Radiation damage on silicon photo-multipliers

Erika Gautti

Relevance of radiation damage in SiPM

Scientific motivation:

- SiPMs considered as photo-sensor of choice in many upcoming experiments
- Up to now limited investigation of radiation damage in SiPM is available

Imaging calorimeters for collider experiments:

- Hadronic calorimeter for ILC (CALICE)

  ➔ ~ 10^{10} n/cm^2 in the endcap region (after 500 fb^{-1})
- Upgrade of hadronic calorimeter for CMS

  ➔ $6x10^{13}$ n/cm^2 (after 300 fb^{-1})

Space experiments:

- Very high radiation expected for detectors in space

  ➔5 10^{10} n/cm^2, AGILE gamma ray detector in geostationary orbit

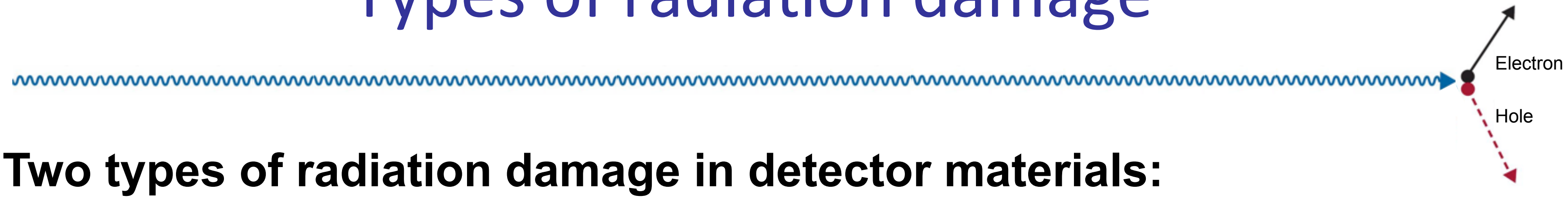
Outline

- Radiation damage in silicon
- Silicon Photo-multipliers
- Surface damage in silicon photo-multipliers
- Bulk damage in silicon photo-multipliers

Radiation damage in silicon

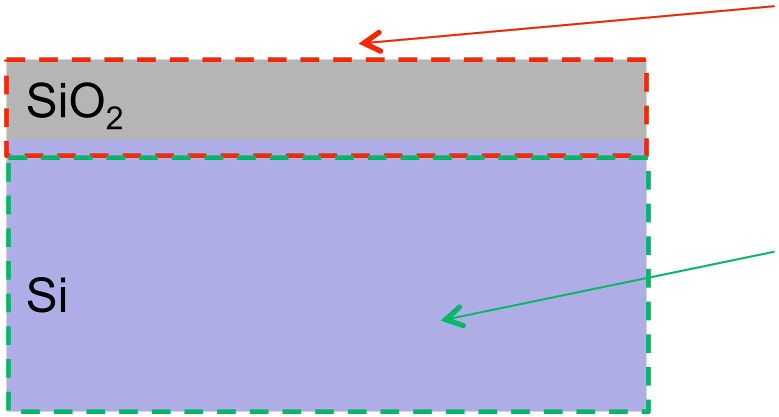
Note: for a detailed and complete treatment see Michael Moll lecture last week

Types of radiation damage



Two types of radiation damage in detector materials:

- **<u>Bulk (Crystal) damage</u>** due to **<u>Non Ionizing Energy Loss</u> (<u>NIEL</u>)**
  - displacement damage, built up of crystal defects –
- **<u>Surface damage</u>** due to **<u>Ionizing Energy Loss</u> (<u>IEL</u>)**
  - accumulation of charge in the oxide (SiO_2), traps at Si/SiO_2 interface –

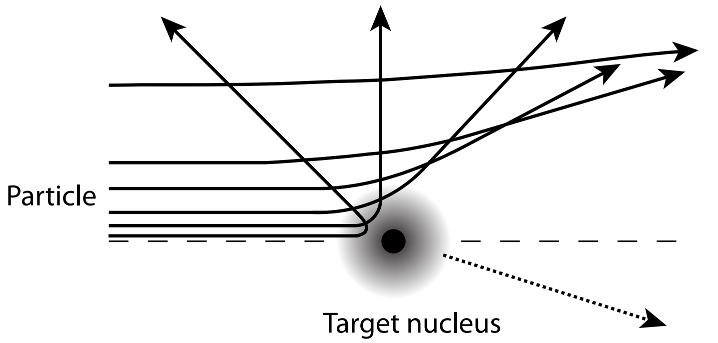


Region affected by ionizing energy loss - surface damage

Region affected by non-ionizing energy loss - bulk damage

Bulk damage by Non Ionising Energy Loss (NIEL)

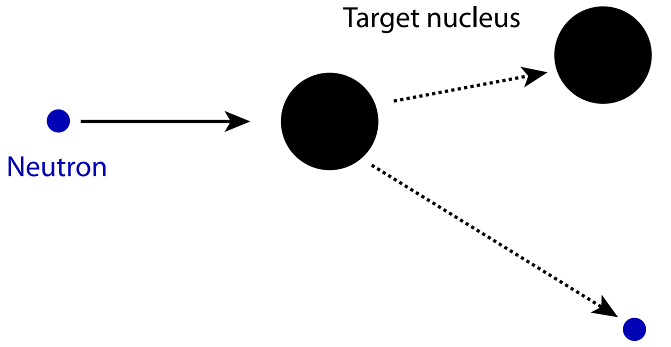
Coulomb scattering

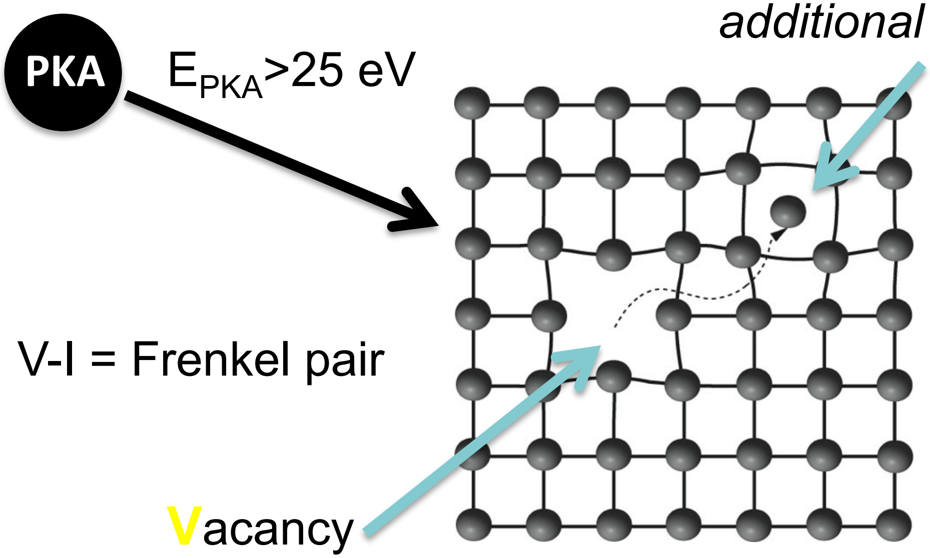


Gamma/ X-ray	**Electrons**	**Protons**	**Neutrons**
Compton electrons	Coulomb scattering	Coulomb & elastic nuclear scattering	elastic nuclear scattering

Primary Knock on Atom (PKA)

Elastic nuclear scattering





E_{PKA}>25 eV

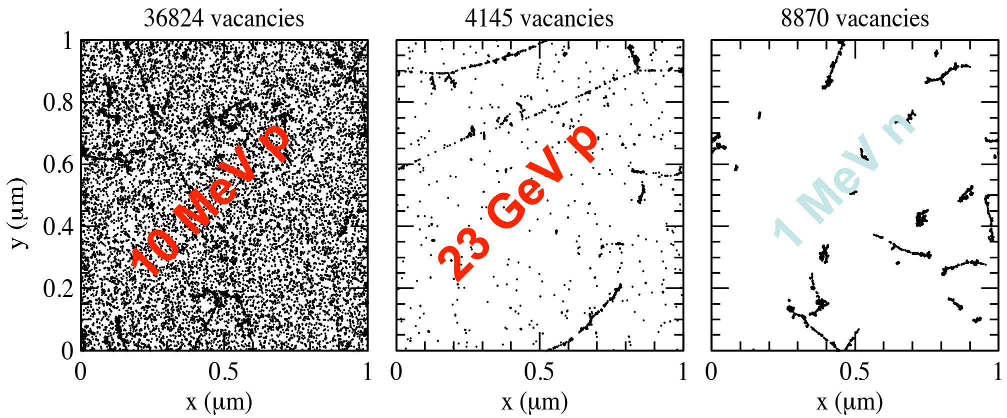
Interstitial
additional Si atom

V-I = Frenkel pair

Vacancy
missing Si atom

Bulk damage: cluster formation

Depending on particle charge and mass

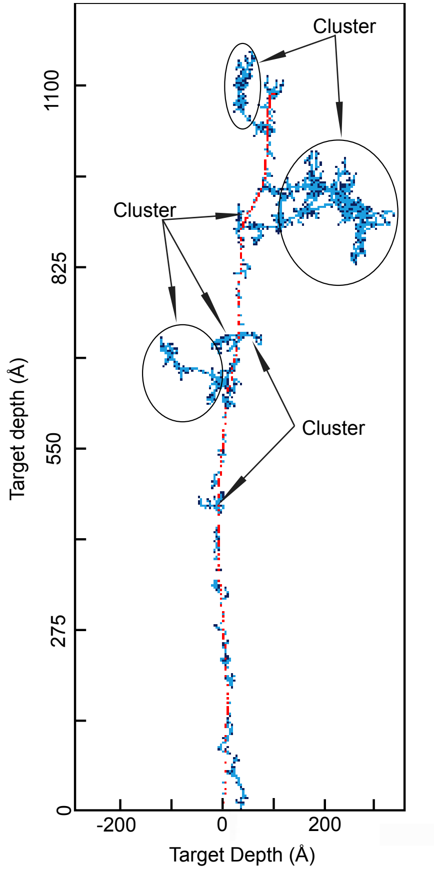


[Mika Huhtinen NIMA 491(2002) 194]

Simulation: Distribution of vacancies after $\Phi_{eq}=10^{14}$ cm^{-2}

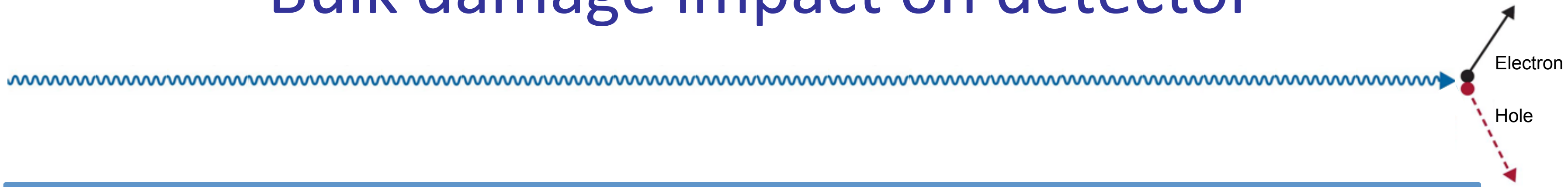
Energy threshold for bulk defects generation:

Particle	Gamma/ X-ray	Electron	Proton	Neutron
Frenkel pair	300 keV	255 keV	185 eV	185 eV
Cluster defects	-	8 MeV	35 keV	35 keV

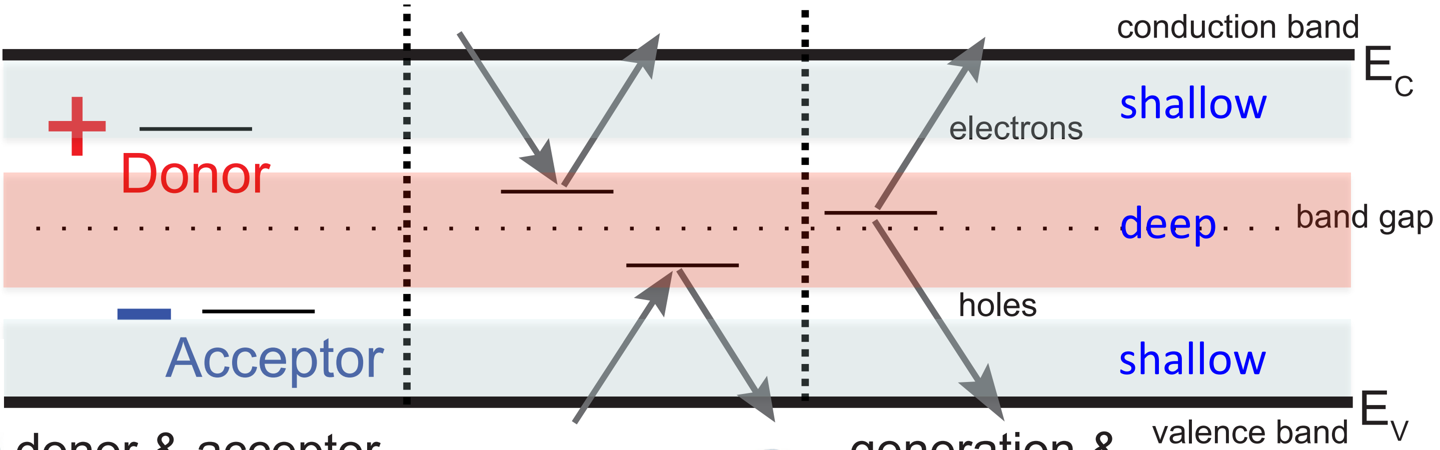


Simulation of 50 keV PKA damage cascade (1 MeV n)

Bulk damage impact on detector

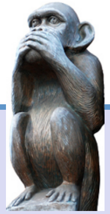


Determined by Shockley-Read-Hall statistics



donor & acceptor generation

trapping



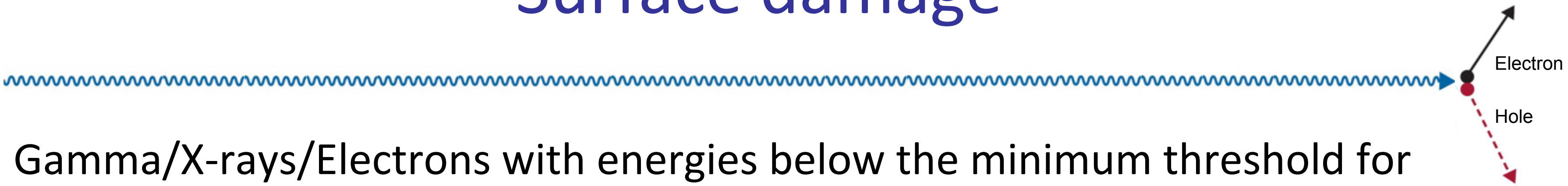
generation & recombination

Charged defects (at RT)
→ change of E-field, V_{dep}
(Acceptors in the lower half and donors in the upper half of the band gap)

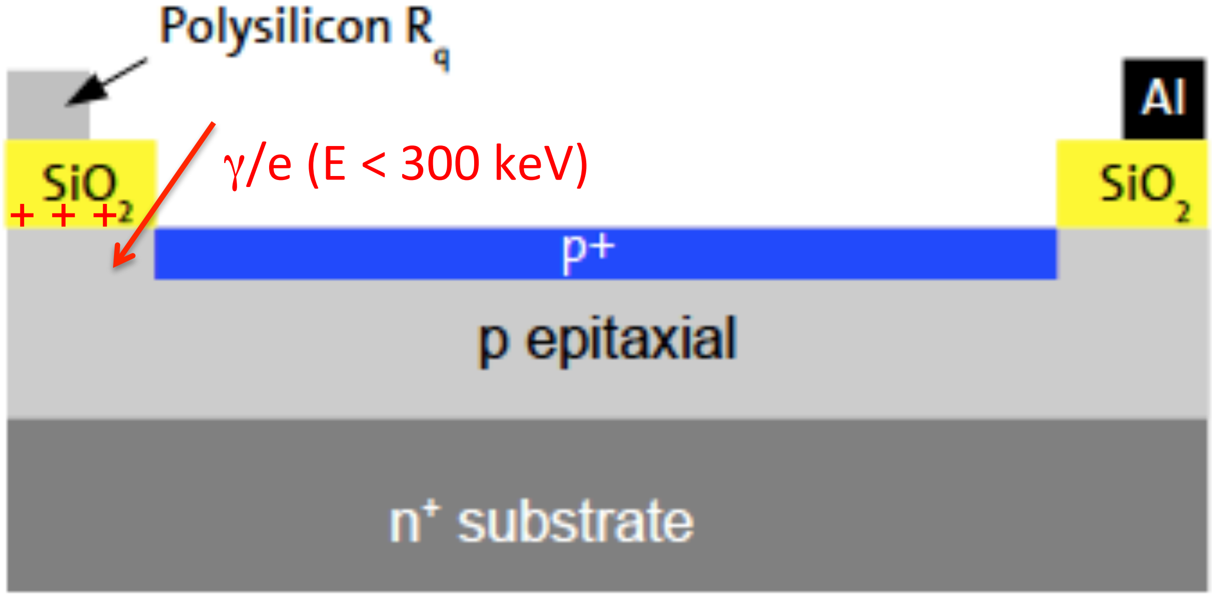
Deep defects
→ signal drop
(Shallow defects do not contribute due to de-trapping)

Levels close to midgap
→ current increase
→ Cooling during operation helps!

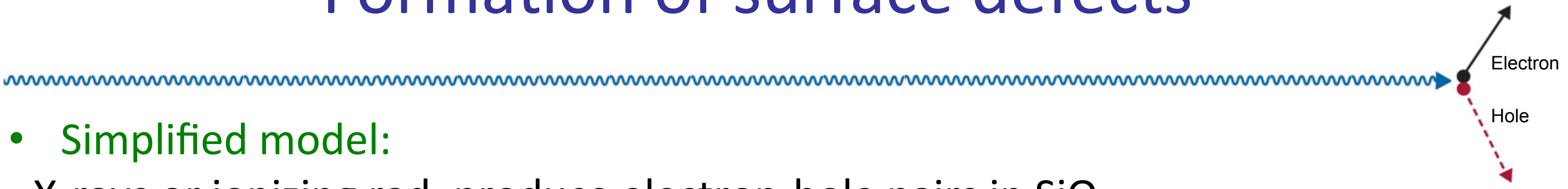
Surface damage



Gamma/X-rays/Electrons with energies below the minimum threshold for bulk defects (~300 keV) generate only defects in the dielectrics, at the Si-SiO$_2$ interface and at the interface between dielectrics (~18 eV / e/h pair)



Formation of surface defects



- Simplified model:

- X-rays or ionizing rad. produce electron-hole pairs in SiO_2
- Fraction of electron-hole pairs recombine
- Remaining electrons escape from SiO_2
  $[\mu_e \sim 20\ cm^2/(Vs)]$
- Remaining holes move toward the Si-SiO2 interface
  $[\mu_h \sim 5\ 10^{-5}\ cm^2/(Vs)]$

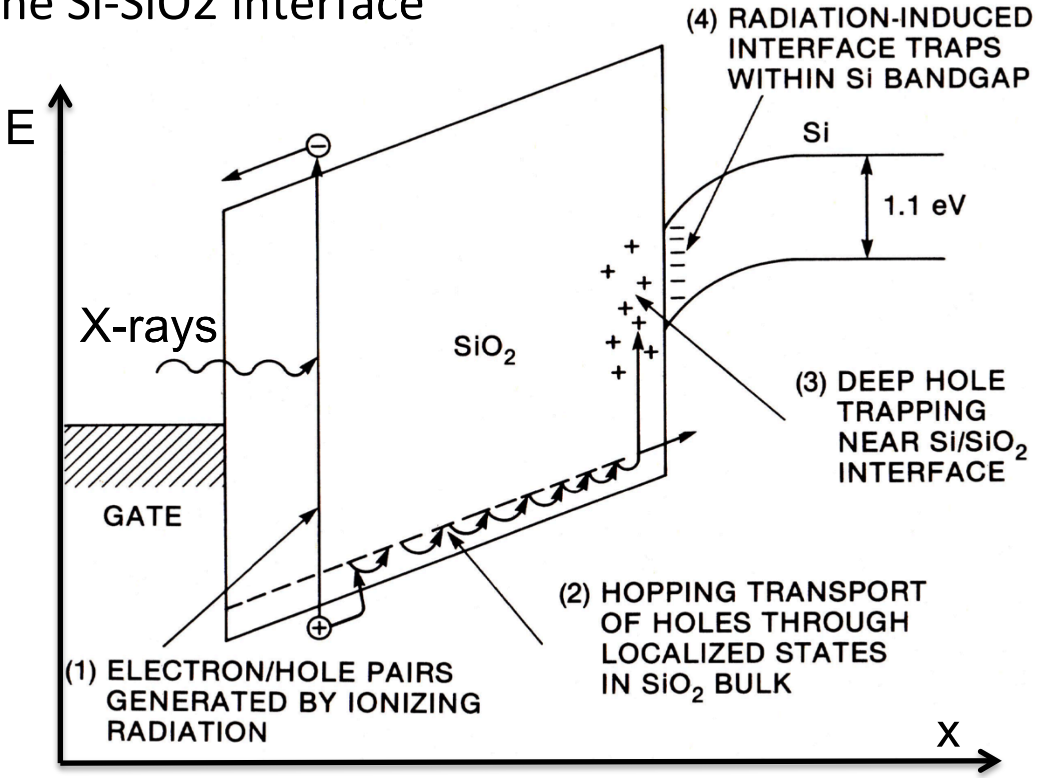
1. Fixed oxide charges: N_{ox}
2. Interface traps: N_{it}, $D_{it}(E)$

- Details depend on:

Oxide thickness, growth and annealing, electrical field, dose, dose rate, temperature, crystal orientation

- Also electrons can be trapped

(cross-section ≈ $10^{-17}\ cm^2$)



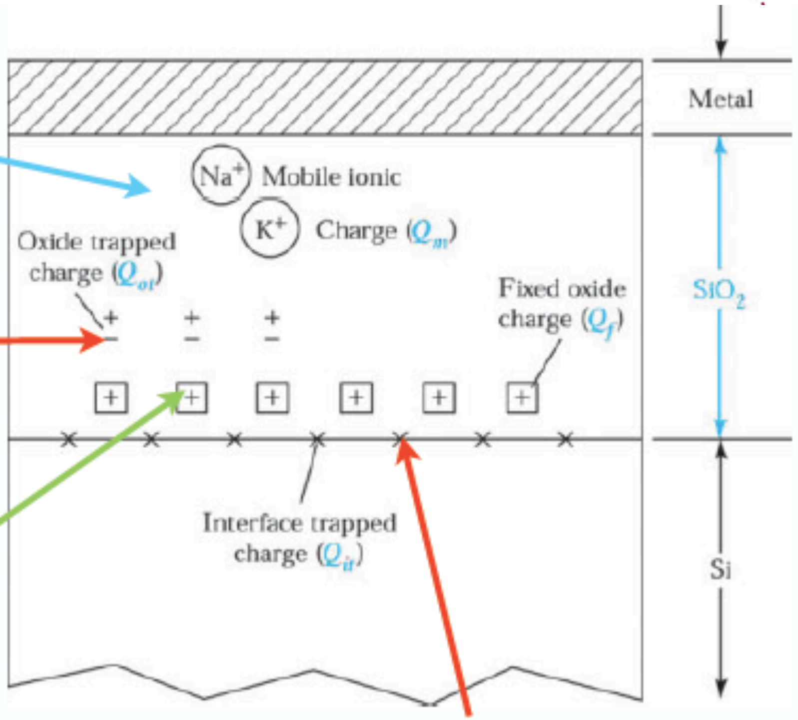
Defects/Impurities in SiO_2

Mobile Ionic Charge Q_m (N_m)
Affected early stage of MOS structures, sometimes also an issue today

Oxide Trapped Charge Q_{ot} (N_{ot})
May be positive or negative due to holes or electrons trapped in the bulk of the oxide. Trapping may result from ionizing radiation, avalanche injection, or other similar processes.

Fixed Oxide Charge Q_f (N_f)
Positive charge, due primarily to structural defects (ionized silicon) in the oxide layer less than 2.5 nm from the Si-SiO_2 interface.

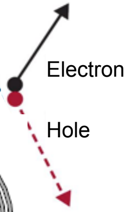
Border Traps
Near-interface oxide traps located within approximately 3 nm of the Si-SiO_2 interface. Those traps can communicate with the Si on the time scale of interest via capture and emission.



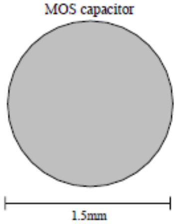
Interface Trapped Charge Q_{it} (N_{it})
Positive or negative charges, due to 1) structural, oxidation-induced defects 2) metal impurities, or 3) other defects caused by radiation or similar bond breaking processes. They are located at the Si-SiO_2 interface.

For this talk an „effective“ oxide-charge density N_{ox} with units cm^{-2} is used!

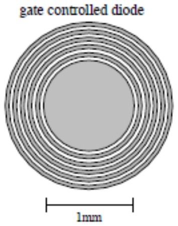
Measured damage on MOS and GCD



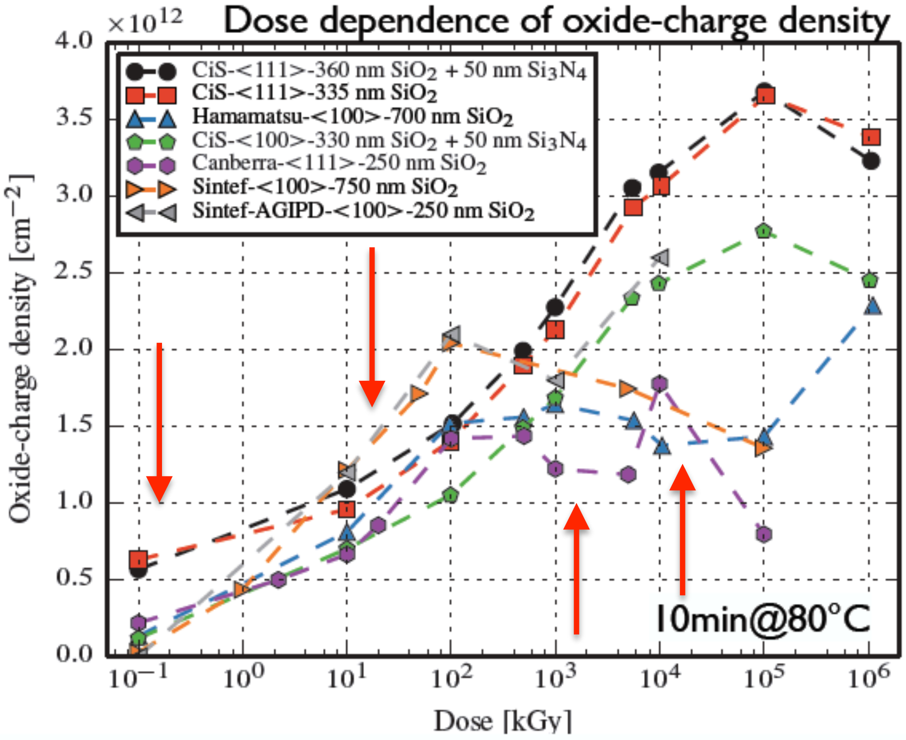
Test structure:
MOS capacitors
from different vendors
Measure: C/G-V vs. f (1 kHz - 1 MHz)

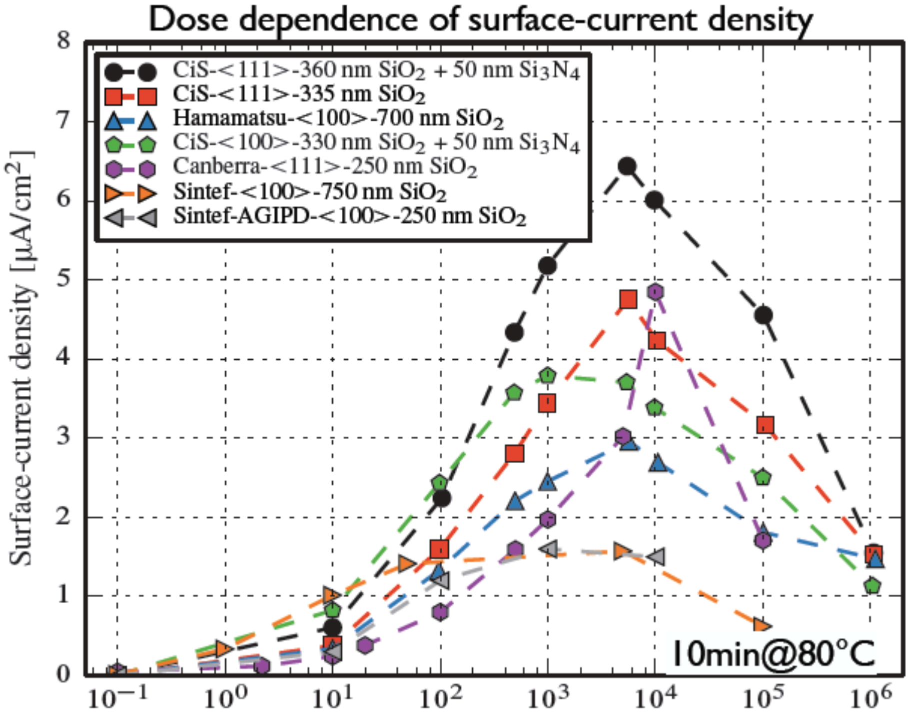


Test structure:
Gate controlled diodes
from different vendors
Measure: I-V



R.Klanner et al., NIM A 732 (2013) 117

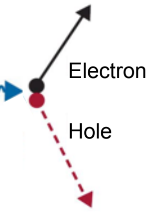




Oxide-charge densities saturate!!!
(max. value: N_{ox} = 1.5 - $4 \cdot 10^{12}$ cm^{-2})

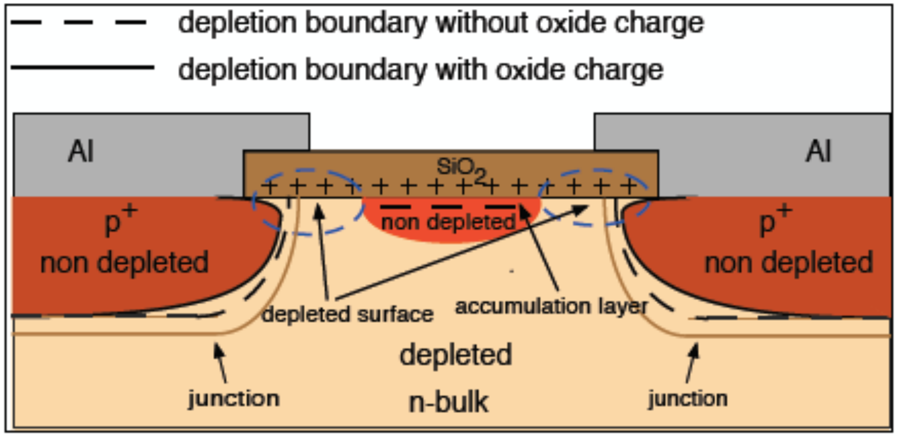
Surface-current densities saturate
(decrease?) with dose
(max. value: J_{surf} = 1.5 - 6 $\mu A/cm^2$)

Effects of surface defects



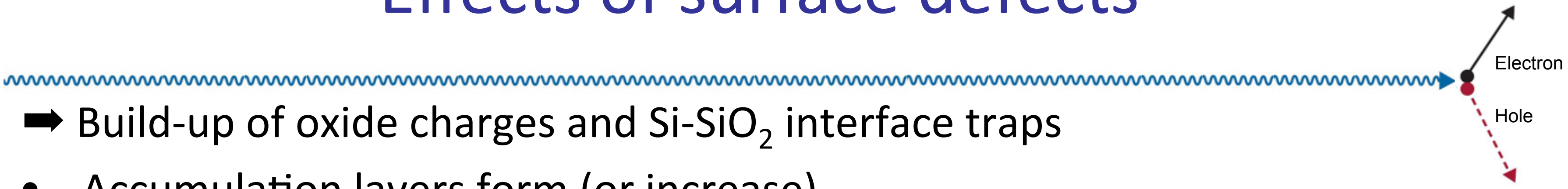
➡ Build-up of oxide charges and Si-SiO$_2$ interface traps

- Accumulation layers form (or increase)
- High field regions appear reducing the breakdown voltage
- Leakage currents increase due to interface states
- Depletion voltage and inter-pixel capacitances increase
- Charge losses close to the Si-SiO$_2$ interface occur (or increase)



Schematic picture of surface damage induced effects on a pixel detector

Effects of surface defects



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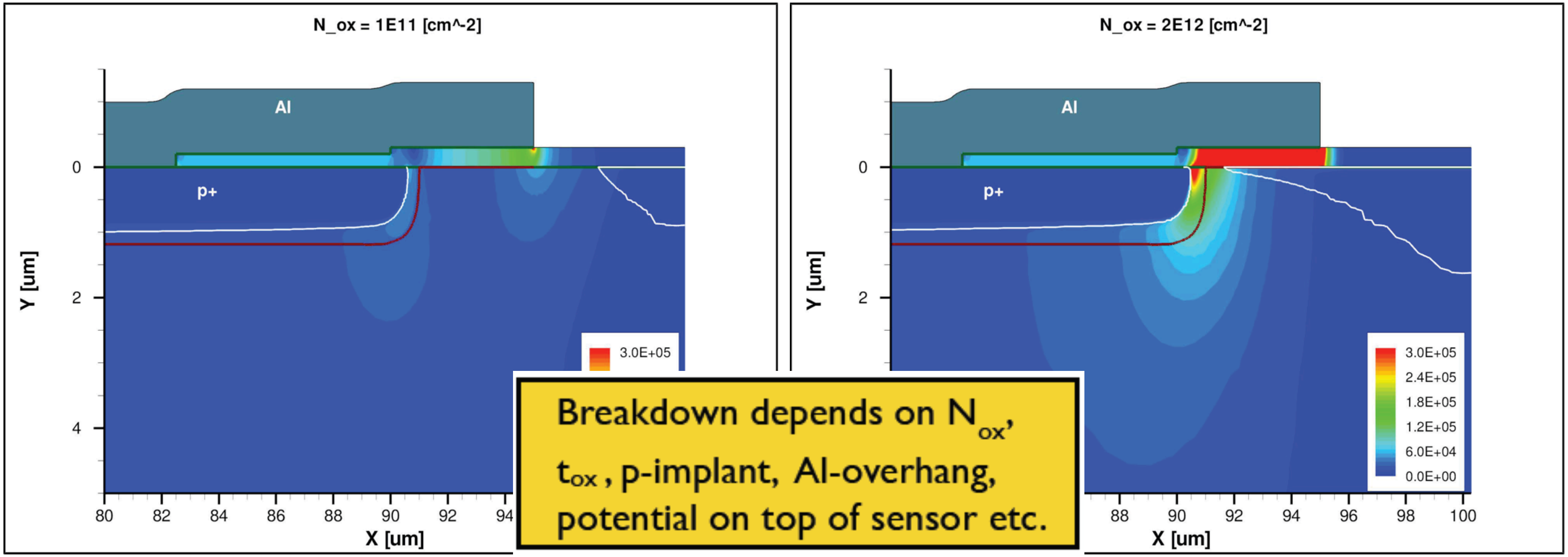
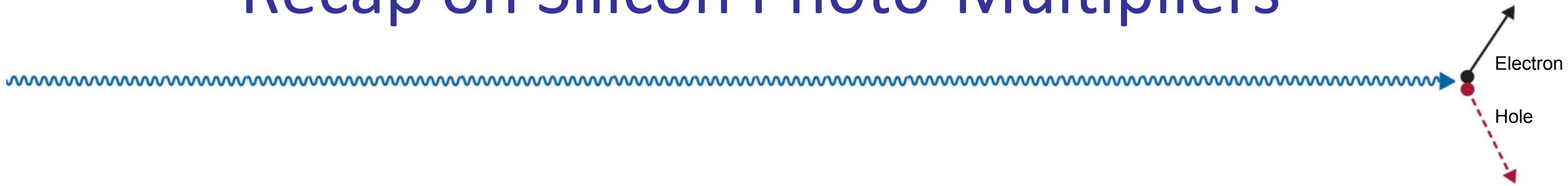


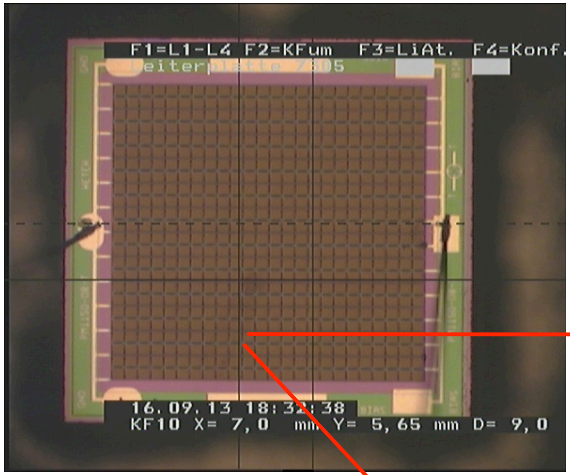
Breakdown depends on N_{ox}, t_{ox}, p-implant, Al-overhang, potential on top of sensor etc.

TCAD simulation of a pixel detector

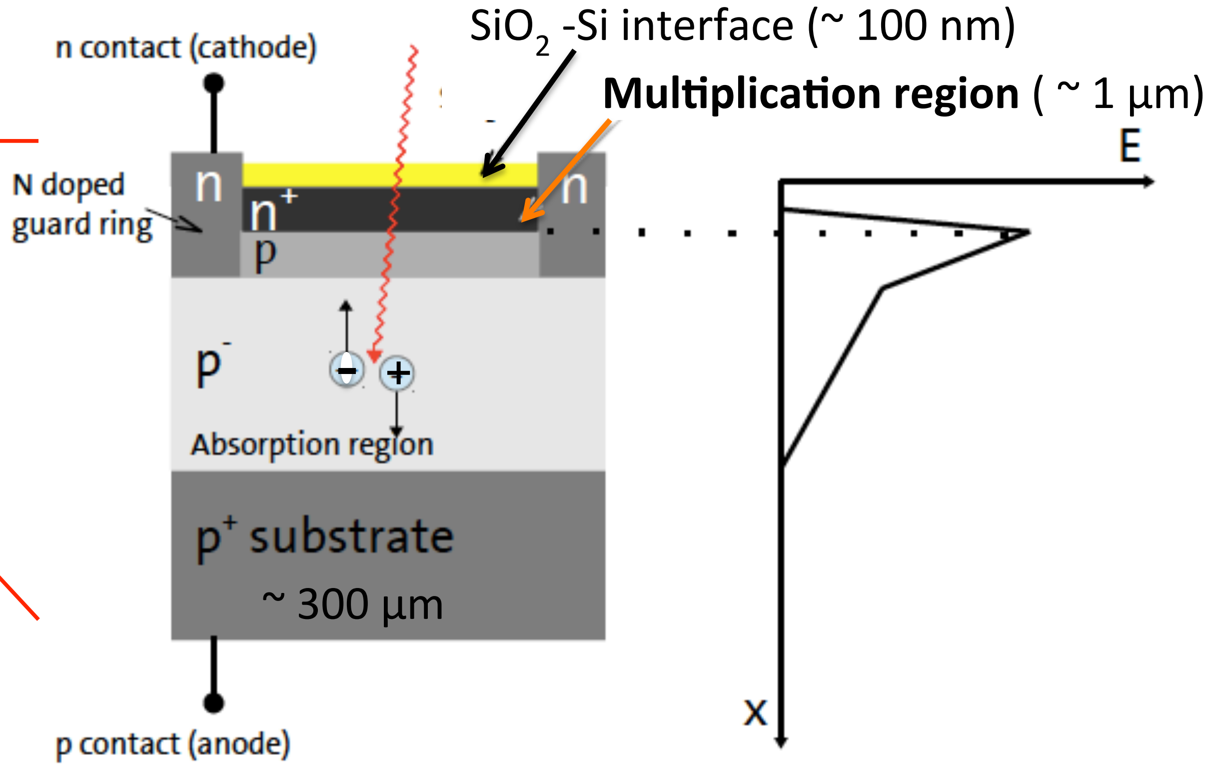
Silicon Photo-multipliers

Recap on Silicon Photo-Multipliers

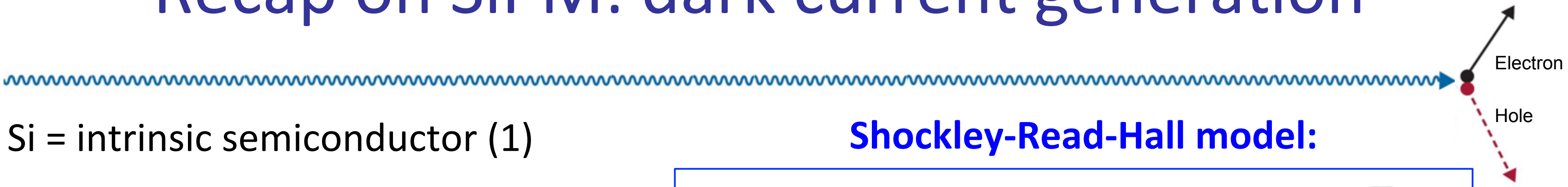




Array of parallel diodes operating in Geiger-Müller regime ($V_{bias} > V_{bd}$)



Recap on SiPM: dark current generation



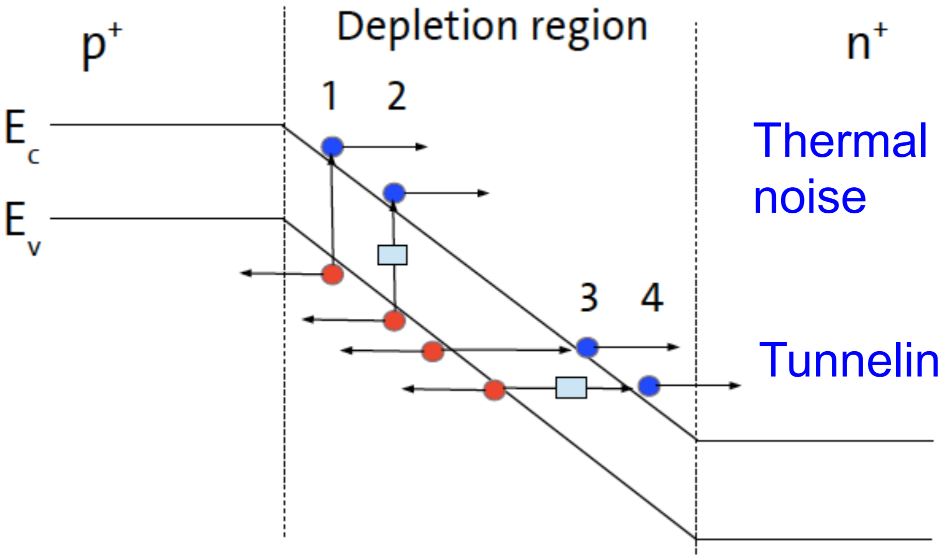
Si = intrinsic semiconductor (1)

Shockley-Read-Hall model:

$$\mathrm{DCR}_{\mathrm{SHR}} \propto N_t \cdot W_D \cdot \sigma_n \cdot T^2 \exp\left(-\frac{E_a}{k_B T}\right)$$

N_t :intrinsic carrier density,
W_d :width of depletion region,
σ_n :defect cross section,
E_a :activation energy (E_c-E_{trap})

The generation of free charge carriers in the depletion region at room temperature is facilitated by trap levels in the band gap introduced by crystal impurities

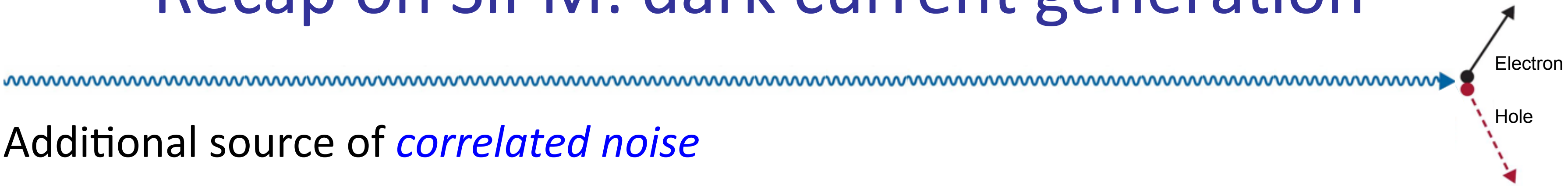


Thermal noise ➔ Dominates at room T and E < 10^6 V/cm

Tunneling ➔ Dominates at low T and E > 10^6 V/cm

1. Direct transition of electron from v-band to c-band (very rare);
2. Trap assisted thermal generation;
3. Tunneling effect; 4. Tunneling effect through a trap level.

Recap on SiPM: dark current generation



Additional source of *correlated noise*

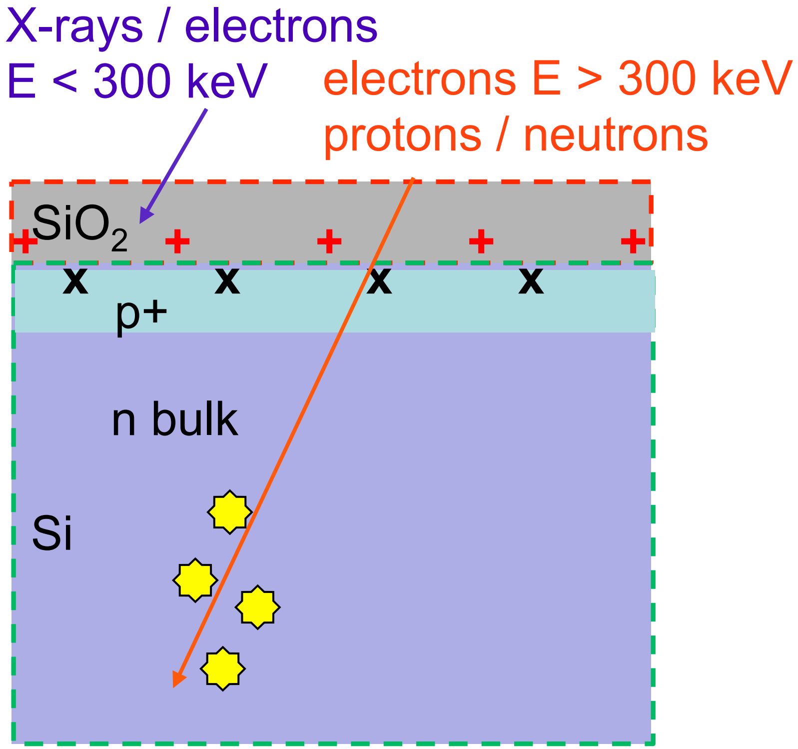
After-pulse: Free charge carriers generated during an avalanche can be captured by trapping centers (impurities) with energy level in the band gap and released with a characteristic time constant.

If $\tau_t >$ avalanche time, the released free carrier can cause an additional avalanche (or pulse) in the same pixel

$$P_{ap}(t) = P_t \cdot \frac{\exp(-t/\tau_t)}{\tau_t} \cdot P_{tr}$$

P_t : trap capture probability, depends on the density of impurities and the carrier flux during the avalanche (gain)
τ_t : trap lifetime, depends on the energy level of the trap and on temperature,
P_{tr} : avalanche triggering probability, it depends on the strength of the local electric field thus the excess bias voltage

Radiation damage in SiPMs



Surface damage:

Generate traps at the Si-SiO_2 interface

Fixed positive oxide charge:

➔ Change in the electric field (V_{bd} reduction)

➔ Accumulation layers

➔ Increase in leakage current

Bulk damage:

(by non-ionising energy loss)

- Locally distorted Si lattice with new energy states
- Add donor and acceptor levels

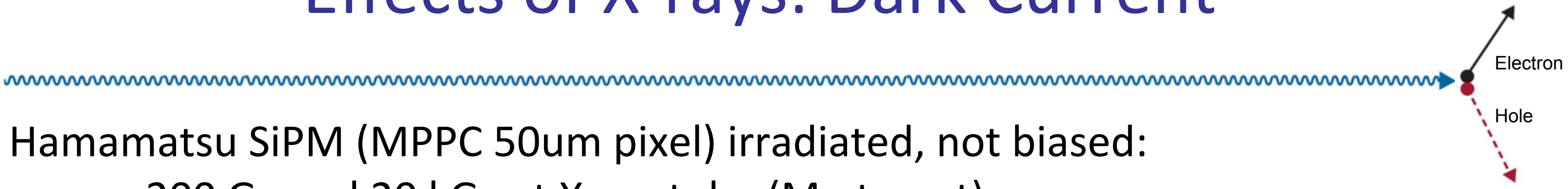
➔ Increase DCR

➔ Increase after-pulsing

➔ Change in charge collection

Surface damage in silicon photo-multipliers

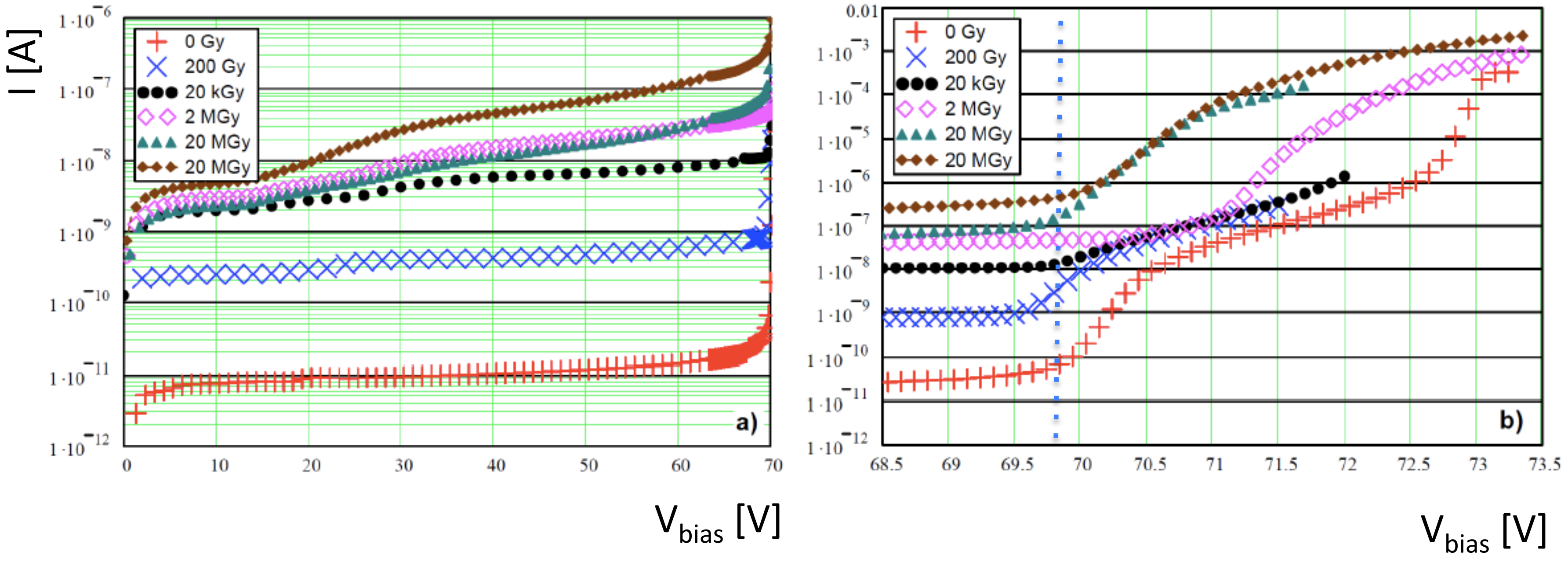
Effects of X-rays: Dark Current



Hamamatsu SiPM (MPPC 50um pixel) irradiated, not biased:

- 200 Gy and 20 kGy at X-ray tube (Mo target)
- 2 and 20 MGy at PETRA III

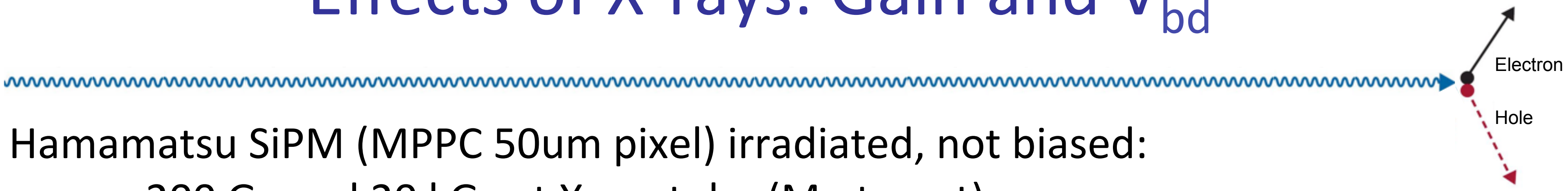
X-ray < 300 keV only surface damage ➔ N_{ox} and J_{surf}



Below V_{bd}: I increases by x10^4 at 20MGy Above V_{bd}: I increases x2 from 0 - 200 kGy and by x10^3 above 20 MGy

C. Xu, W. L. Hellweg, E. Garutti, and R. Klanner, "Influence of X-ray Irradiation on the Properties of the Hamamatsu Silicon Photomultiplier S10362-11-050C", submitted to NIM.

Effects of X-rays: Gain and V_{bd}



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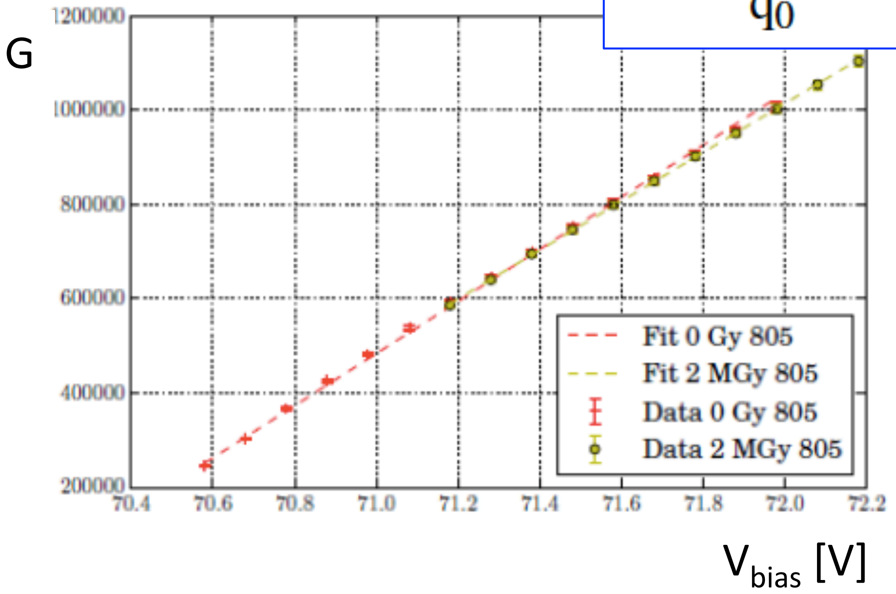
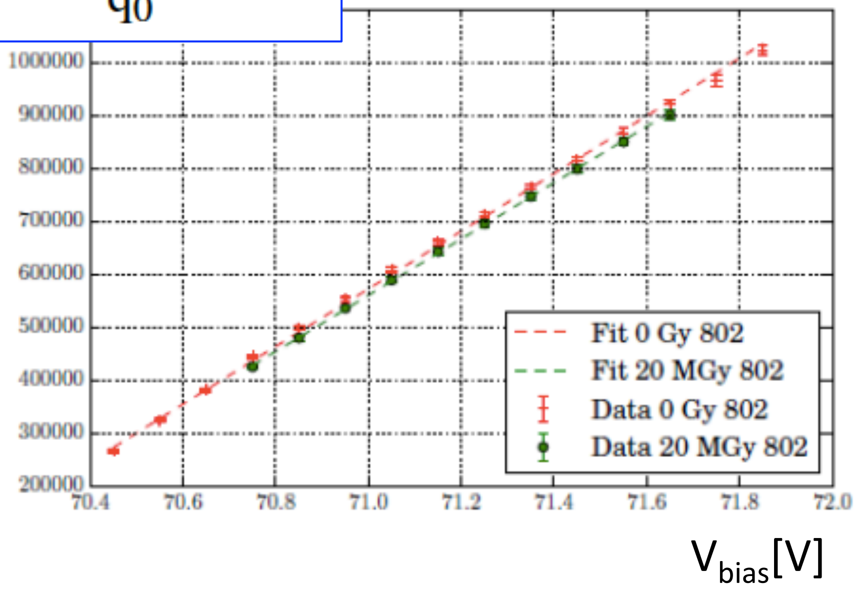
X-ray < 300 keV only surface damage ➔ N_{ox} and J_{surf}

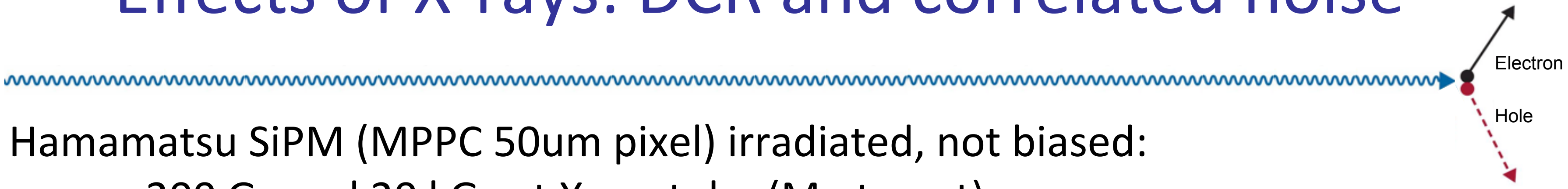
$$G = \frac{Q_{out}}{q_0} = \frac{C_{pix}\cdot(V_{bias}-V_{bd})}{q_0}$$





- V_{bd}: changes < 50mV for 0 – 20 MGy (compatible with 0: T-dependence)
- Gain: changes < 5% for 0 – 20 MGy (small, probably significant reduction)

Effects of X-rays: DCR and correlated noise



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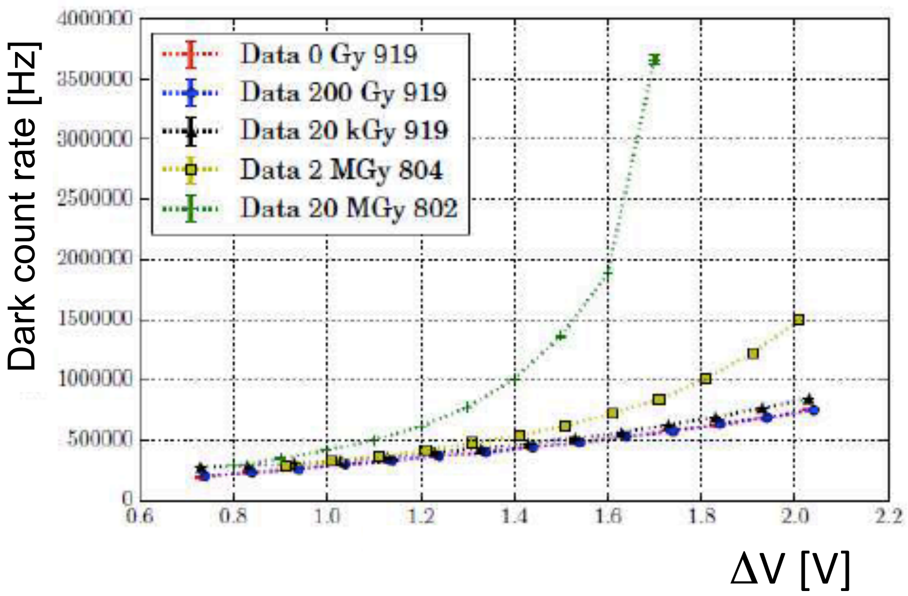
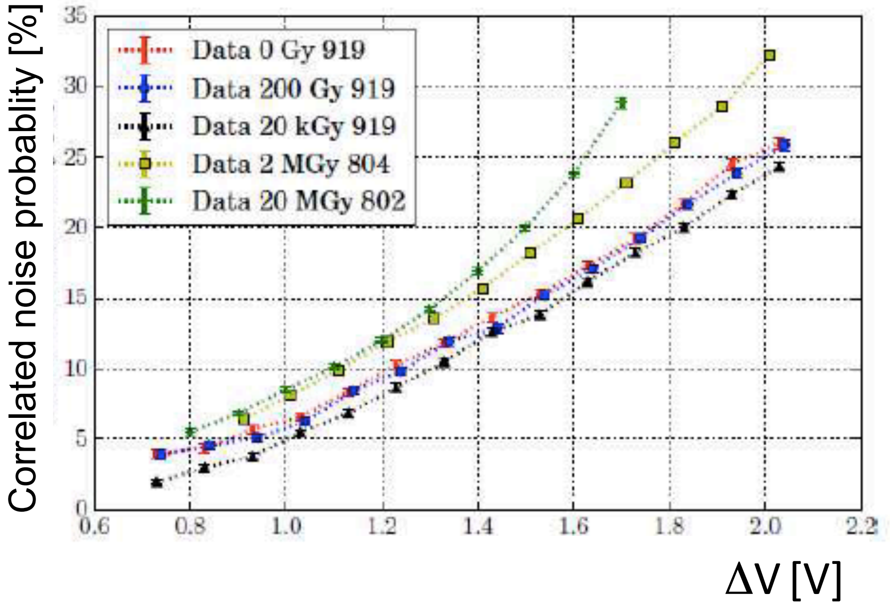
X-ray < 300 keV only surface damage ➔ $N_{o}x$ and J_{surf}





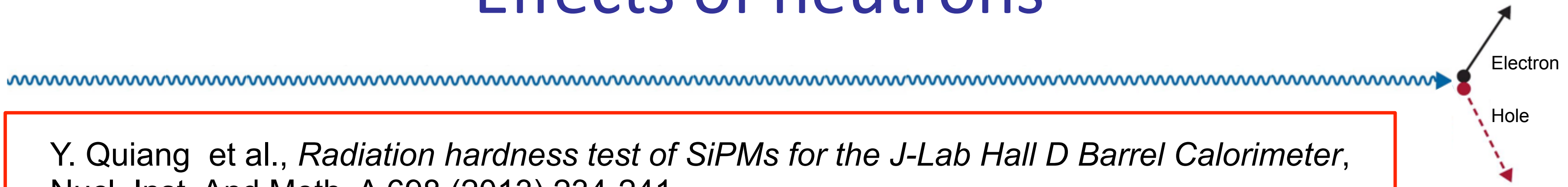
- small increase ~10% for 0-20 kGy
- increase by x3 for V_{ex}>1.5V and 20 MGy
- rapidly increasing with ΔV
  ➔maximum useful gain limited

- negligible change for 0-20 kGy
- unexpected increase for > 2 Mgy

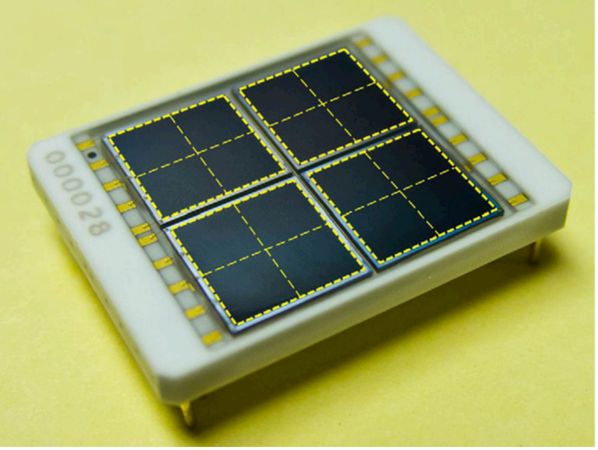
Note: correlated noise includes XT and after-pulse

Bulk damage in silicon photo-multipliers

Effects of neutrons



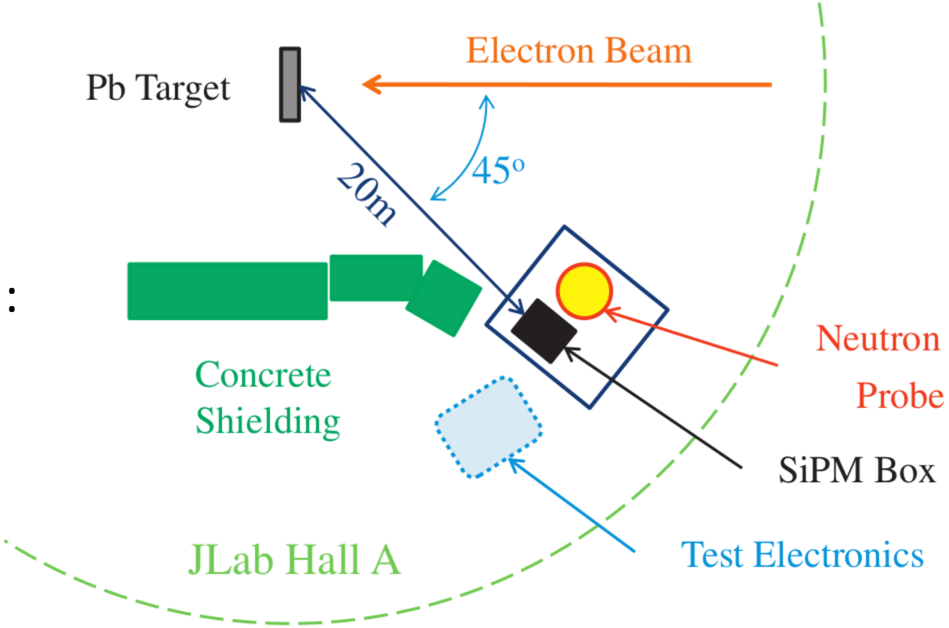
Y. Quiang et al., *Radiation hardness test of SiPMs for the J-Lab Hall D Barrel Calorimeter*, Nucl. Inst. And Meth. A 698 (2013) 234-241



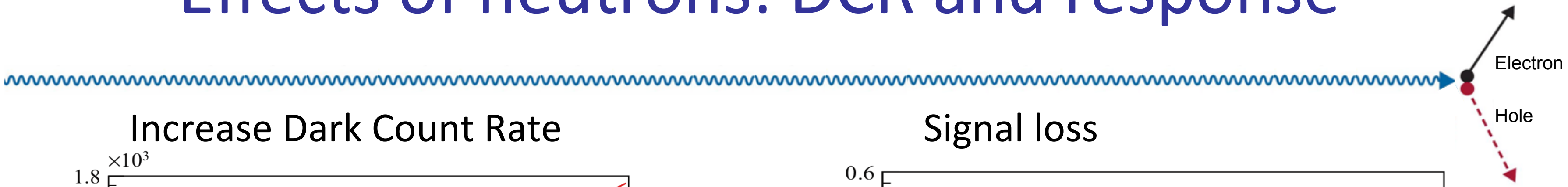
J-Lab Hall D Barrel Calorimeter:
SiPM arrays coupled to scintillator
Test radiation hardness of SiPMs to neutrons

1 GeV e- beam against 0.5 mm Pb target :

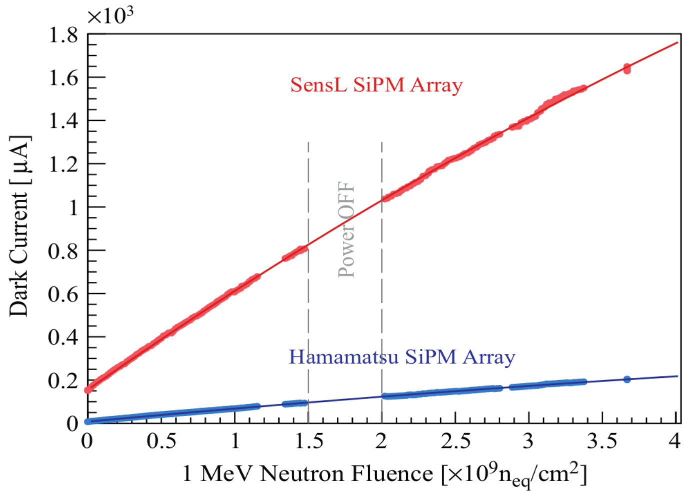
- One array from Hamamatsu
- One array from SensL
- → Monitored during irradiation
  - → Operated at fixed gain of 0.75 x 10^6
- Total final dose: 3.7 x 10^9 n_{eq}/cm^2
  - → 13 years of calorimeter operation



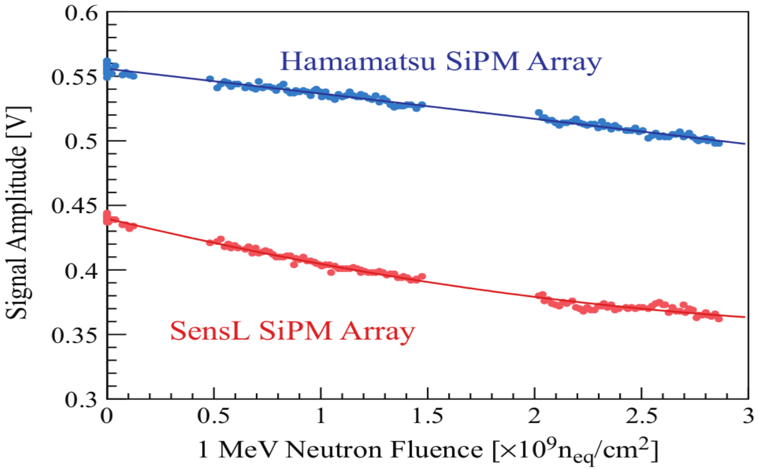
Effects of neutrons: DCR and response



Increase Dark Count Rate

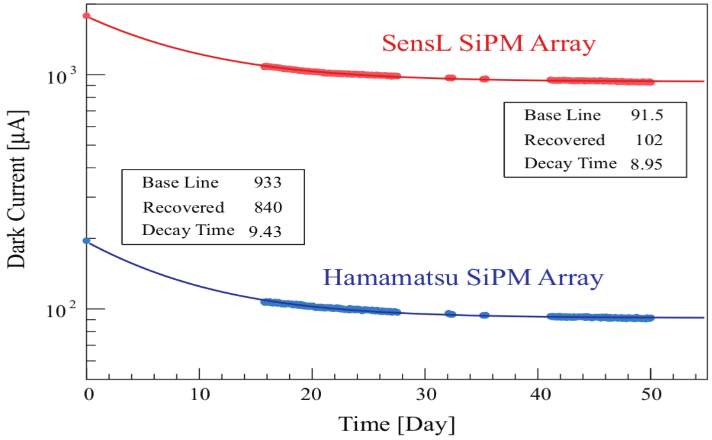


Signal loss

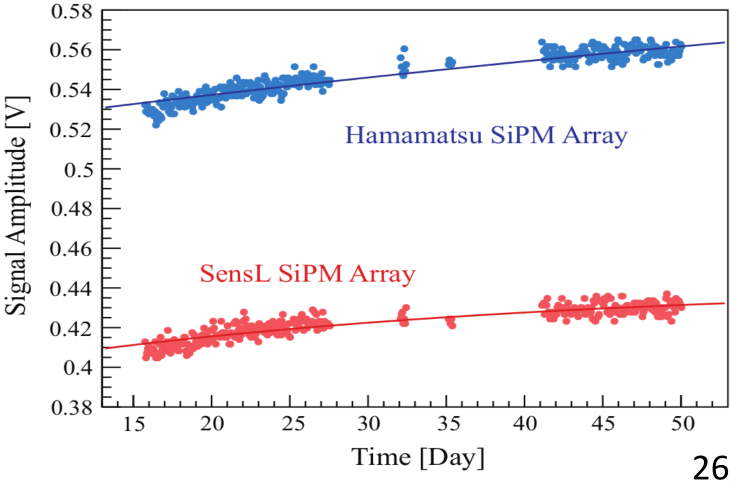


R.T. annealing

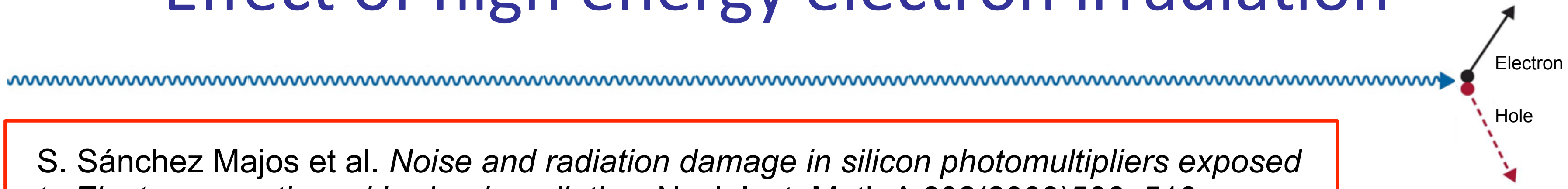
~50% recovery



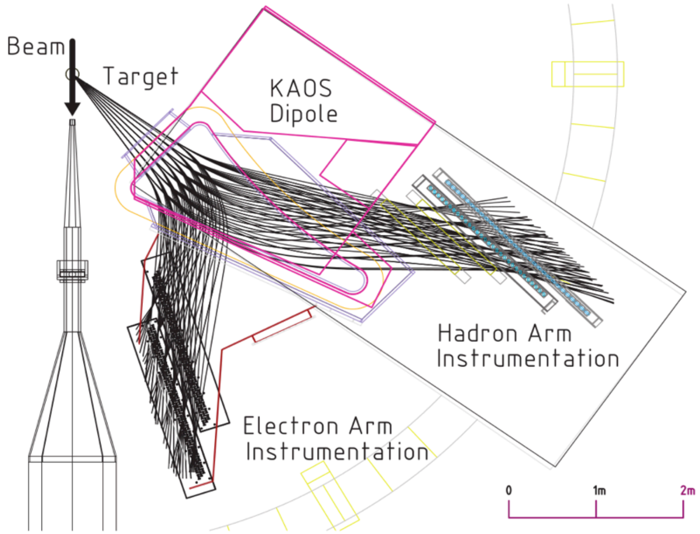
~100% recovery



Effect of high energy electron irradiation



S. Sánchez Majos et al. *Noise and radiation damage in silicon photomultipliers exposed to Electromagnetic and hadronic radiation,* Nucl. Inst. Meth.A 602(2009)506–510



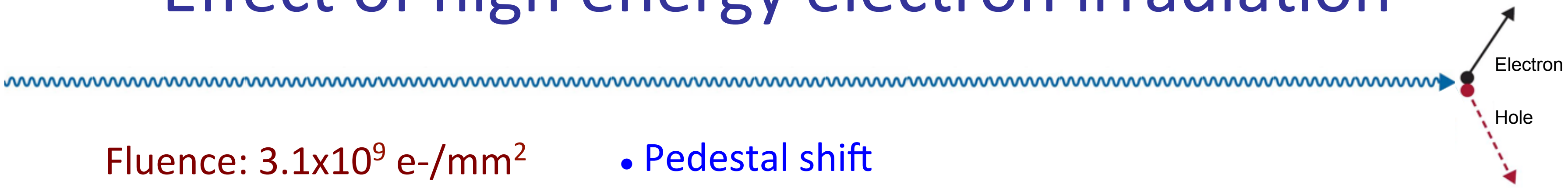
KAOS Spectrometer in Mainz

- Two planes of fiber arrays
- SiPM candidate for fiber read out (Photonique):
  - 1 x 1 mm^2
  - 500 pixels
  - green sensitive (PDE = 40% at λ= 560 nm)
- Electron arm subject to mix of electrons and hadrons

Irradiation with:

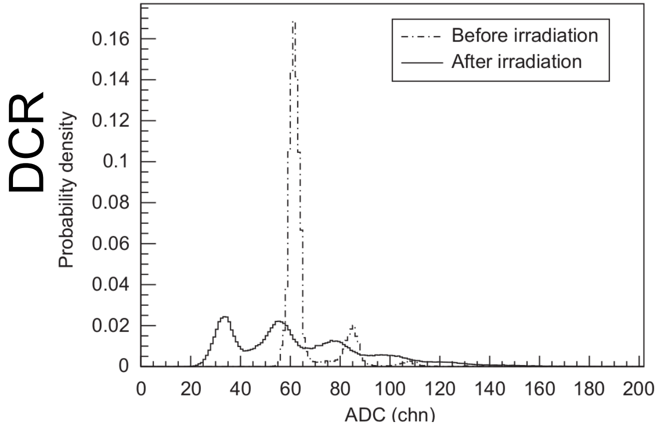
- 14 MeV electrons (NIEL: 1.1×10^{-4} MeV cm^2/g)
  - total fluences: 3.1×10^9 -3.8×10^{10} electrons/mm^2
- mixed hadronic and electromagnetic radiation (to simulate hall irradiation)
  - 10 µA electron beam current
  - Carbon target

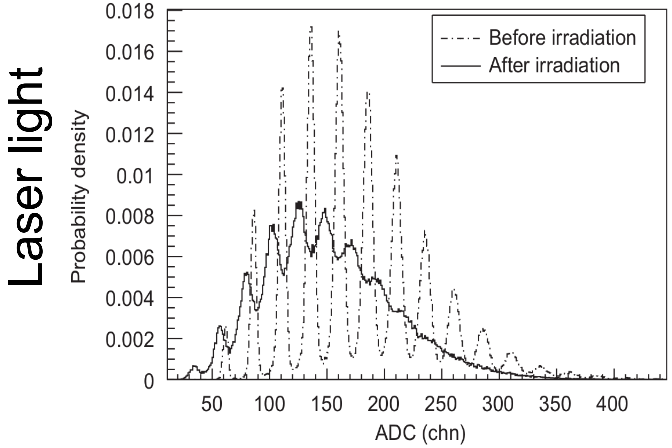
Effect of high energy electron irradiation

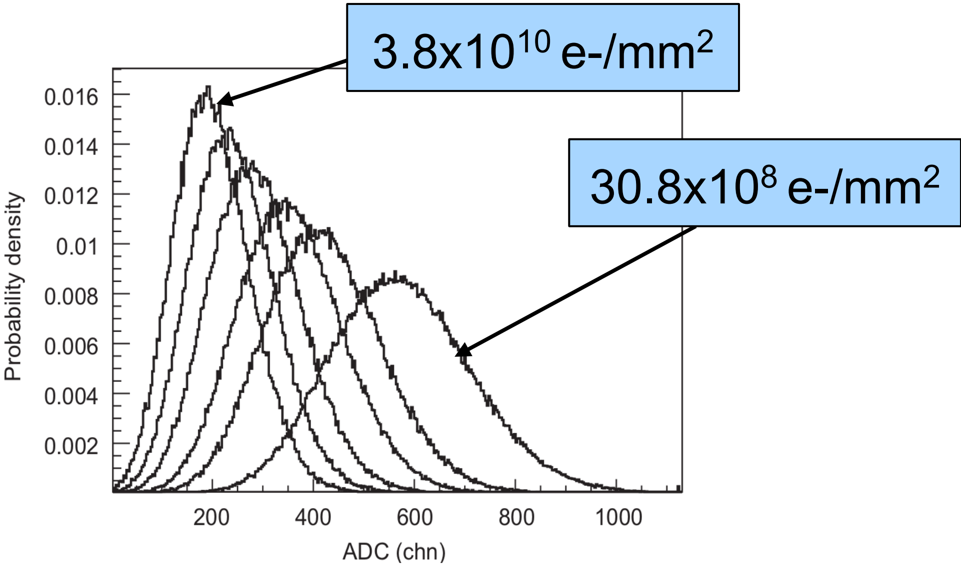


- Pedestal shift
  - → Increment of leakage current
- Change in relative peak height
  - → Increment of DCR
- Peak broadening
  - → Increment of noise
- No peak separation for higher fluences

Fluence: 3.1×10^9 e-/mm^2

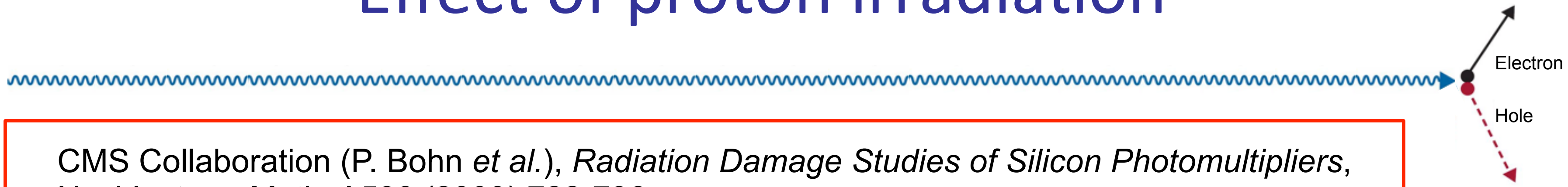






Response at fixed light intensity decreases with fluence

Effect of proton irradiation



CMS Collaboration (P. Bohn *et al.*), *Radiation Damage Studies of Silicon Photomultipliers*, Nucl.Instrum.Meth. A598 (2009) 722-736

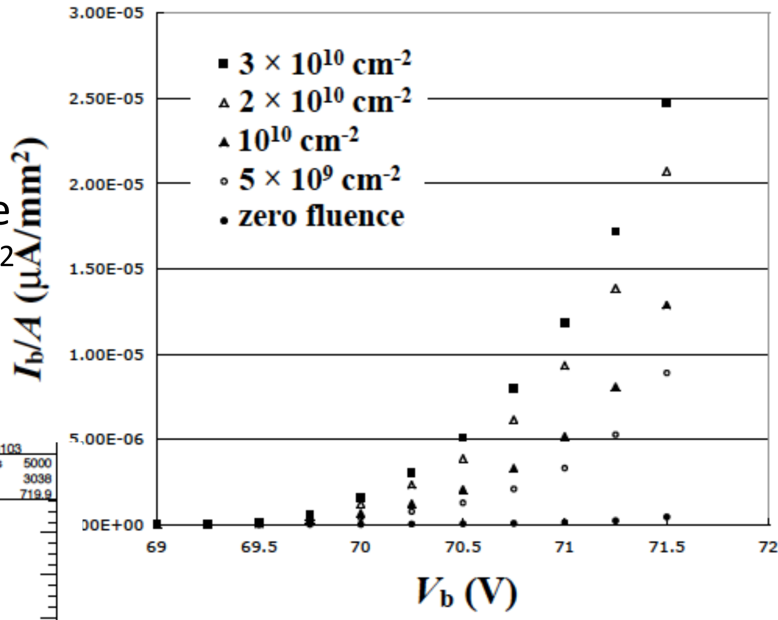
In preparation for the high luminosity CMS upgrade various SiPMs were tested: FBK (1 mm^2 and 6.2 mm^2), CPTA (1 mm^{2}and 4.4 mm^2), MPPC (1 mm^2).

Irradiation with:

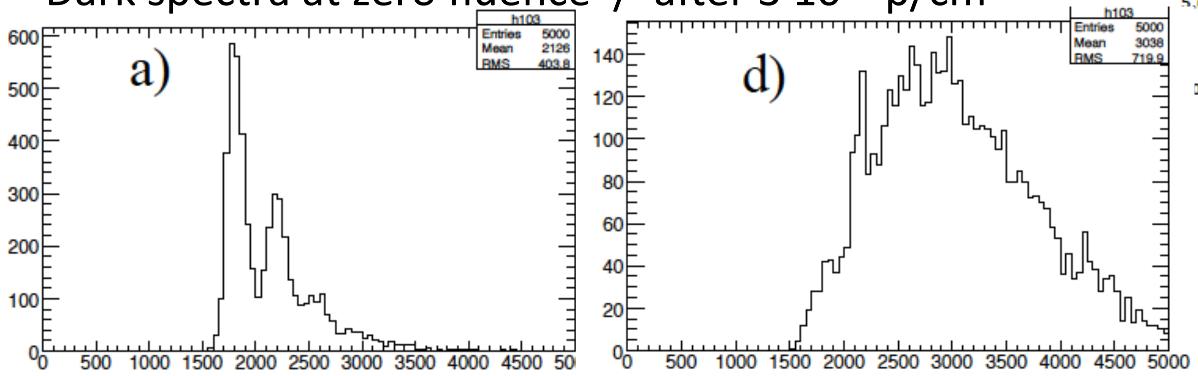
212 MeV protons up to 3 10^{10} p/cm^2, at fixed bias

➔Leakage current increase due to random pixel noise

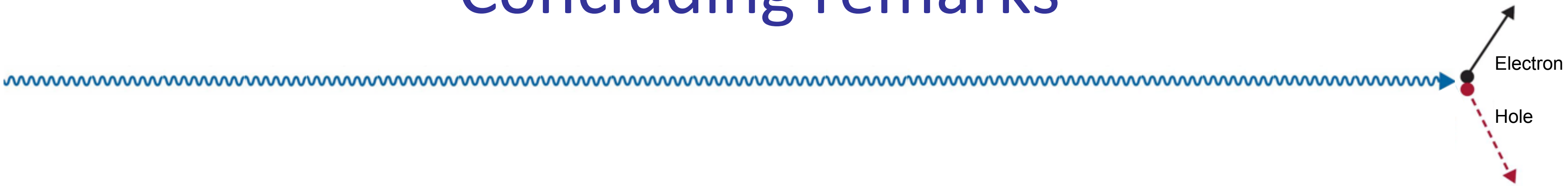
➔ Signal response drop by 15% - 50% for 310^{10} p/cm^2 (FBK 1.0 mm^2 only 4%)



Dark spectra at zero fluence / after 3 10^{10} p/cm^2



Concluding remarks



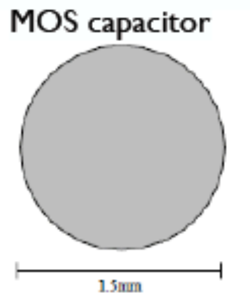
- SiPMs are widely used photo-detectors in HEP and medical detectors
- Up to now limited investigation of radiation damage in SiPM is available
- Mainly experimental observations / little fundamental studies to guide design optimization

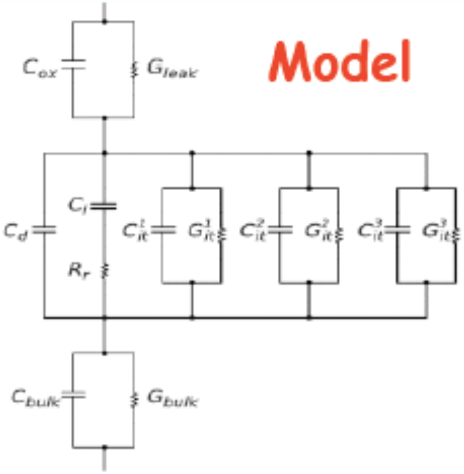
- Some topics for further investigation:
  - Separation of surface and bulk damage
  - Optimization of SiO_2 layer
  - Understanding of bulk damage and impact on design
  - Link between trapping and after-pulse
  - …

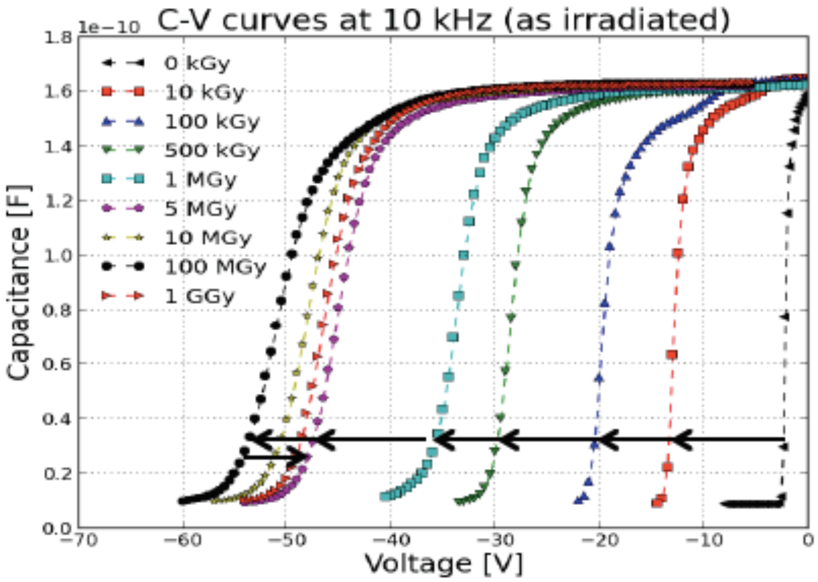
backup

Measurement: Oxide-charge density (N_{ox})

- Test structure: MOS capacitors from 4 different vendors
- Measure: C/G-V vs. f (1 kHz - 1 MHz)
- Analysis: RC model

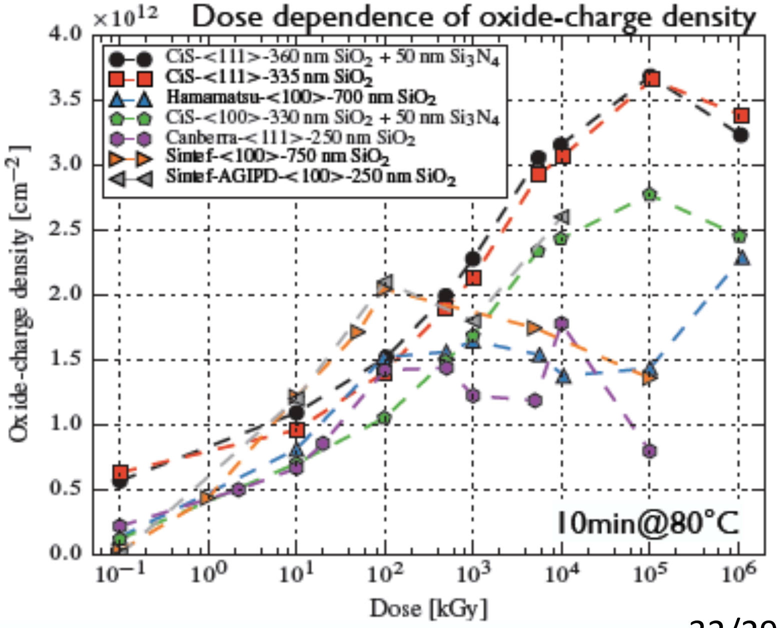




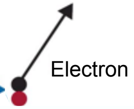


- $N_{ox} \propto$ flatband voltage shift

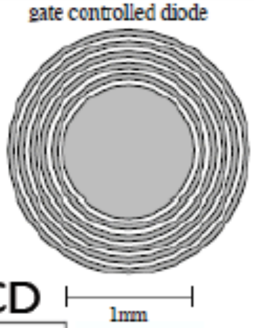
Oxide-charge densities saturate!!!
(max. value: N_{ox} = $1.5 - 4 \cdot 10^{12}$ cm^{-2})



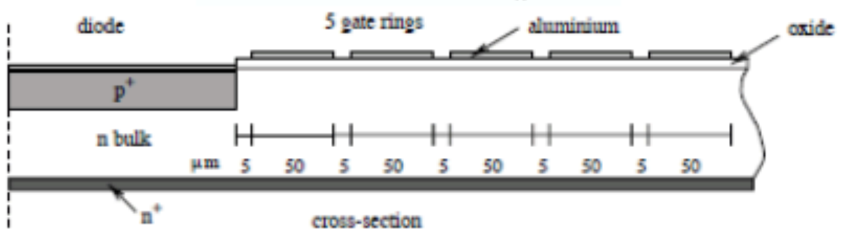
Measurement: Surface-current (J_{surf})



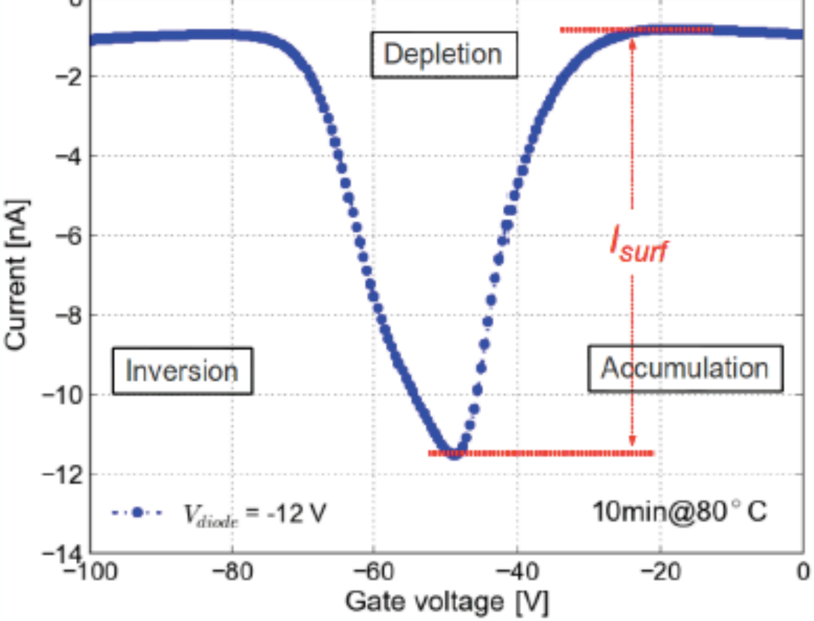
- Test structure:
  Gate controlled diodes
  from 4 different vendors
- Measure: I-V



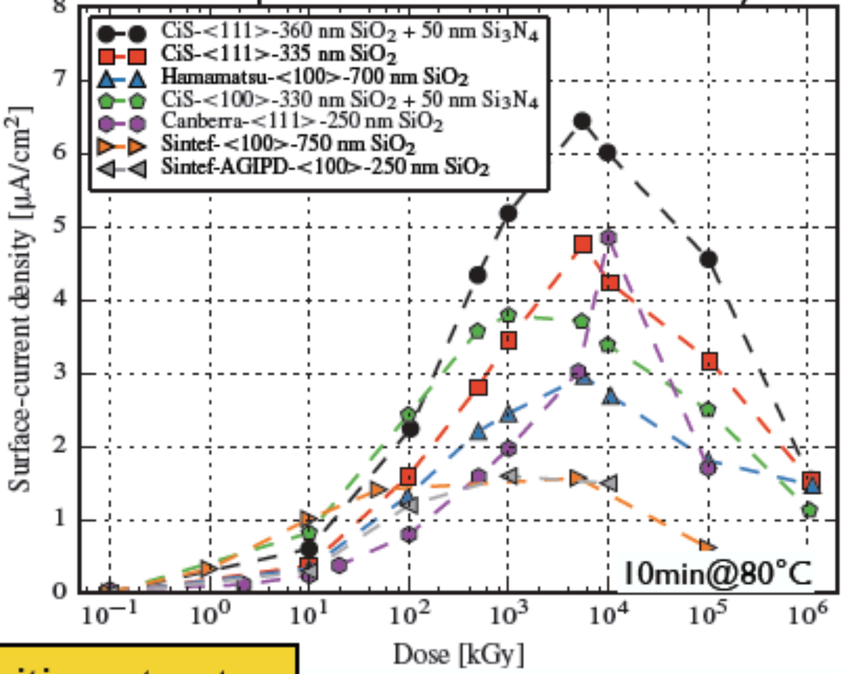
Gate controlled diode „GCD“



I-V measurement of irradiated GCD



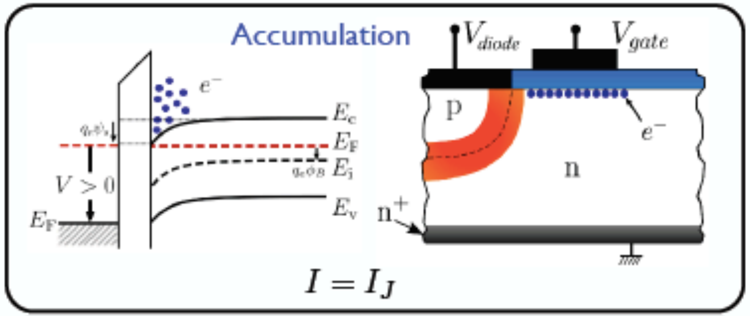
Dose dependence of surface-current density

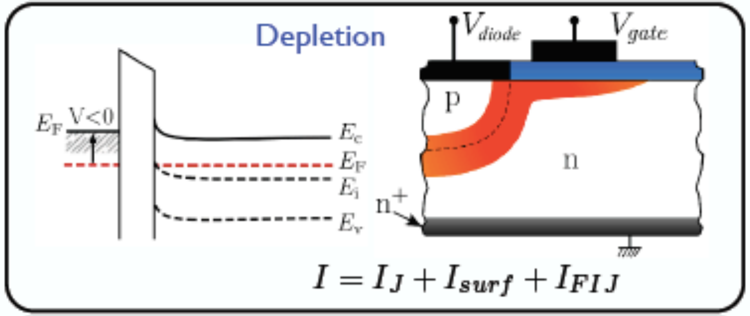


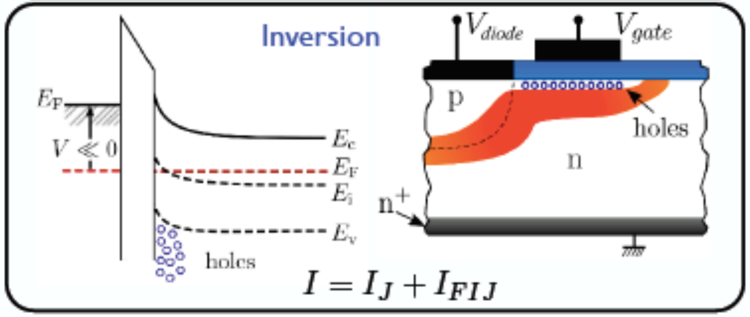
Surface-current densities saturate (decrease?) with dose
(max. value: J_{surf} = 1.5 - 6 μA/cm²)

X-Ray damage: J_{surf}

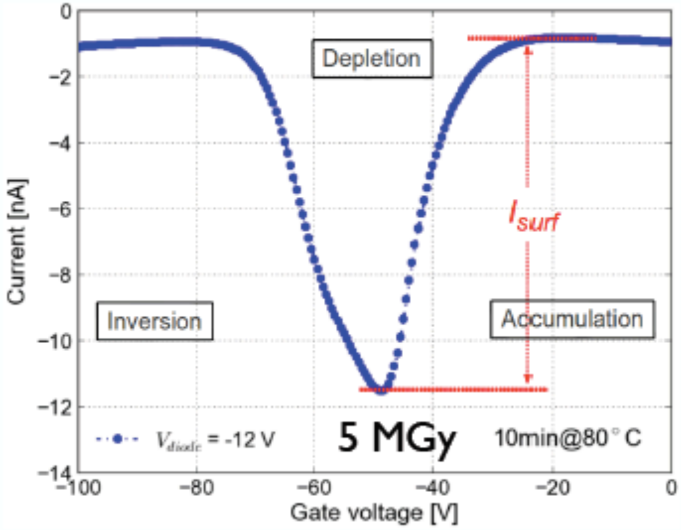
- Surface current density J_{surf} from GCD:
  - Measure I-V curve
  - J_{surf} dominated by mid-gap traps







I-V measurement of irradiated GCD



$$I_{surf} = I_{depl-max} - I_{inv}$$

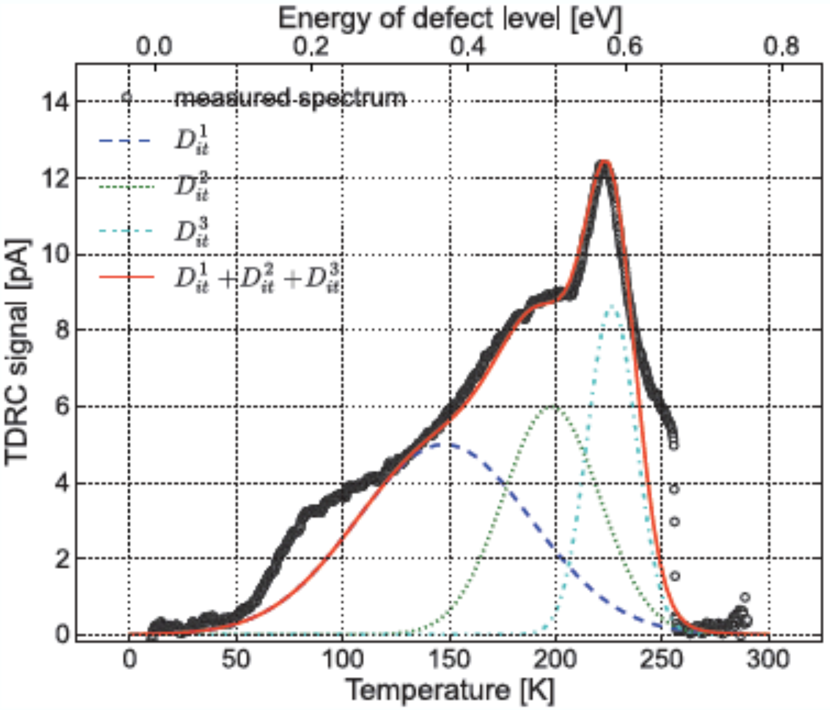
$$J_{surf} = I_{surf}/A_{Gate}$$

- Comments on J_{surf} measurements:
  - For high J_{surf} voltage drop along surface
    ➡Si-SiO$_2$ interface only partially depleted
  - Si-SiO$_2$ interface states decrease of mobility
  - We do not take into account these effects
    ➡Measured I_{surf} = lower limit of surface current

X-Ray damage: D_{it}

- TDRC: Properties of interface traps
  (Thermal Dielectric Relaxation Current)
  - Bias MOS-C in e-accumulation
    ➡fill interface traps with electrons
  - Cool to ~10 K
    ➡freeze e in traps
  - Bias to inversion and heat up to 290 K

➡I_{TDRC} due to release of trapped e's
$I_{TDRC}(T) \rightarrow D_{it}(E)$ *)
➡(Energy levels + widths + densities)$_{it}$



Parameterized by 3 states
Interpretation not unambiguous !

*) Temperature T → $E_c - E_{it}$ (T dependence of Fermi level)