Radiation Damage Effect on SiPMs

(HighRR Bi-Weekly Seminar)

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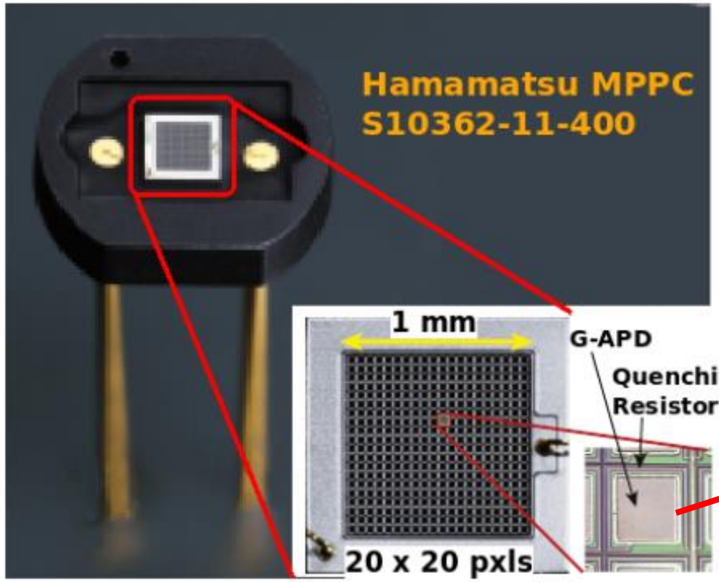
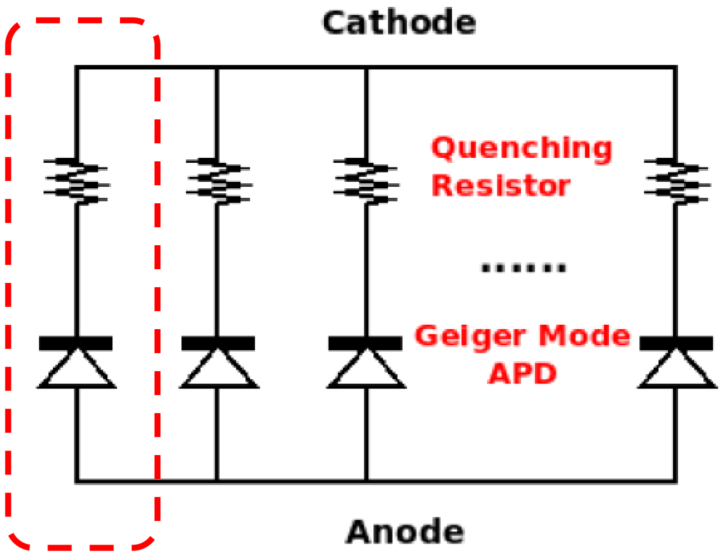
Short reminder of SiPM

Silicon Photomultiplier (SiPM):

- Also named **m**ulti-**p**ixel **p**hoton **c**ounter(MPPC)
- Array of Avalanche photodiode (APD)



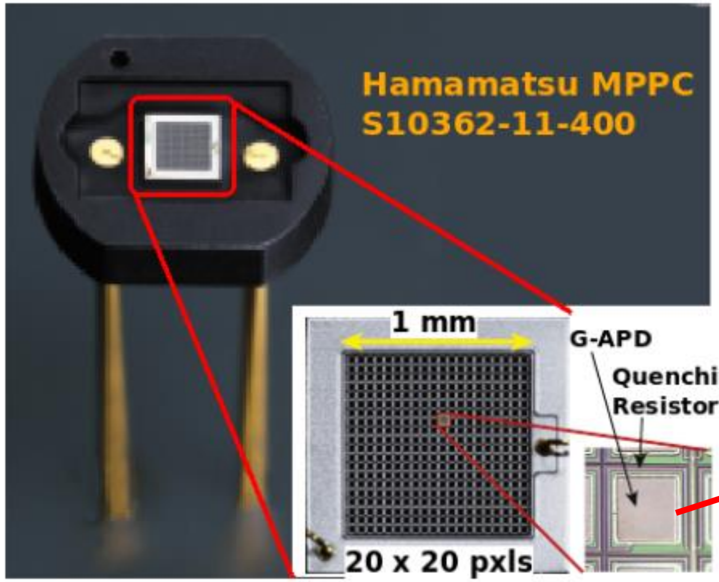


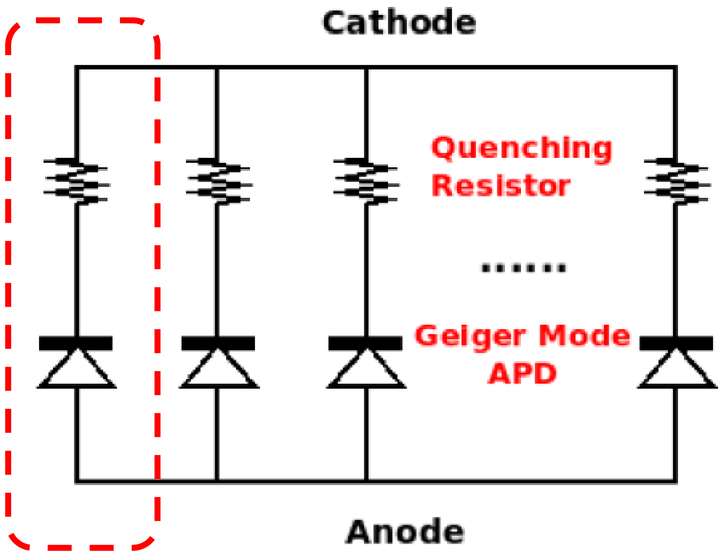
Sketch of a SiPM pixel array

Short reminder of SiPM

Silicon Photomultiplier (SiPM):

- Also named **m**ulti-**p**ixel **p**hoton **c**ounter(MPPC)
- Array of Avalanche photodiode (APD) => silicon semiconductor device





Sketch of a SiPM pixel array

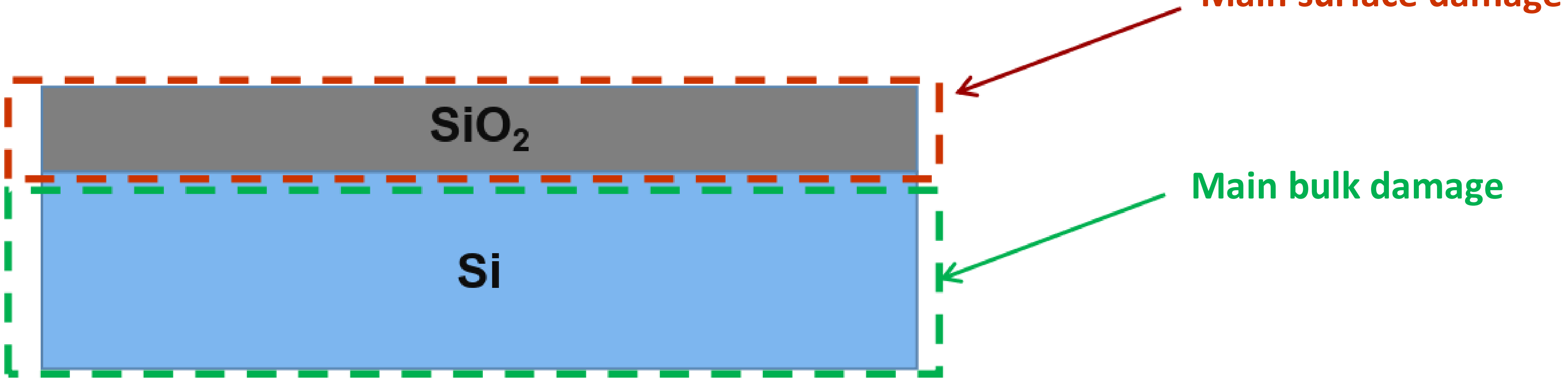
Content

- Radiation damage in Silicon Semiconductor
- Radiation damage effects on SiPM
- Idea to improve radiation hardness
- Summary

Radiation damage in silicon semiconductor

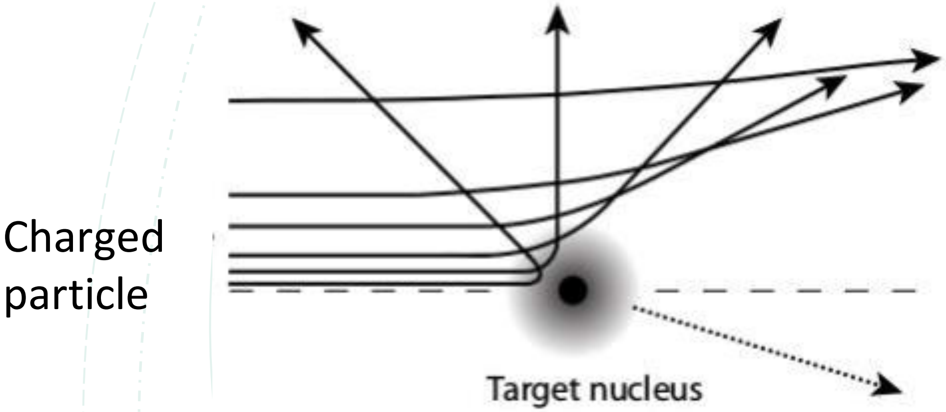
Type of radiation damage

1. **Bulk damage** (displacement damage) due to **N**on-**I**onization **E**nergy **L**oss (**NIEL**)
2. **Surface damage** due to **I**onization **E**nergy **L**oss (**IEL**)

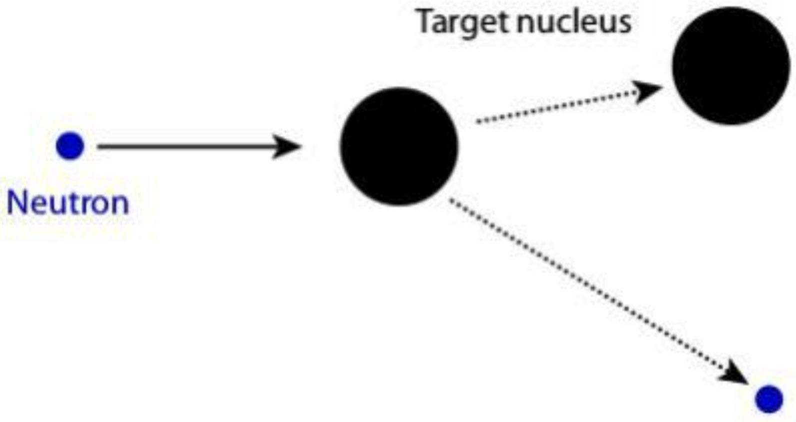


Bulk damage

1. Source: electron, proton, neutron, high energy photon
    - main interactions with nucleus (Coulomb scattering and Elastic nuclear scattering)



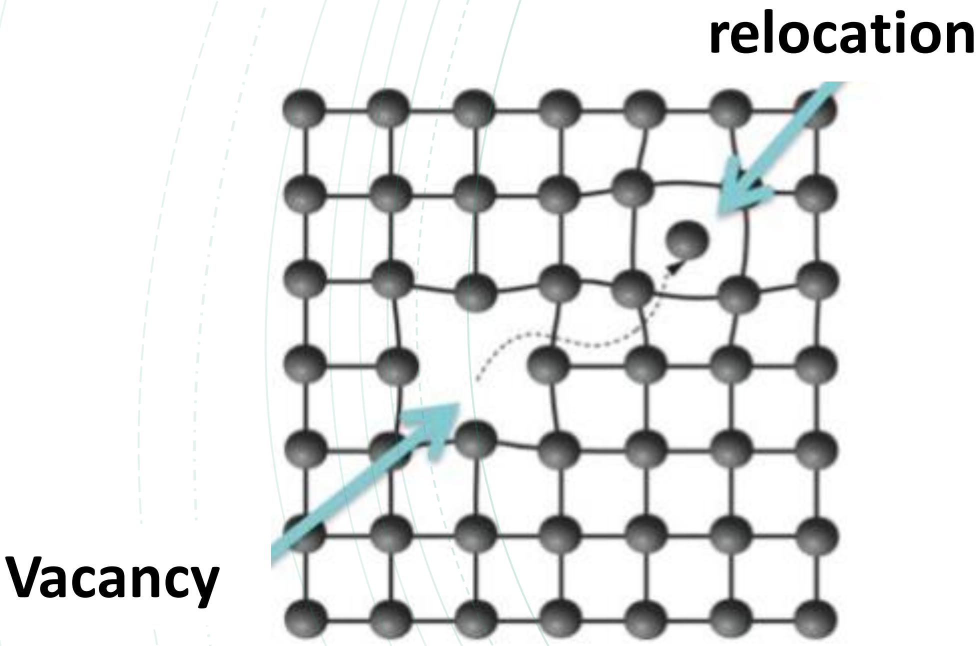
Coulomb scattering (EM)



Elastic nuclear scattering (strong)

Bulk damage

1. Source: electron, proton, neutron, high energy photon
   - main interact with nucleus (Coulomb scattering and Elastic nuclear scattering)
2. Energy transferred to Primary Knock-on Atom (PKA): T
   - **>25eV**: produce Frenkel-pair (relocation-vacancy pair)

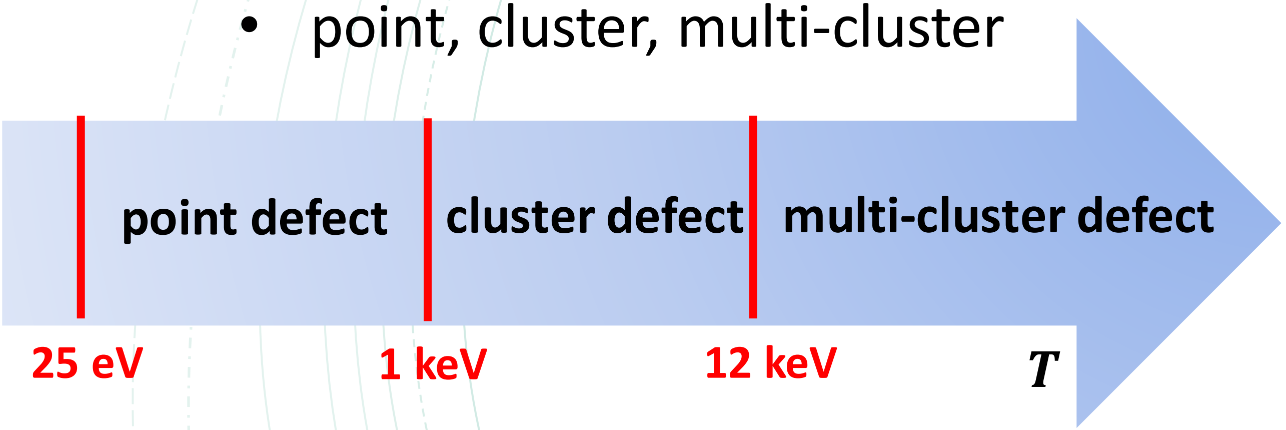


	Electron	Proton	Neutron
Interaction	EM	EM+strong	strong
T_{max}	0.155	133.7	133.9
T_{av}	0.046	0.210	50

Transferred energy to Si atom from 1MeV particle
(unit in table: keV)[1]

Bulk damage

1. Source: electron, proton, neutron, high energy photon
    - main interact with nucleus (Coulomb scattering and Elastic nuclear scattering)
2. Energy transferred to Primary Knock-on Atom (PKA): T
    - **>25eV**: produce Frenkel-pair (ion-vacancy pair)
3. Different transferred energy will give different defect:
    - point, cluster, multi-cluster



point defect **cluster defect** **multi-cluster defect**

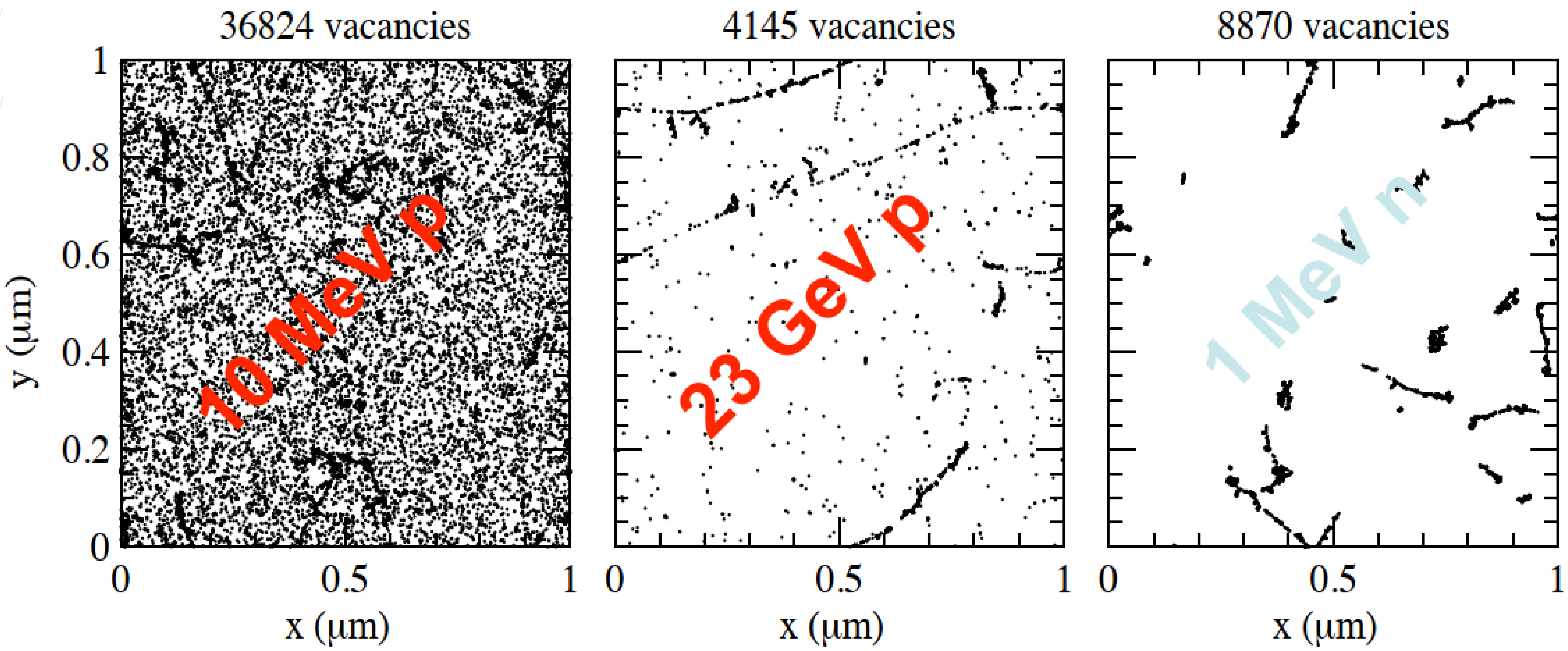
25 eV **1 keV** **12 keV** T

	Electron	**Proton**	**Neutron**
Interaction	EM	EM+strong	strong
E_{min} for point	260	0.19	0.19
E_{min} for cluster	4600	15	15

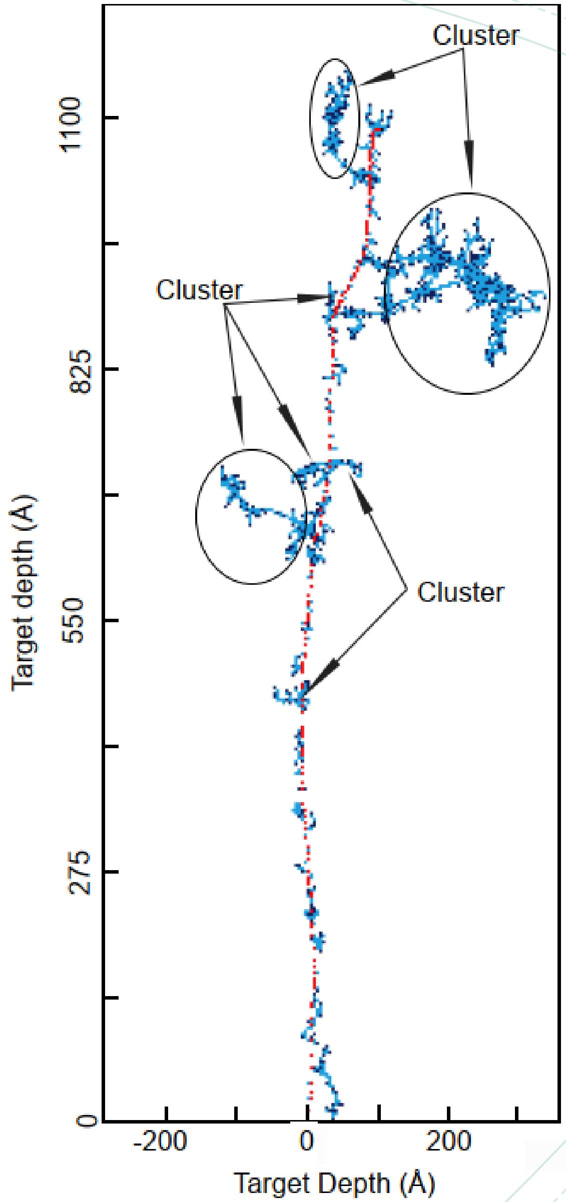
Minimum energy needed for point and cluster effect (unit in table: keV)[1]

Bulk damage

Simulation examples:



10^{14} particles/cm^2 [2]

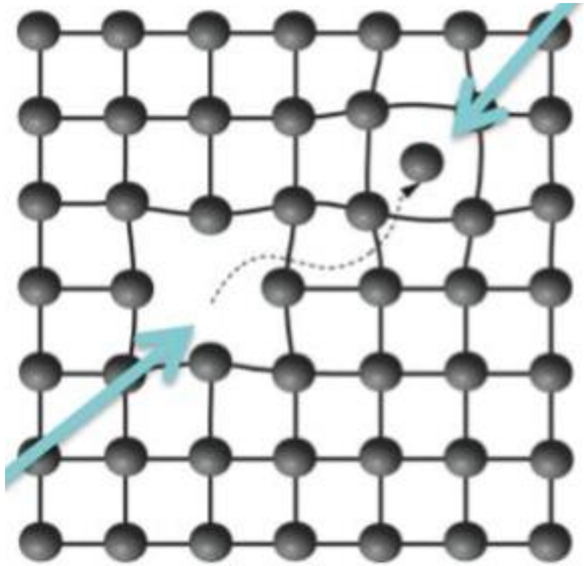


Simulation of 50keV PKA

Bulk damage: quantification[3]

Index of damage effect: (density of Frenkel-pairs)

$$FP \approx \frac{E_{dis}}{2.5T_d}$$

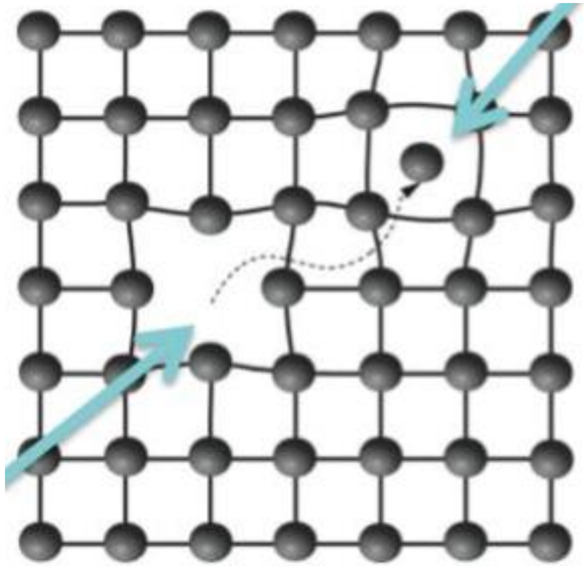


Bulk damage: quantification

Index of effect: (density of Frenkel-pairs)

$$FP \approx \frac{E_{dis}}{2.5T_d}$$

Minimum transferred energy for damage (material dependent, **25eV** for **silicon**).



Bulk damage: quantification

Index of effect: (density of Frenkel-pairs)

$$FP \approx \frac{E_{dis}}{2.5T_d}$$

Energy density goes into displacement [MeV/cm^3]

$$E_{dis} = \int_{E_{min}}^{E_{max}} NIEL(E)\Phi(E)dE$$

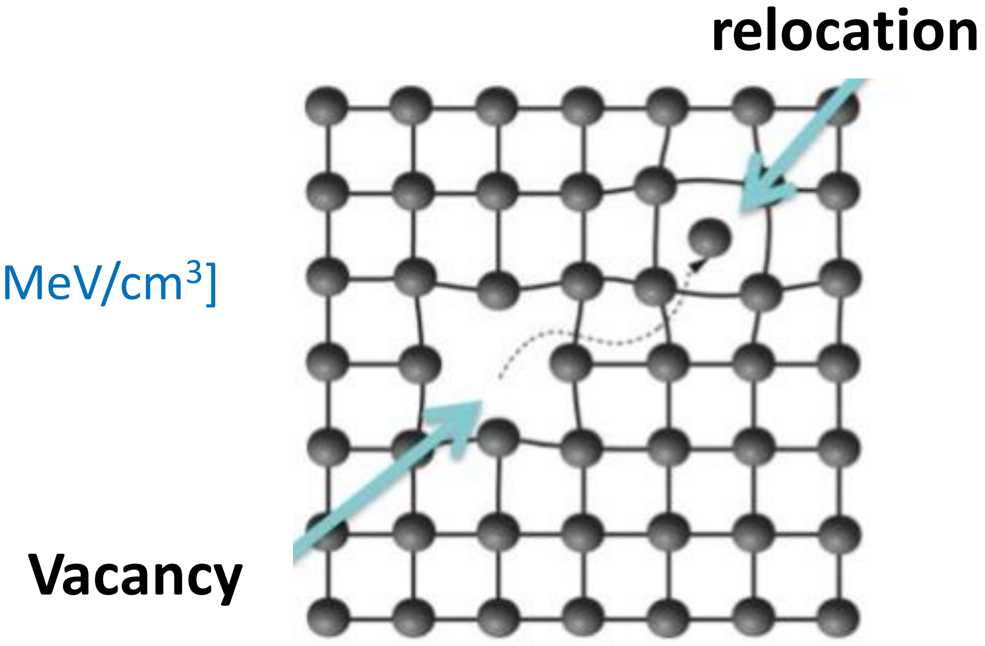
Setup dependent

Spectral Fluence [cm^{-2}]

Minimum incoming energy to generate FP

	Electron	Proton	Neutron
Interaction	EM	EM+strong	strong
E_{min} for point	260	0.19	0.19
E_{min} for cluster	4600	15	15

Silicon (unit: keV)



Bulk damage: quantification

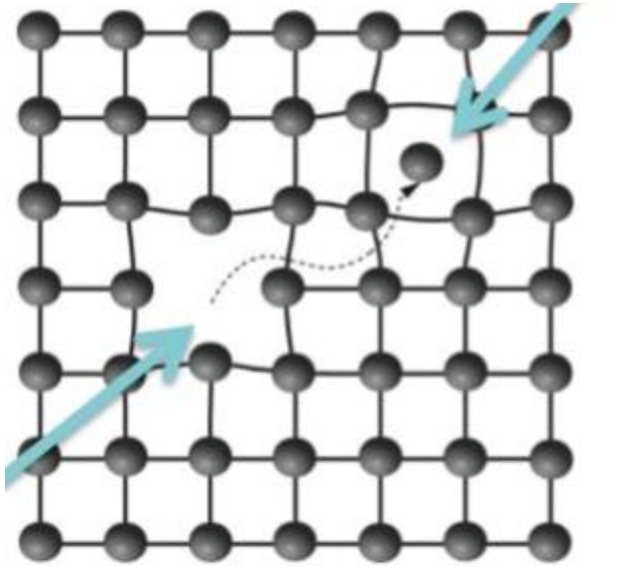
Index of effect: (density of Frenkel-pairs)

$$FP \approx \frac{E_{dis}}{2.5T_d} \longrightarrow$$

Energy density goes into displacement

$$E_{dis} = \int_{E_{min}}^{E_{max}} \boxed{NIEL(E)}\,\Phi(E)\,dE$$

Particle (type and energy) and **material** dependent



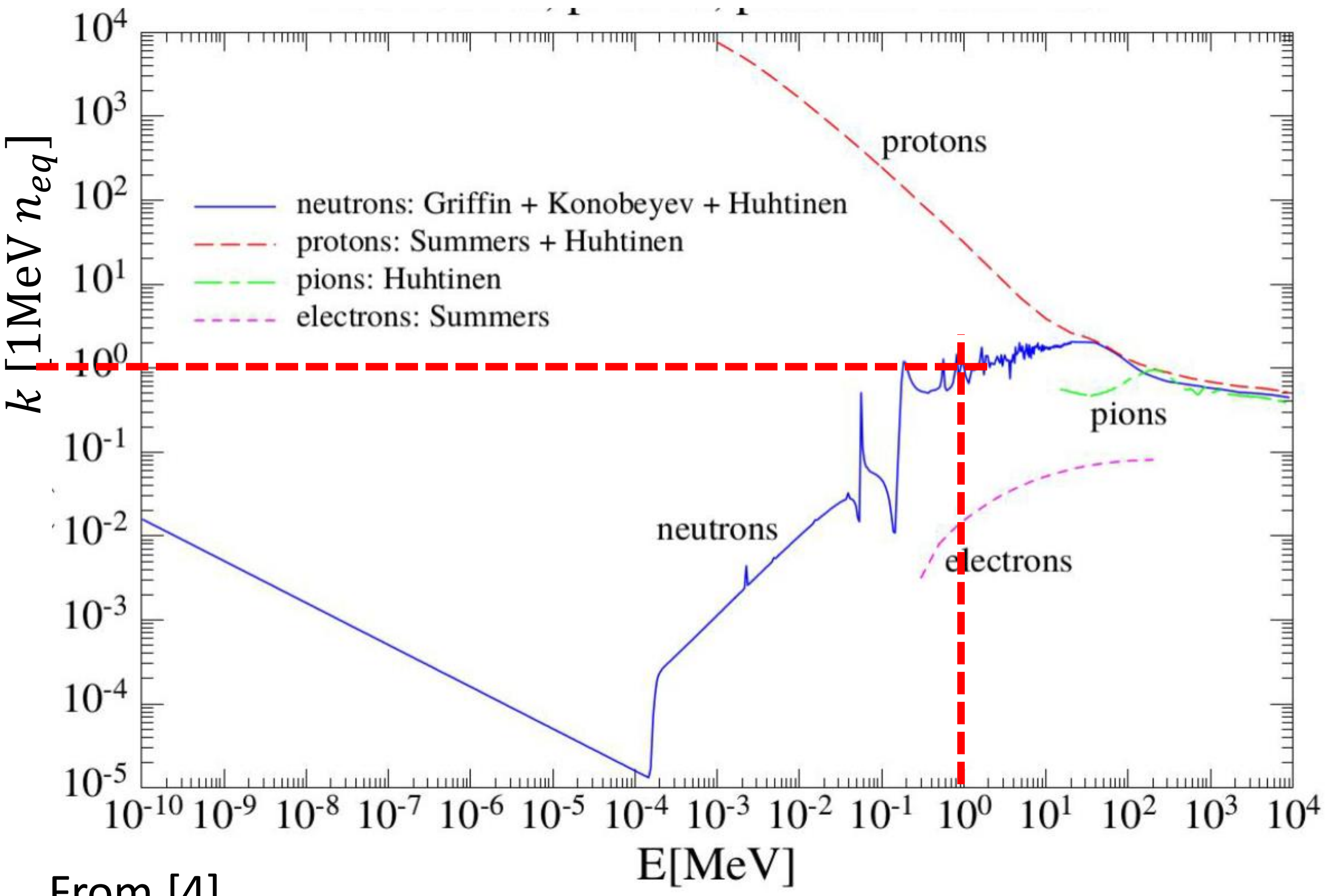
Bulk damage: quantification

Hardness factor k:

- $\boldsymbol{NIEL(E)}$ normalized by **1 MeV neutron**
- most of the particle and energy dependences canceled out
- Hardness factor curve for silicon

Warning of NIEL application:

- **Not** universally and ideally valid rule
- E.g.: electron have less effect
  - more close FPs => easy to recover



From [4]

Bulk damage: effects

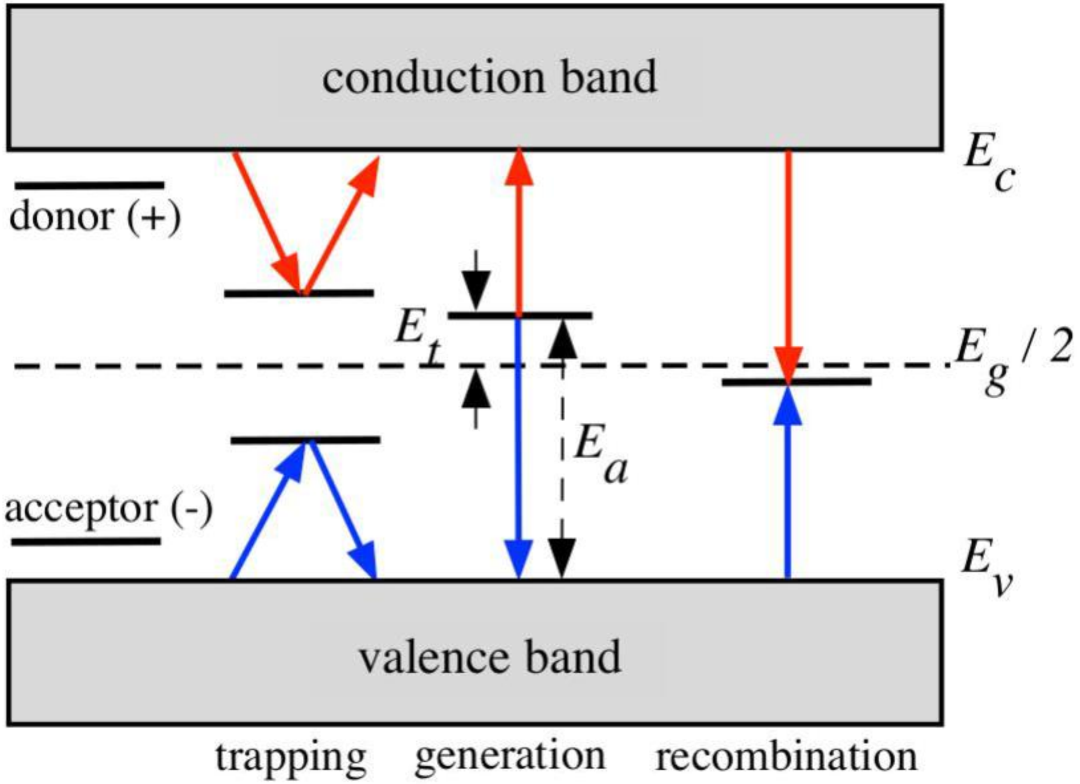
Shockley-Read-Hall model:

- charged defects => donor & acceptor
  =>change E-field; V_{dep}
- deep defects => trapping
  =>reduce signal amplitude
- close to Eg/2 => generation & recombination
  => increase dark current

Effective doping density change @ high dose

=> change V_{br}, V_{dep}

(reported in [5]: in standard silicon detector, effects can be seen @ dose>$10^{12} n_{eq}/cm^2$)

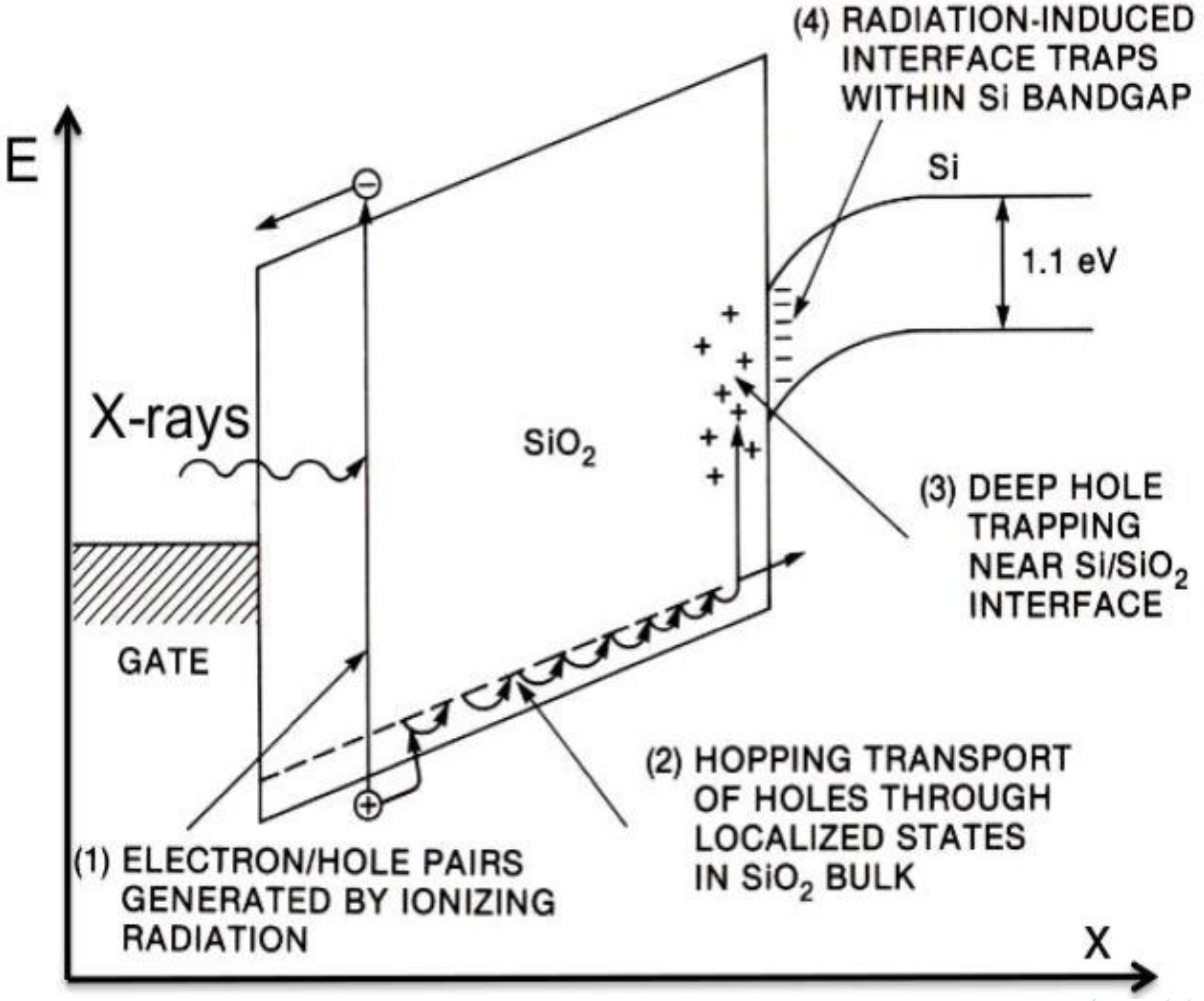


Surface damage

Source: gamma and charged particle (gamma/electron<~**300keV**: surface damage only)

mechanism:

- electron-hole pairs produced in SiO2(~18eV/pair);
- part of e-h pairs combined;
- remaining electrons escaped
- remaining holes move to Si-SiO2 interface
- holes will be captured by deep trap in SiO2 or interface
- results in positive charges state and interface traps



[6]

Surface damage: qualification

Index of effect: (density of holes trapped)

$$N_h \propto N_{e-h} \approx \frac{E_{ion}}{I_0}$$

Energy needed to create one e-h pair 18eV for Silicon

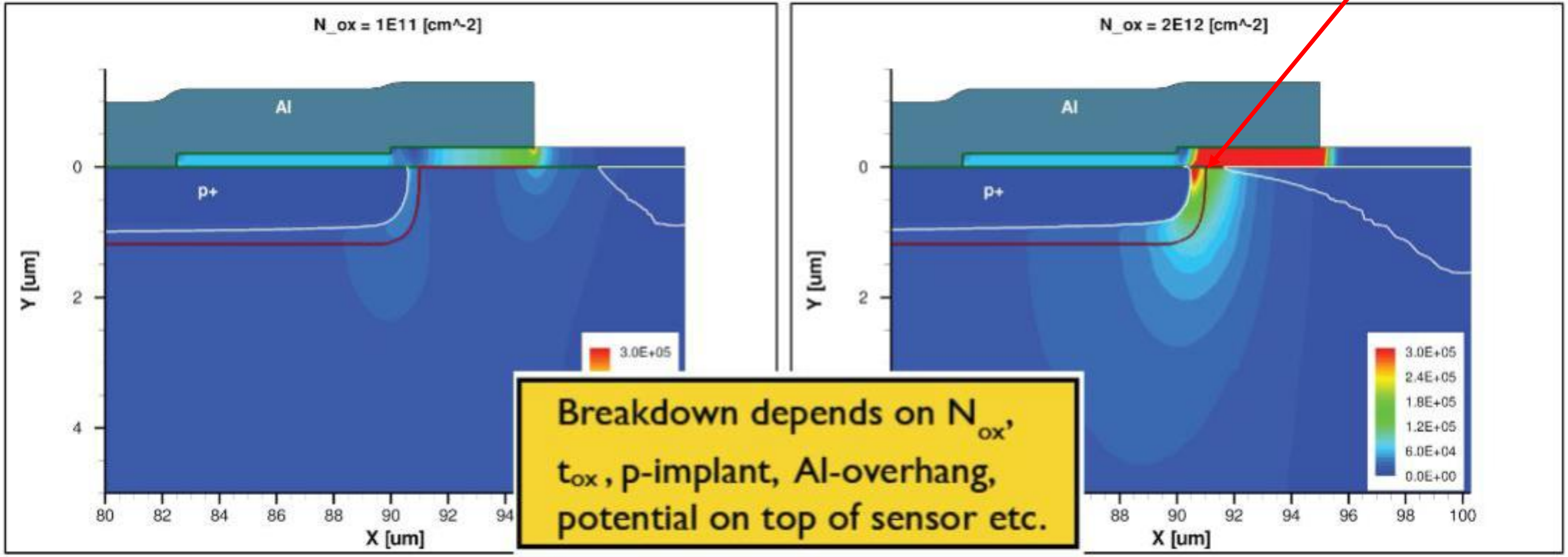
Ionization energy loss density: $$E_{ion} = \sum_N \left(\int \frac{dE}{dx}\, dx\right)$$

N: number of incoming particle

Surface damage: effects

1. High field regions appear => reduce the breakdown voltage

Higher field after irradiatio

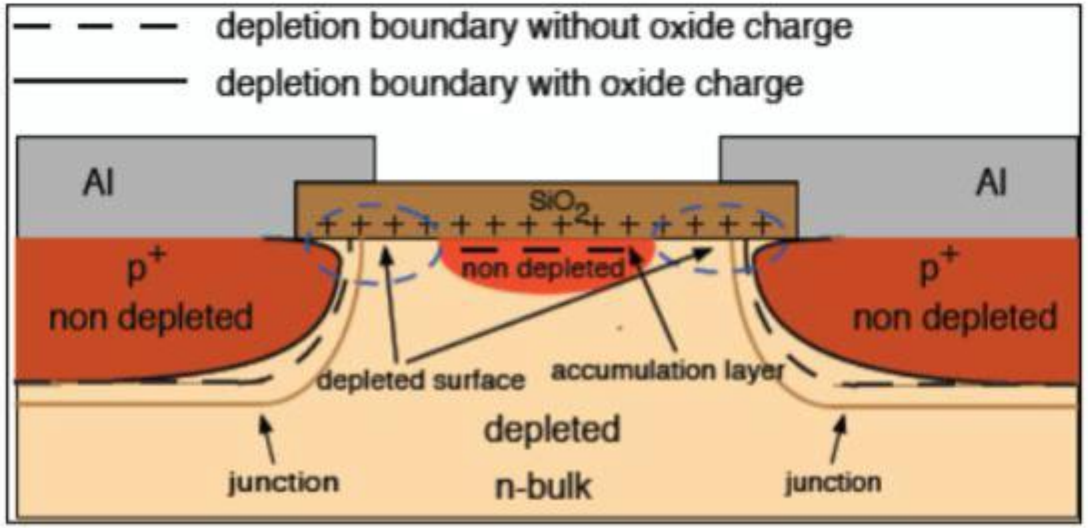


Breakdown depends on N_{ox}, t_{ox}, p-implant, Al-overhang, potential on top of sensor etc.

TCAD simulation from [6]

Surface damage: effects

1. High field regions appear => reduce the breakdown voltage
2. Accumulation layers form (or increase) => depletion voltage increase and inter-pixel capacitance increase
3. Interface states (interface traps) => increase leakage current under breakdown voltage
4. Charge losses close to the Si-SiO2 occur/increase



Schematic picture of surface damage induced effects on a pixel detector [6]

Radiation damage effects on SiPM

Effects on SiPM

Main effects:

- Significant **D**ark **C**ount **R**ate (DCR) increase
- Correlated noise (AP & CT) increase

} **bulk damage**

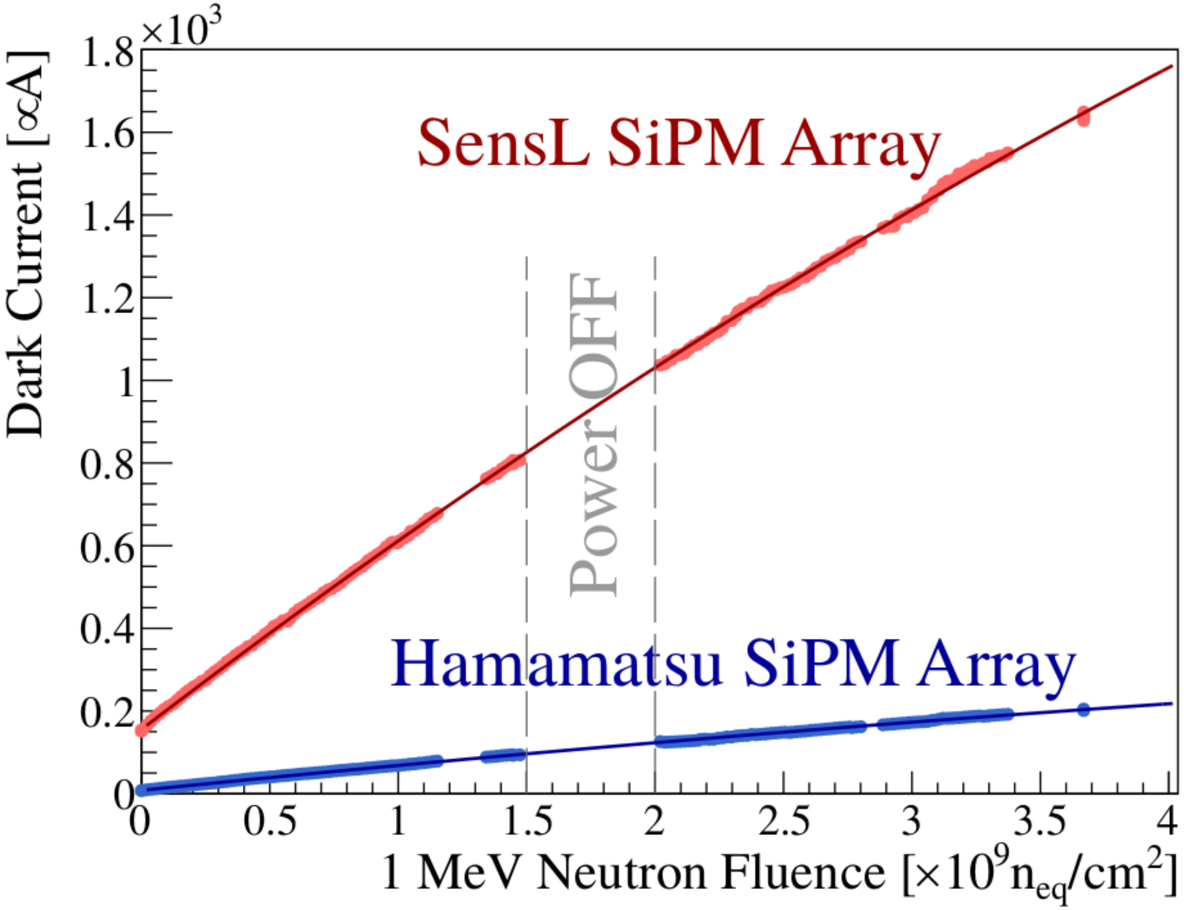
- V_{br} decrease slightly
- Current under breakdown voltage increase **=>** **surface damage**

Performance loss:

- Still working @$10^{14} n_{eq}/cm^2$
- Photon counting lost @$10^{11} n_{eq}/cm^2$

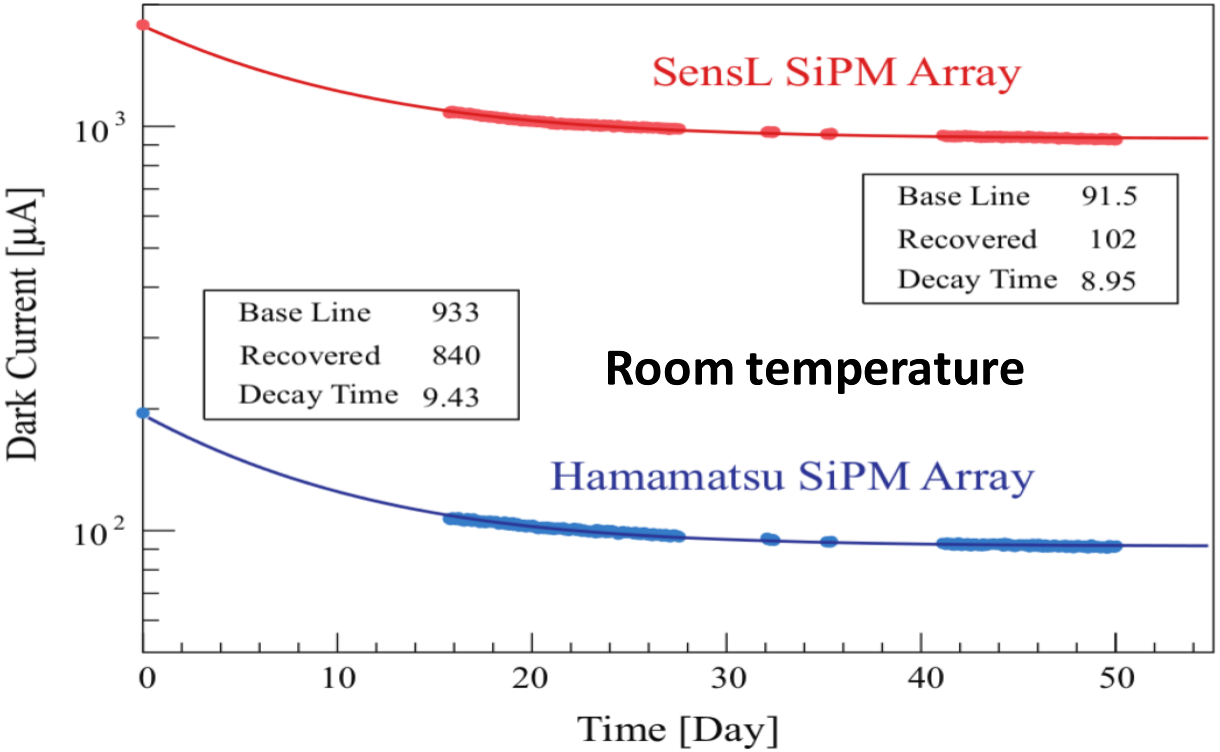
Annealing helps damage recovery

Effects on SiPM



From [7]

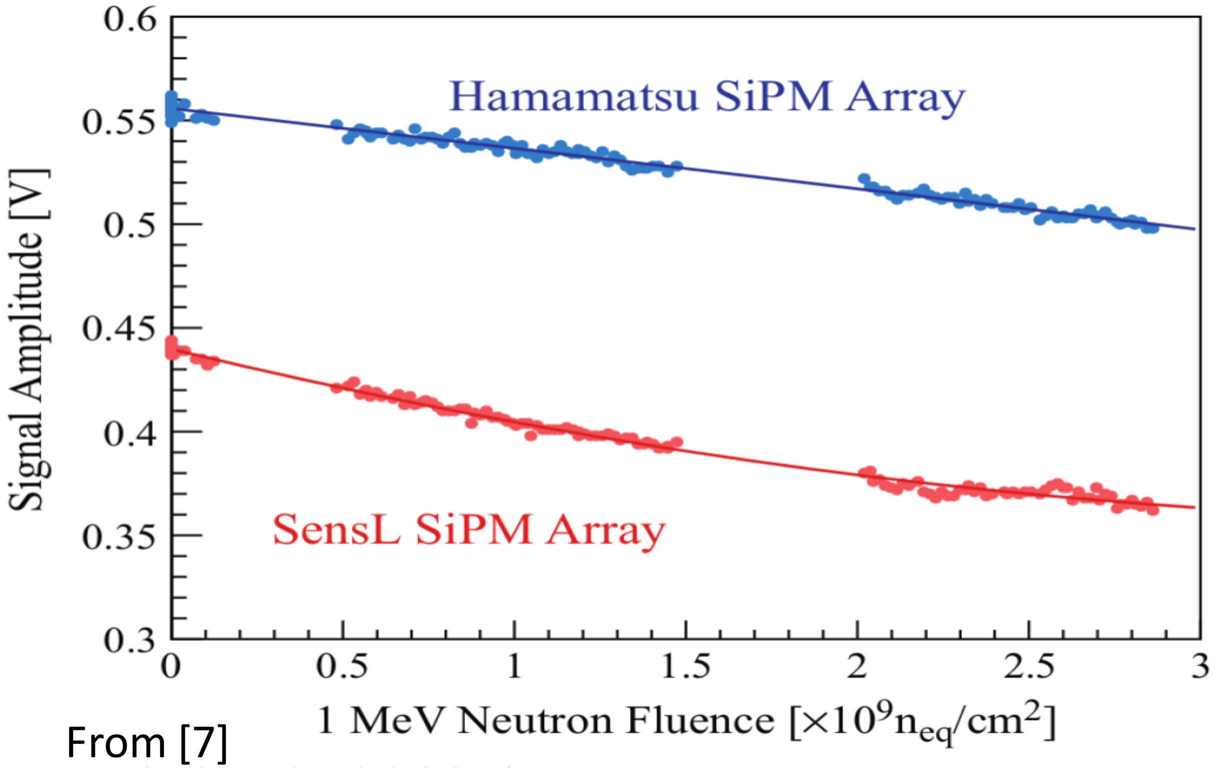
- **Dark current increase linearly**
- **Different SiPM => different effects**
- **HV will not effect the damage**
- **~50% recovery after annealing**



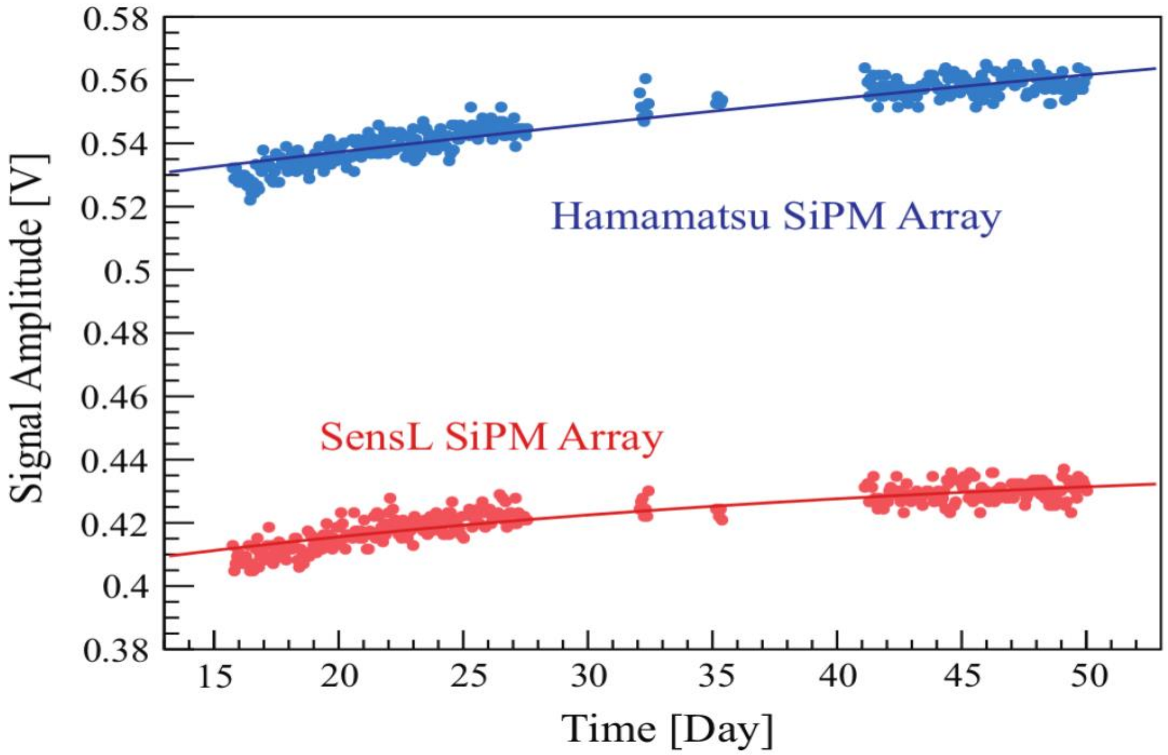
Room temperature

Effects on SiPM

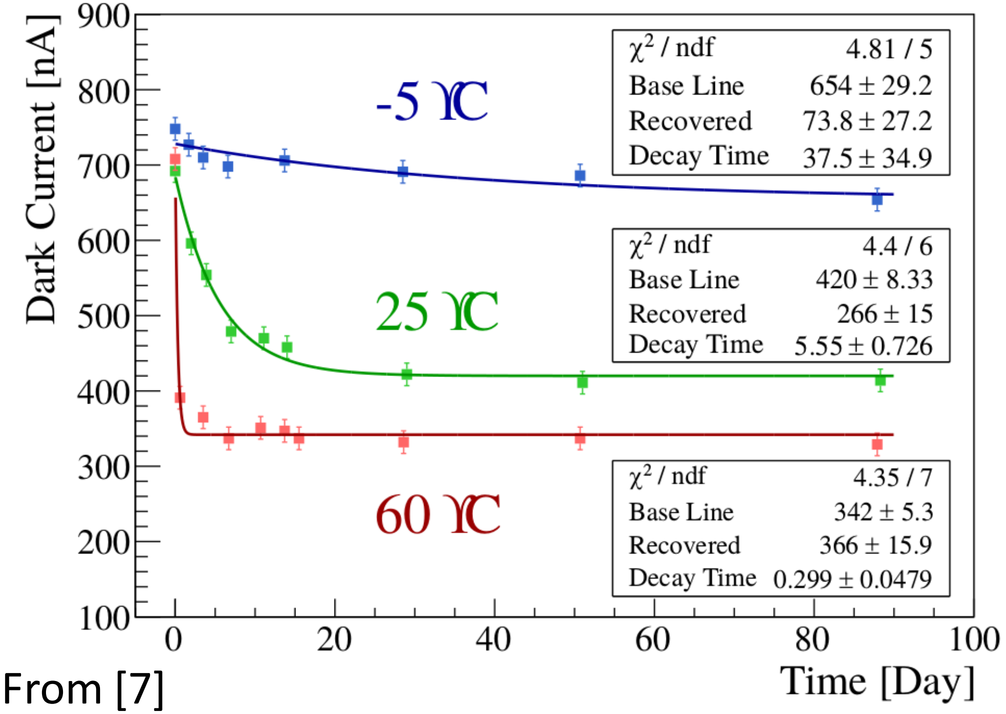
- **Signal loss**
- **~100% recovery after annealing**



From [7]



Effects on SiPM

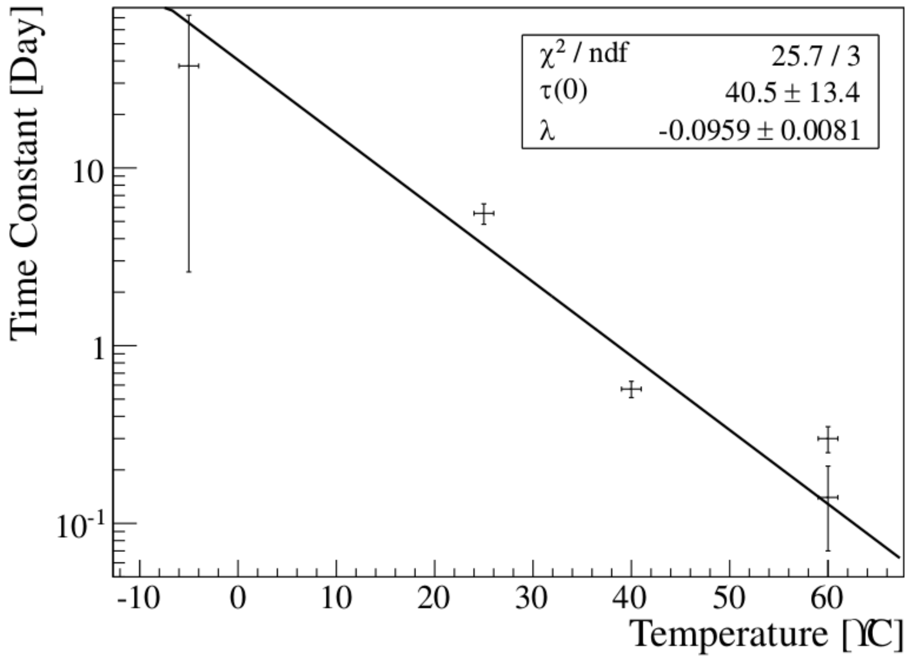


From [7]

$$I = b + a \cdot e^{-t/\tau}$$

Annealing vs. temperature:

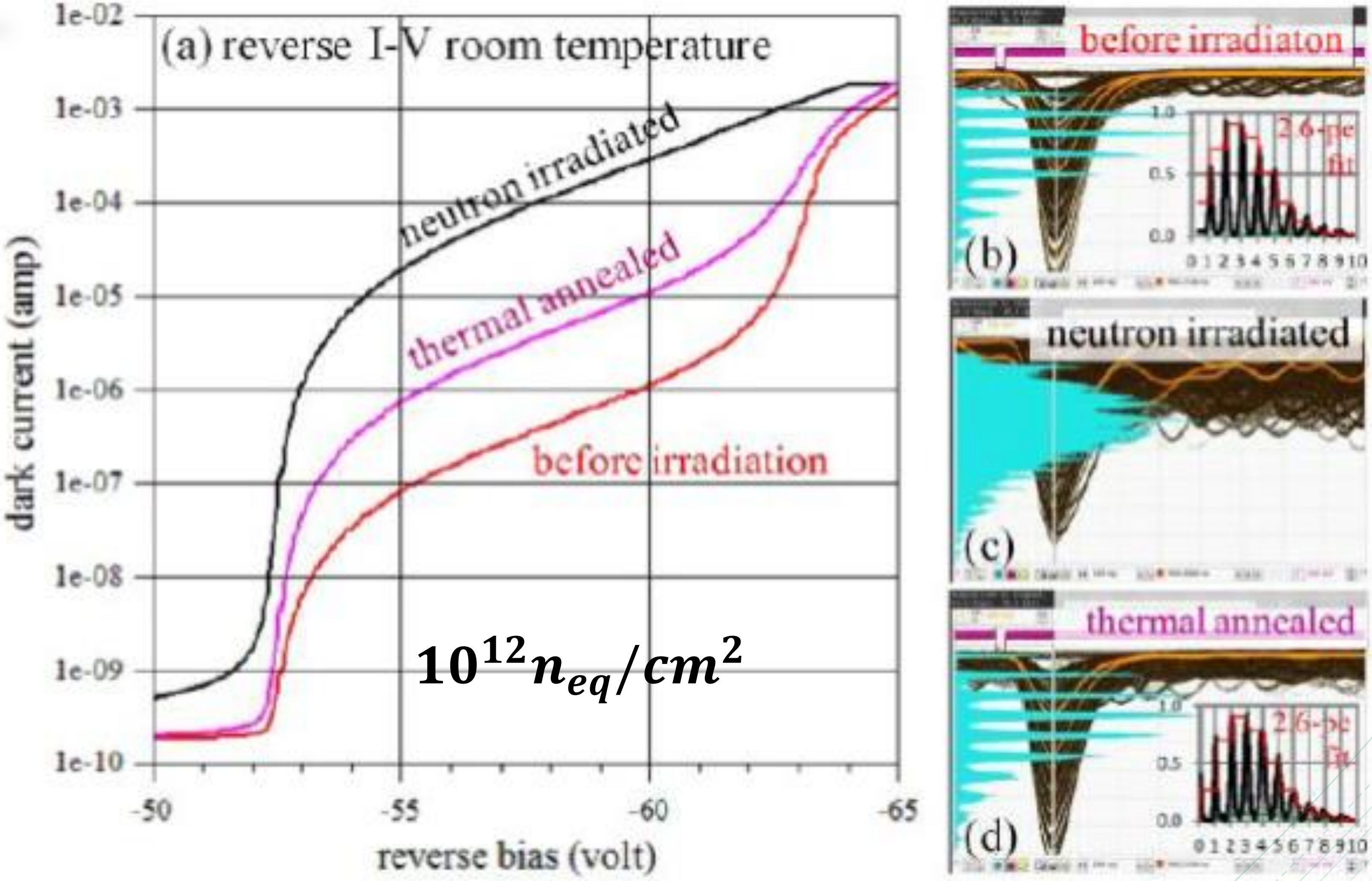
- **Higher T => more recovery**
- **Higher T => faster recovery**



$$\tau(T) = 41 \cdot e^{-0.10 \cdot T}\,\mathrm{day}$$

Effects on SiPM

- 20 times reduction of the DCR after annealing @250°C
- Single photon resolution lost and recovered @-50°C after annealing

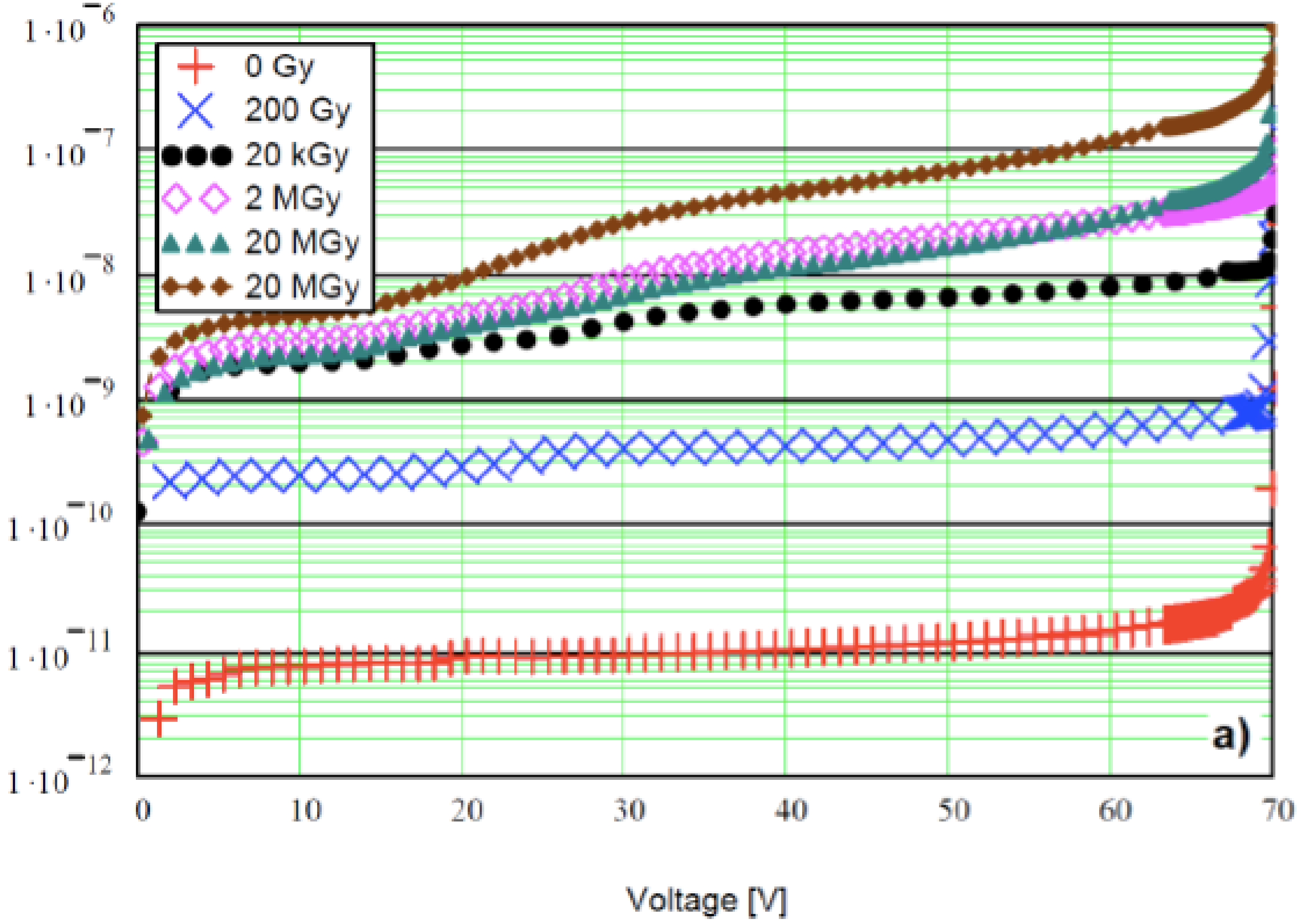


$10^{12} n_{eq}/cm^2$

From [8]

Effects on SiPM

- Surface damage only: X-ray <300keV
- Hamamatsu: S10362-11-050C
- < V_{br}: increase by factor of 10^4 @ 20MGy



Idea to improve radiation hardness

Idea to improve radiation hardness

- **Tiny pixel size** (harsh environments)
  - DCR increase is equivalent to lower effective PDE (high occupancy)
  - lower fraction of “dead” cells due to DCR
  - smaller Cd → reduced recovery time
  - smaller gain → reduced charge trapping

- **Cooling**
  - reduce DCR by factor of 2 when temperature decrease by 8-10 °C @room temperature

- Optimization of **entrance window**
  - reduce light losses
  - avoid trapping

Summary

- Radiation damage in silicon
  - Bulk damage (NIEL) & Surface damage (IEL)

- Effect on SiPM
  - Significant **D**ark **C**ount **R**ate (DCR) increase
  - Correlated noise increase
  - V_{br} decrease slightly
  - Current under breakdown voltage increase

- Ways to compress the effect:
  - Annealing
  - Lower T
  - Smaller cells
  - Optimization in design

reference

[1]: Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2010 Nov 21;623(3):921-6.

[2]: Mika Huhtinen NIMA 491(2002) 194

[3]: sr-niel.org

[4]: https://rd50.web.cern.ch/NIEL/

[5]: Gunnar Lindström, "Radiation Damage in Silicon Detectors"

[6]: Erika Gautti, University Hamburg, Radiation damage on silicon photo-multipliers

[7]: Radiation Hardness Tests of SiPMs for the JLab Hall D Barrel Calorimeter

[8]: T.Tsang et al – JINST 11 (2016) P12002

[9]: Status and Perspectives for Silicon Photo-Multipliers, 2020 November 13th, CERN Detector Seminar

Backup slides

TODO:

- add more radiation hardness
- Finish the reference
- Check everything

NIEL

$$\boxed{NIEL(E) = N \int_{T_d}^{T_{max}} T L(T) \frac{d\sigma(T,E)}{dT} dT}$$

N: Atoms number density

T: Transferred energy

$L(T)$: Lindhard's partition function →

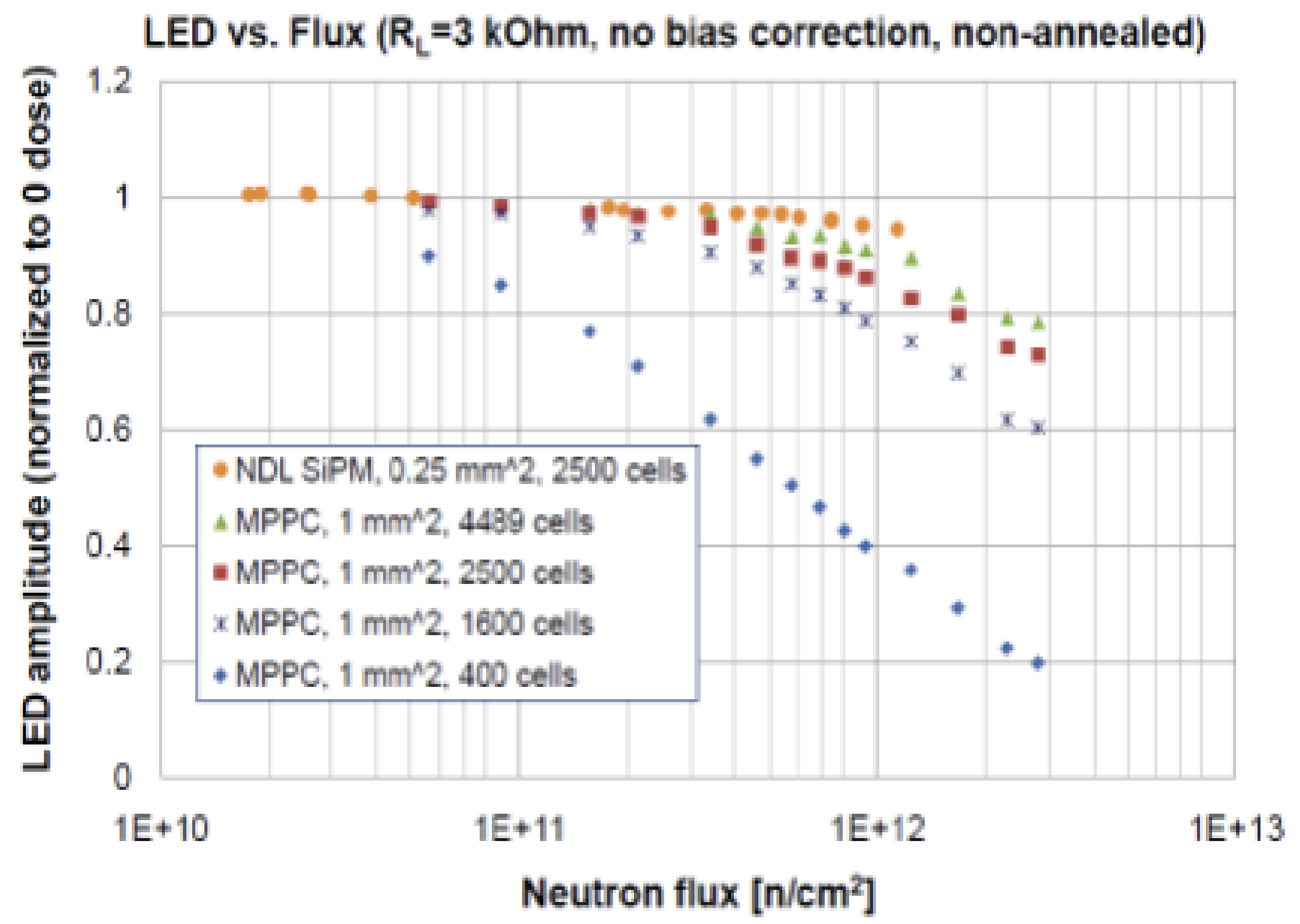
$\frac{d\sigma(T,E)}{dT}$: Differential cross section

J. Lindhard, V. Nielsen, M. Scharff and P.V. Thomsen (1963), Kgl. Danske Vidensk. Selsk. Mat.-Fys. Medd. 33 (no. 10), 1.

D vs. NIEL for bulk damage

- Numerous observations => **displacement damage cross section *D***.
- D is equivalent to the **N**on **I**onizing **E**nergy **L**oss (***NIEL)***
- the proportionality between the NIEL-value and the resulting damage effects is referred to as the ***NIEL-scaling hypothesis*** (for deviations to this rule see below).
- D is normally quantified in [MeVmb], whereas the NIEL-value is given in [keVcm^2/g].
- silicon (A=28.086 g/mol) the relation between ***D*** and ***NIEL*** is: **100MeVmb=2.144 keVcm^2/g**.
- The D or NIEL value is depending on the particle type and energy.
- the displacement damage cross section for 1 MeV neutrons is set as a normalizing value: ***Dn(1MeV) = 95 MeVmb***.
- On the basis of the NIEL scaling the damage efficiency of any ***particle*** with a given kinetic energy ***E*** can then be described by the **hardness factor *k***, defined as ***kparticle (E)=Dparticle/Dn(1MeVn)***.

Smaller cell size better radiation hardness



Smaller cell size better radiation hardness

Surface damage only: X-ray <300keV

- $> V_{br}$: dark current increase by:
  - 2 @dose <20kGy
  - 10^3 @dose >2MGy