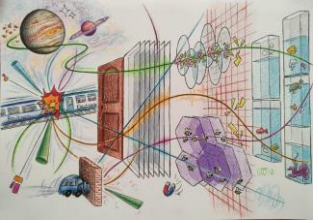


WG 6: Wide Bandgap Materials

Diamond, Silicon Carbide, Gallium Nitride, 2D

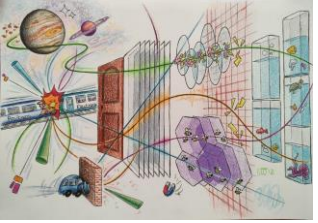
Strategic R&D and activities

Thomas Bergauer

HEPHY Vienna

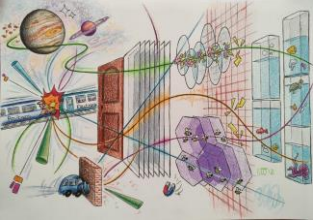
on behalf of the DRD3 proposal writing team

Input from Alexander Oh, Thomas Koffas, Giulio Pellegrini, Xin Shi



Diamond

….are a girl's best friend © Marilyn Monroe



Diamond: RD42 collaboration

DRD3

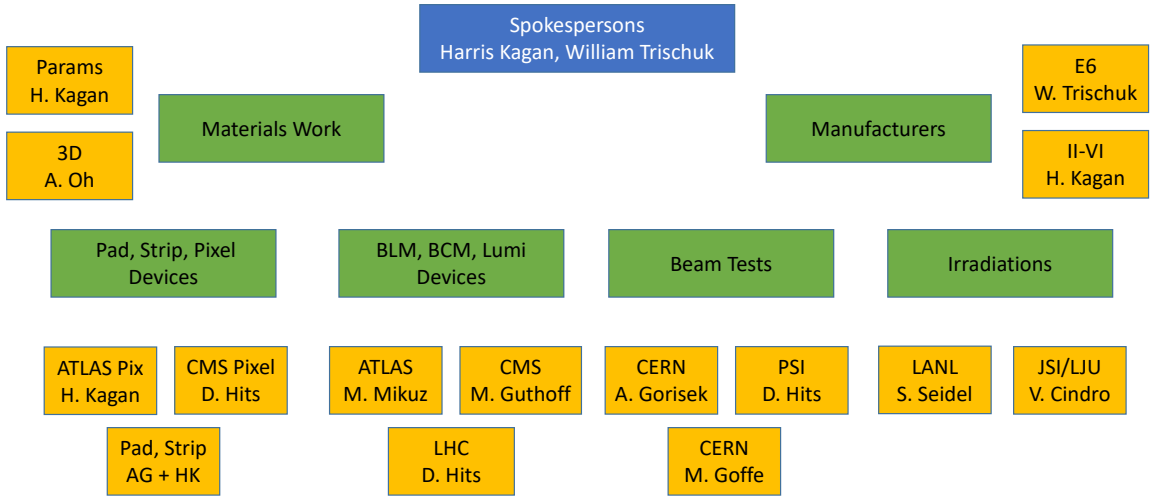
- Diamond has been studied by RD42 collaboration for 29 years(!) for tracking and beam-monitoring devices.
  - Successfully deployed diamonds for beam monitors in ATLAS, CMS
  - Large-area tracking devices have not been realized (yet)
- Could get new momentum due to access to different tools and expertise

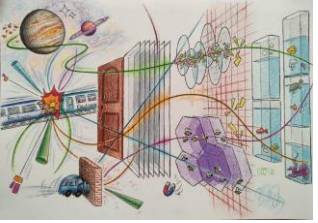
CERN/DRDC 94-21
DRDC/P56
May 5Γ1994

R & D Proposal

Development of Diamond Tracking Detectors for High Luminosity Experiments at the LHC

RD42 Organization Chart

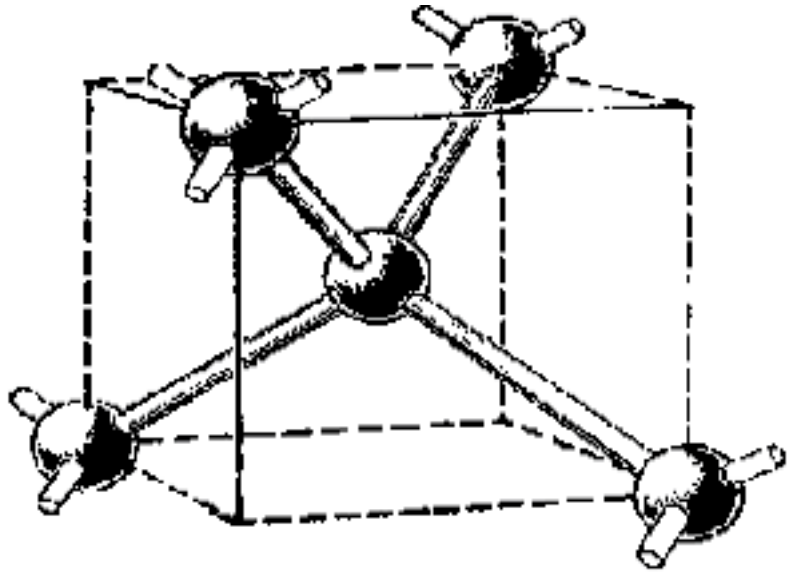




Diamond Properties

DRD3

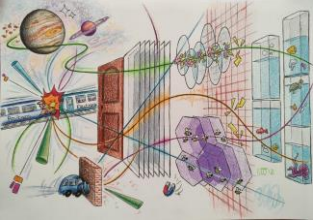
Property	Diamond	Silicon
band gap	5.47	1.12
mass density [g/cm^3]	3.5	2.33
dielectric constant	5.7	11.9
resistivity [Ωcm]	>10^{11}	2.3e5
breakdown [kV/cm]	1e3...20e3	300
e mobility [cm^2/Vs]	1700	1400
h mobility [cm^2/Vs]	2100	440
therm. conductivity [W / cm K]	10..20	1.5
radiation length [cm]	12	9.4
Energy to create an eh-pair [eV]	13	3.6
ionisation density MIP [eh/mm]	36	89
ion. dens. of a MIP [eh/ 0.1 ‰ X_0]	450	840



- Low dielectric constant ➔ low capacitance
- Low leakage current ➔ low noise
- Room temperature operation
- Fast signal collection time

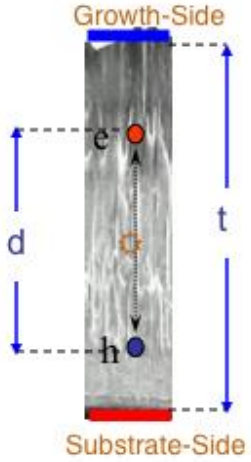
–MIP signal ~2 smaller at same X_0

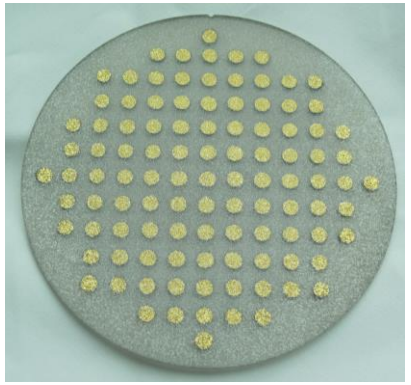
–Efficiency < 100% (pCVD)



RD42 Development goals

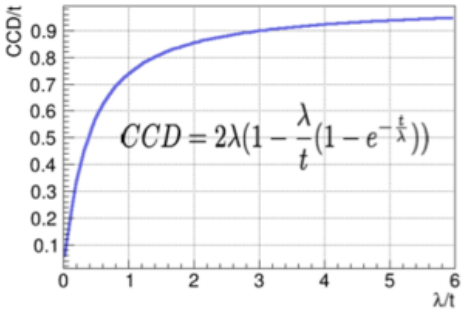
- removal of surface defects
  - few per cm^2 → **< 1 per cm^2**
- wafer charge collection distance (d) in pCVD
  - 400 um → **500 um**
- size of polycrystalline wafers = 15cm (6 inch) state of the art
  - Fixed by microwave frequency (not expected to change)
  - Today two main manufacturers of detector-grade diamond
    - **ElementSix Ltd Uk** (also small single crystal diamonds)
    - **II-VI Inc. USA**
- wafer uniformity
  - 5% → **2% across whole wafer**.
- price per cm^2
  - ~1500USD / cm^2 → **800USD /cm^2**

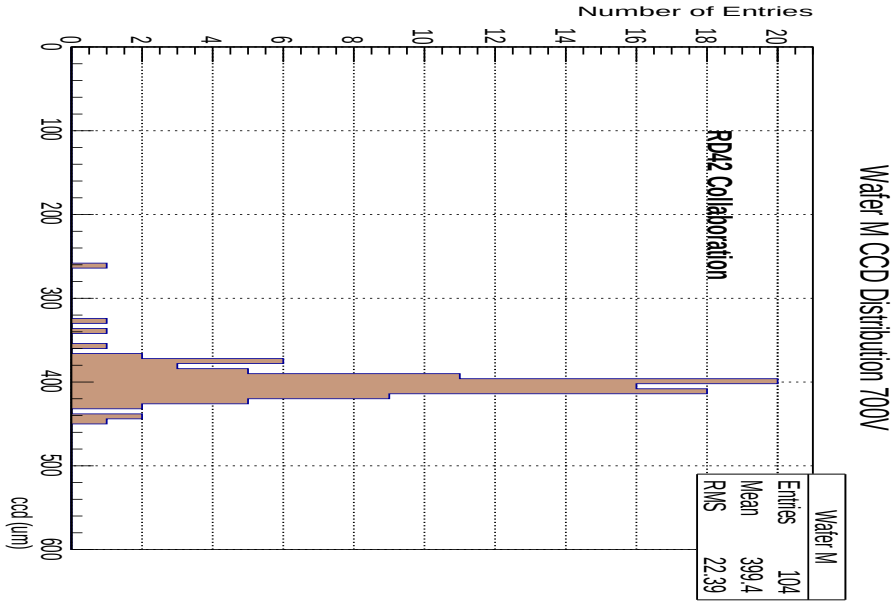


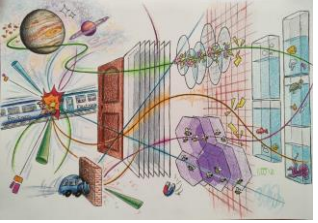


poly crystal 5 inch wafer, II-VI Inc.

Relation between *CCD* and schubweg λ:





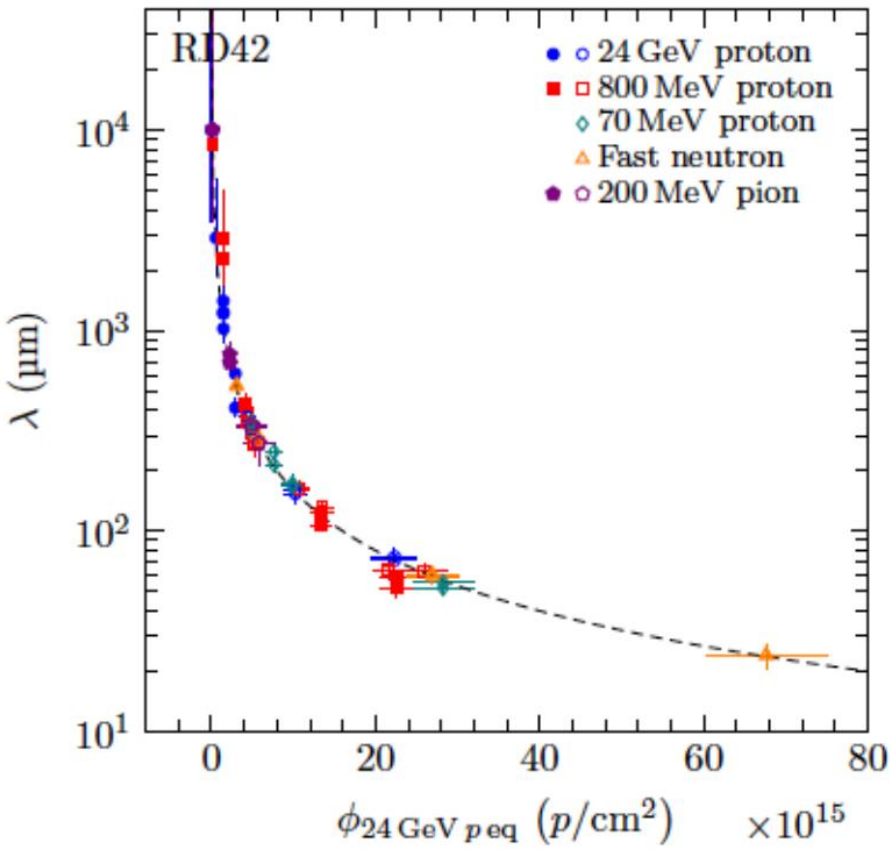


Radiation Hardness

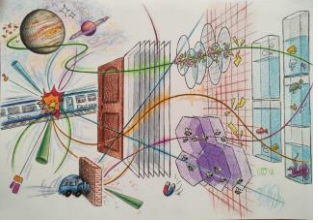
DRD3

- **Scaling to 24 GeV protons**
  - Universal scaling for all particle types with fluence.
  - Poly and single crystal diamond show consistent damage constants.
  - Predictions are possible for any particle type and fluence.
  - Traps reduce the life-time of charge carriers, or "Schubweg" (λ).

"Back-of-an-envelope calculation, expect Schubweg of:
λ ~ 16μm at 10^{17} cm^{-2} protons_24 GeV_eq



- After large radiation fluence all detectors are trap limited
- Mean free paths (Schubweg) λ< 50μm
- Need to keep drift length (L) smaller than mfp(λ)

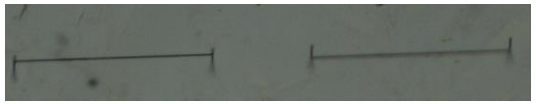


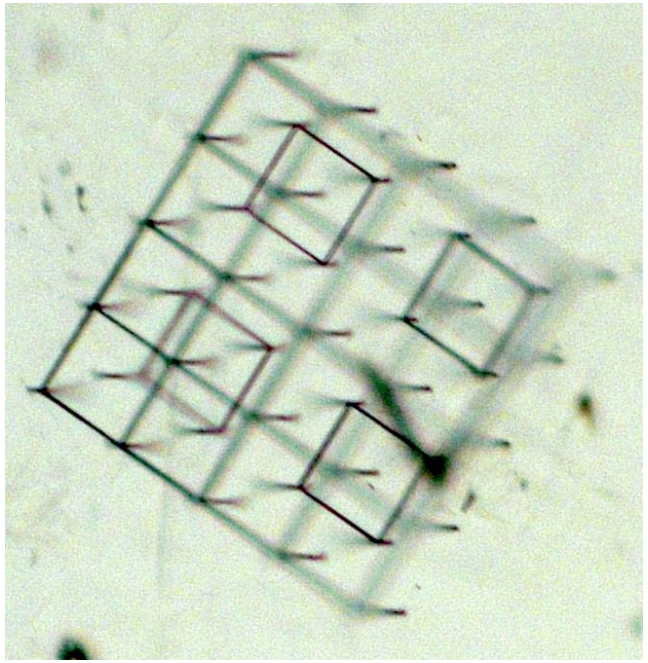
3D Diamond Detectors

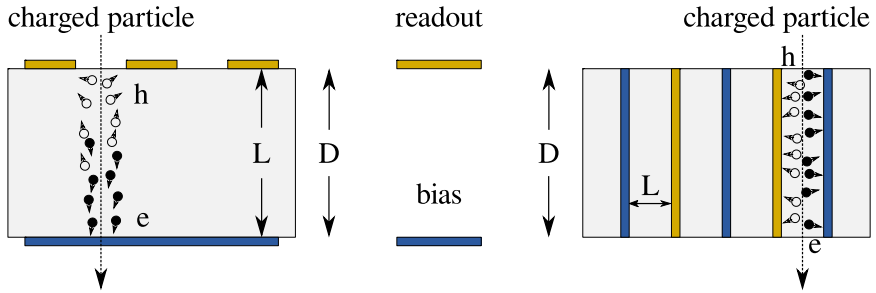
DRD3

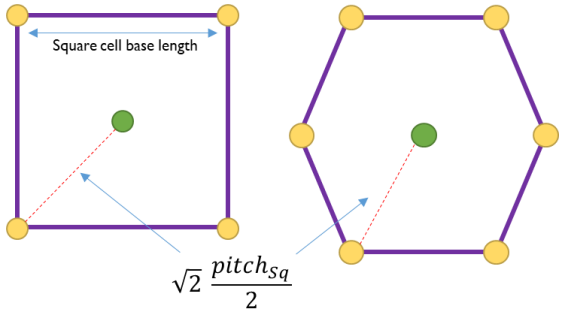
- Laser processing allows any geometry, including horizontal wires.
  - Exiting possibility to optimize the electric and weighting field.
  - Small cell sizes realizable, wire diameter at about 1μm.
  - Simulation studies currently ongoing
- Future research in this area:
  - Optimize geometry
  - **Resistivity**: currently at (1 - 0.1Ωcm), aim for <0.1Ωcm.
  - **Processing speed**: currently O(10um/s), aim to speed up and/or parallel processing of wires.
  - **Wire thickness / uniformity**: Little data available, needs more research effort.

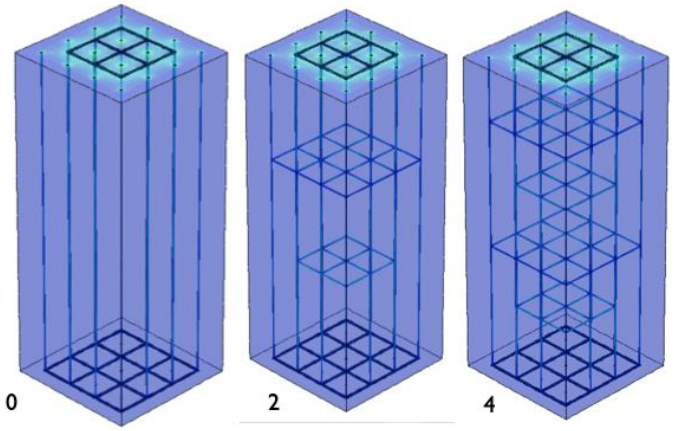
Laser graphitization : "burning" the diamond with a laser, creating a thin layer of graphite, which is conductive.

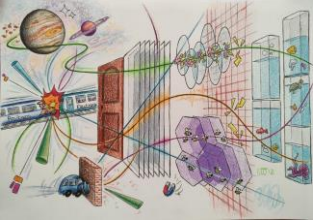










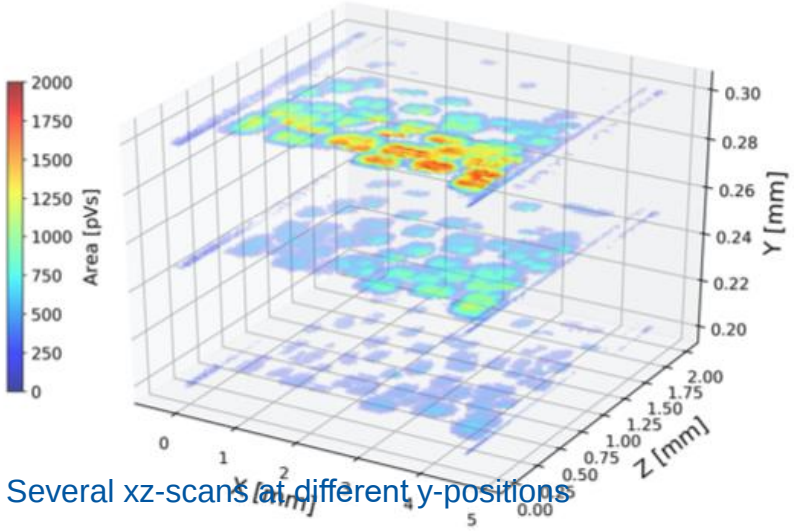


3D Diamond TCT and Irradiation

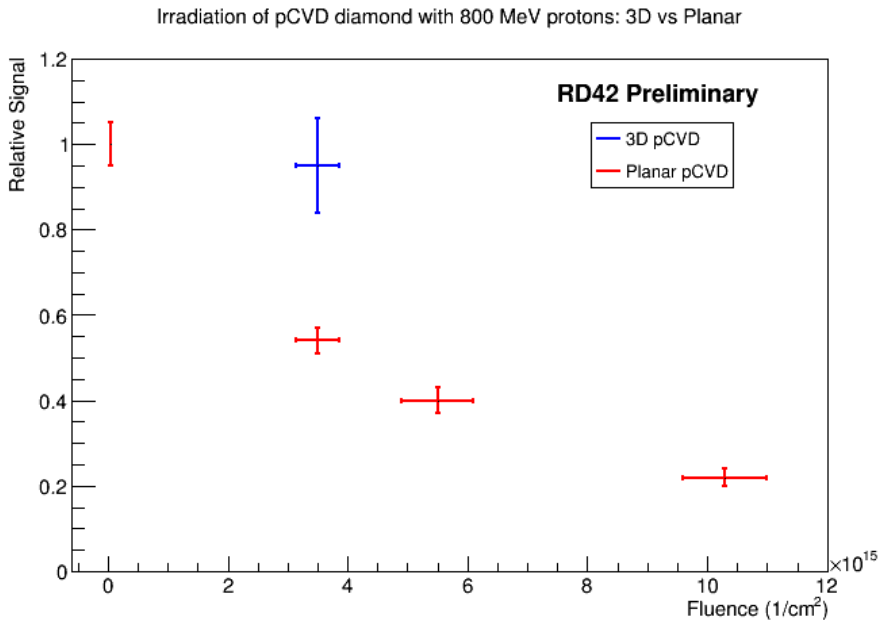
DRD3

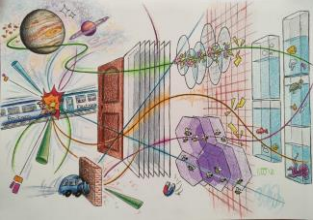
- TPA-TCT demonstrated
  - PhD thesis Univ. Zurich [1]

    [1] https://www.research-collection.ethz.ch/handle/20.500.11850/445547
  - More accurate ionization profiles possible using same beam shaping techniques as in production of wires.
  - Research is needed to fully exploit technique for characterizations
- Few radiation hardness data available, but promising:
  - Compare signal loss in 3D pixels to published results from planar
  - **3D sensors collect twice as much charge**

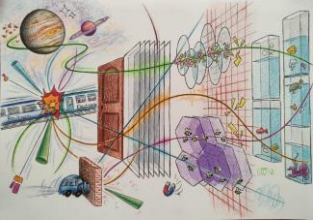


Several xz-scans at different y-positions





Silicon Carbide

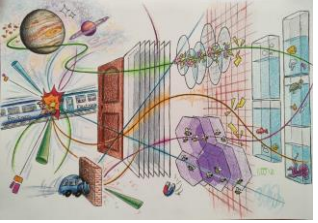


Interest in SiC: old and new

DRD3

- Material known in principle for 100 years
- Investigated as detector material within RD50 already 20 years ago
  - I. Pintile [1], F. Moscatelli [2], F. Nava [3] and others
- Recently got attention because of European chip industries' interest in the renewable energy revolution:
  - Power-efficient transistors in power supplies
  - Photovoltaic inverters
  - Electric car drive train
- Higher quality material
- Re-gained interest
  - SiC-CMOS process offered by Frauenhofer IIHS; two MPW submissions per year

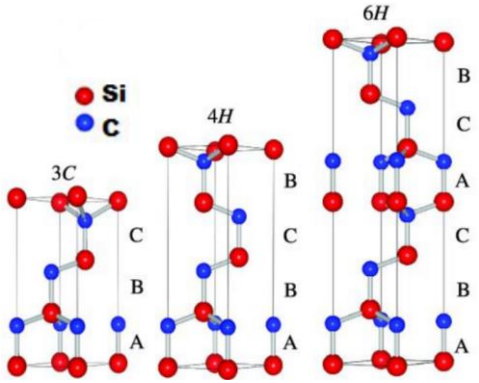
[1] 10.1063/1.3457906
[2] 10.1016/j.nima.2005.03.048
[3] 10.1109/TNS.2004.825095



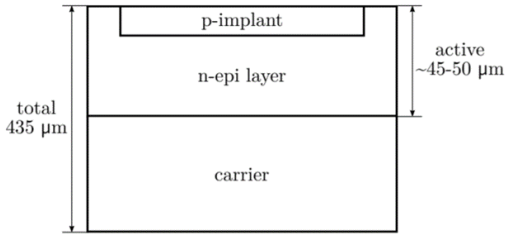
Silicon Carbide Properties

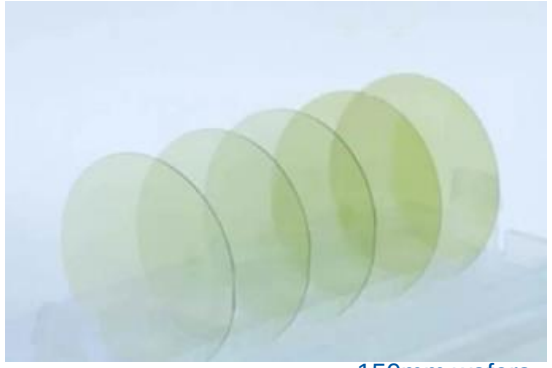
DRD3

Property	4-H SiC	Diamond	Silicon
band gap	3.26	5.47	1.12
mass density [g/cm^3]	3.21	3.5	2.33
dielectric constant	9.66	5.7	11.9
breakdown [kV/cm]	⊥ 4e3; ∥ 3e3	1e3...20e3	300
e mobility [cm^2/Vs]	⊥ 800; ∥ 900	1700	1400
h mobility [cm^2/Vs]	115	2100	440
therm. conductivity [W / cm K]	4.9	10..20	1.5
Energy to create an eh-pair [eV]	7.6	13	3.6
ionisation density MIP [eh/mm]	57	36	89

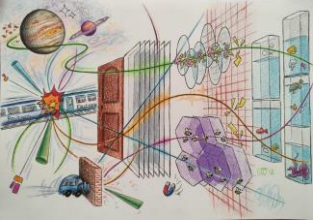


- Many properties in between Silicon and Diamond
- Pros:
  - Commercially available 6” wafers
- Cons:
  - different polytypes, anisotropy
  - Active volume limited by high-resistivity epi layer
  - Epitaxial layer thickness is limited by increasing defect density (< 200 µm) -> 3D, LGAD, etc…





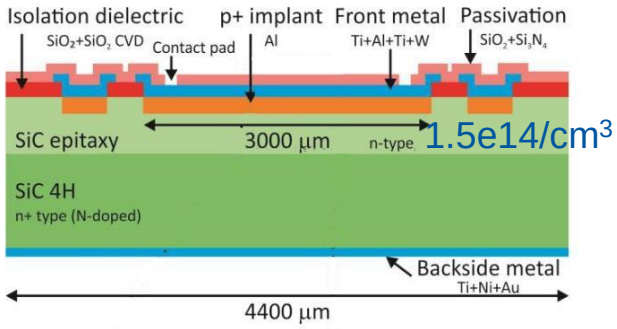
150mm wafers

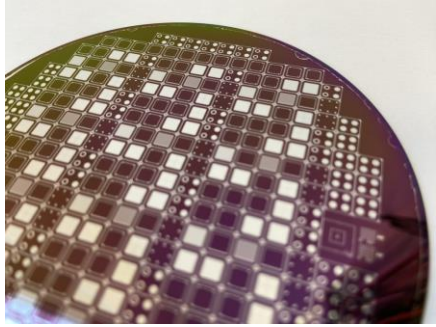


Current work on Silicon Carbide

DRD3

- Production runs by CNM, on 50µm epi p-on-n wafers
  - Runs on 4” wafers, new run on 6” substrate imminent (also 100µm)
  - Commercial wafers by Ascatron AB, now II-VI Inc.
  - Studied at CNM and HEPHY
    - UV-TCT, Alpha & beam response, TCAD Simulations,…
  - Graphene layer

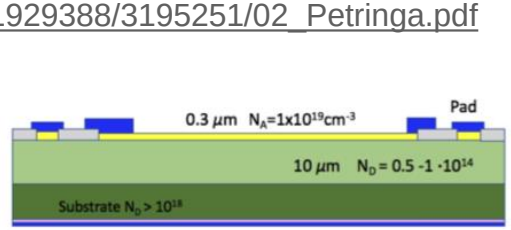


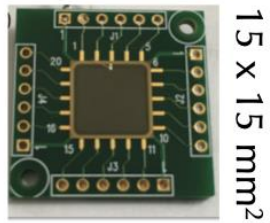


4-inch CNM run

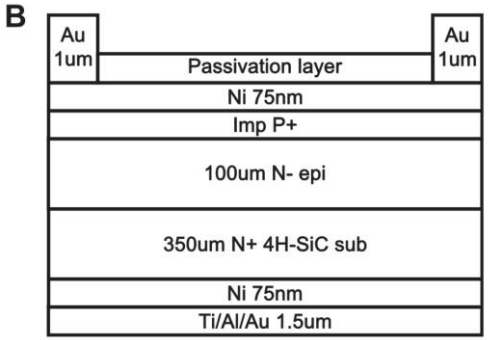
- SiCILIA project (INFN-LNS Catania) [1]
  - Processing at STMicroelectronics
  - characterization at INFN

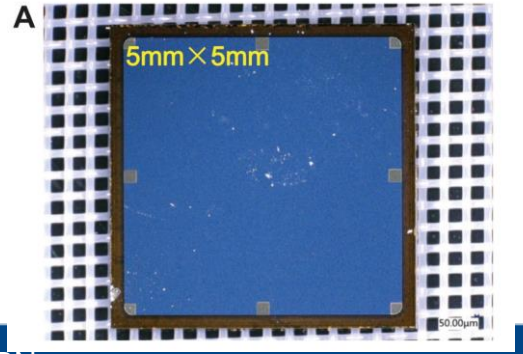
https://indico.cern.ch/event/843258/contributions/3610707/attachments/1929388/3195251/02_Petringa.pdf



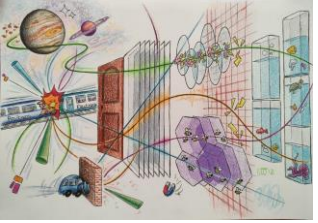


- Activities in China (IHEP Beiing, JLU, DLUT, ShanghaiTech) shown in recent RD50 meetings
  - Sample production, characterization
  - Simulations (RASER: https://pypi.org/project/raser/)
  - First SiC-LGAD





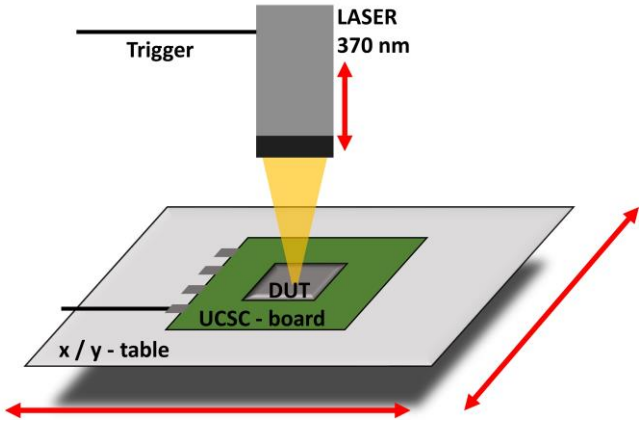
[1] 10.3390/s18072289

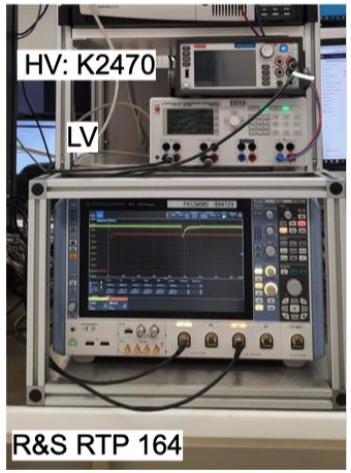


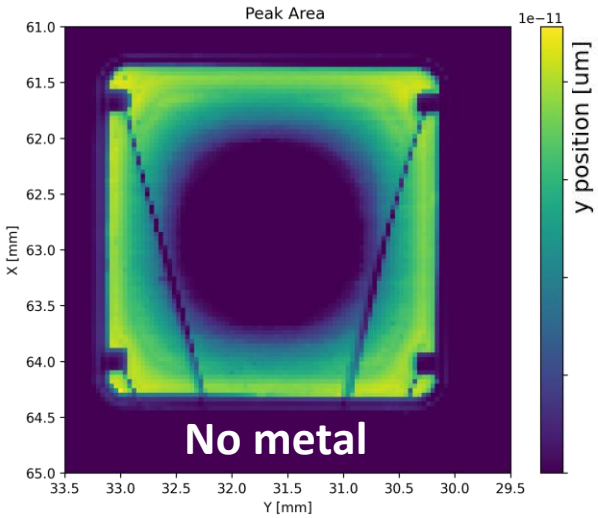
UV-TCT on Silicon Carbide

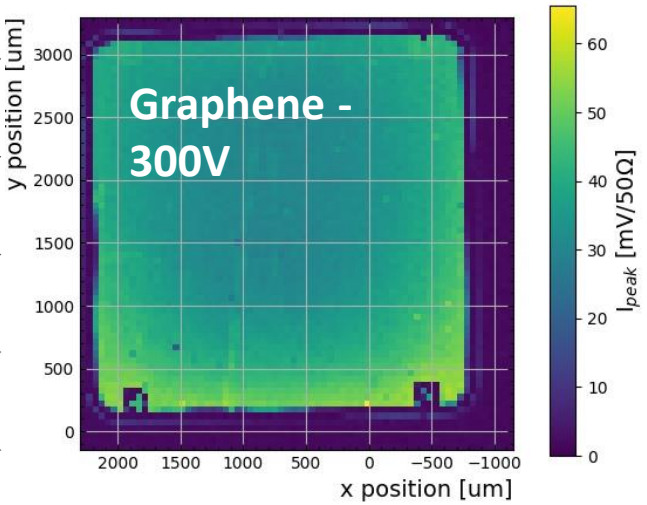
DRD3

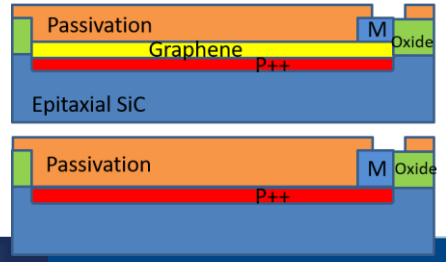
- "Top/Edge" TCT: UV laser needed to overcome band-gap
  - 370 nm PILAS Laser @ HEPHY and CNM
  - Absorption coefficient in 4H-SiC: $\alpha \approx 42.2\ cm^{-1}$ similar to 1060nm (IR) laser in Silicon
  - custom UV beam optics, spot size < 20 µm.
  - Laser intensity calibration to MIP with Sr-90 challenging due to very small signal
  - Signals of samples distorted without metallization due to low conductivity of implant (RC-circuit)
    - Recovered by graphene layer











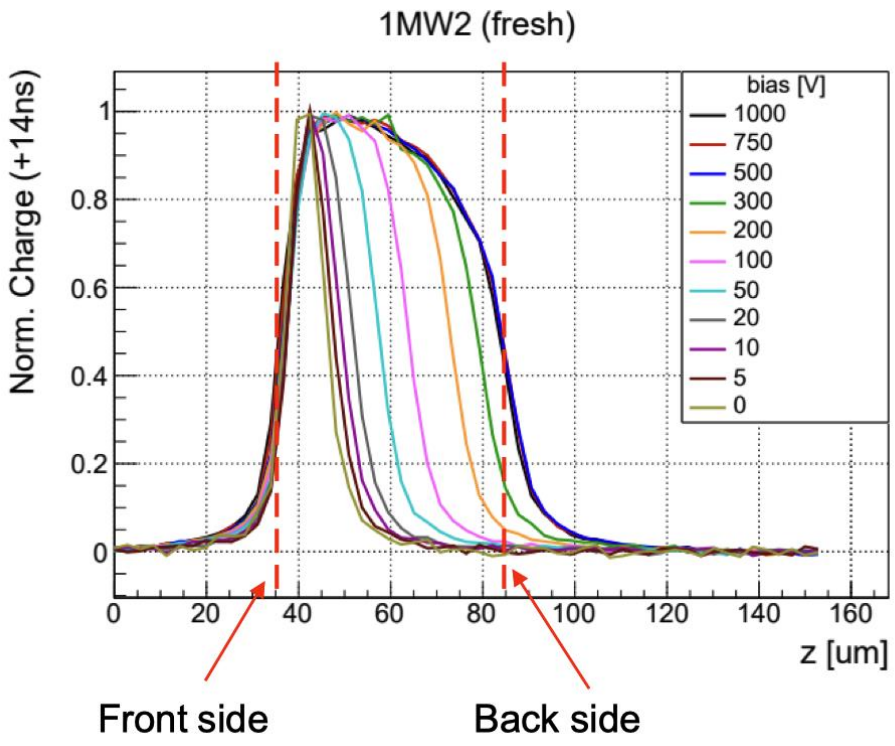
HEPHY

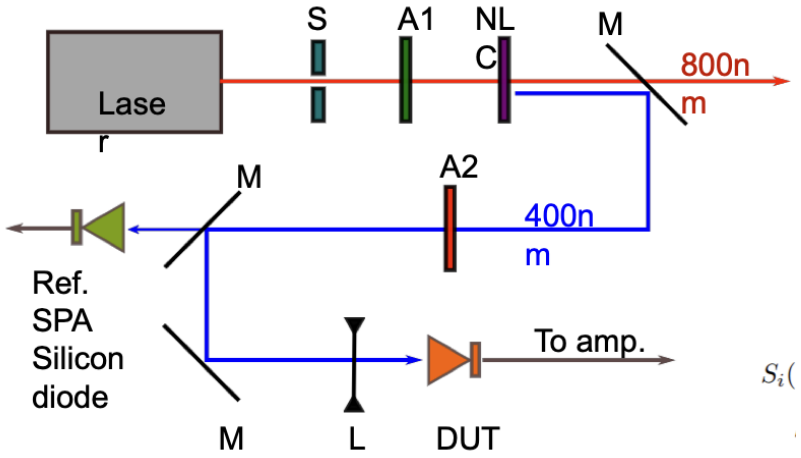
cnm Centro Nacional de Microelectrónica IMB

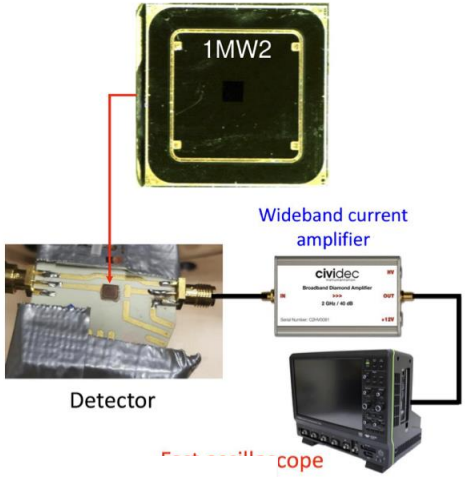
I. Lopez Paz
41st RD50 meeting

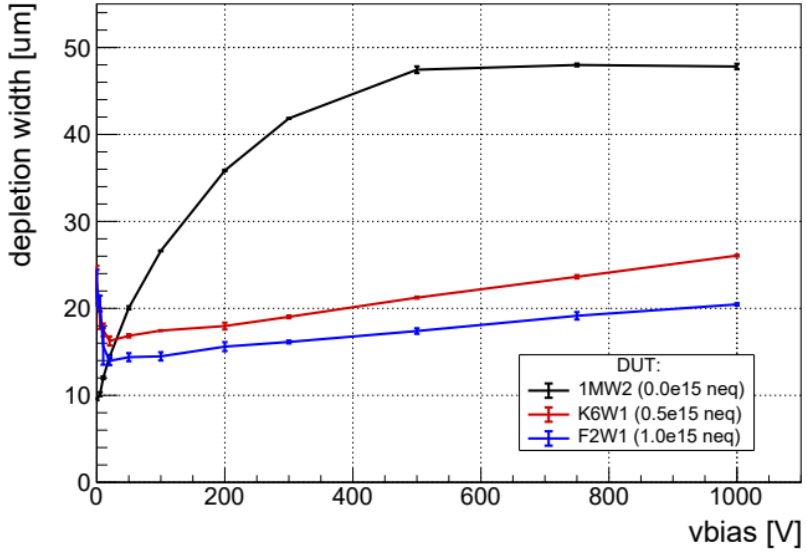
TPA-TCT on Silicon Carbide

- CNM samples non metalized
- Depletion zone grows as expected

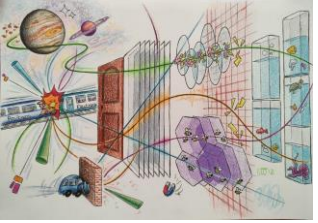








https://indico.cern.ch/event/1223972/contributions/5262058/attachments/2603339/4495686/2023-03-02_TREDI18-FINAL.pdf

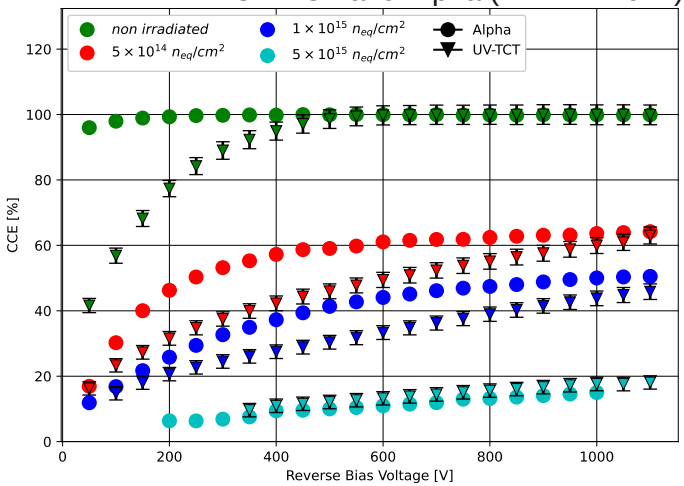


Silicon Carbide Radiation Hardness

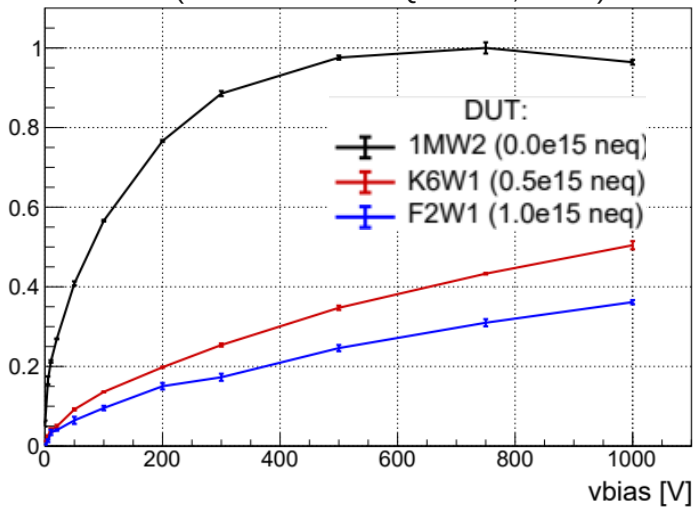
- Recently studied under neutron irradiations
  - 1E15 $n_{eq}cm^{-2}$ has CCE 30-40%
  - 1E16 $n_{eq}cm^{-2}$ shows CCE of <20%
    - Not fully depleted
    - Would need > 1100 V bias which is a challenge for the current TCT boards
  - Previous study shows higher CCE for proton irradiation

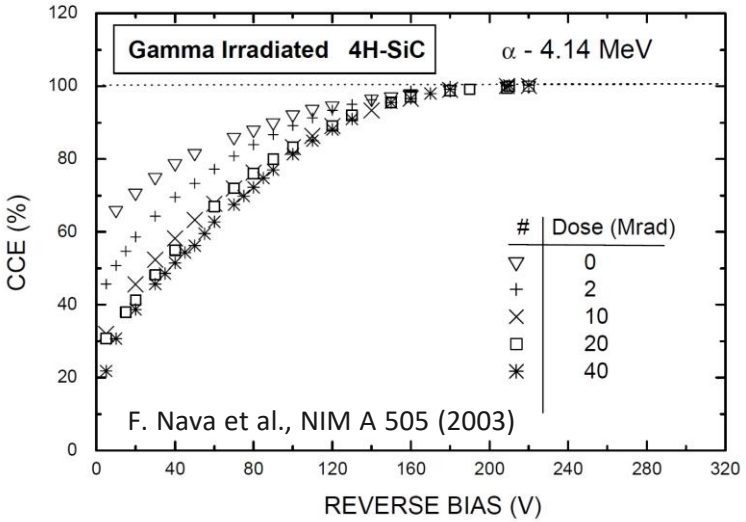
- Earlier studies:
  - Higher signal for p-irradiated rather than n-irradiated shown
    - Materials defect study needed!
  - TID irradiation shown earlier

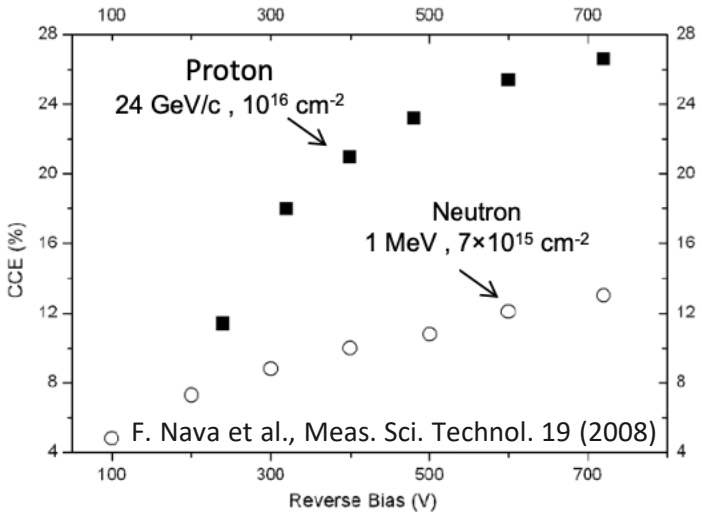
UV-TCT and Alpha (HEPHY 2022)

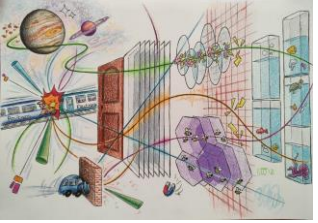


TPA-TCT (TREDI2023 – C. Quintana, I. Vila):





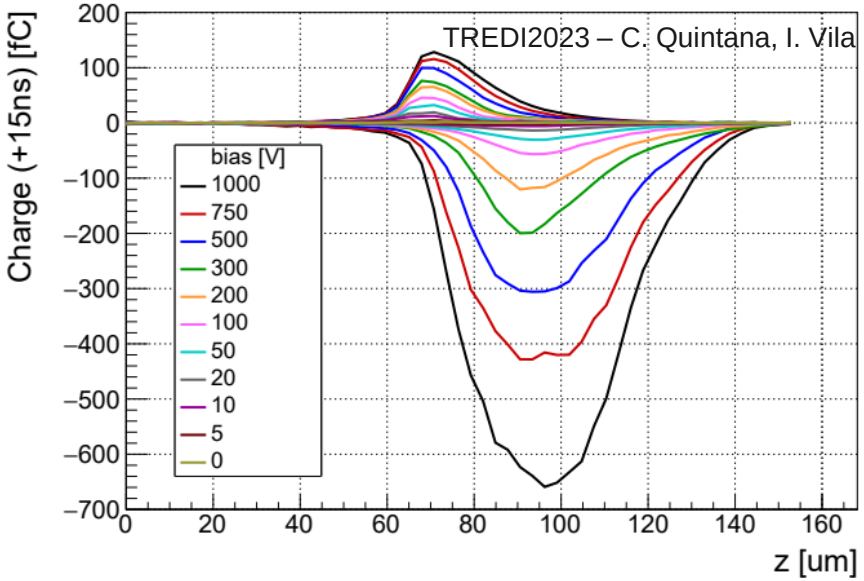




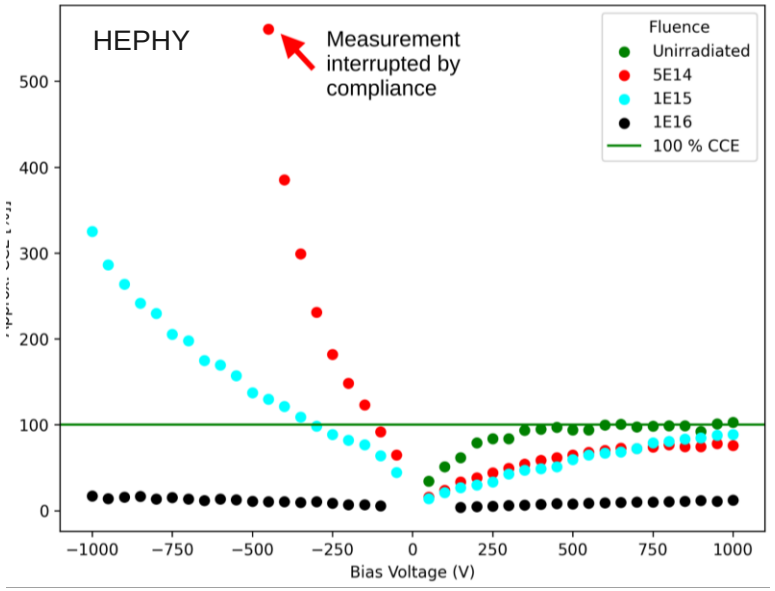
SiC charge amplification in forward

- Diode behavior vanishes for irradiated samples and material becomes “intrinsic”
- **Almost a X10 increase of the signal for 1e15 n_{eq}/cm^2**
  - Not visible in Alpha measurements hints to amplification effects on the backside

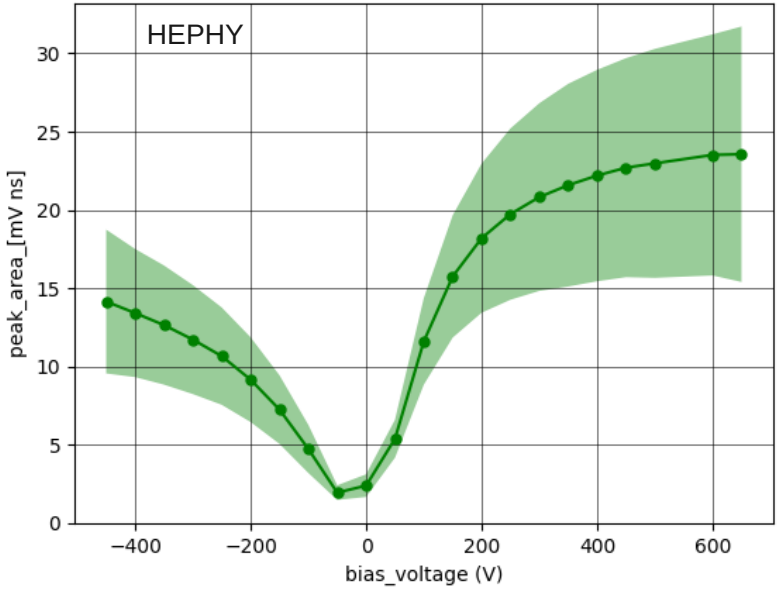
TPA-TCT



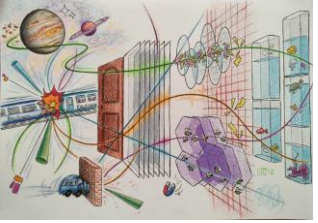
UV-TCT



Americium-241 Alpha

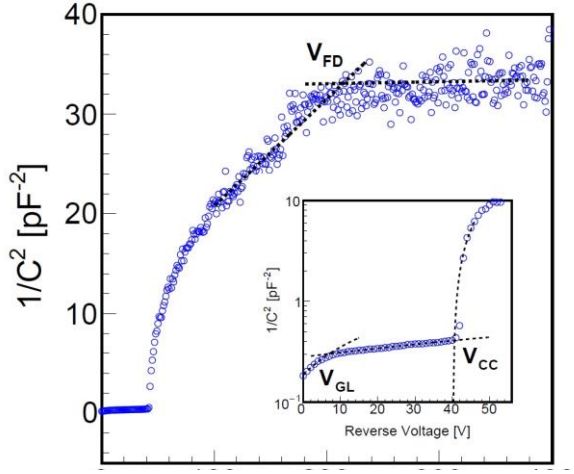


- Work in progress: **New effect opens the door to new ideas**

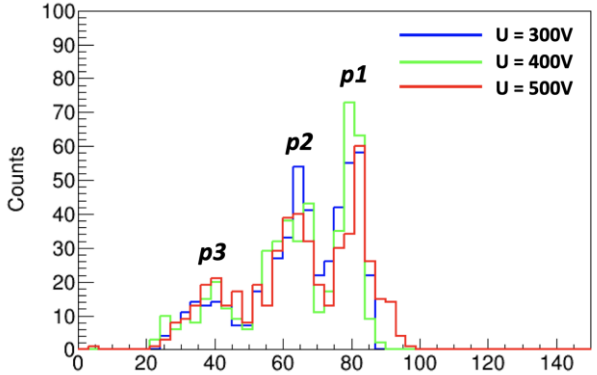


SiC-LGAD

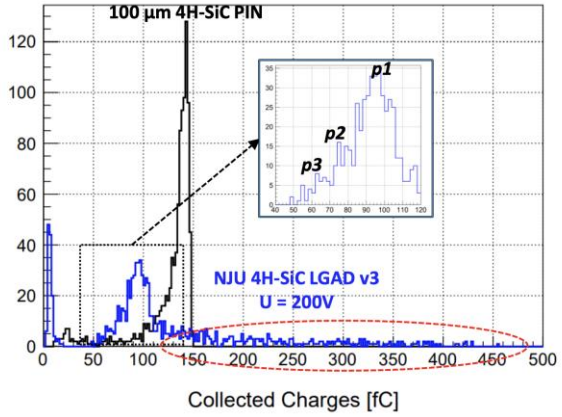
- **Implement a gain layer into Silicon Carbide to mitigate the small signals**
  - Technological challenges:
    - Only n-type substrates available→ N-LGAD
    - Deep gain layer implant needs very high energy or epitaxy
  - Progress at Nanjing University (NJU):
    - v2: verify the process for 4H-SiC LGAD, but no high gain signals are observed.
    - v3: gain <5 observed, with large signal spread. Early breakdowns
    - TODO: optimized v4 optimizes production by NJU is in progress...
  - **Recently established a new RD50 common project** for SiC-LGAD (HEPHY, CNM, CERN, Perugia, Santander, NIKHEF)
  - TCAD simulation needed to optimize gain layer structure
    - Lack of proper material description in Synopsis

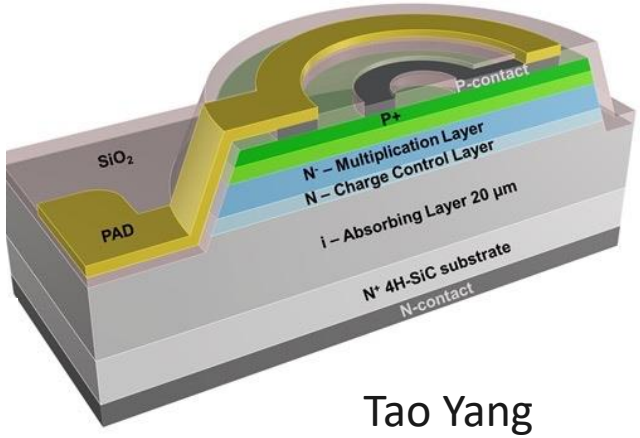


Collected charges spectrum for v2

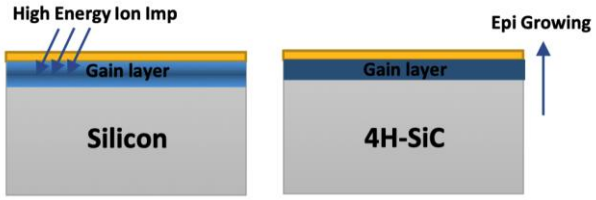


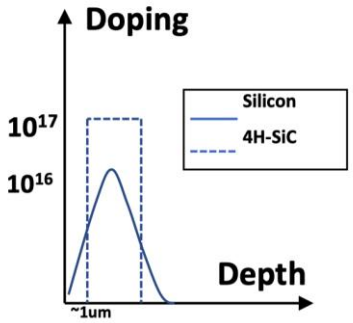
Collected charges spectrum for v3





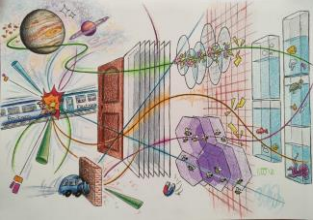
Tao Yang
40th RD50





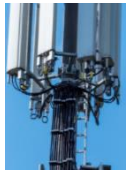
Yang Tao, 39th RD50 workshop

Gallium Nitride



Global GaN Industry

- Global deployment of GaN technology is significant
  - Communications – cell phone chips, 5G base stations, LEO satellites, VSAT, wireless chargers
  - Automotive – LiDAR for autonomous vehicles, power switch for hybrids/Evs, power distribution
  - Aerospace – power amplifiers, radiation-hardened RF electronics
  - Military and defense – radar, military communications, electronic warfare
  - Oil and gas, geothermal power generation



(a)

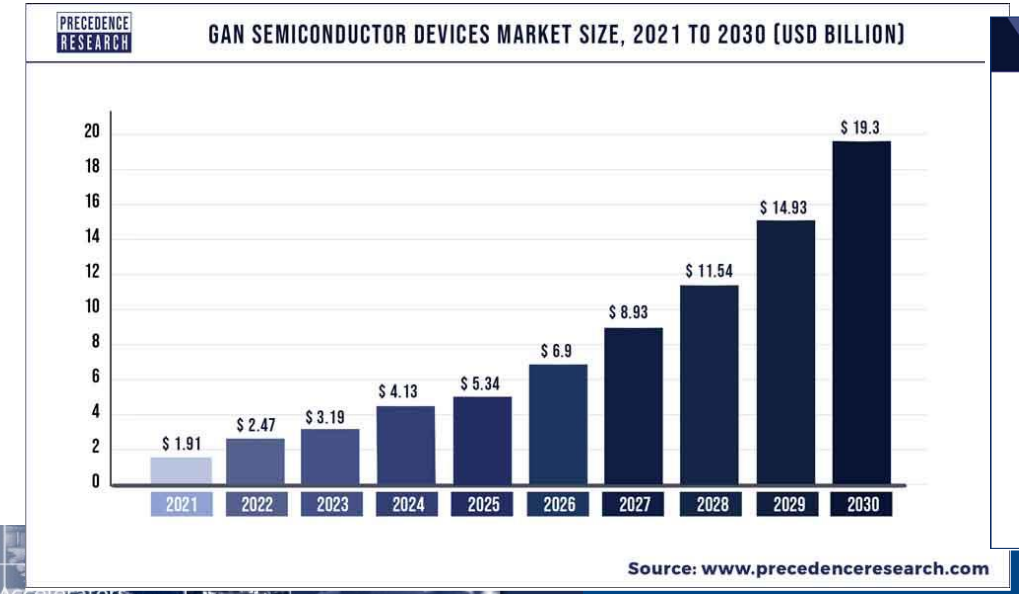
(b)

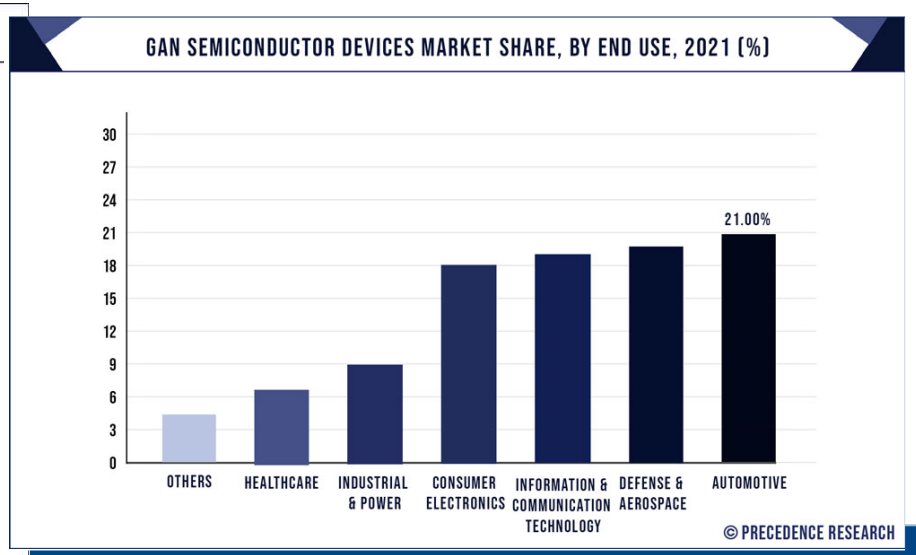
(c)

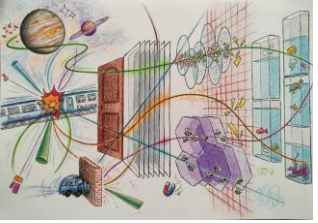
(d)

(e)

Identify industrial partnerships – industry is far ahead with GaN applications





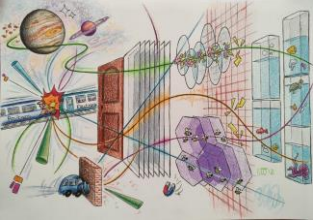


Gallium Nitride Properties

DRD3

Property	GaN	4-H SiC	Diamond	Silicon
band gap	3.39	3.26	5.47	1.12
mass density [g/cm^3]	6.15	3.21	3.5	2.33
dielectric constant	8.9	9.66	5.7	11.9
breakdown [kV/cm]	5	⊥ 4; ∥ 3	1-20	0.3
e mobility [cm^2/Vs]	1000	⊥ 800; ∥ 900	1700	1400
h mobility [cm^2/Vs]	30	115	2100	440
Saturated e drift velocity [10^7 cm/s]	3	2	2.7	1
therm. conductivity [W / cm K]	1.3	4.9	6..20	1.5
Threshold displacement energy	18-22	20-35	35	13-20
Energy to create an eh-pair [eV]	8.9	7.6	13	3.6
ionization density MIP [eh/mm]		57	36	89

- Similar, but a bit higher bandgap compared to SiC
- High-Z material suitable for X-ray and gamma-ray detection
- GaN has higher electron mobility compared, e.g. to SiC
- Many GaN radiation damage issues still not understood
  - Asymmetry in carrier removal rates in n- and p-type materials
  - Poor understanding of interaction of radiation defects with dislocations, dopants, annealing

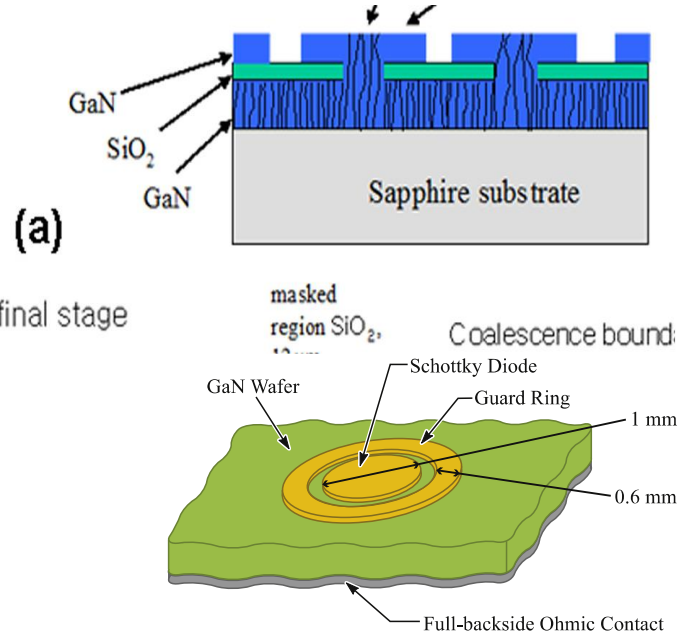


Gallium Nitride

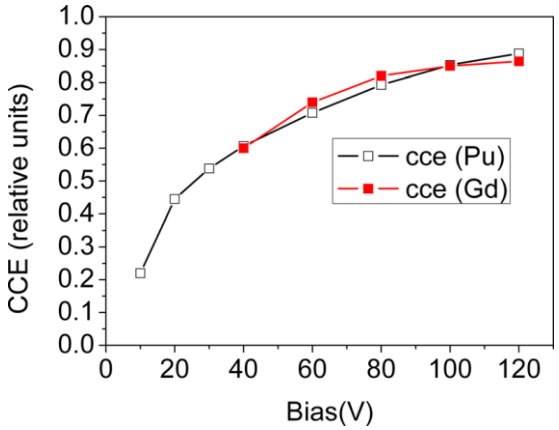
- GaN is grown on SiC or sapphire substrate
  - high density of threading dislocations in the GaN epilayer,

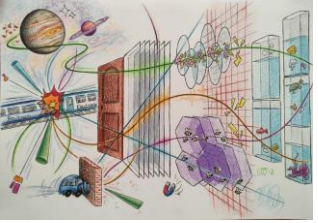
- Commercialization of GaN detectors for ionizing radiation detection is still impeded by the lack of high-quality materials
  - Dislocation defect density due to growth on lattice mismatch substrates results to further deterioration
    - Loss of carriers due to capture by deep traps decorating dislocations
  - Better GaN growth methods holds the key to the future:
    - Better photoelectric performance will also improve radiation hardness
    - High-temperature operation will also improve radiation hardness
  - Allow large-scale production, 8”+ wafers, material development

- GaN as Alpha and Neutron detector demonstrated
  - Sandwich structure grown on HVPE free-standing bulk GaN
  - Schottky contact on Ga side by depositing circular Ni/Au pads



https://doi.org/10.1016/j.nima.2013.04.019

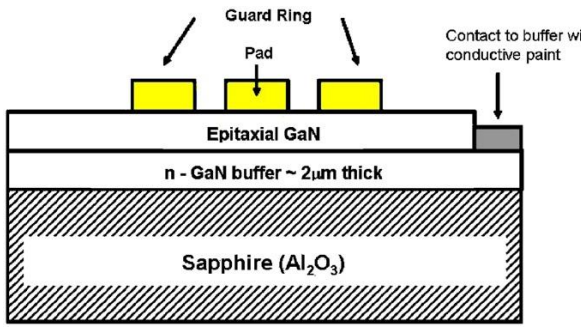




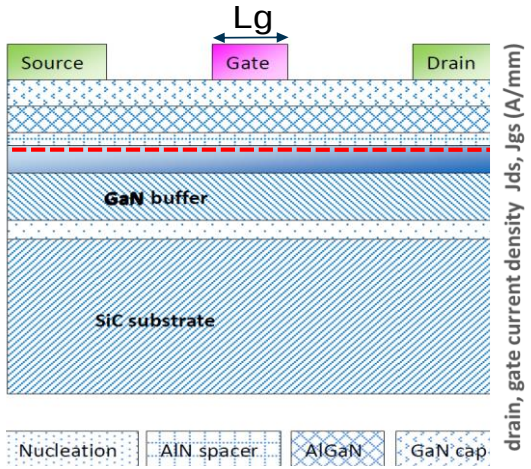
GaN Radiation Hardness

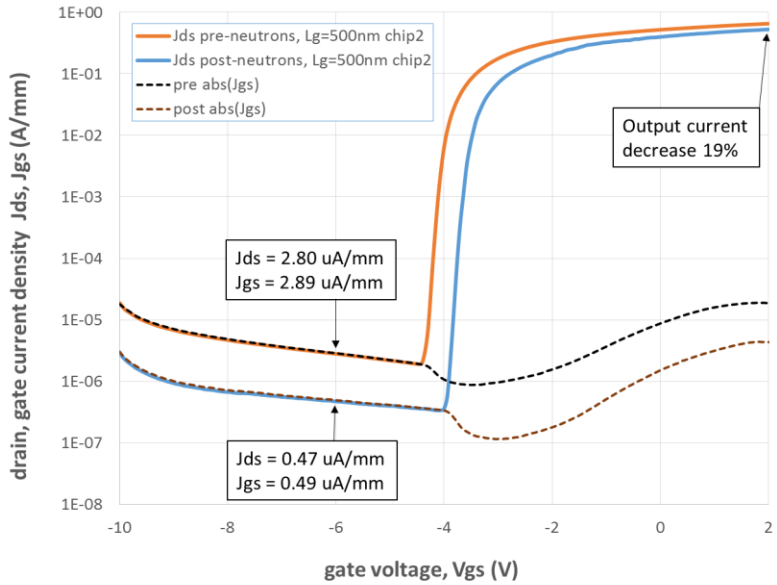
DRD3

- Studied within RD50 in 2007 (Glasgow & Vilnius) [1]
  - wafers obtained from Tokushima University Japan, and from LUMILOG, France
  - 2 inch diameter, 12 mm thick epitaxial
- Radiation-hard HEMT Fabrication
  - High Electron Mobility Transistor: heterostructure AlGaN/InAlN barrier on GaN
  - Mobility ~2000 cm^2/V-s → high-speed devices
  - Density ~$10^{13}cm^{-3}$ → high-current devices
- GaN FETs still perfectly functional after ~$10^{18}n_{eq}/cm^2$ protons irradiation [2]
  - Studied at RAL/Birmingham for ATLAS ITk



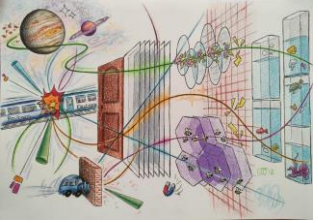
Detector material	Irradiation fluence	CCE_{MAX} (%)
GaN12	Unirradiated	54
GaN12	10^{16} p cm^{-2}	26
GaN12	10^{16} n cm^{-2}	20
GaN45	Unirradiated	97
GaN45	10^{16} p cm^{-2}	13
GaN45	10^{16} n cm^{-2}	42
25 μm epi Si n-type	Unirradiated	100
25 μm epi Si n-type	6×10^{15} p cm^{-2}	82
25 μm epi Si n-type	10^{16} n cm^{-2}	86





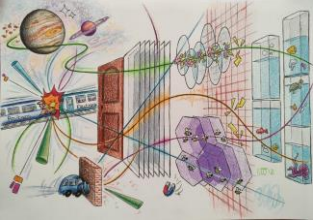
Schottky fabrication on-going at NRC and CNM

[1] doi:10.1016/j.nima.2007.01.121
[2] 10.1088/1748-0221/15/05/C05003

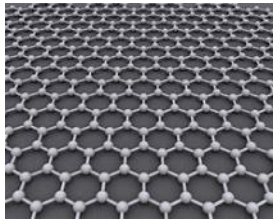


DRD3

2D Materials



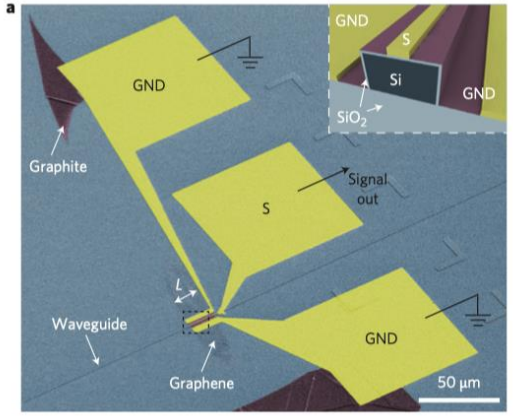
2D materials

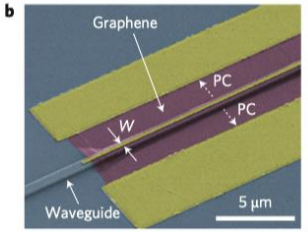


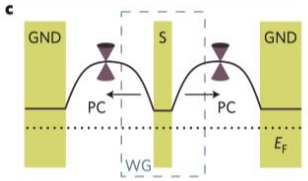
DRD3

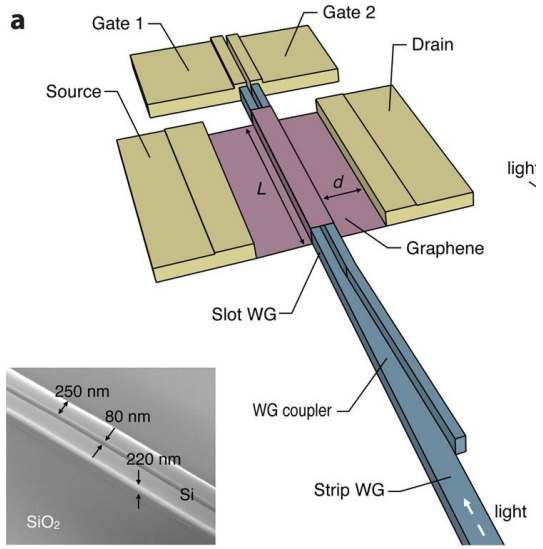
Graphene – the perfect atomic lattice

- Incredibly rapid and surprising developments, mainly in photonics:
  - CMOS-compatible graphene photodetector (Nature paper) [1]
  - Graphene photodetector using FET transistor modulated by light [2]



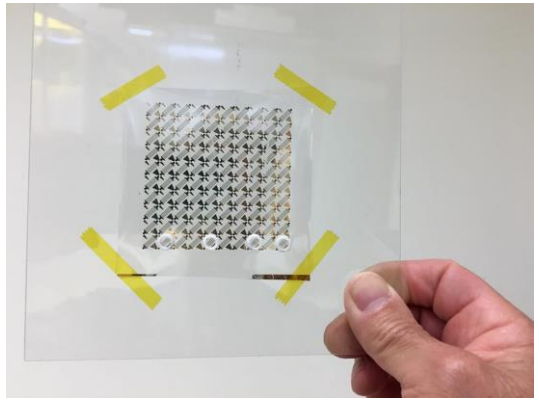


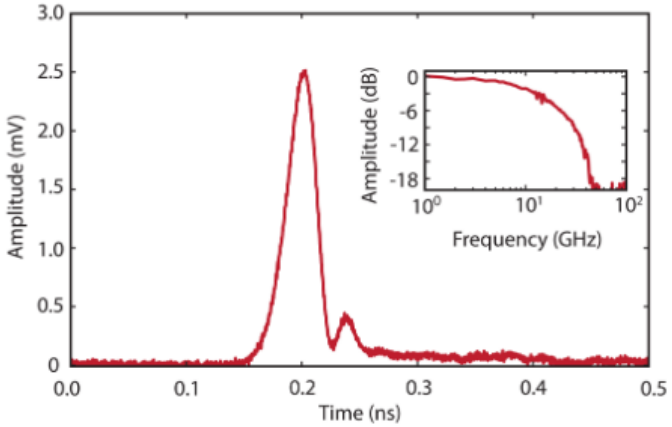




[1] 10.1038/nphoton.2013.240
[2] 10.1021/acs.nanolett.6b03374

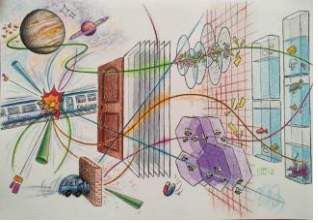
(https://www.graphenelabs.at)





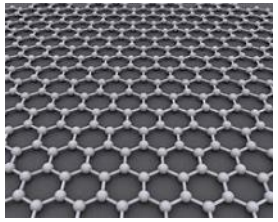
Biosensing, strain, blood pressure,…

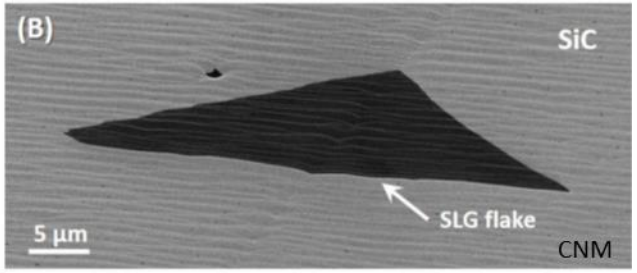
- https://grolltex.com/graphene-sensors/



2D materials for HEP

DRD3



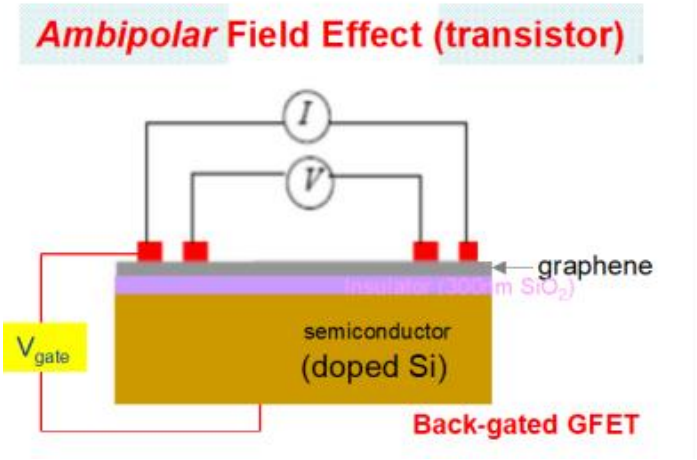


The resistance of graphene changes with induced charge in the semiconductor substrate below graphene, which produces a local change in the electric field near graphene.

Graphene properties:

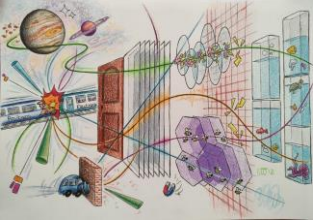
- Ultra-thin, High mobility (x10 Si), good thermal conductor, flexible, gain possible, integrable etc...
- Graphene (or other 2D materials) in radiation detection systems is in its infancy-> mainly based on Gr-FET.
- New ideas for direct detection of radiation are necessary.
- Radiation hardness not clear.

- **Try to understand possible applications**
  - No clear/easy solution.
  - Fun to look at new things (many 2D materials available).
  - Low costs to get started.
  - High potential.



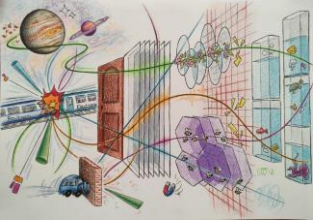
K. Geim and K. S. Novoselov, The rise of graphene, nature materials VOL 6 MARCH 2007.

M. Brener et al., **Innovation in Radiation Detectors: New Designs, Improvements, and Applications,** Transactions of the American Nuclear Society, Vol. 104, Hollywood, Florida, June 26–30, 2011.



DRD3

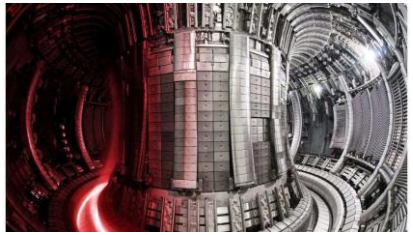
Summary: Synergies, differences, limitations

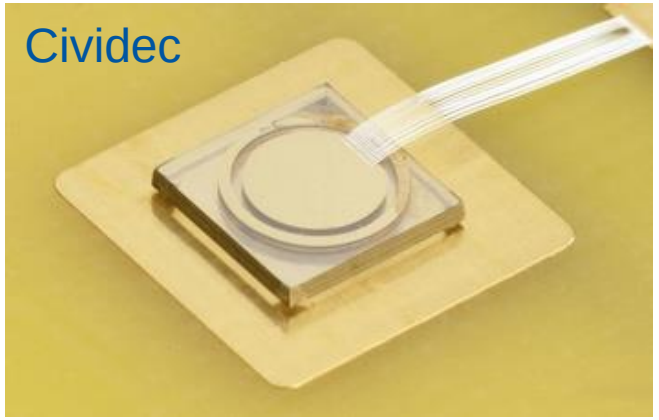


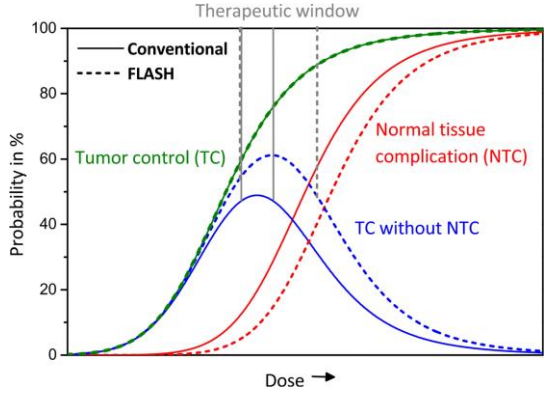
WBG Material Applications

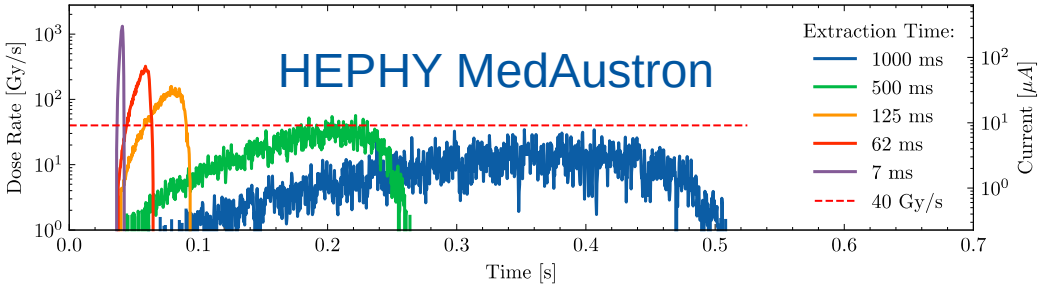
DRD3

- Beam Position/Intensity/Loss monitor
  - Alternative to diamond
- Nuclear Fusion:
  - High-temperature compatibility allows particle detection in plasma and fusion
- Aerospace/satellites
  - Sensors and electronics (e.g. SiC rectifier diodes)
  - X-ray detectors
- Medical Applications (tissue equivalence of SiC)
  - Medical imaging, FLASH radiotherapy
  - Micro-dosimetry

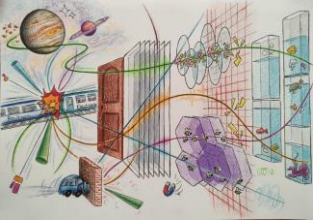








Generate more funding than HEP

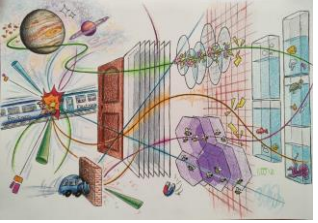


WBG Challenges: Material

- Material engineering
  - Larger wafers, thicker epi layers
  - Lower defect density, study microscopic defects (TSC for WBG needs high temperatures)
  - High-resistivity substrates
  - Radiation hardness and annealing to be understood
    - NIEL valid?, >1E16 not even understood for Silicon
- MIP detection by different concepts: 3D (diamond), impact ionization (SiC)
  - Rate capabilities
  - Study timing properties

My wishes:

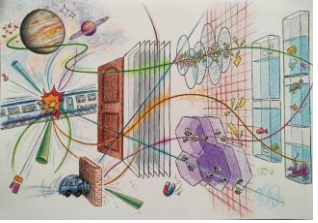
- **Strategic approach for collaboration with wafer industry** (using “CERN-label power”, similar to HPK contracts for ATLAS/CMS or TSMC contracts for CMOS electronics)
- **Common readout electronics**: high-bandwidth amplifier electronics (readout boards for ultra-fast TCT) similar to Caribou



WBG Challenges: Simulation

DRD3

- WBG Materials are poorly implemented in most material databases
  - NOTHING can be taken for granted when simulating non-silicon material
    - Parameters missing like bandgap narrowing, mobility models, permittivity, SRH, laser absorption coefficient,…. → need to be determined experimentally if not “common knowledge”
  - Synopsis TCAD mixes up different SiC polytypes and does not consider anisotropy
    - Lack of Synopsis built-in models for pCVD diamond: traps, polarization, polycrystalline CVD diamond, grain boundaries, graphitic wire simulation
  - Silvaco includes existing GaN models – including process simulation
- Convergence issues for WBG due to low charge carrier densities
  - Suffer from numeric precision of simulation
- Radiation damage models need a lot of input (trap and defect levels,…)

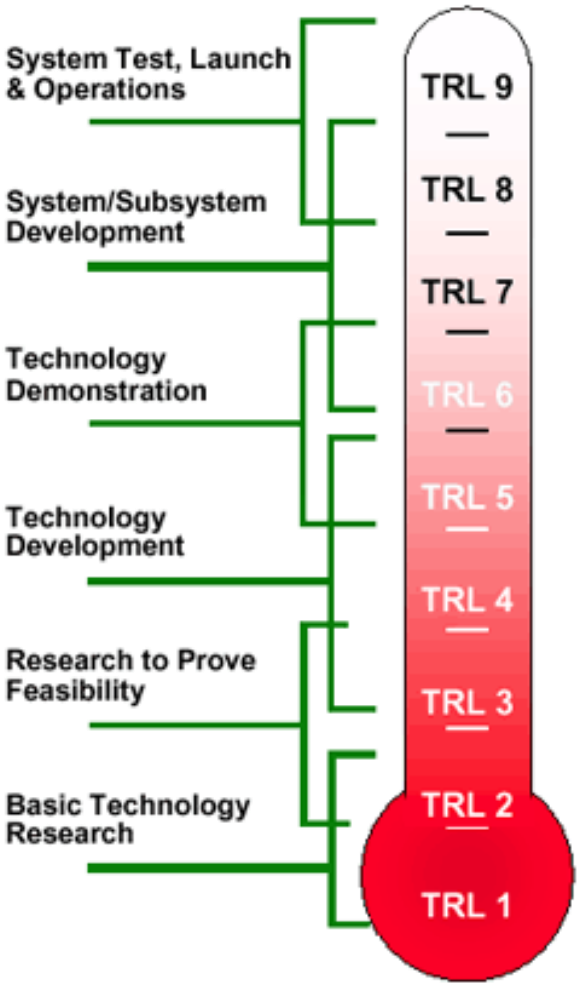


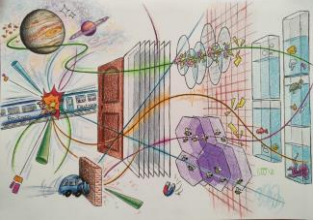
Summary

DRD3

	Economic interest	Wafer availability	Current status	TRL	
Diamond	Jewelry ☺, power electronics, quantum computing	Polycrystalline 1500$ / cm^2	RD42: very mature project; New momentum by 3D laser milling (amorphisation)	9 (planar) 5-7 (3D)	Strategic R&D
Silicon Carbide	Power electronics (European industry!)	6” @ $2-7k depending on epi-thickness (20-200µm)	Studied 20 years ago; Now new momentum due to large low-defect wafer availability	4-7	Strategic R&D
Gallium Nitide	HF and opto (LED)	$10k per 2” wafer	Wafer diameter and substrate engineering	3-5	Blue Sky
2D Materials	Opto-electronics	Monolayer graphene on 8-inch Si/SiO2: $865		1-2	Blue Sky

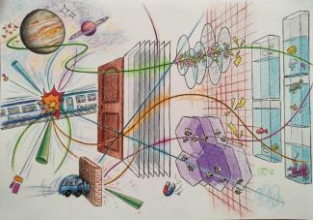
Technology Readiness Level





Fin.

Backup slides follow

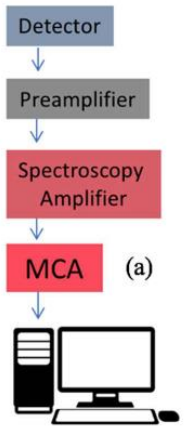


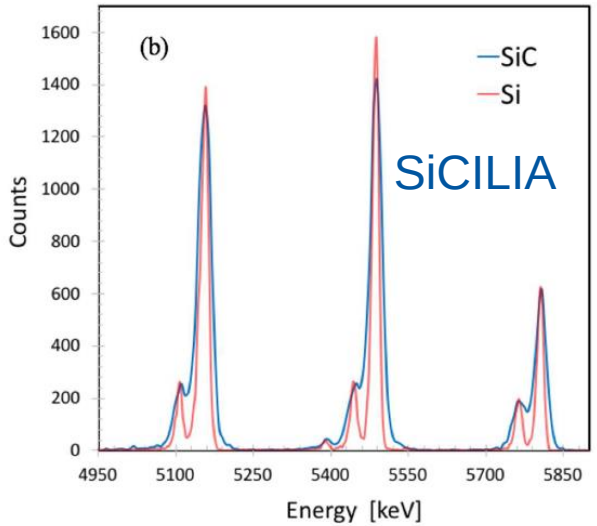
Current work on Silicon Carbide

DRD3

- Characterization by different methods to understand material properties
  - ionization density MIP: 57 e/h pairs per µm *)
  - Ionization energy: ϵSiC= 7.6 *)
  - Fano factor = 0.103 *)

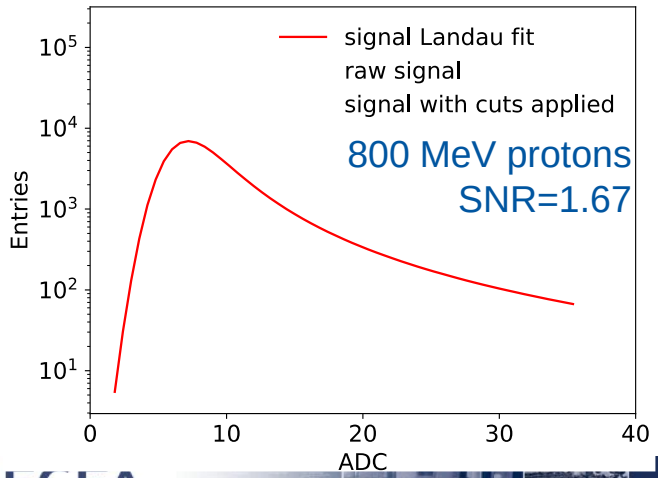
*) measured at HEPHY

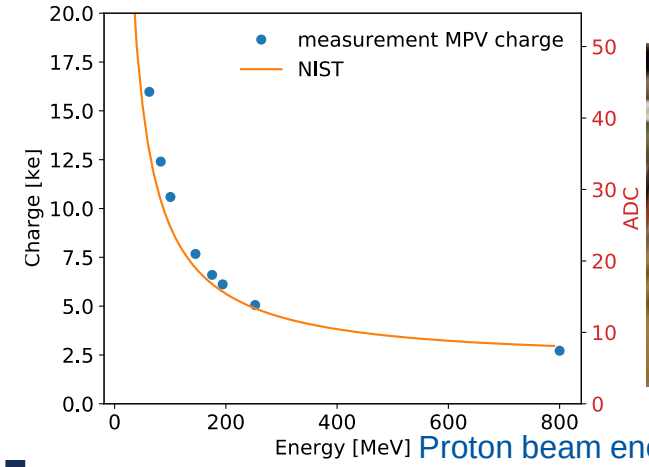


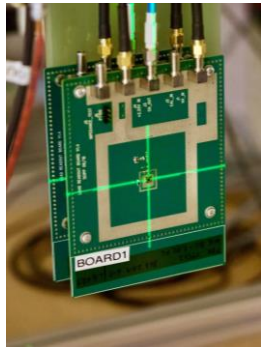


Mixed Alpha Source (Am-241, Cm-244, Pu-239)

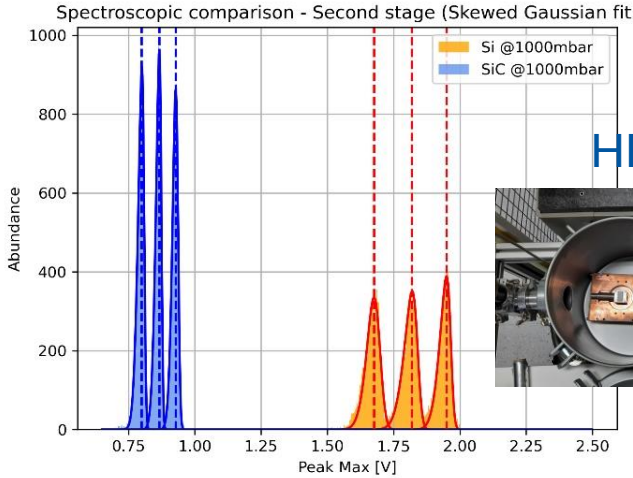
Proton Beam at MedAustron:



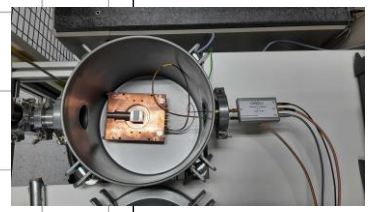


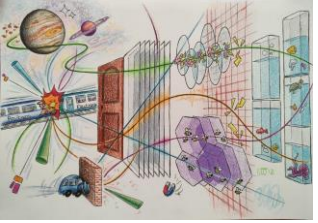


Proton beam energy



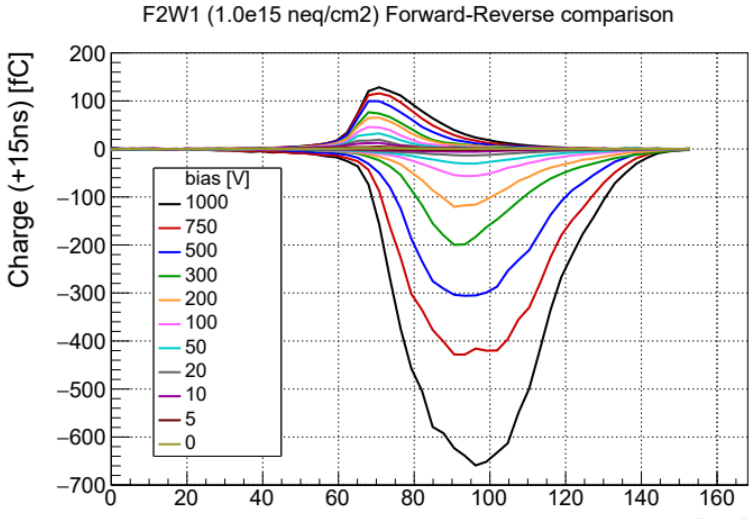
HEPHY

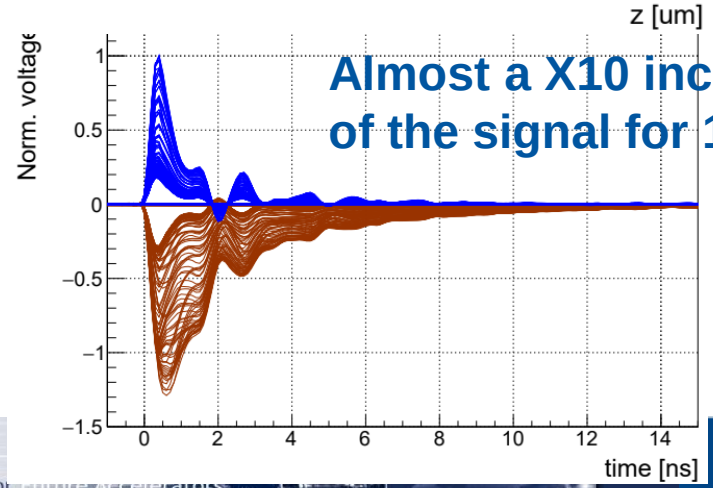




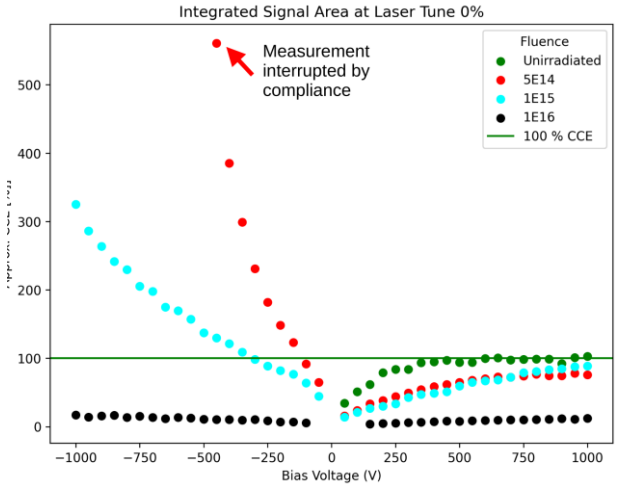
SiC charge amplification in forward

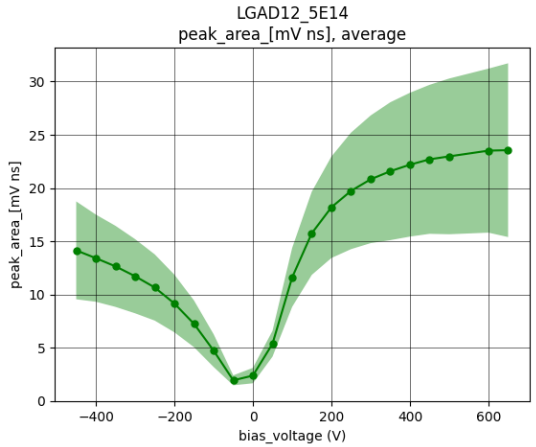
- Diode behavior vanishes for irradiated samples and material becomes intrinsic
  - CCE in “forward direction” >100% compared to reverse visible in TPA-TCT and UV-top TCT
  - Not visible in Alpha measurements (charge deposition on surface)

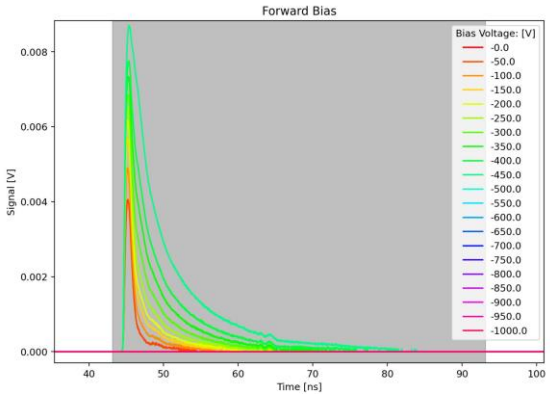


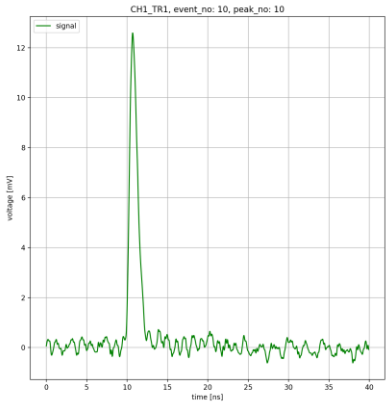


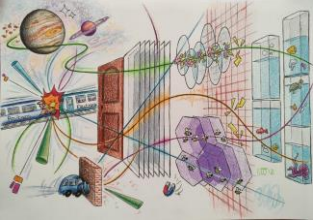
Almost a X10 increase of the signal for 1e15 n_{eq}/cm^2





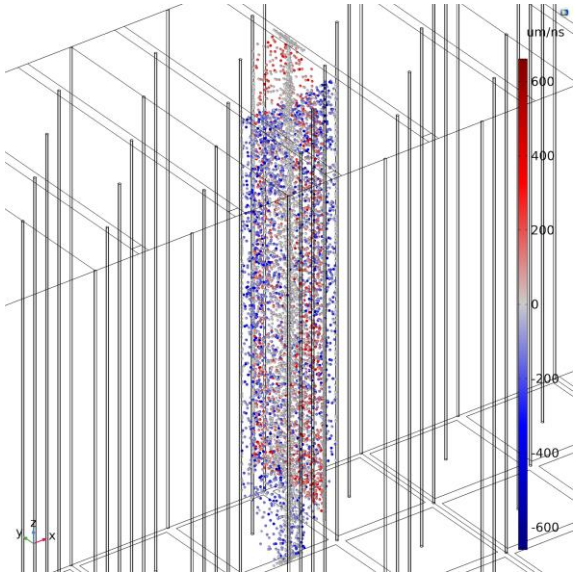


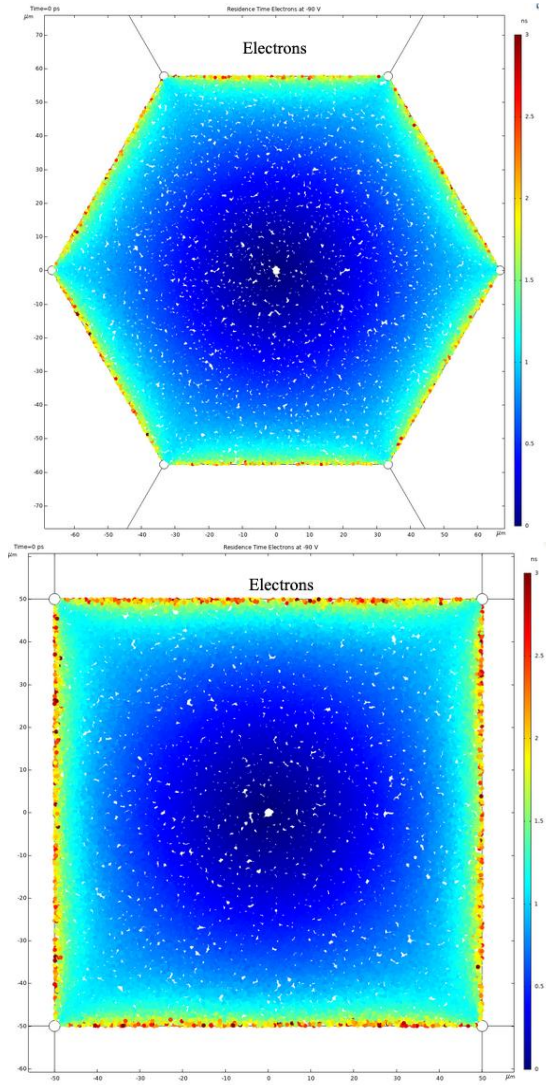




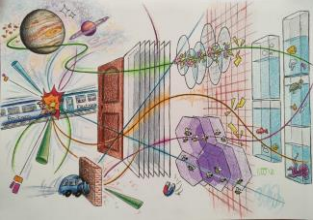
Diamond Simulation challenge

- Lack of build-in models, especially pCVD and traps / polarisation in current TCAD tools being addressed.
- Need effort to improve simulations:
  - polycrystalline CVD diamond, grain boundaries.
  - graphitic wire simulation
  - radiation damage
  - new geometries





3D diamond simulation examples from RD42



TCAD

DRD3

ÖAW AUSTRIAN ACADEMY OF SCIENCES

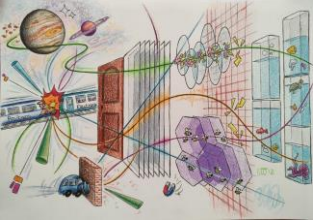
HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

4HSiC parameter file, current status

- Searched and implemented literature values from >30 sources
- Mostly HEP publications + diploma theses
- Anisotropy considered as good as possible (marked with *)

Band structure	Charge carriers	Recombination
– Permittivity*	– Mobility:	– SRH
– Bandgap (BG)	Temperature dep.*	– SRH-surface
– BG-narrowing (old SB)	Doping dep.*	– Auger
– Effective DOS-masses	High field saturation*	– Radiative
– Incomplete ionization	– Impact ionization	
Al (p) and N (n) doping	Okuto Crowell*	

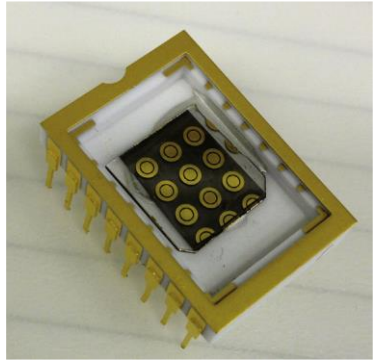
6

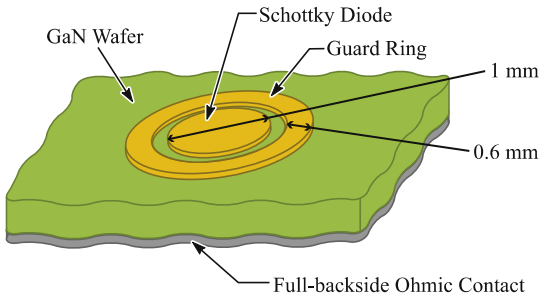


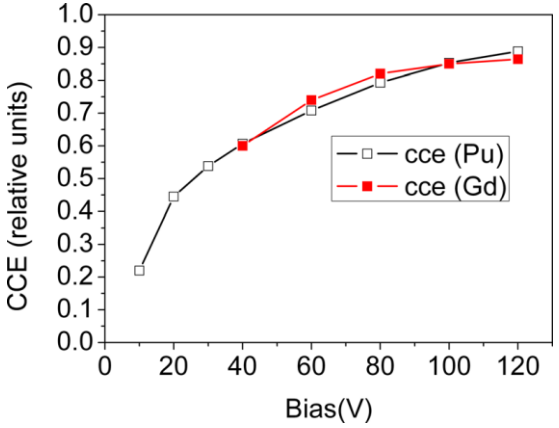
GaN as detector

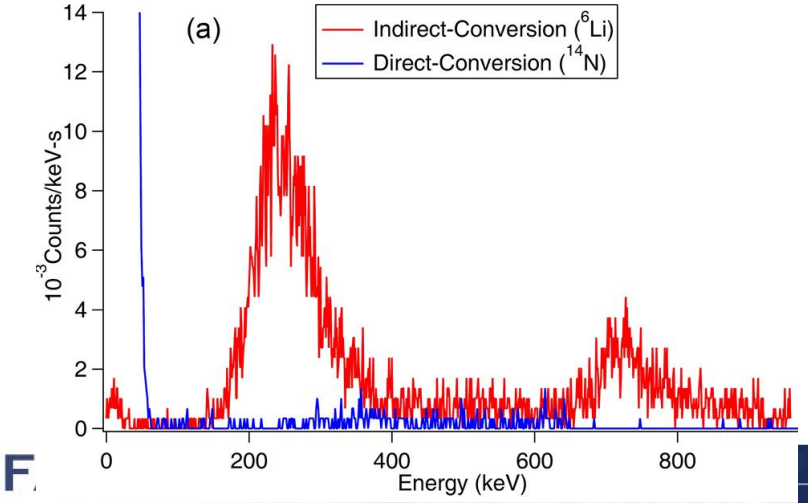
https://doi.org/10.1016/j.nima.2013.04.019

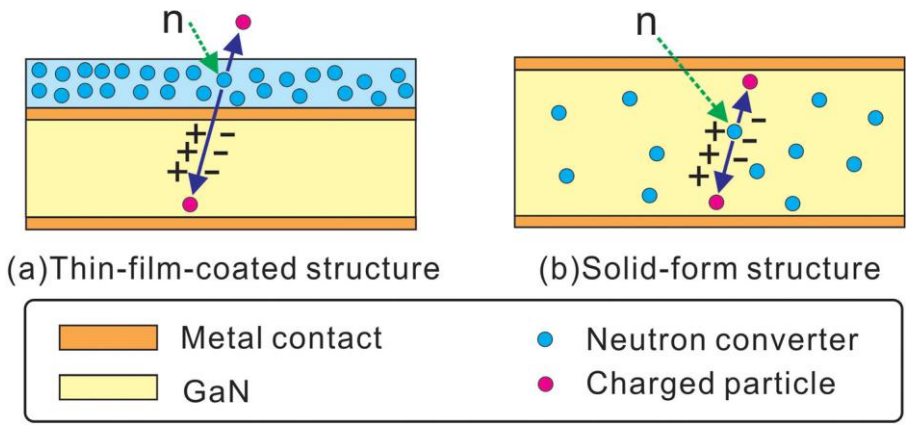
- Alpha detector
  - Sandwich structure grown on HVPE free-standing bulk GaN
  - Schottky contact on Ga side by depositing circular Ni/Au pads
- Neutron Detector
  - Thin-film coated neutron converter (a)
  - Converter incorporated through doping (b)



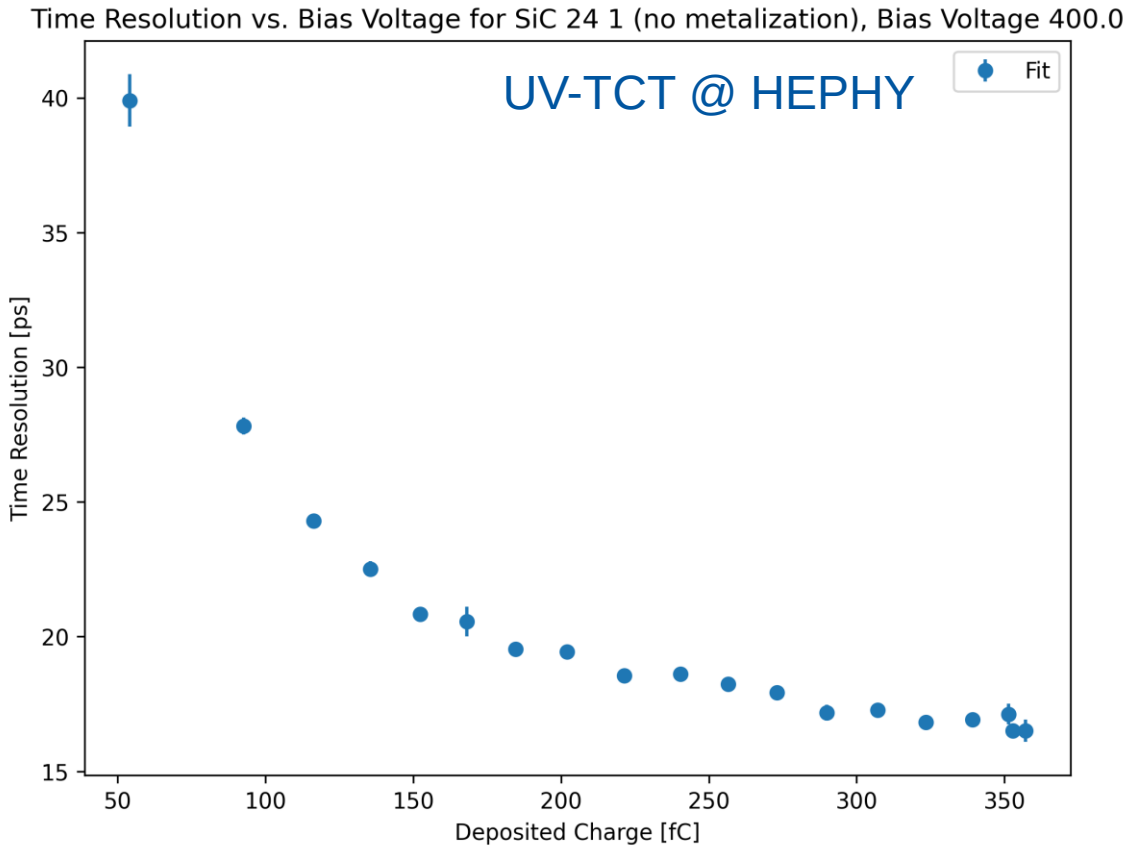


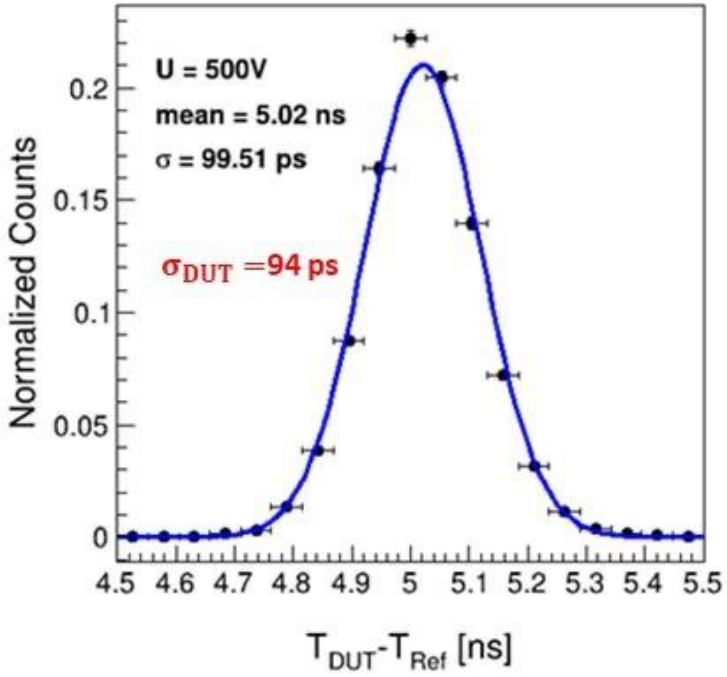






SiC Timing Capabilities





https://www.frontiersin.org/article/10.3389/fphy.2022.718071

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