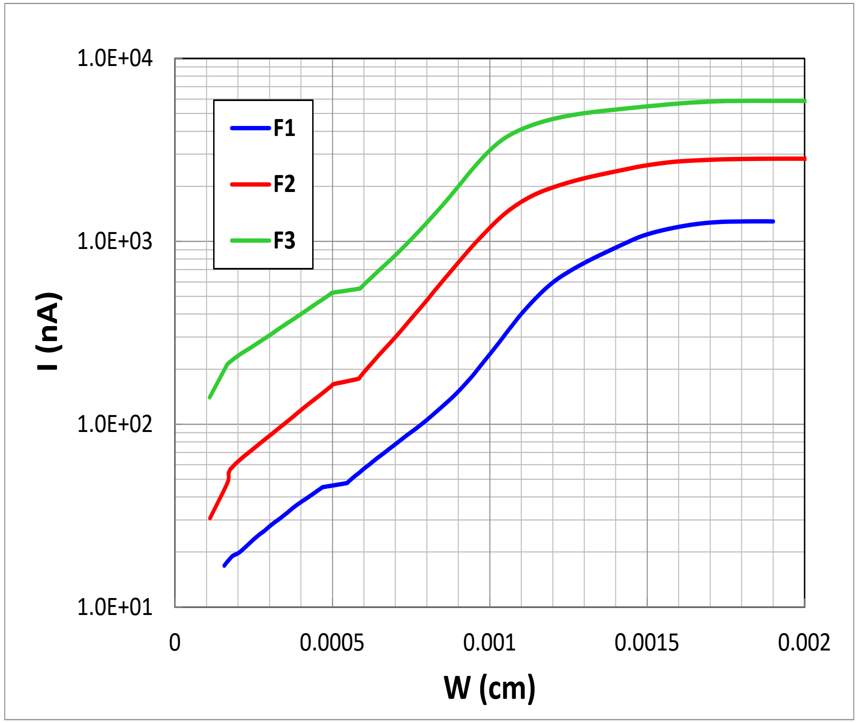


2



Done in 3 steps:
extraction of random leakage from I-V,
V → W, I-V → I-W, W >>>> X

3



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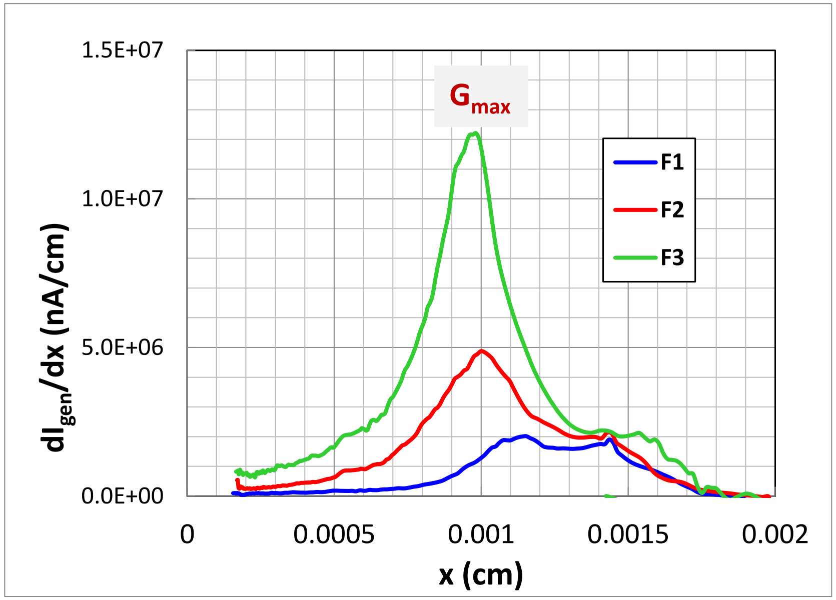
3. Profiles of the current generation rate

Profiling of the current generation rate G = dI_{gen}/dx is based on the continuity equation

$$G = divI_{gen}(x) = eU(x)S$$



- G(x) dependences are nonmonotonous
- G increases with F over **the most part of LDR**
- G_{max} is not in the BPR
- G_{max} depends on F

Reduction beyond G_{max}

- F1: G only slightly changes within 11-14 μm
- F2 and F3: reduction of G beyound 10 μm
- In the BPR (13-15 μm) G is almost insensitive to F and shows a plateau with a width dependent on F

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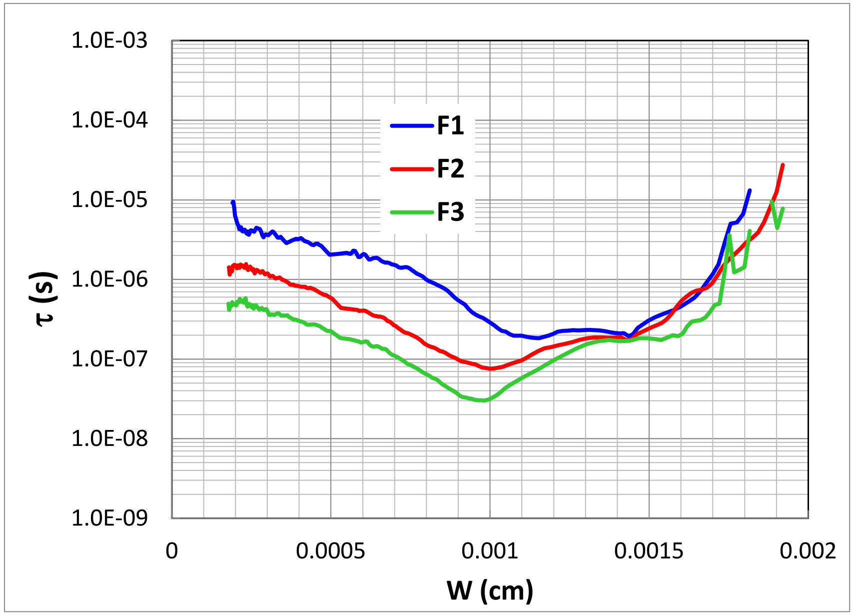
Related parameters

- Current-related damage rate: in the region of I rise $\alpha = 6.7\times10^{-12}$ A/cm

agrees with **α = 4.9×10^{-12} A/cm** for 20 MeV ^{40}Ar ions *[M. Kurokawa, et al., IEEE Trans. Nucl. Sci. 42 (1995) 163].* *For n_{eq}* $\alpha = 4\times10^{-17}$ A/cm

- Generation lifetime τ_{gen}



$$\tau_{gen} = \frac{en_iS}{dI/dW} = \frac{en_iS}{G}$$

$\tau_{gen} = 3\times10^{-8}$-$2\times10^{-5}$ s

Shapes of the curves reflect G(w)

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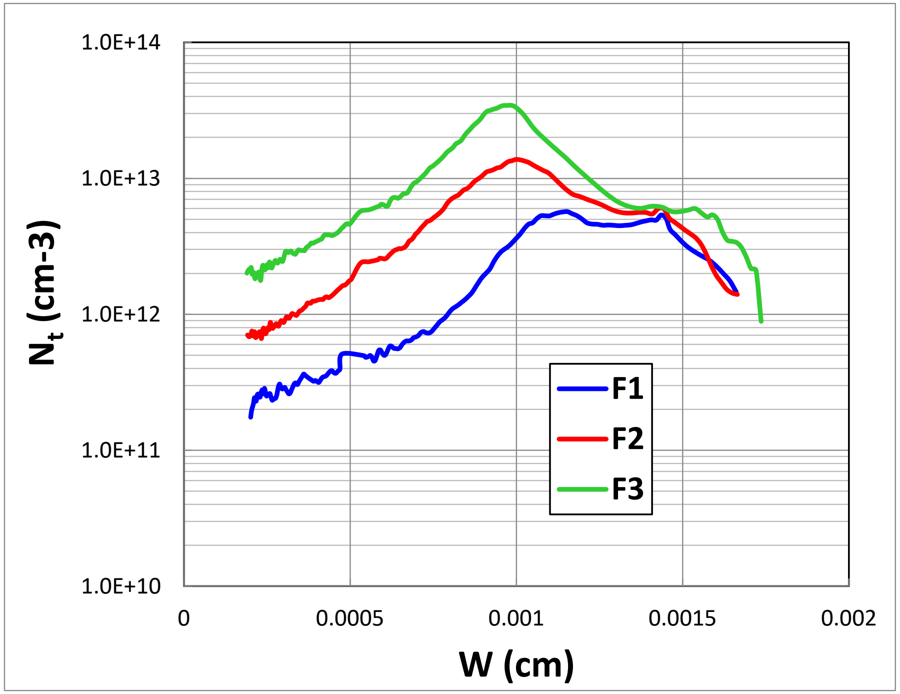
Related parameters

Concentration of generation centers N_t: rough estimation



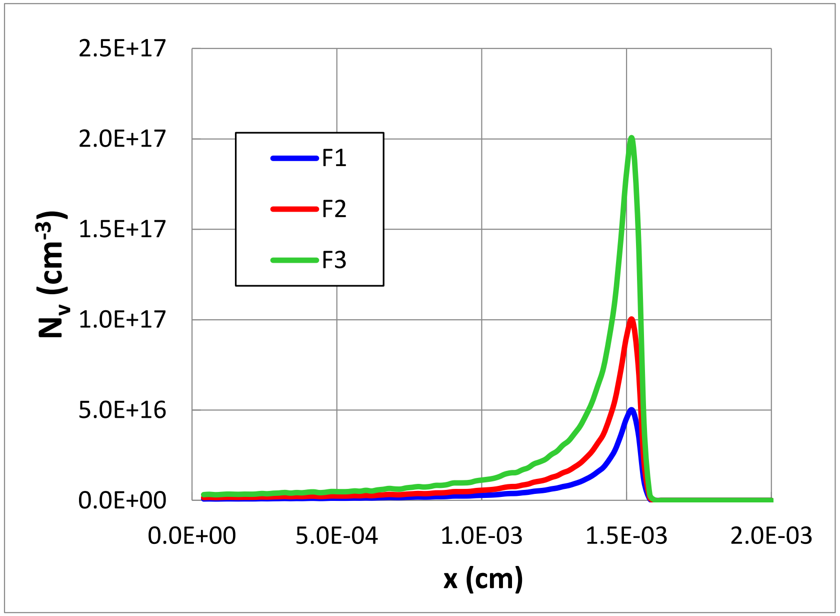
$$\tau_{e,h} = \left(\sigma_{e,h} v_{th} N_t\right)^{-1}$$

$\sigma = 8\times10^{-14}$ cm^2

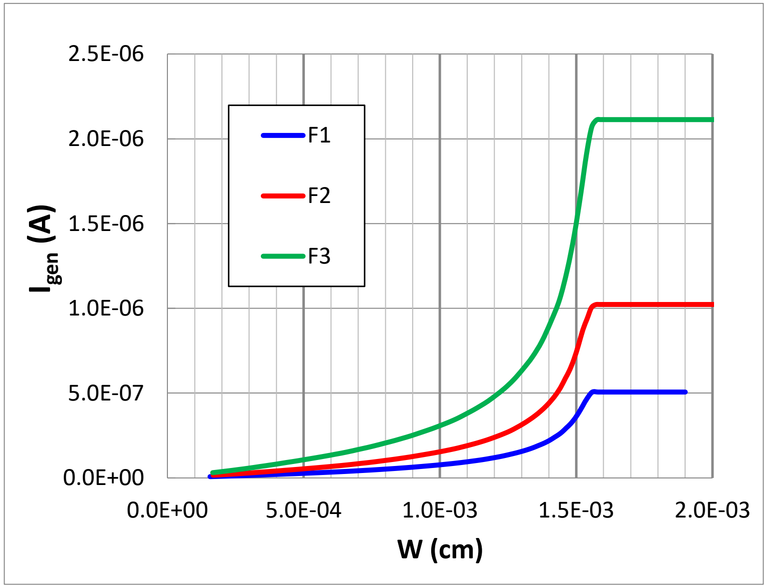
[E. Verbitskaya et al., NIM A 754 (2014) 63]

4. Comparison of I-V characteristics

TRIM: concentration of primary vacancies



Validity of algorithm: simulation of I-W characteristics using vacancy distribution



Simulation: position of maximal I_{gen} is independent of F and agrees with TRIM data

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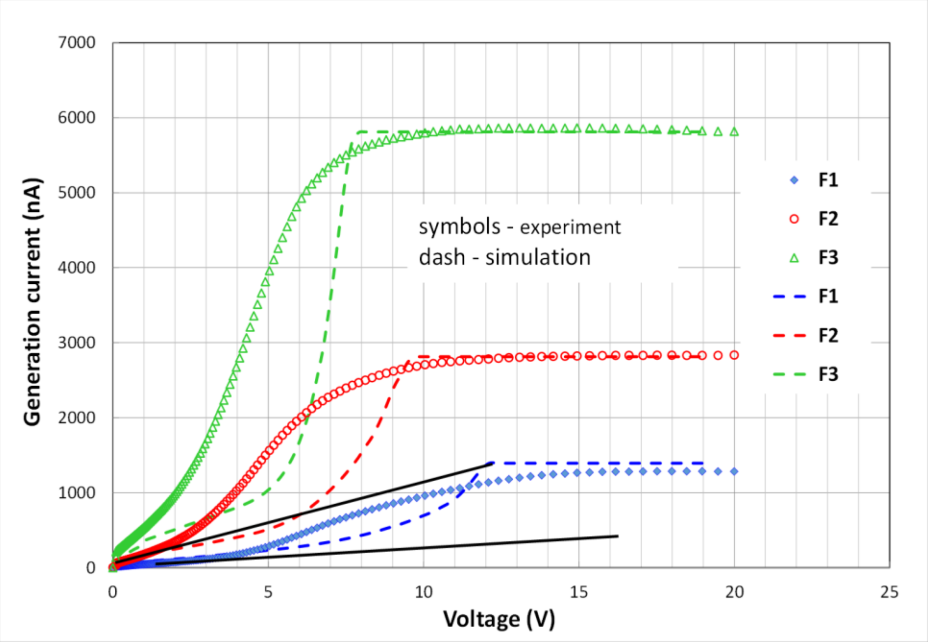
4. Comparison of I-V characteristics

I-V comparison



Simulation:

N_v scaling factor = 0.027

→ **agrees** with the statement that only few % of **Vacancies** and **Interstitials** escape annihilation and contribute to defect formation

E. Monakhov, et al., Phys. Rev. B ***65*** *(2002) 245201*

Agreement only within initial few μm

Assignment of I_{gen} sharp rise to BPR is unlikely!

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Summary

Approach

Measurement of the basic characteristics of p-n diodes, I-V and C-V.

Extraction of the current generation rate .

Observed features

The suppressed current generation rate inside the BPR.

The effect Increases with the fluence..rise.

Possible reason:

Different composition of point defects and clusters along the track.

The increased concentration of clusters suppresses the current generation in the BPR

Thank you for attention!