New vision of I-V characteristics in irradiated Si sensors with heavily damaged region

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38 RD50 Collaboration Workshop
on-line, June 21-23, 2021

The study extends our presentation at 37 RD50 workshop
(V. Eremin, et al.….)

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!

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Goal

Perform analysis of I-V characteristics aimed at disclosing the mechanisms contributing to the bulk current of heavily damaged Si sensors

For this:

- Enforce formation of clusters by irradiating Si sensors with ions creating **local heavily damaged region** at a known position (medium energies, ion range less than sensor thickness);
- Build the algorithm of I-V characteristic analysis,
- Derive the profile of the current and current generation rate,
- Give insight into the influence of heavily damaged region on the bulk current in irradiated Si sensors.

Experimental

Samples

- Pad **p^+-n-n^+**
- n-type CZ Si, ρ ~ **60 Ωcm, $N_0 = 7.1\times10^{13}$ cm^{-3},** d **=** 300 μm , S = 0.23 cm^{-2}

Irradiation:

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

Measurements:

- I-V characteristics
- C-V characteristics

Simulation:

TRIM

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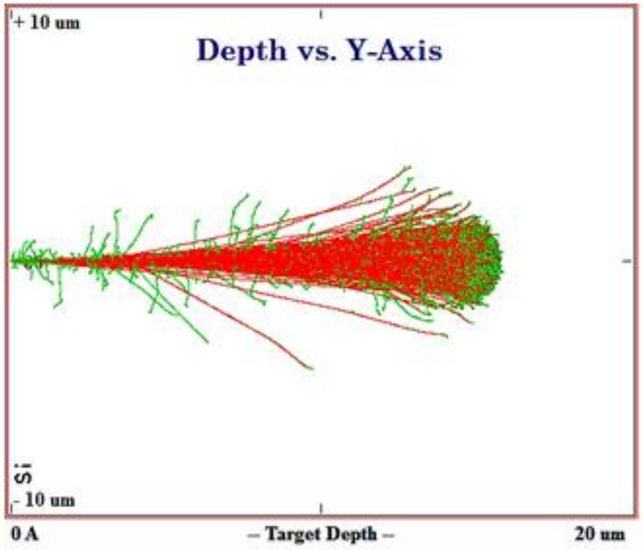
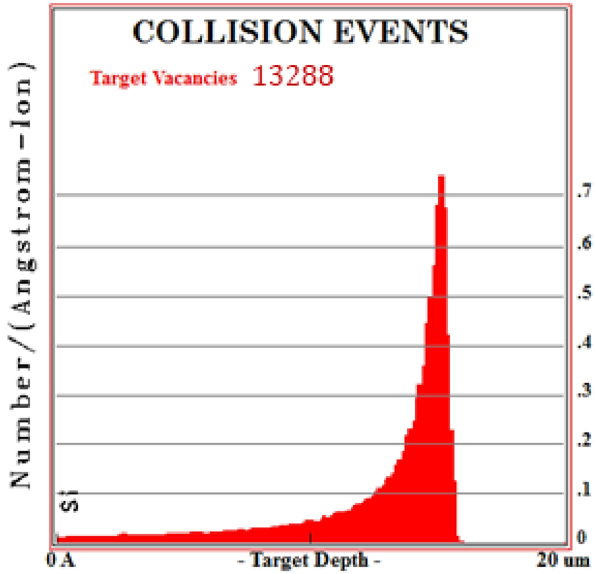
Simulations of collision events produced by 53.4 MeV ^{40}Ar ions (TRIM)



Collision cascades
red – moving ions,
green – recoils



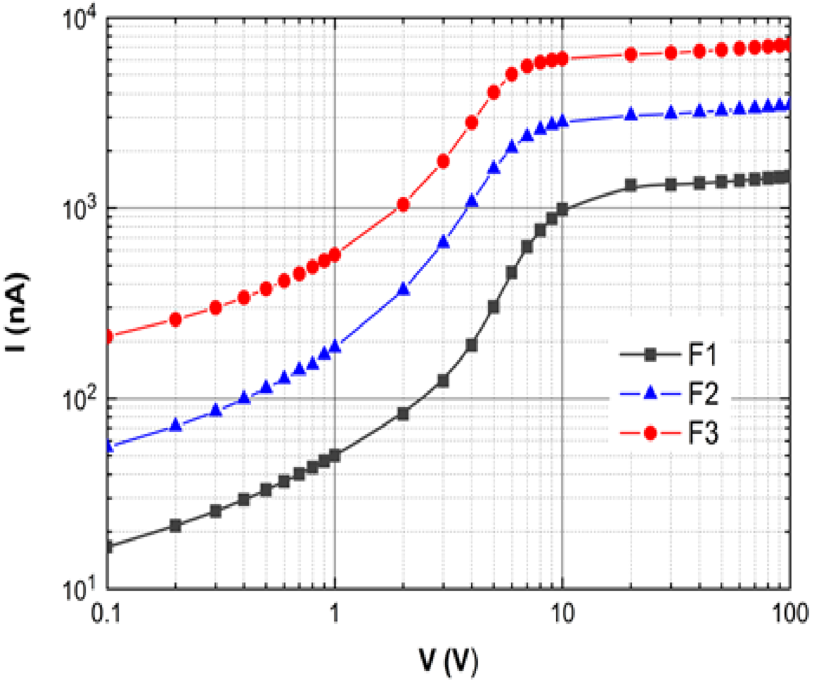
Profile of primary defect (vacancies) concentration $N_v(x)$ along the track

5000 ^{40}Ar ions
range 15 μm
13288 vac/ion

Maximum introduction rate 2×10^7 cm^{-1}/ion

- $N_v(x)$ has a shape with a Bragg peak at the track end
- N_v maximum at x = 15.2 μm
- Within the BPR (x = 13-15 μm), $N_v(x)$ is up to 100 times higher than at the beginning of the track

I-V characteristics



Preliminary assignment:
three regions:

- ✓ moderate rate of current rise ~0-(1-2) V, Low Damaged Region (LDR)
- ✓ higher rate, Bragg Peak Region (BPR)
- ✓ slow rise, Non-Damaged Region (NDR), insignificant current increase (ohmic leakage?)

Algorithm of I-V characteristic analysis

1. Determinating the voltage dependence of SCR depth **W-V** using C-V characteristics,
2. Translating I-V characteristics to **I-W** (I-x) characteristics,
3. Profiling the derivative of the current density J $\rightarrow$ **current density gradient dJ/dx** over the depth of the damaged region,
4. Calculating the **diffusion current – new point in the study.**

1. Determinating SCR depth W from C-V characteristics

$$W = \left[\frac{2\varepsilon\varepsilon_o(V + V_{bi})}{eN_{eff}}\right]^{0.5}$$

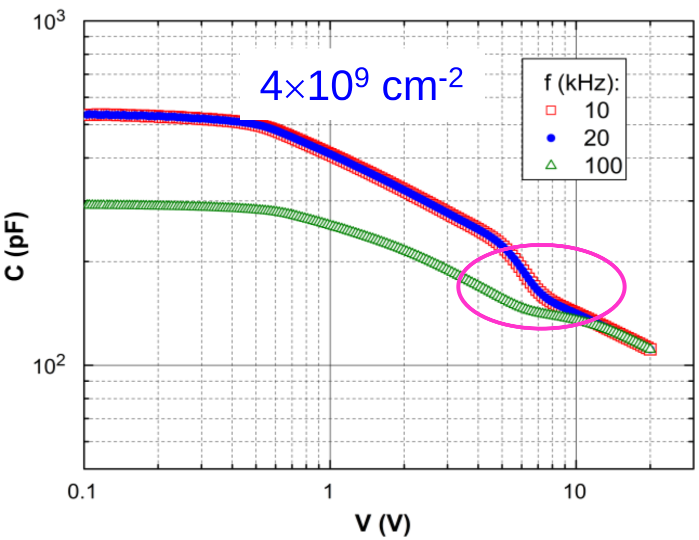
$$C = \frac{\varepsilon\varepsilon_o S}{W}$$

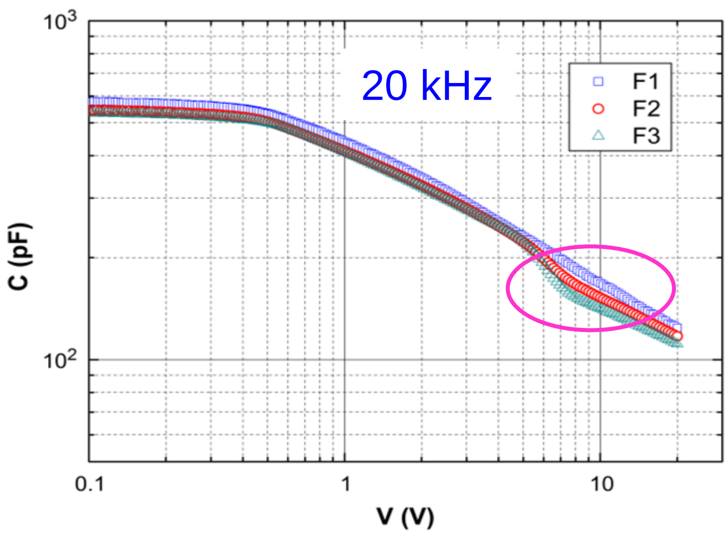
N_{eff} is nonuniform and unknown

In Si samples irradiated with neutrons capacitance depends on frequency f

Z. Li and H.W. Kraner, IEEE Trans. Nucl.Sci. 38 (1991) 244

E. Borchi, et al., Sol. State Electron. 42 (1998) 2093





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

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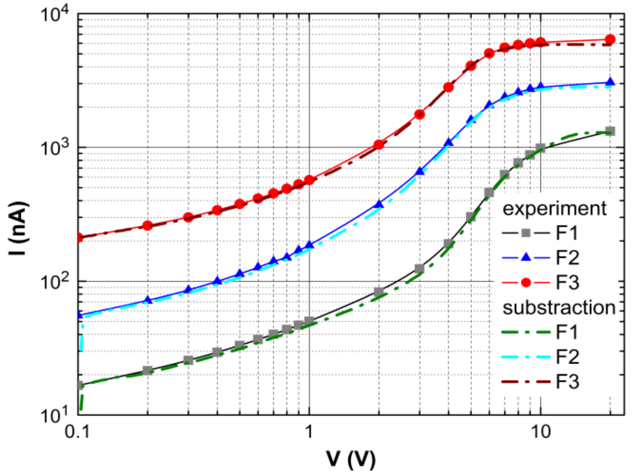
2. Translation of I-V characteristics to I-W characteristics

1



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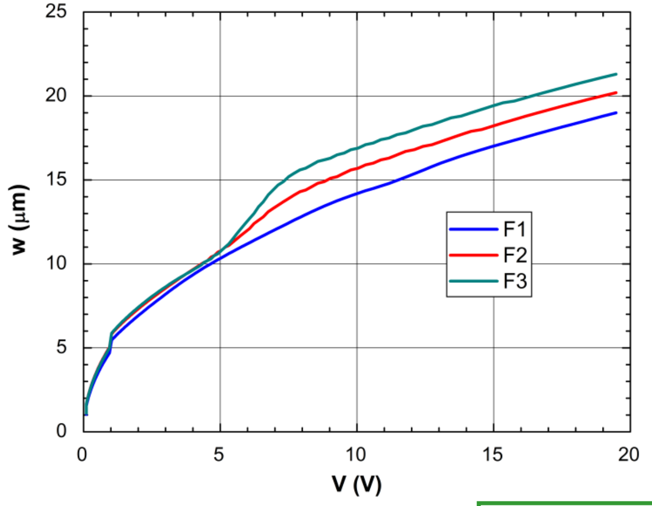
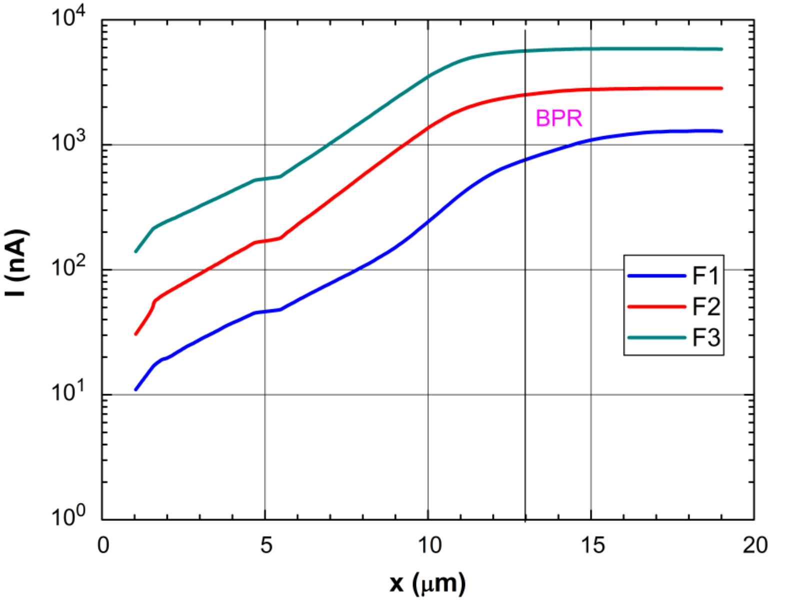


Done in 3 steps:
1) subtraction of leakage from I-V,
2) V → W, 3) I-V → I-W; W is x

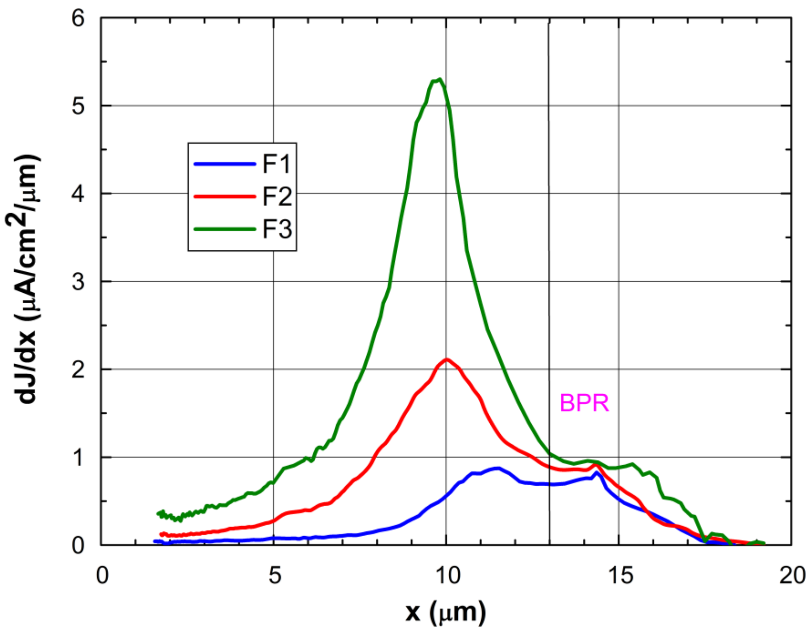
3



Highest current increase is not in the BPR!

3. Profiles of the current density gradient

Current density gradient (current generation rate) **dJ/dx**



- ^{40}Ar, 53.4 MeV: **α = 6.7×10^{-12} A/cm**
- 23 GeV protons and 1 MeV neutrons: **α = 4×10^{-17} A/cm**

- Dependences are nonmonotonic
- dJ/dx increases with F over **the most part of LDR**
- dJ/dx maxima are not in the BPR (shifted towards p$^+$-n junction)!
- dJ/dx depends on F:

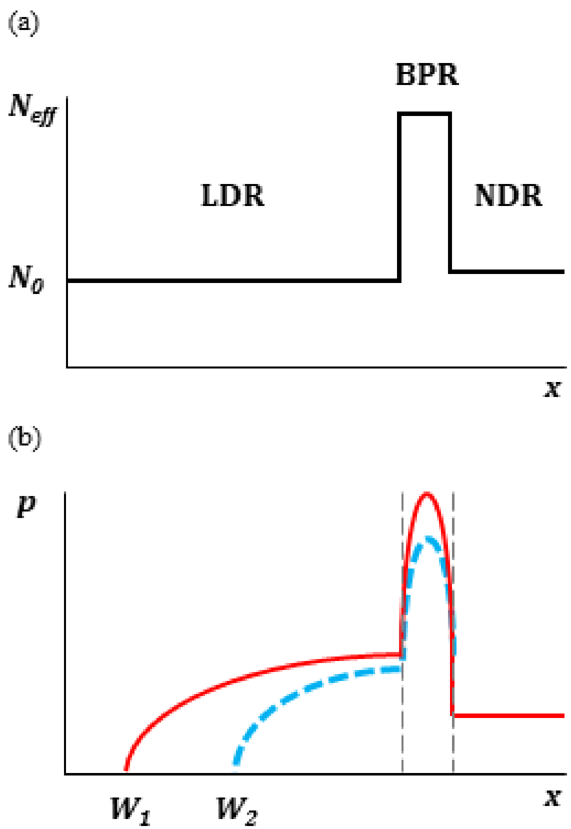
F1: only slightly changes within 11-14 μm

F2 and F3: reduction beyond 10 μm including BPR

- In the BPR (~13-15 μm) dJ/dx is almost insensitive to F and shows a plateau

4. Calculating the diffusion current

$$I_{dif} = \frac{eD_h p_n}{L_h} S$$



Nondepleted BPR:

- diffusion of holes from BPR to LDR due to their gradient p/L_h, $p_{LDR} < p_{BPR}$
- nonuniform hole profile according to the boundary condition: $p_n = 0$ at $x = W$,
- within BPR hole concentration depends on F, i.e., on defect concentration,
- $L_{LDR} > L_{BPR}$, therefore
- holes having reached LDR diffuse and can arrive to W contributing to the diode current.

Depleted BPR:

Exhaustion of hole source

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Estimation of diffusion current

Assumption:

Compensation of N_0 (7.1×10^{13} cm^{-3}) in BPR occurs due to the dominant introduction of acceptor-type radiation defects:

- point defects VV^-, E_c – 0.42 eV,
- cluster-related defects H152 K acting as hole traps in the lower part of Si bandgap, $\Delta H_{152K} = E_v + 0.42$eV *(I. Pintilie et al., NIM A 611 (2009) 52)*

$$I_{dif} = \frac{eD_h p_n}{L_h} S$$

$$n = N_{DA} exp\left(-\frac{E-E_F}{kT}\right)$$ - occupancy of DLs

$$L_h = \sqrt{D_h \tau_{rec\_h}}$$

$$p - n + N_o - N_{DA} = 0 \quad - \text{neutrality condition}$$

$$\tau_{rec\_h} = \left(v_{th\_h} \sigma_h N_{DA}\right)^{-1}$$

N_{DA} – concentration in BPR, variable

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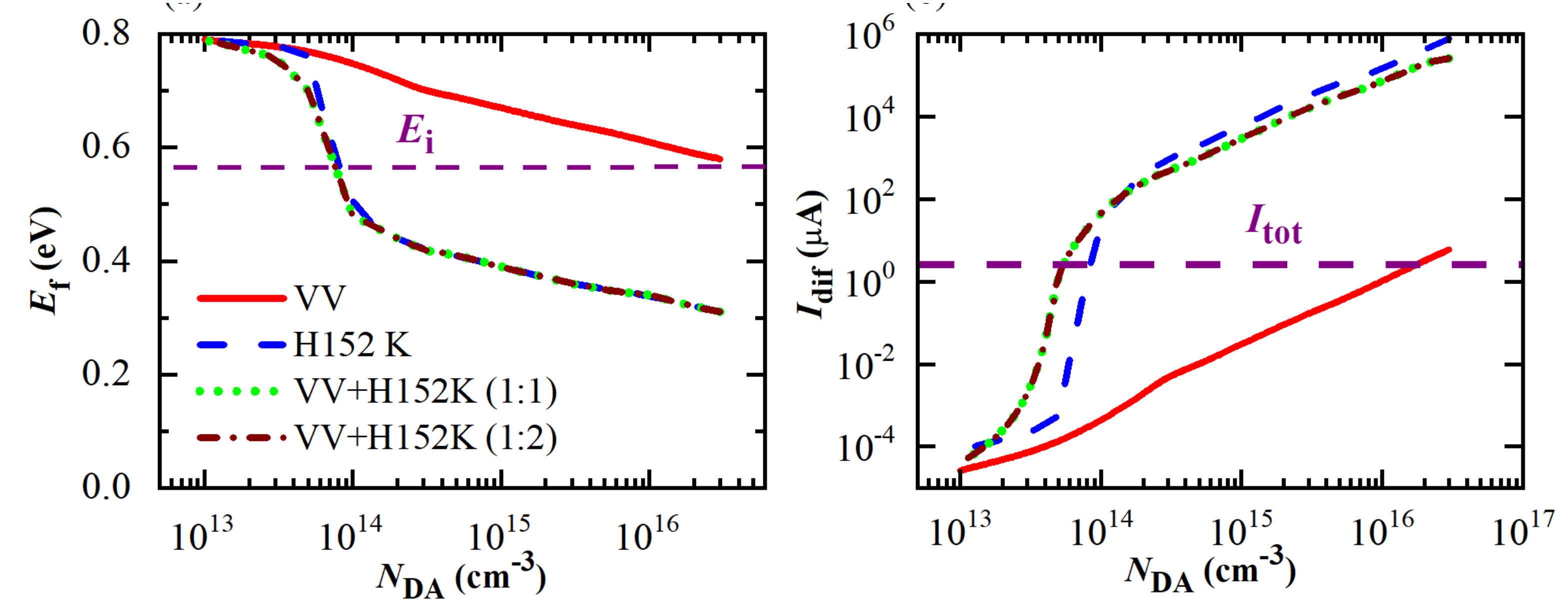
Contribution of diffusion current

F = 4×10^9 cm^{-2}

N$_{DA}$: 1×10^{13} - 3×10^{16} cm^{-3}



VV$^-$: gradual changes of E$_f$ and I$_{dif}$; compensation at N$_{DA}$ ≥ 3×10^{16}

H152 K or VV- + H152 K: compensation and sharp I$_{dif}$ increase at N$_{DA}$ ≥ (3-5×10^{13}

NB: area of clusters may be **less** than S, and I$_{dif}$ rise may be lower

Conclusion: both defects can contribute to the diffusion current

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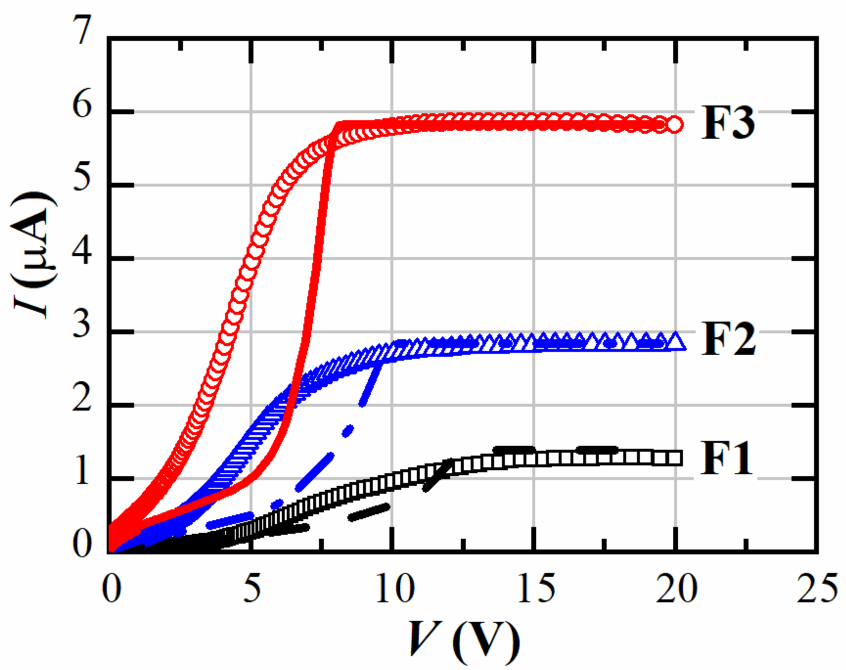
Comparison of I-V characteristics



Symbols: experimental
Dash: simulation of generation current using TRIM data

Simulation of generation current:
N_v scaling factor = 0.019

→ only few % of vacancies and interstitials escape annihilation and contribute to defect formation
e.g. E. Monakhov, et al., Phys. Rev. B ***65*** *(2002) 245201*

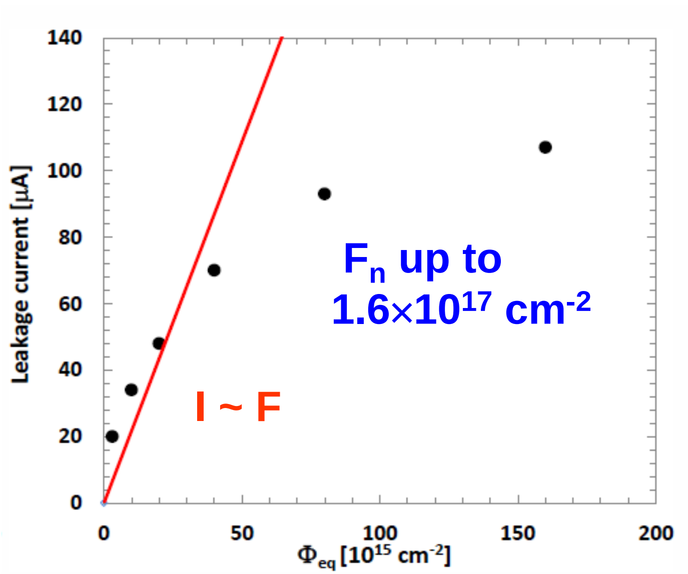
Agreement only within few initial μm

Assignment of sharp current rise in I-V characteristics to the bulk generation current in BPR is incorrect!

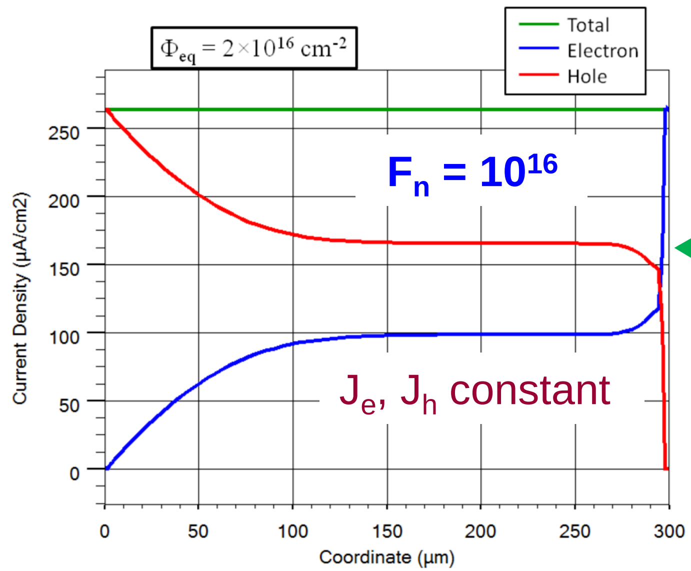
Additional mechanism affecting I-V and dJ/dx shapes

Reduction of dJ/dx and plateau in dJ/dx(x):

- Exhaustion of hole flow from BPR,
- Additional mechanism: formation of local compensated regions in BPR acting as neutral conductive base without a contribution to the current



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



All current components are accounted

V. Eremin, et al., 2017 JINST 12 P0900

Neutrons: $F \geq 2\times10^{16}$ cm^{-2} → conversion from I ~ F to I ~ √F

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Summary

- A new finding in the study of Si sensors irradiated with medium energy Ar ions is that dJ/dx profiles are nonmonotonic. Contrary to expected, their maxima are not located in the BPR.
- Nondepleted BPR acts as a source of diffusion current of holes generated in the BPR and flowing towards the SCR border, thus contributing to the total current.
- Suppression of dJ/dx inside the depleted Bragg peak region is explained by two factors:

1) exhaustion of the hole diffusion from the BPR,
2) formation of local compensated high resistivity regions within the BPR acting as neutral conductive base without contribution to the sensor current.

- Effect of current rise suppression with fluence is common for Si sensors with heavily damaged regions enriched with clusters, such as track ends of short-range ions, or uniformly distributed regions produced by 1 MeV neutrons at F > 10^{16} n_{eq}/cm^2 and ions with GeV energy.

Thank you for attention!