# Radiation hard sensors overview

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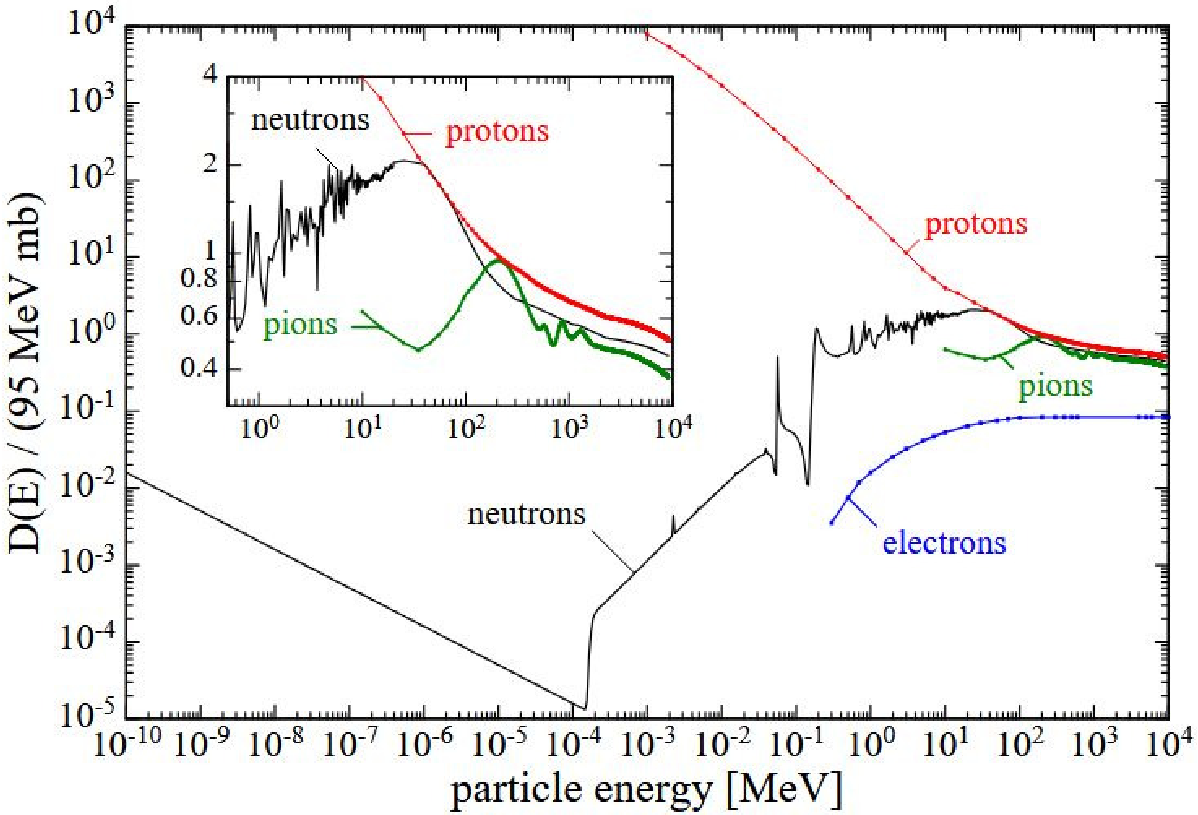
CEPC2025 Workshop

# Radiation damage

Incoming particle produces ionisation in a detector => accumulated dose
It also produces so called non ionizing energy loss (NIEL) => leads to displacement of the atoms in the detector material lattice, that is the actual radiation damage.



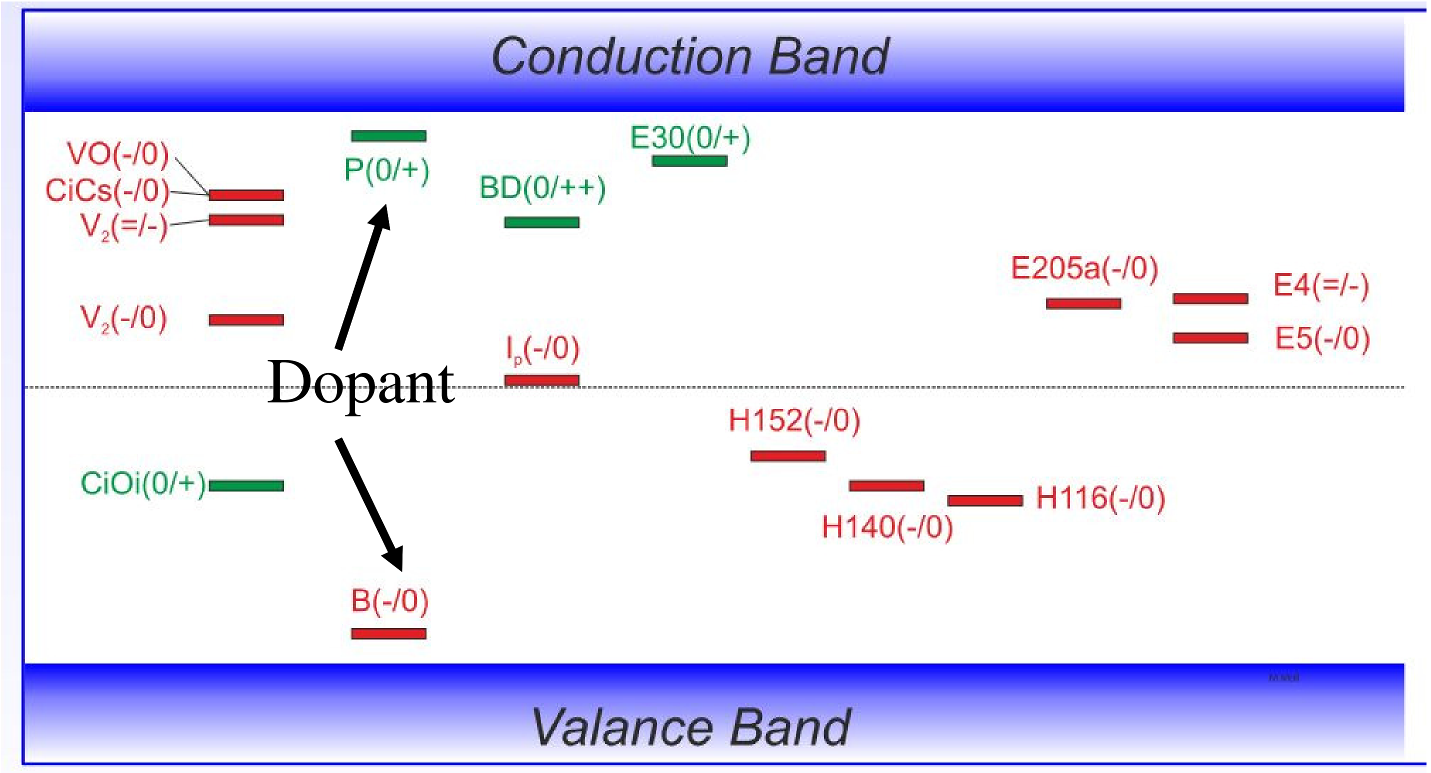

NIEL allows to compare the effect of different types of particles. As a first order approximation.

<= NIEL normalized to 1 MeV neutrons for Silicon

From "Radiation effects in the LHC experiments: Impact on detector performance and operation" CERN Yellow report 2021

# Radiation damage

NIEL => atom displacement => introduces lattice defects

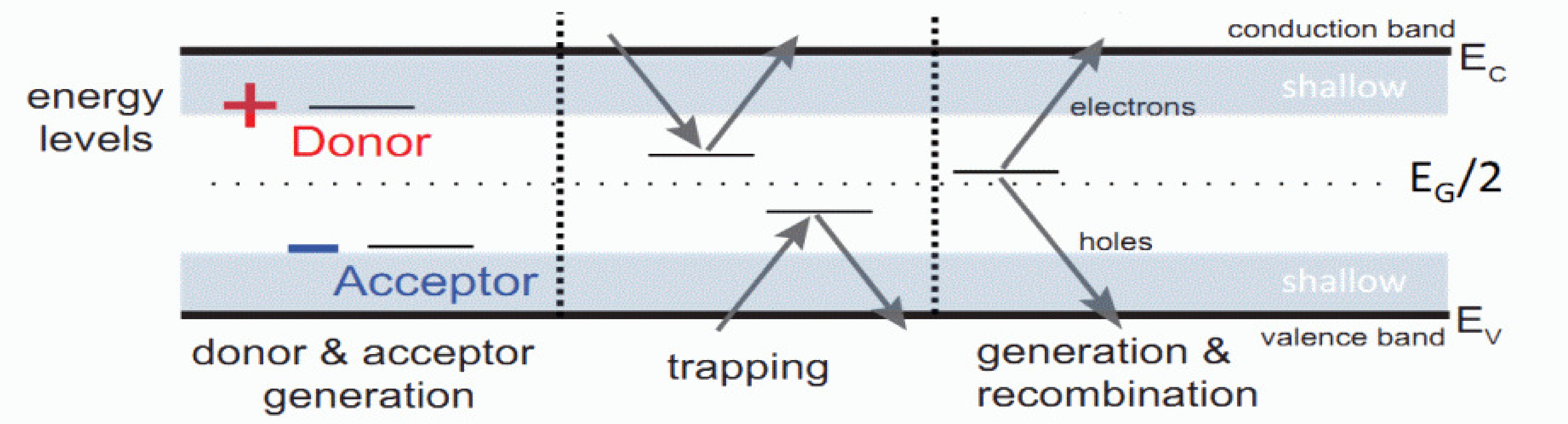



Radiation induced defects in silicon from RD 50 data.
Silicon is the most well studied detector material

Picture from https://indico.cern.ch/event/468478/contributions/2135148/attachments/1290271/1921271/1600613-RD50-AIDA2020.pdf

# Radiation damage

NIEL => atom displacement => introduces lattice defects
These defects could act in different ways




I. Change of $N_{eff}$, $V_{dep}$
⇒ type inversion ,
⇒ decrease of signal

II. Increase of charge carrier trapping
⇒ loss of charge

III. Increase of leakage current
⇒ increase of noise
Cooling during operation!

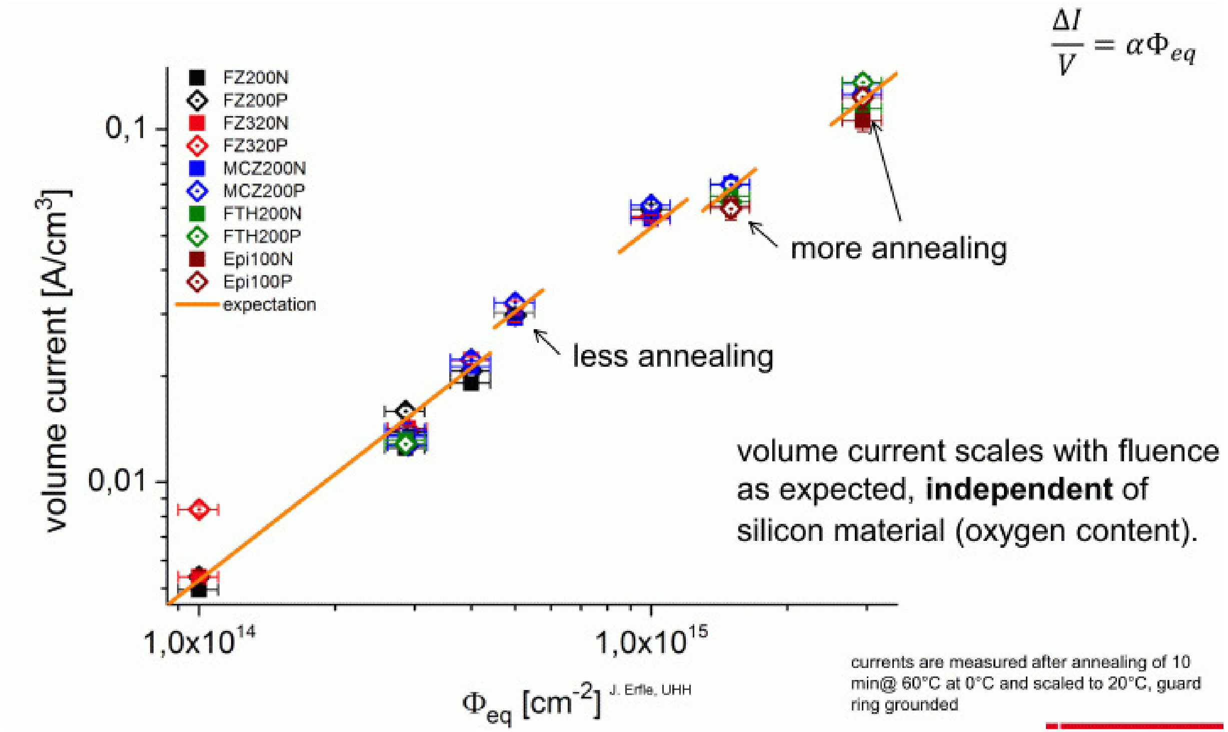
Not so important
For unstructured materials

Not so important
For wide bandgap materials

+ surface effects (charge trapping in $SiO_2$) affects electronics

## Dark current rises linearly with the fluence

*RD 50 data*

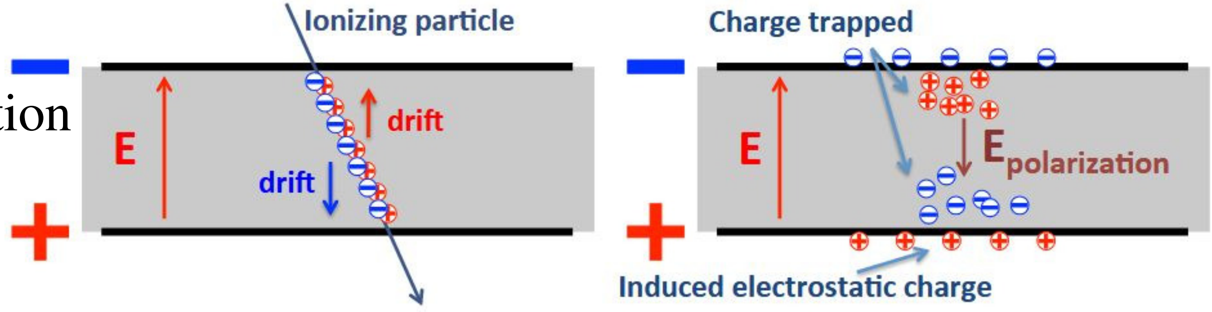



This means for 10x10x0.3 mm detector $I_{dark}$ ~ 1 mA @ room temp.
S/N goes down, heat goes up.
⇒ Needs cooling to at least -20C and up to -50C depending on the damage.
LHC silicon operates with liquid $CO_2$ cooling
Wide bandgap materials are required to operate without cooling

# Radiation damage. Trapping and polarisation

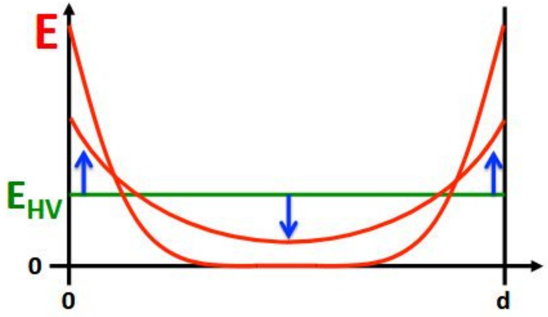
Defects will trap some of the charge carriers during transit. This will reduce the signal

The trapped charge will also create a space charge distribution in the detector. It will modify the internal electric field and reduce the signal even further




(a)

Depending on the detrapping time the effect will look like a decrease in a radiation damaged detector response with relatively small absorbed dose (time dependence).



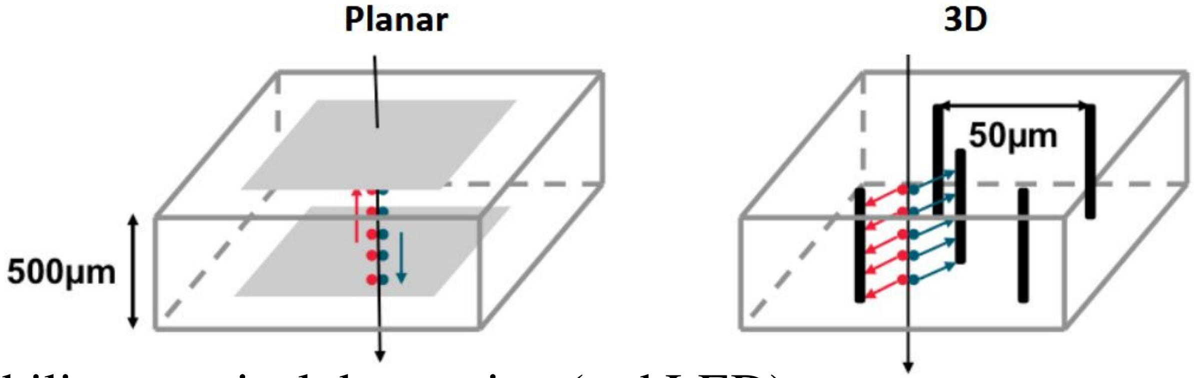

(b)

This will be more pronounced in wide bandgap materials, since no easy thermal detrapping at RT Well know effect in diamond for example.

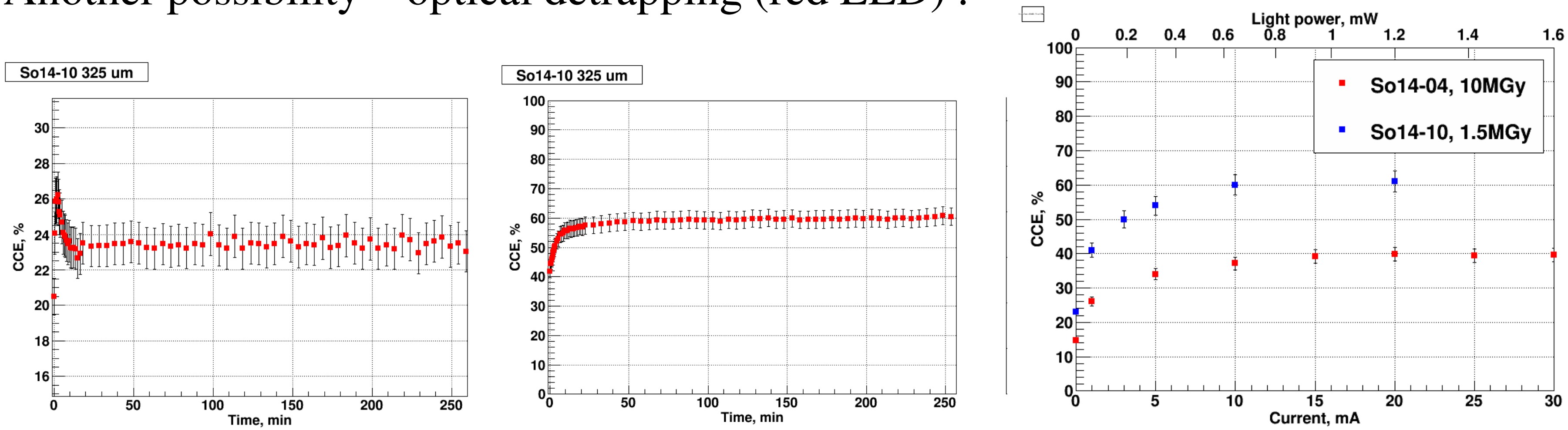
Picture from "Radiation Damage to the diamond-based Beam Condition Monitor of the CMS Detector at the LHC" M. Guthoff thesis.

# Radiation damage. Trapping and polarisation

One way to mitigate the effects of trapping and polarization is to use thin sensors
The shorter is the charge carrier path, the smaller is the trapping probability. But also signal size decreases since the $E_{dep}$ by a particle in a thin sensor is lower. => 3D sensors




Another possibility – optical detrapping (red LED) .




Picture from "Status of 3D Diamond" (http://www-adamas.gsi.de/ADAMAS03/talks/Oh_UManchester.pdf)

# Perspective materials

| | GaAs | Si | Diamond | Sapphire | GaN | SiC |
|---|---|---|---|---|---|---|
| Density, g/cm$^3$ | 5.32 | 2.33 | 3.51 | 3.98 | 6.1 | 3.16 |
| Pair creation eV/pair | 4.3 | 3.6 | 13 | 27 | 8.9 | 7.6-8.4 |
| Band gap, eV | 1.42 | 1.12 | 5.47 | 9.9 | 3.4 | 3.23 |
| Electron mobility | 8500 | 1450 | 4000 | >600 | 1500 | 900 |
| Hole mobility cm$^2$/Vs | 400 | 500 | 1600 | - | ~50 | ~100 |
| Dielectric const. | 12.85 | 11.9 | 5.7 | 9.3-11.5 | 8.9 | 9.7 |
| Rad. length, cm | 2.3 | 9.4 | 18.8 | 7 | 4.6 | 7 |
| MIP MPV pairs /100 μm | ~15000 | 7200 | 3600 | 2200 | >10000 | ~5000 |
| Structure | insul. p-n | p-n | insul. | insul. | p-n p-i-n | p-n p-i-n |
| Displacement energy, eV | 10 | 13-15 | 40 | 20-80 | 11-20 | 30-40 |

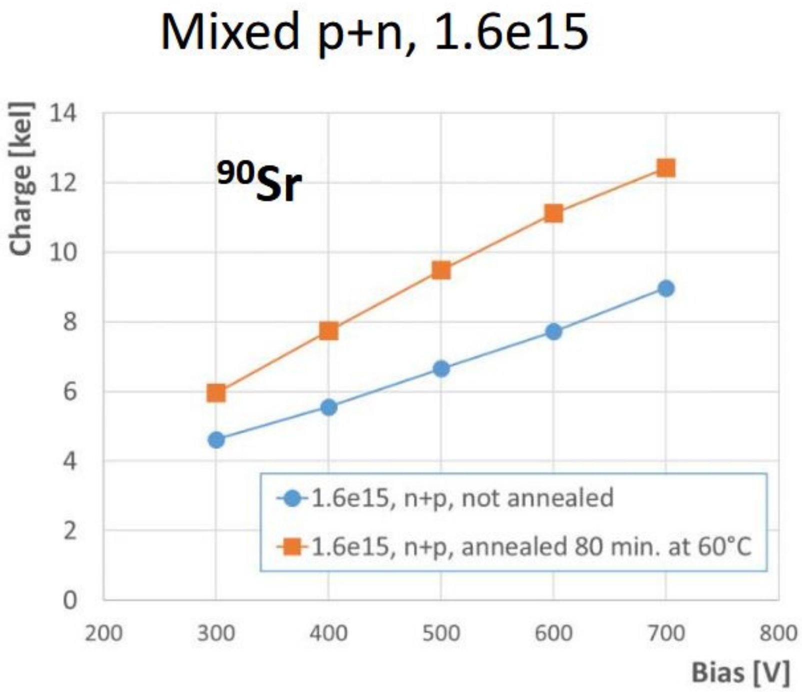
Diamond, GaN and SiC are considered as perspective materials by DRD3

Silicon is the most studied

# Silicon results

A lot of data available from LHC runs
A lot of research was done by RD 50
Some of the sensors accumulated fluence up to $10^{15}$ $n_{eq}$
The next goal of the DRD3 are sensors that can withstand $10^{16}$ $n_{eq}$ or more

ATLAS strip sensors
Results from DRD3




Picture from https://indico.cern.ch/event/1507215/contributions/6539551/attachments/3079193/5449925/DRD3_Mandic_Jun_2025.pdf

# Diamond

Diamond: polycrystalline (pCVD) and mono (ScCVD)
Size still limited for ScCVD but there is improvement

pCVD – growth defects, CCE ~ 40% at best
ScCVD – up to 100% CCE, expensive, size limited

Significant effort was done in research (ADAMAS, RD42, now DRD3). Only a few manufacturers.

Most significant application CMS Fast beam condition monitor (BCM1F) instrumented with both pCVD and ScCVD sensors. ScCVD sensors later replaced with pCVD and cooled silicon pad sensors.

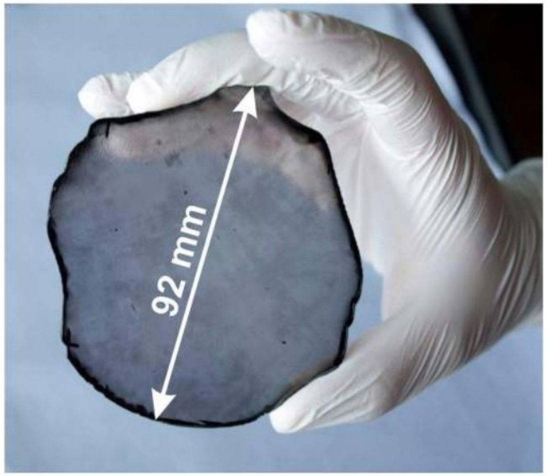
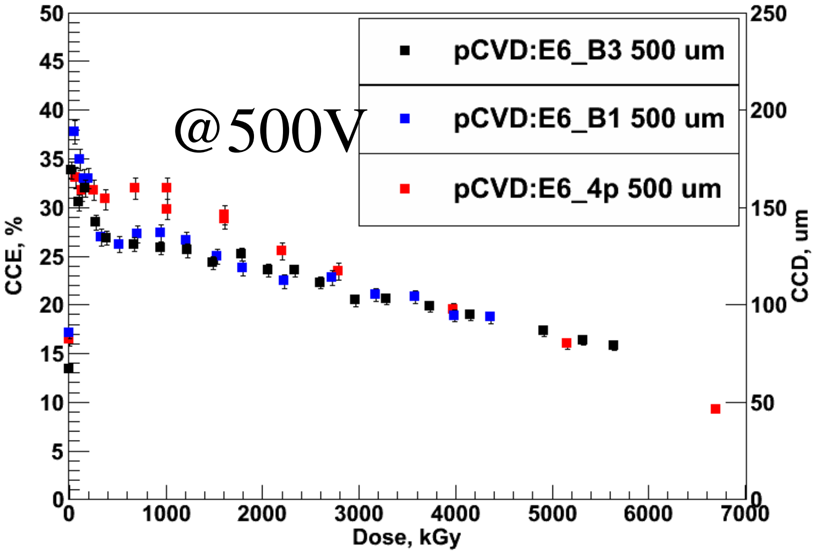


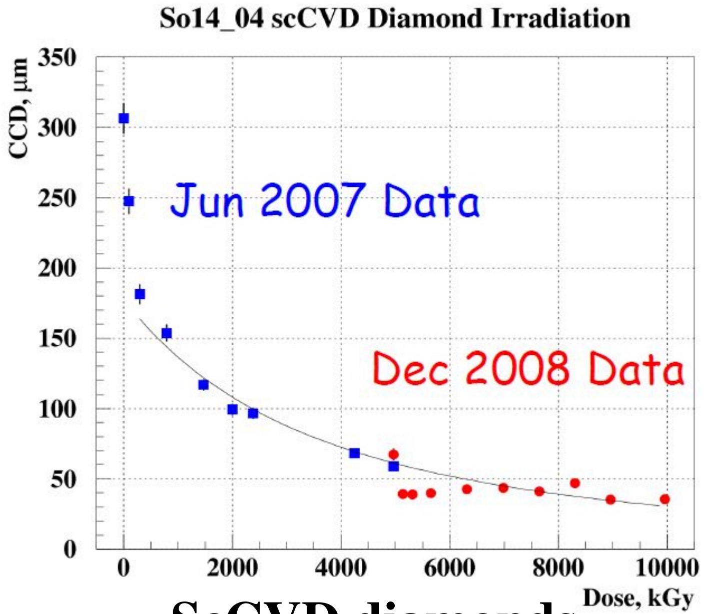

**Figure 5. Freestanding unpolished diamond single crystal synthesized**
From DOI: 10.1038/srep44462

# Diamond. Radiation damage

A number of samples were irradiated (10 MeV electrons)




**pCVD diamonds**



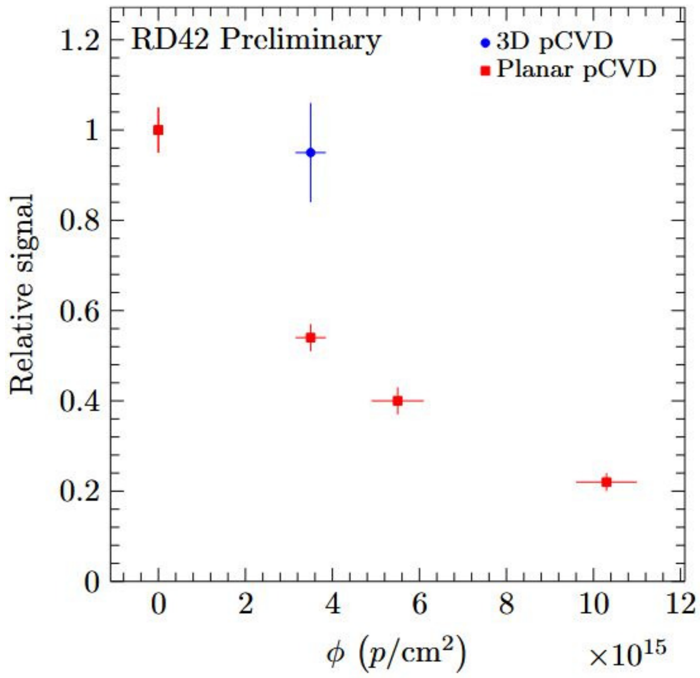

**ScCVD diamonds**

No significant increase in the dark current after the irradiation (still in pA range)

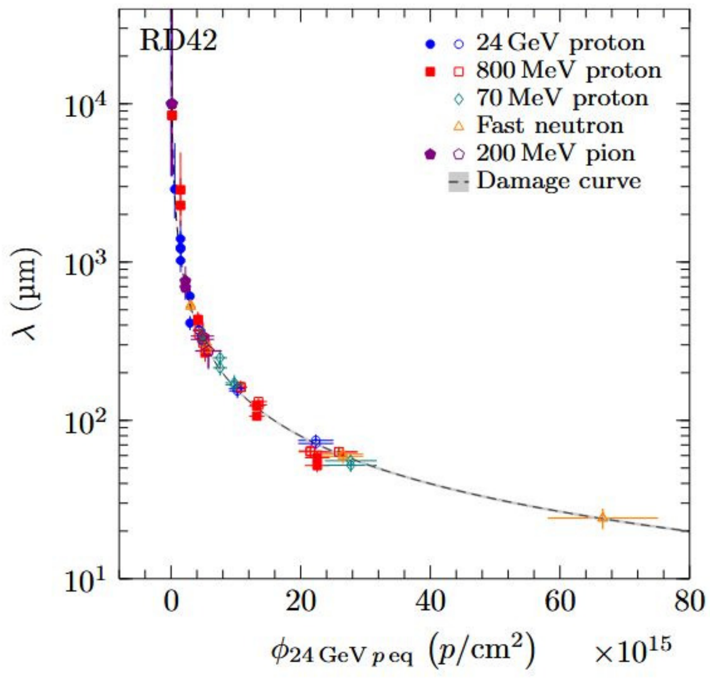
10 MGy for diamond roughly correspond to $10^{16}$ n/cm$^{-2}$ for Si

From "Radiation hard sensors for the beam calorimeter of the ILC" 2007

# Diamond. Radiation damage




pCVD, 800 MeV p

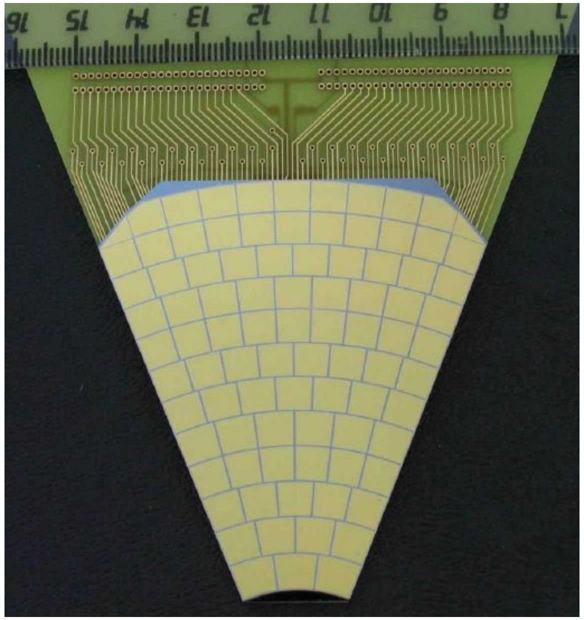



Mean drift distance vs fluence

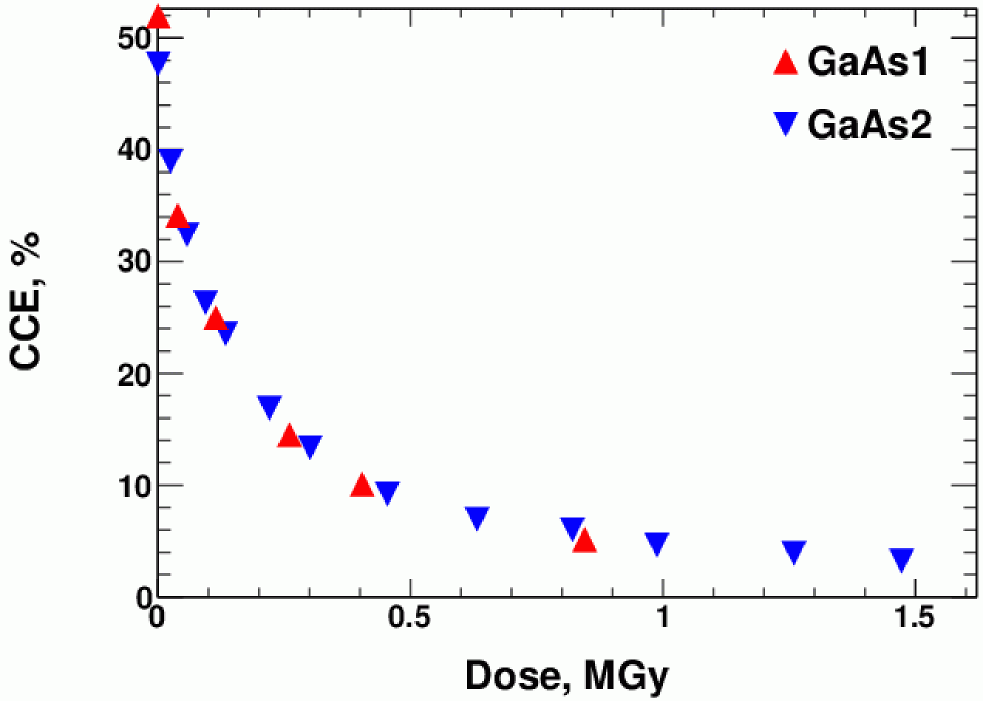
According to RD42, high radiation hardness, 3D diamond looks promising
DRD3 will continue development of 3D diamond sensors it seems.

RD42 data from “Radiation tolerance of diamond detectors” doi:10.1088/1742-6596/2374/1/012172

# GaAs. Irradiation results.



Charge transport by electrons only.
CCE ~ 50% by default.

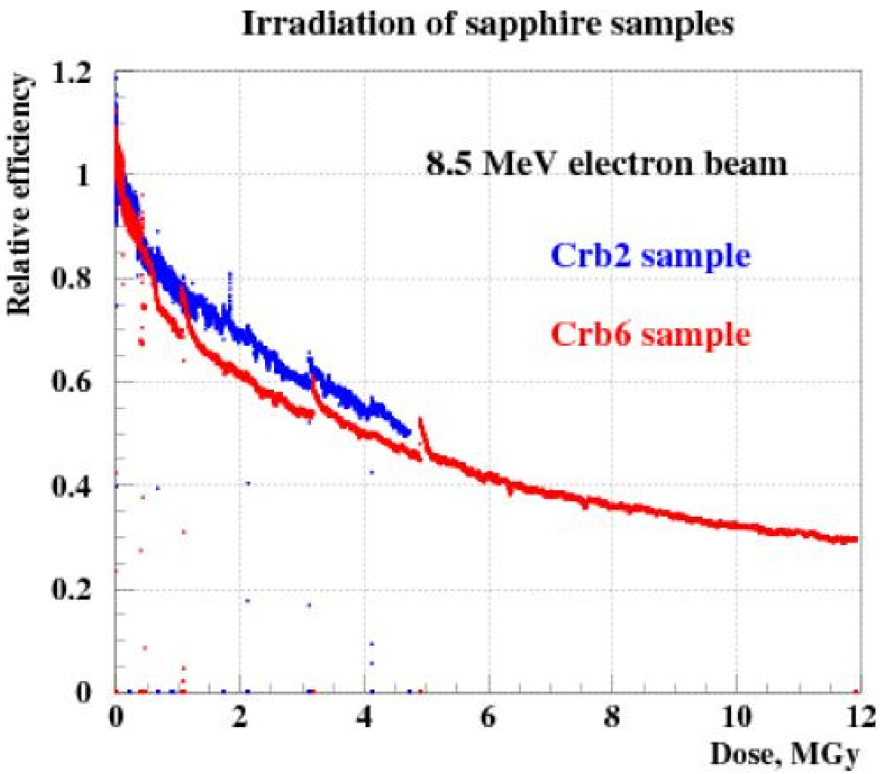



Semi insulating GaAs
1.5 MGy by 10 MeV electrons. MIP signal charge ~ 2000e

Data from "Investigation of the Radiation Hardness of GaAs Sensors in an Electron Beam", 2012, DOI 10.1088/1748-0221/7/11/P11022

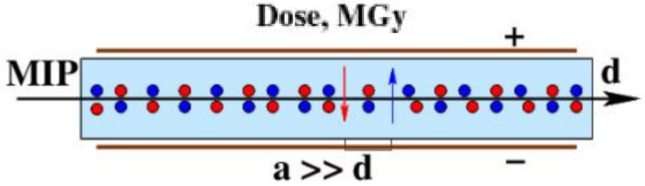
# Sapphire ($Al_2O_3$)

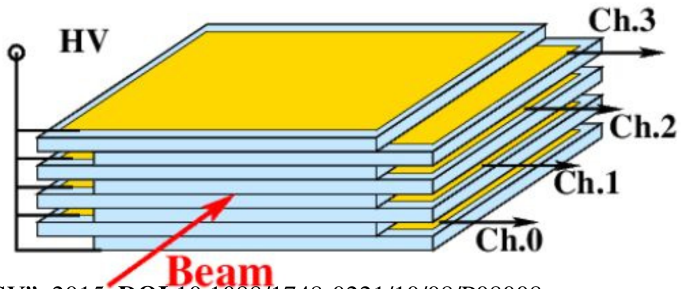
Low charge collection efficiency (~5%) => signal from MIP in Typical 500 um detector ~500 e




Response measured in current mode.
Good radiation hardness
Dark current ~pA before and after irradiation

Tested as a direction sensitive detector

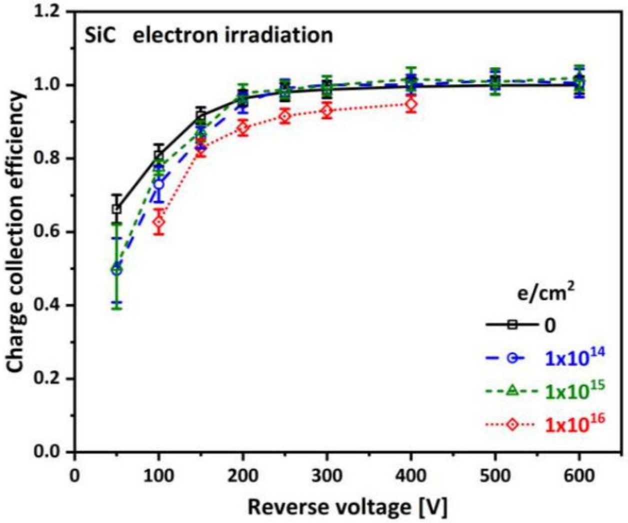


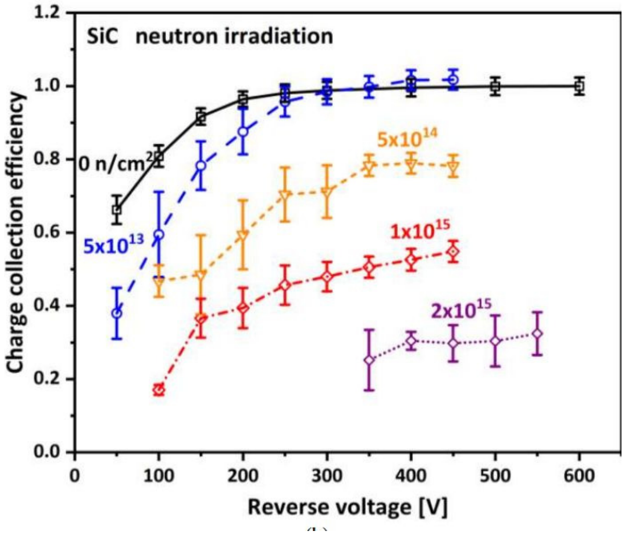

From "Investigation of a direction sensitive sapphire detector stack at the 5 GeV electron beam at DESY", 2015, **DOI** 10.1088/1748-0221/10/08/P08008

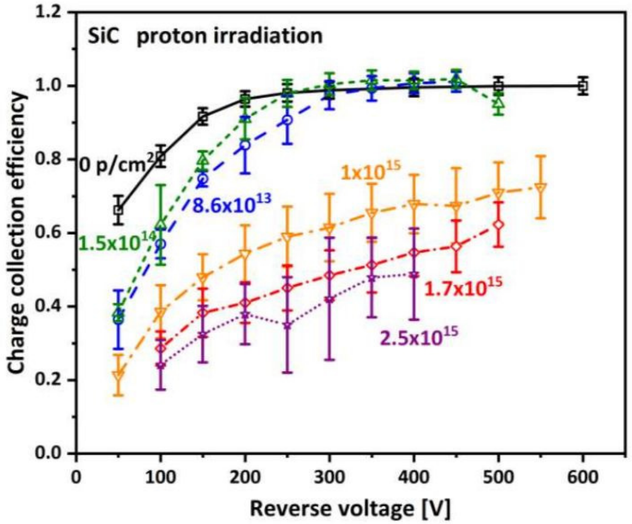
# Silicon Carbide

Widely used in power electronics, good industrial base.
Epitaxial growth, wafer size high quality material available. (Same goes for GaN)
Could be used as a particle detector, is a promising material for radiation hard sensors




2 MeV e-



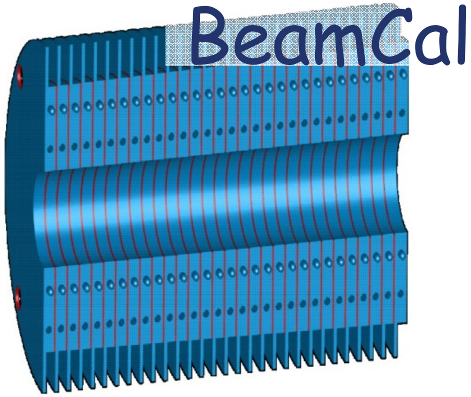

24 GeV p

There should be better experts on SiC at this workshop

Data from “Electron, neutron and proton irradiation effects on SiC radiation detectors”, 2020, DOI: 10.1109/TNS.2020.3029730

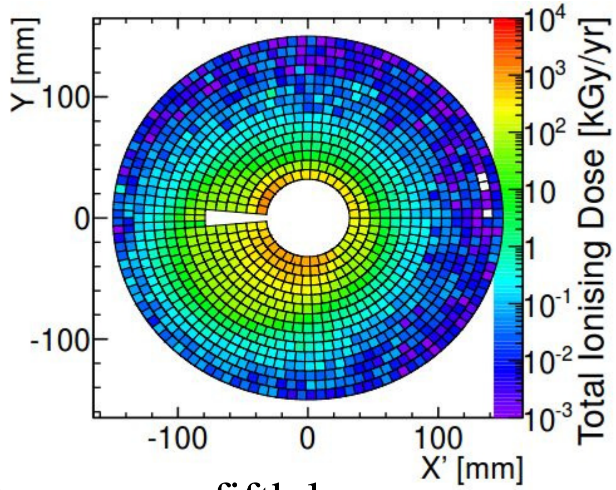
# THANK YOU

# Motivation. ILC\CLIC Very Forward Region




EM calorimeter with sandwich structure: 30 layers of 1 $X_0$, 3.5mm W and 0.3mm sensor, Moliére radius $R_M \approx$ 1cm

From A. Sailer




fifth layer

Beamstrahlung (beam-beam interaction) => Coherent and incoherent pairs => Hit BeamCal

It is possible to extract some information on beam parameters from pair distribution. See. Ch. Grah and A. Sapronov Beam parameter determination using beamstrahlung photons and incoherent pairs

Max expected dose about 1 MGy per year of operation (3TeV CLIC), or ~0.5 (ILC). Background from beamstrahlung-generated pairs. Mostly EM, energy ~ 10 MeV (showers). Radiation hard sensors required, cooling is difficult.