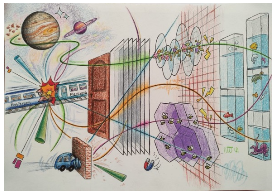
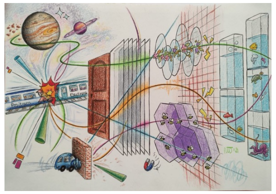


V1.2

Wide band-gap material sensors for applications in high energy physics experiments

Alexander Oh
University of Manchester
for WG6 of the DRD3 collaboration

Acknowledgements
Inputs and material from the RD42 & RD50 collaborations



Introduction

DRD3

Collaboration board
CB Chair: G. Pellegrini (CNM)
Deputy: R. Arcidiacono (INFN-TO)

Steering committee:
DRD3 management + CB Chair + WG conveners

DRD3 management
G. Kramberger (JSI) - SP
M. Moll (CERN)-DSP
I. Gregor (DESY)-DSP
S. Seidel (UNM)-DSP

DRD3 bodies
- Secretariat/administration
- Resource coordinator /Project office (D. Muensterman, HRM/Lancaster)
- Cross-DRD coordination
  CPAD coordination
- Speakers committee
  (U. Parzefall - Freiburg)

R&D activities

WG 1
Convener(s)
Monolithic silicon technologies
H. Pernegger (CERN)
E. Vilella (Liverpool)
J. Baudot (Strasbourg)

WG 2
Convener(s)
Hybrid silicon technologies
A. Macchiolo (UZH)
M.v.Beuzekom (NIKHEF)
A. Tricoli (BNL)

WG 3
Convener(s)
Radiation damage & extreme fluences
Ioana Pintilie (NIMP)
J. Schwandt (Uni. HH)
TBD

WG 4
Convener(s)
Simulations
H. Wennloef (DESY)
M. Mandurrino (INFN-TO)

WG 5
Convener(s)
Characterizatio techniques an facilities
I. Vila (IFCA)
B. Hiti (JSI)

WG 6
Convener(s)
Wide band-gap and innovative sensor materials
A. Oh (Manchester)
X. Shi (IHEP) + TBD

WG7
Convener(s)
Interconnections and device fabrication
G. Calderini (LPNHE)
D. Dannheim (CERN)
F. Huegging (Bonn)

WG 8
Convener(s)
Dissemination & outreach
C. Nellist (NIKHEF)
TBD

WP1
Leader(s)
Monolithic CMOS sensors

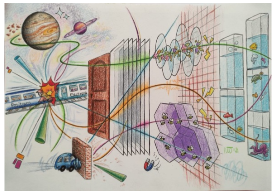
WP2
Leader(s)
Sensors for 4D-tracking

WP3
Leader(s)
Sensors for extreme fluences

WP4
Leader(s)
3D-integration& Interconnections

…………………………………

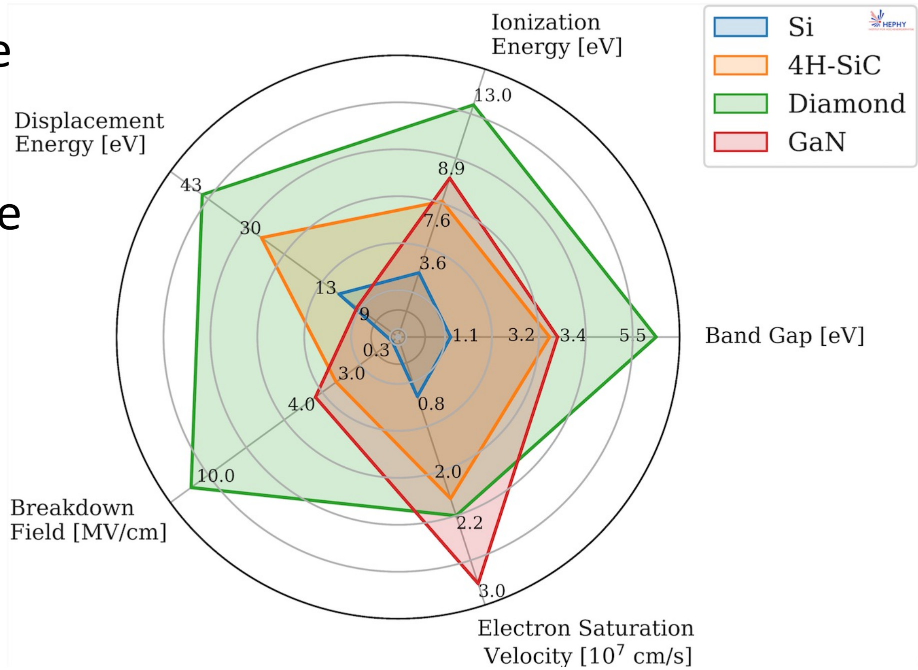
Strategic/Targeted R&D projects

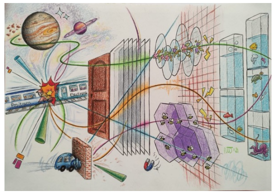


Introduction

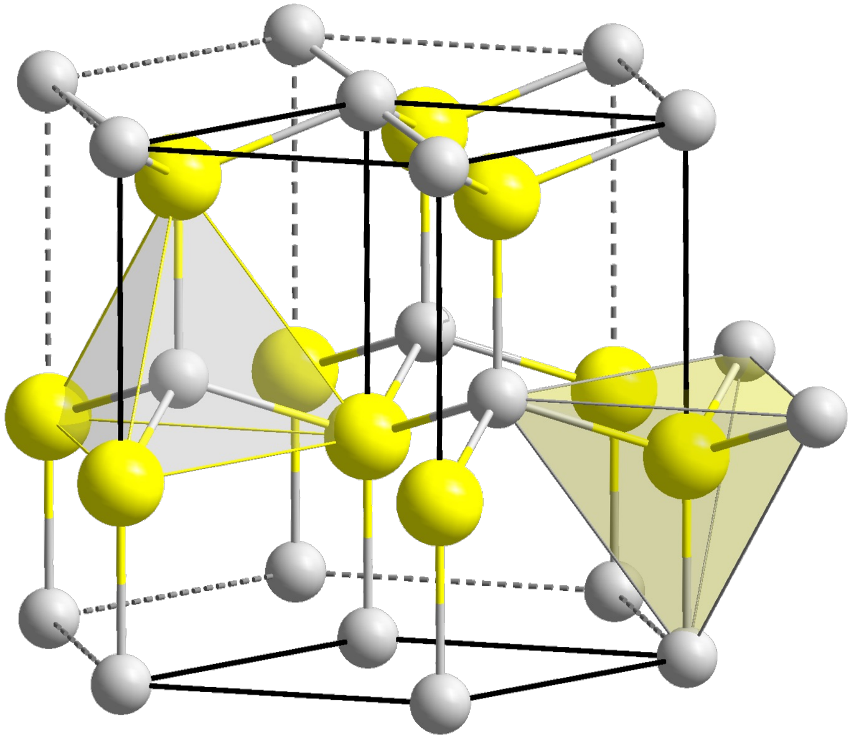
Materials under investigation in WG6:

- Silicon Carbide
- Diamond
- Gallium Nitride

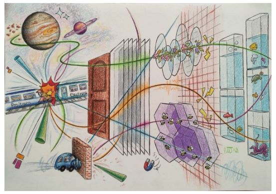




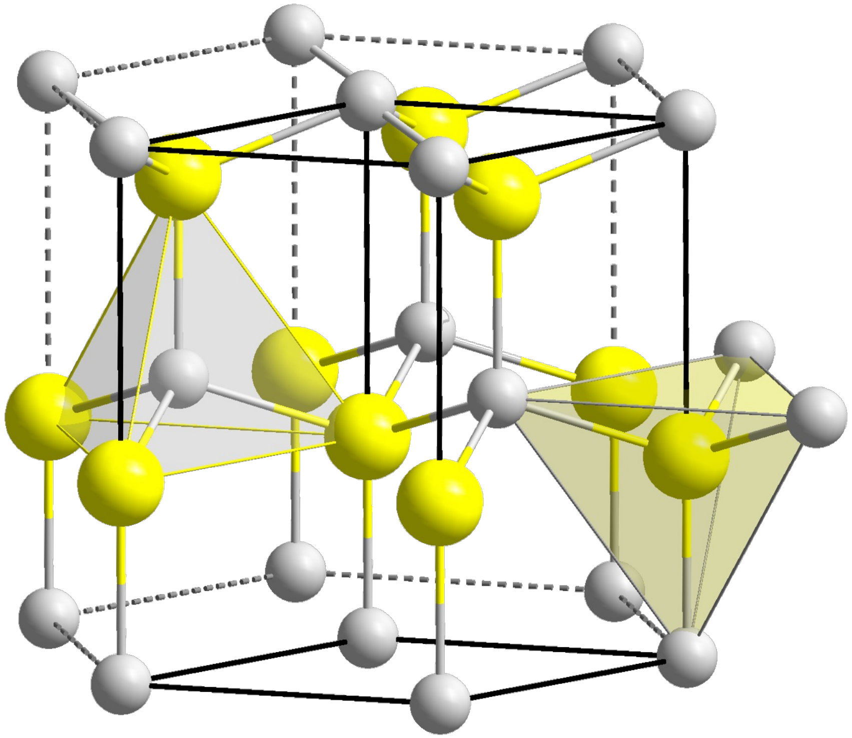
Gallium Nitride



- Wide direct bandgap semiconductor, E_g = 3.4 eV wurtzite crystalline structure
- High electron mobility (up to 2000 cm^2/Vs)
- High breakdown voltage (600-1200 V/µm)
- High atomic bond energy (~9 eV/atom)
- Higher power density and faster switching speed compared to silicon, use in power electronics



Gallium Nitride

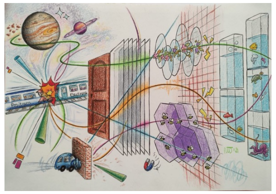


However,
less mature technology,
typically, with high dislocation density >1E6 cm^2

Better GaN growth methods holds the key to the future

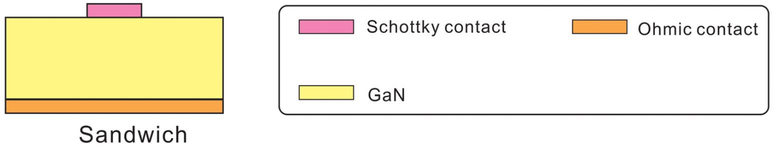
- **Improvements in photoelectric performance and high temperature operation will also improve radiation hardness**

material from T. Koffas, Carleton

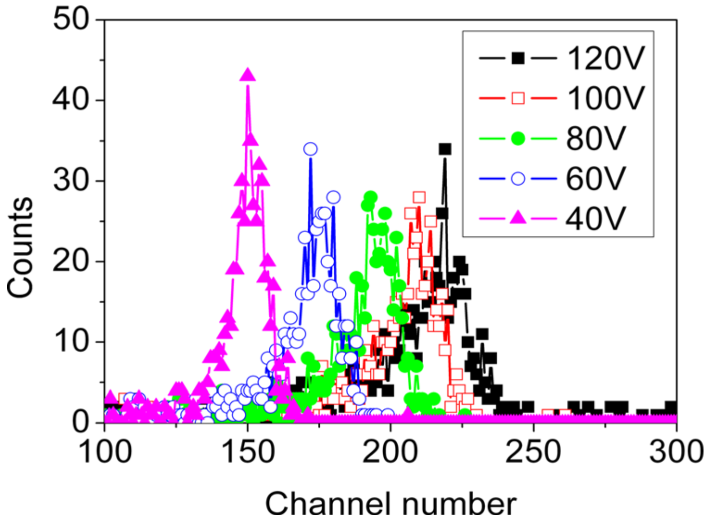


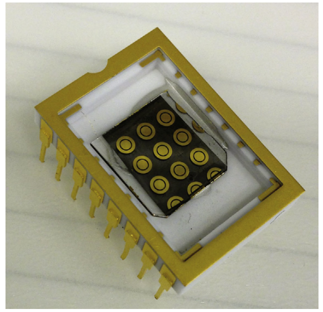
Gallium Nitride: α detection

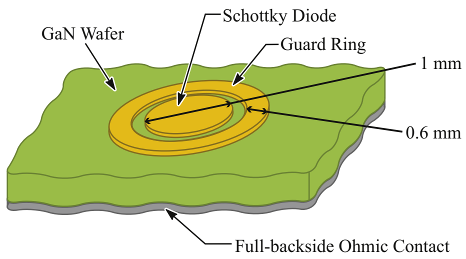
- Sandwich structure grown on HVPE* free-standing bulk GaN
- Schottky contact on Ga side by depositing circular Ni/Au pads

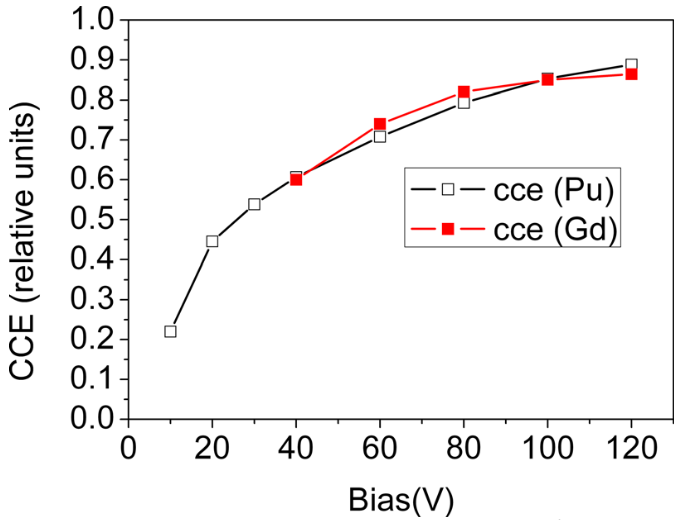


https://doi.org/10.1116/1.3690644
J. Vac. Sci. Technol. B 30, 021205 (2012)



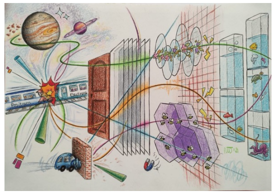






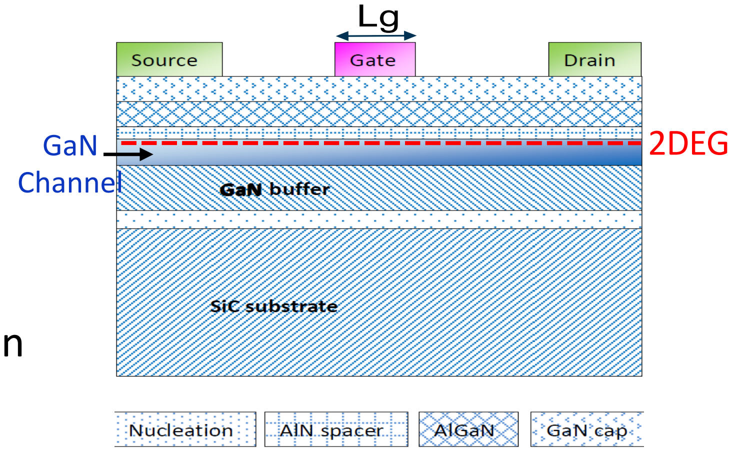
* hydride vapor phase epitaxy

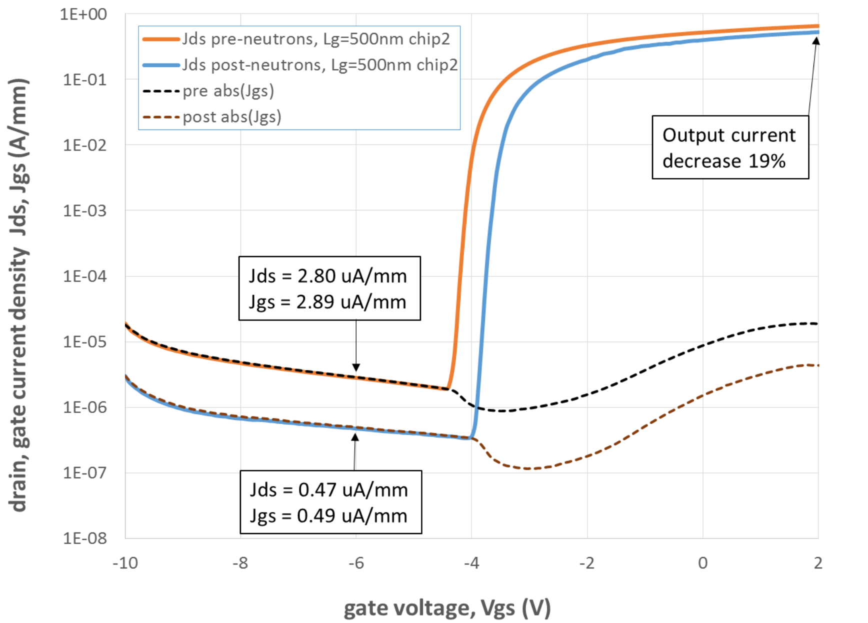
material from T. Koffas, Carleton



GaN High Electron Mobility Transistor

- GaN HEMT epitaxial structures fabricated at National Research Council Canada:
  - AlGaN/AlN barrier on GaN
- High-mobility 2D-electron gas (2DEG)
  - Between AlGaN/AlN – GaN interface

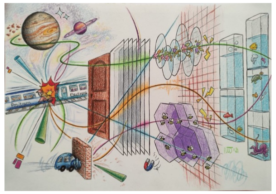




See: GaN-AlGaN high electron mobility transistor characteristics
40th RD50 Workshop, 21-24 June 2022

- "Engine" for high-electron mobility transistors → 2DEG
  - Mobility ~2000 $cm^2/V\text{-}s$ → potential for high-speed devices
  - Density ~$10^{13} cm^{-2}$ → potential for high-current devices
- Pre-/post irradiation (10^{16}neq) transfer curves and gate currents
  - Drain leakage current reduce, i.e. improved
  - V_{th} shifted by +0.4V – acceptable within IC design limits
  - Output current decreased by 19%
  - Fabrication process already rad-hard to HL-LHC fluences – starting point for development

material from T. Koffas, Carleton

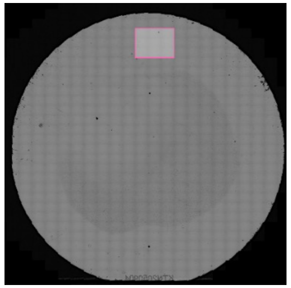


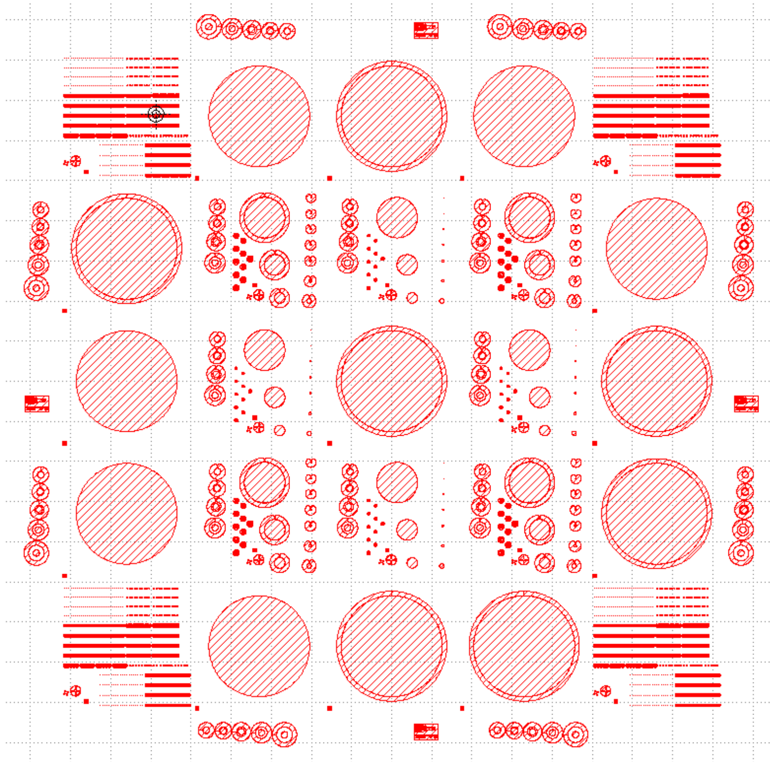
GaN Schottky device

Fabricating GaN Schottky devices using 8 µm GaN epi-layer on GaN native substrate

- At the Canadian National Research Council (NRC) and CNM-Barcelona

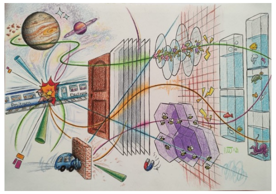
- Initial processing plan on 2” Kyma wafer:
- Deposit rear-side Ohmic metal with high temperature anneal
- Deposit front-side Schottky metal to test rectification
  - Ni/Au Schottky metal with ~0.8 eV barrier after rapid thermal anneal
  - Variable area devices with & without guard rings to suppress surface leakage
  - Ring devices for charge collection





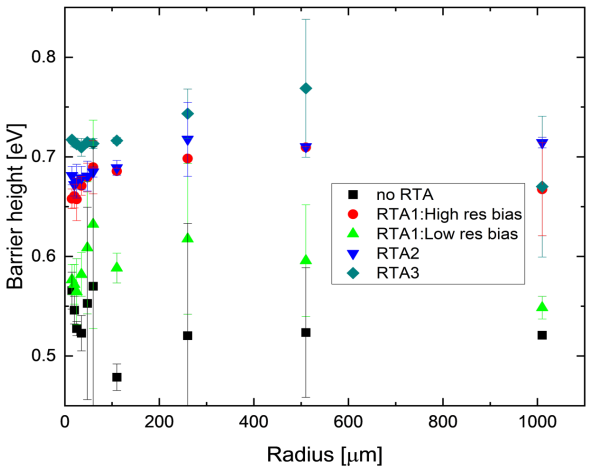
See 43rd RD50 Workshop

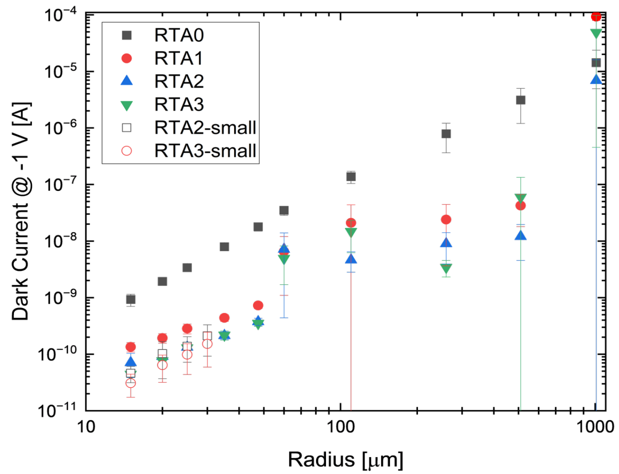
material from T. Koffas, Carleton



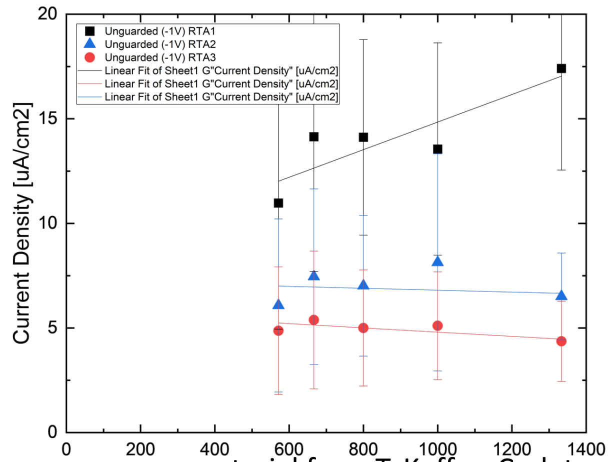
GaN Schottky device

- Significant impact of rapid thermal anneal on dark current and barrier height
  - Provides additional knob in improving device fabrication for rad-hard applications





- Current density vs perimeter/area
  - Reveals bulk and surface contributions
- Shows a clear decrease in perimeter contributions for increasing RTA
- Bulk contributions are in agreement (within uncertainty)



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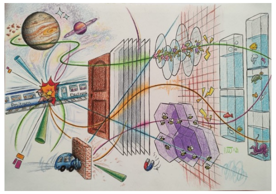


Response to UV Laser Light

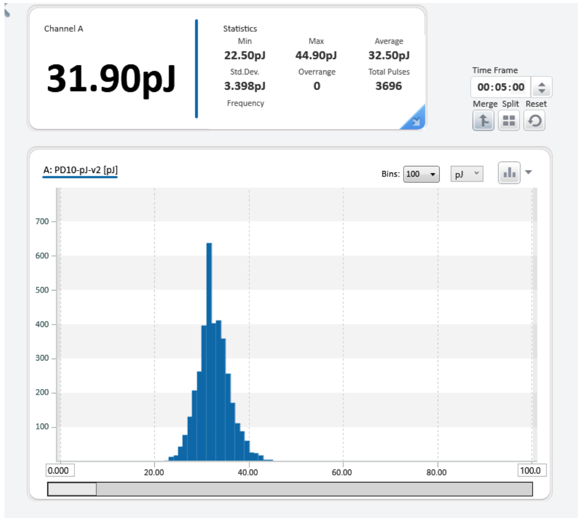
material from T. Koffas, Carleton

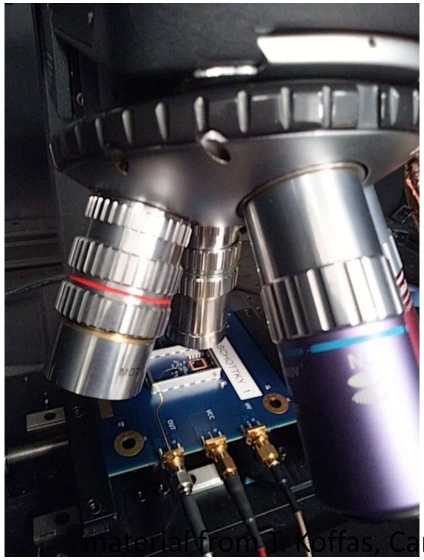
Single Photon Absorption with UV laser

Charge collection efficiency test at RAL.

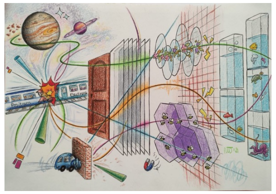
Laser characteristics:

- Type: Nd:YAG
- Wavelength: 1064, 532, **355** nm (~3.492 eV)
- Beam size : 5x5 mm, <E> = 32.5, 62.5 pJ
- Average photon number @ 355 nm:
- 5.82e7 (32.5 pJ) and 1.12e8 (62.5 pJ).





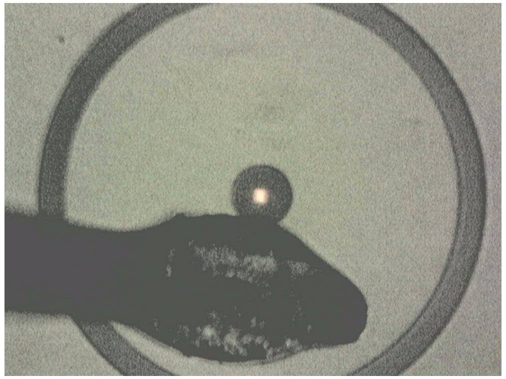
material from T. Koffas, Carleton

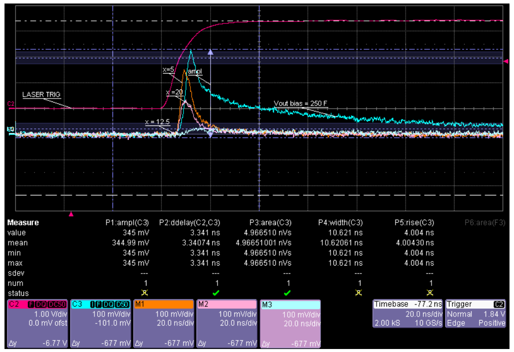


Response to UV Laser Light

material from T. Koffas, Carleton

DRD3

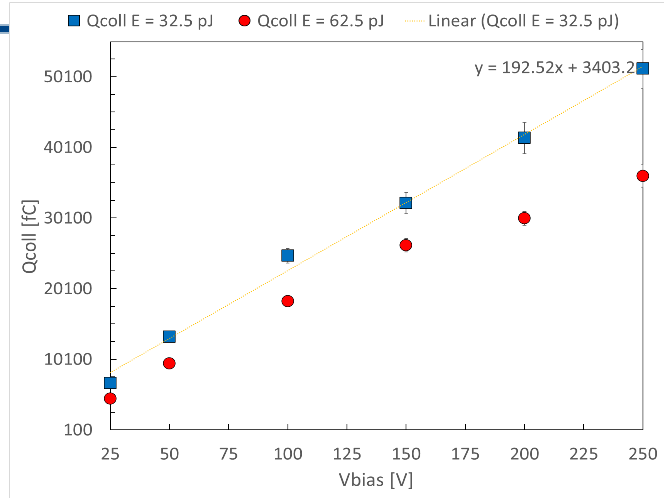


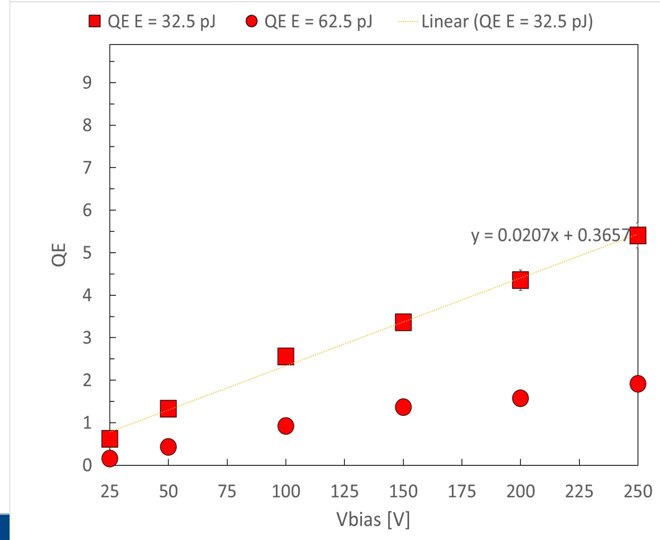


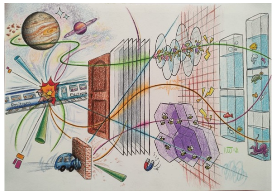
Focusing on the middle point of cathode stepping the bias voltage [25,250]V, two different injected charges

- Signal increases linearly vs. bias
- Further studies needed due:

1. Lateral collection of carriers along surface
2. Unknown contribution of surface fields/charges, critical due to short absorption length of UV light in GaN (~100 nm)
3. Possible charge amplification, but not sufficiently strong E-fields



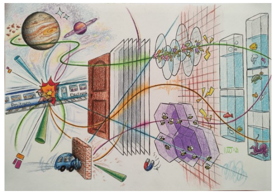




GaN future work

- Perform RF measurements on neutron-irradiated HEMTs
  - Pre-irradiation (L_g=500nm), f_t=18 GHz, f_{max}=36 GHz
  - Assess GaN devices as potentially high-rate, high timing precision devices
- Continue with Schottky device fabrication at NRC and CNM
  - More irradiations, material defects measurements, CCE
  - Many GaN radiation damage issues still not understood
    - Poor understanding of interaction of radiation defects with dislocations
    - Effect of defect transformation upon annealing not understood
- Improve radiation-hardness to $>10^{17}$ n_{eq}/cm^2
  - Incorporate fab process modifications with demonstrated robustness during 500^0C aging
  - Neutron irradiation to 10^{18} neq/cm^2 in August 2024 at JSI
    - Note: GaN FETs still functional after $>10^{17}$ neq/cm^2 protons irradiation
      - See: https://iopscience.iop.org/article/10.1088/1748-0221/15/05/C05003
- New fabrication run at NRC for GaN HEMTs
  - Probably ICs, e.g. TIA for hybridizing with Si LGADs
  - First step towards monolithically integrating transistor+sensor
- Identify industrial partners – industry far ahead with GaN applications
  - Allow for material development – will certainly require several iterations
  - Investigate possibility of large-scale production, e.g. ≥6" wafers
    - Main issue: particle physics a low-priority customer due to small size

material from T. Koffas, Carleton



Silicon Carbide

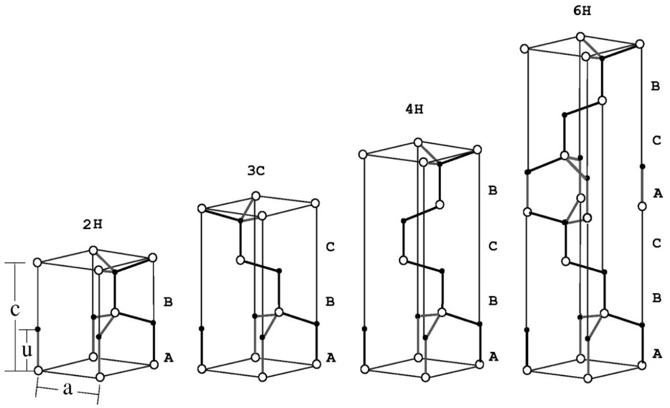
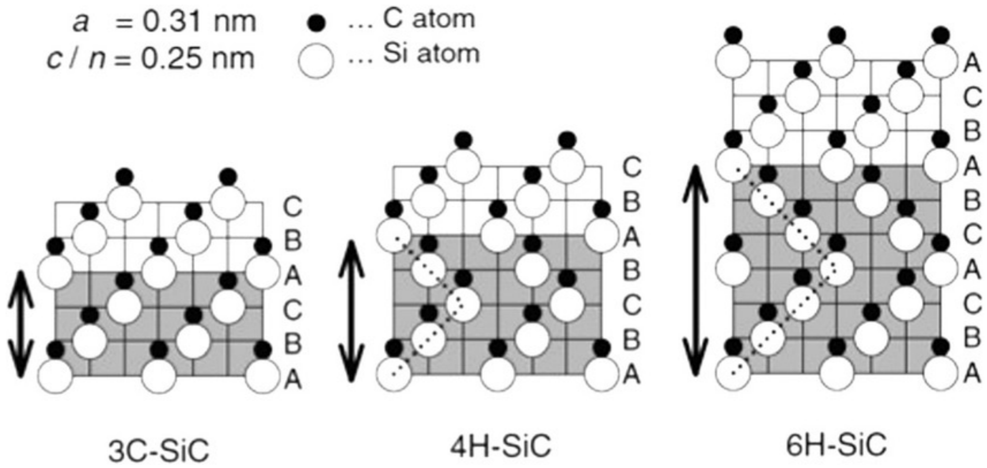
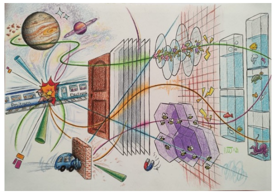


FIG. 1. Hexagonal unit cells of the $2H$, $3C$, $4H$, and $6H$ polytypes of SiC. The stacking sequence AB ($2H$), ABC ($3C$), $ABCB$ ($4H$), $ABCACB$ ($6H$), and the lattice parameters a, c, u, are indicated.



See also: “**First generation 4H-SiC LGAD production and its performance evaluation**“ by Radek Novotný (CVUT)
Nov 20, 2024, 9:30 AM

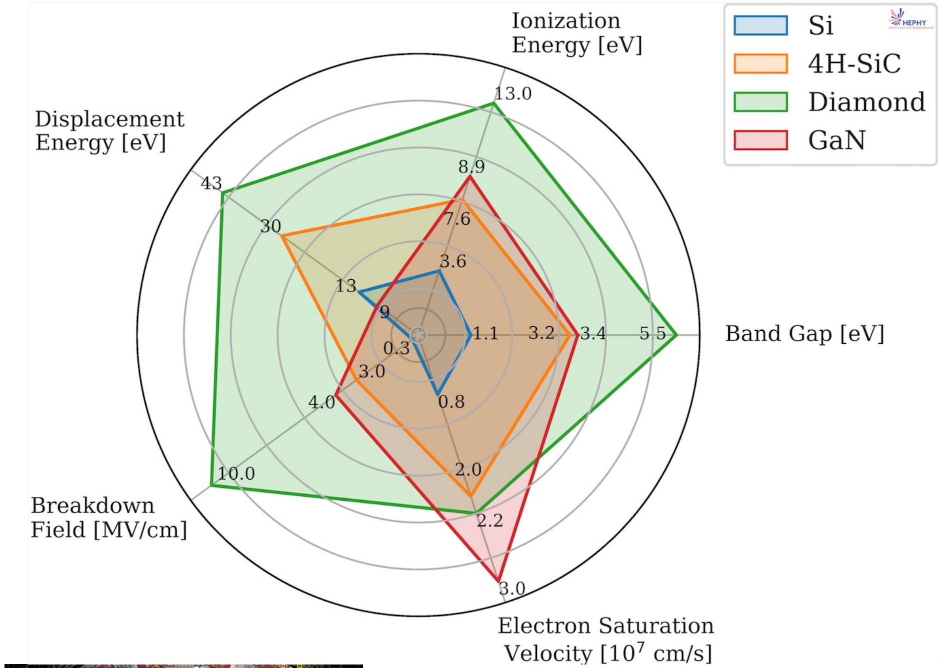
from H. Matsunami, Jpn. J. Appl. Phys., Part 1 43(10), 6835-6847 (2004). Copyright 2004 The Japan Society of Applied Physics



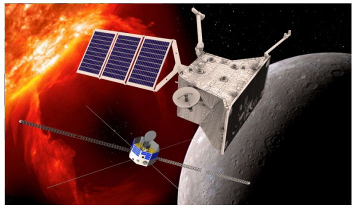
Silicon Carbide

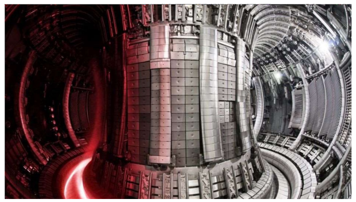
- **Wide bandgap semiconductor (3.26 eV)**
  Low leakage currents, insensitivity to visible light
- **Renewed interest:**
  High quality wafers for power electronics industry

+ **High breakdown field and saturation velocity** :
  Timing applications
+ **Potentially higher radiation hardness** (displacement energy),
  no cooling needed after irradiation
- **Higher ionization energy** (~30% less signal per µm) [9]
- **Limitations in wafer thickness and resistivity**

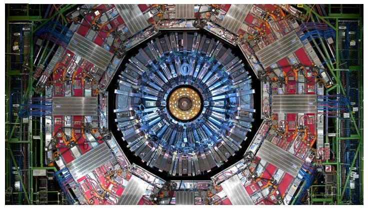


Dosimetry:
µDOS, FLASH [1]



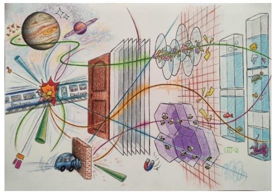


Space, harsh environments (fusion) [3]



Beam monitoring, radiation hard large area detectors [4]

material from HEPHY



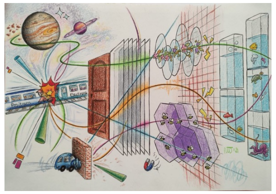
SiC-LGAD RD50 Common Fund Project

- **RD50, now DRD3 project started about a year ago**
- Aiming to produce planar diodes and LGADs on 6-inch wafers at CNM

- First results from planar run
- Update on LGAD progress

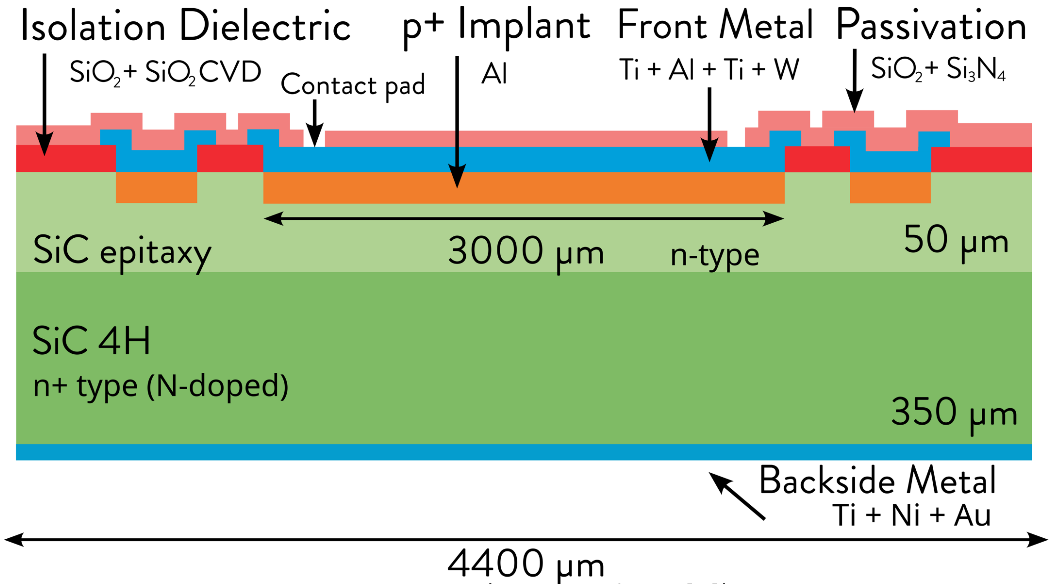
Activity	Institute	Year 1				Year 2				Year 3			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
TCAD simulations	*HEPHY, CNM*	Planar			LGAD run1			LGAD run2					
Wafer layout	*HEPHY, CNM*												
Production	*CNM*												
IV, CV characterization	*HEPHY, CNM, Perugia, NIKHEF*												
UV-TCT Measurements	*HEPHY, CNM*												
TPA-TCT Measurements	*Santander*												
Alibava	*CERN*												
Neutron Irradiations	*HEPHY*												
X-Ray irradiations	*Perugia*												

material from HEPHY

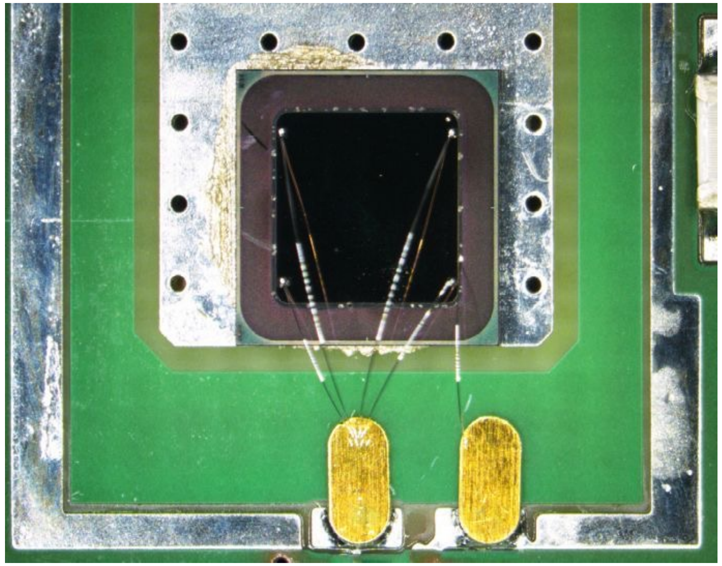


Silicon Carbide

- 4H-SiC p-n planar diodes from Run 13575 of CNM [5]
- 3 x 3 mm² active area, 50 µm epi
- Full depletion voltage : 400 V, C_{det} = 18 pF



Device cross-section (adapted from [5])

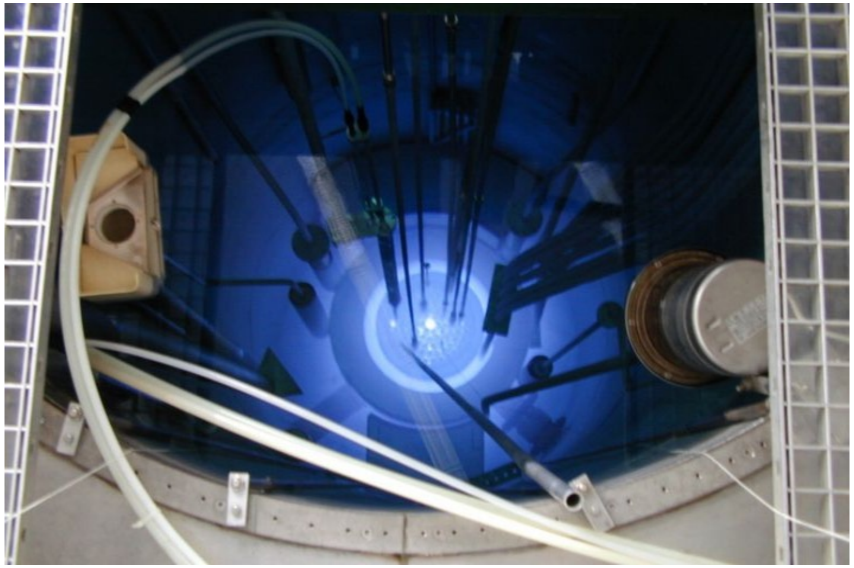

4H-SiC pad diode on readout board

material from HEPHY

Silicon Carbide: Neutron Irradiation studies

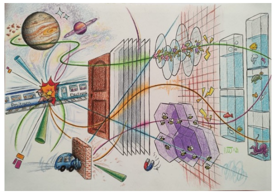
DRD3

- Neutron irradiated (**5 $\cdot 10^{14}$ – 1 $\cdot 10^{16}$ n_{eq}/cm^2**) at ATI Vienna [6] (previous studies [7,8])
- Deep level defects ($Z_{1/2}$ and $EH_{6/7}$) introduced by radiation damage [9]
- Electrical Characterization (I-V, C-V)
- Particle detection (α, p^+, UV-TCT)
- Simulation Results



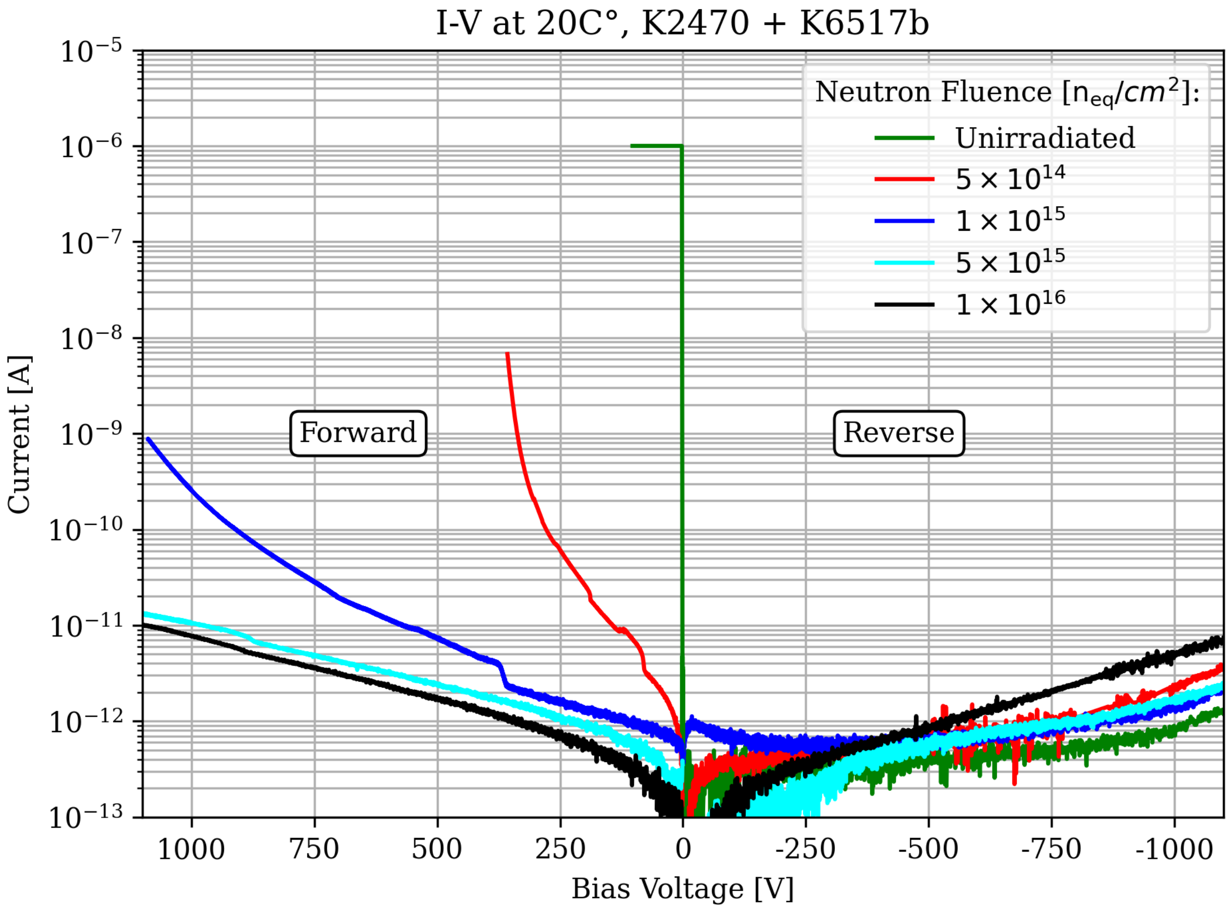
TRIGA Mark II reactor at ATI Vienna

material from HEPHY



Silicon Carbide: IV characterisation

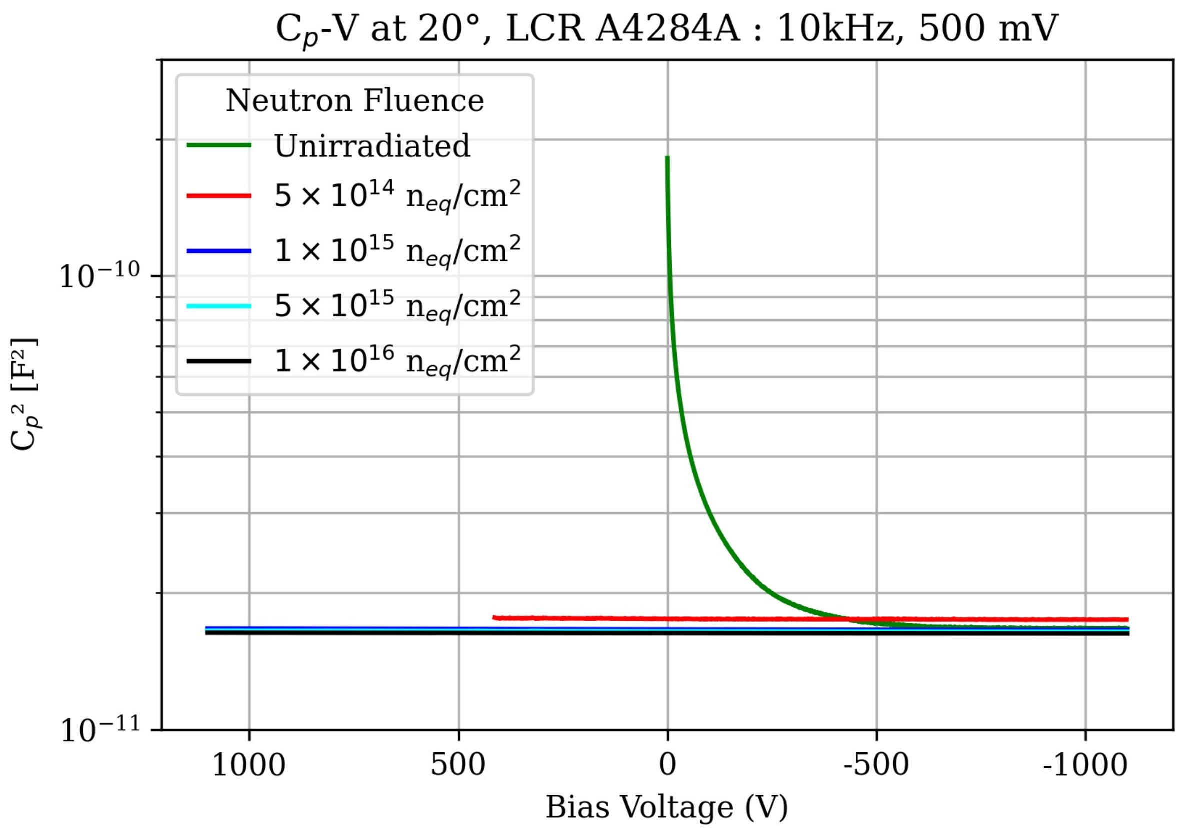
- **Leakage currents < 10 pA** after irradiation (up to 1 kV) at room temperature
- Forward Bias: increased resistivity
  - Indicative of n-doped epi layer becoming intrinsic due to deep-level defects [11, 12]
- Reverse bias limited by sparking on surface around 1.6 kV



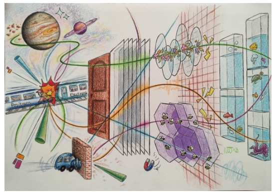
material from HEPHY

Silicon Carbide: CV characterisation

- Full depletion at 400V for unirradiated sample
- **Diode-like depletion lost after irradiation,** fixed capacitance regardless of forward / reverse bias
  - Fixed capacitance compatible with 50 µm thickness
- Intrinsic epi layer after irradiation



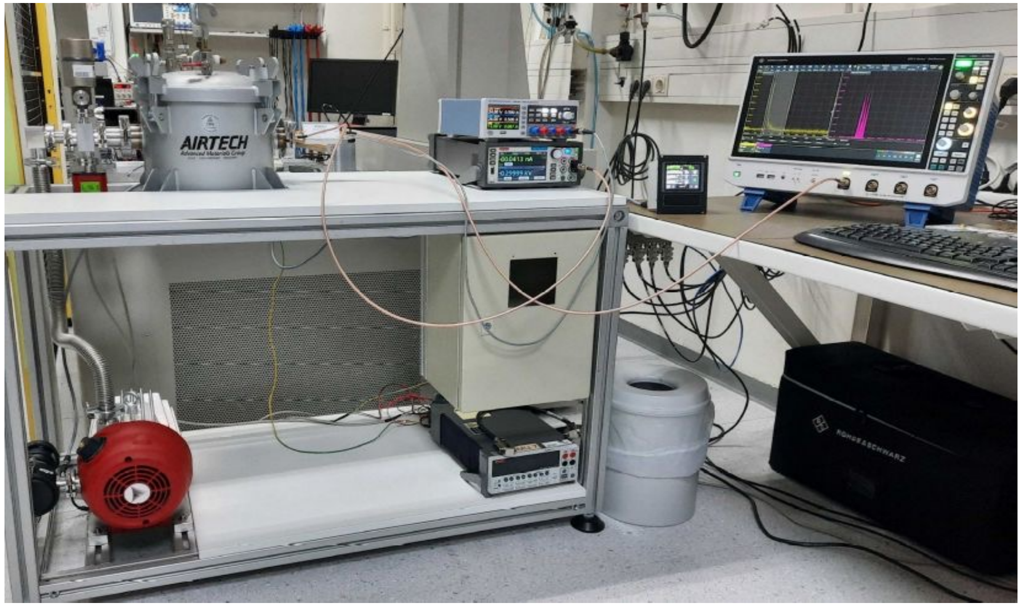
material from HEPHY



Silicon Carbide:
CCE characterisation

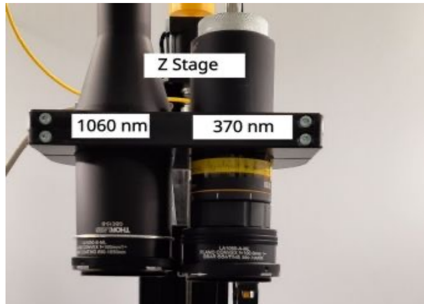
material from HEPHY

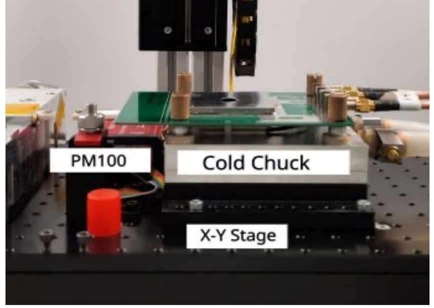
- Room temperature measurements
- Signals collected in forward and reverse bias



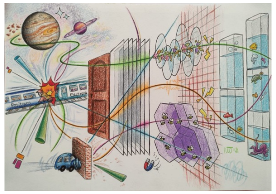
Tri-Alpha in Vacuum (^{239}Pu, ^{241}Am, ^{244}Cm)

62.4 MeV p$^+$ at MedAustron (AT)





UV-LASER (370nm)
< 100 ps pulse length

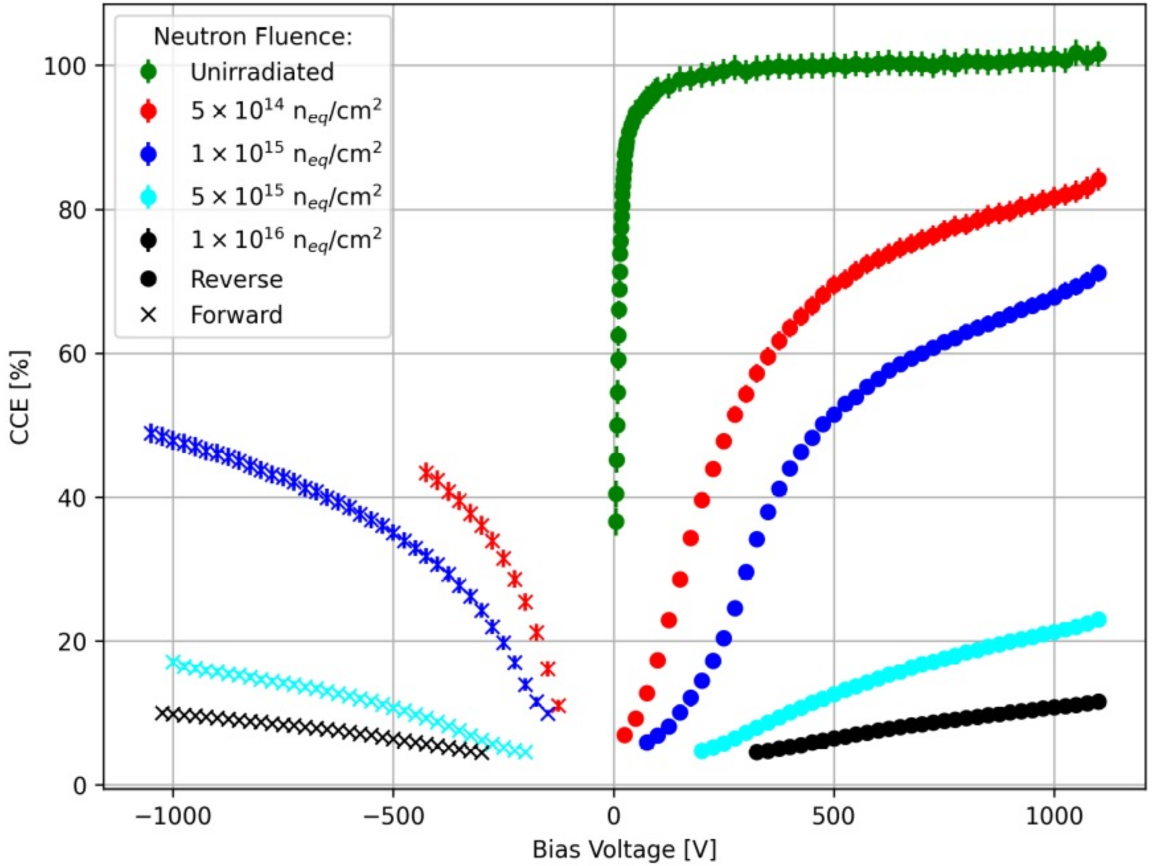


Silicon Carbide: CCE characterisation

DRD3

Alpha measurements

- Signals obtained even at highest fluences, in forward and reverse bias
- Bias voltage limited by readout
- At highest fluences, forward and reverse bias identical

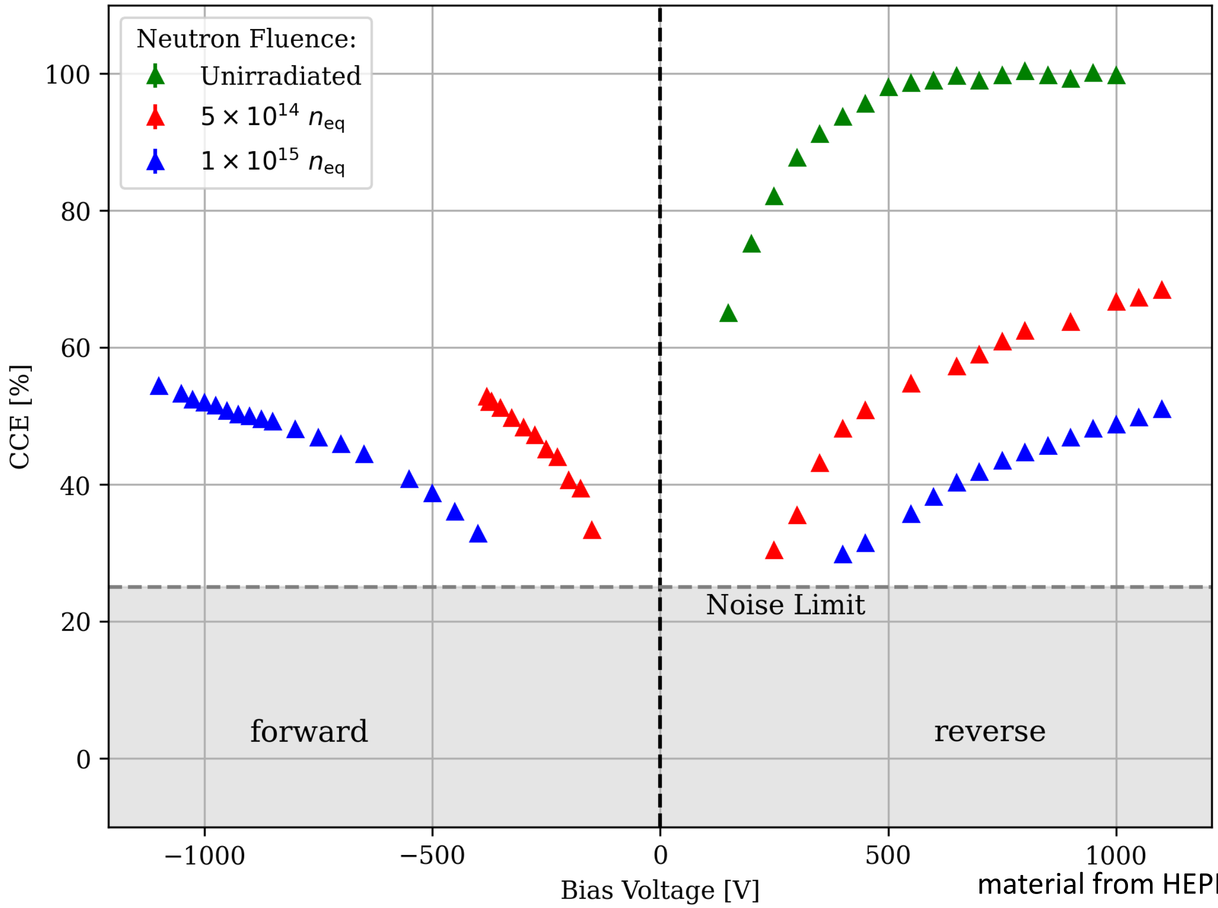


material from HEPHY

Silicon Carbide: CCE characterisation

62.4 MeV p^+ at MedAustron

- Signals obtained for fluences up to $1 \cdot 10^{15}$ n_{eq}/cm^2 (limited by noise and thin detectors)
- Unirradiated sensors signal consistent with depletion width
- Slightly higher signal in forward bias than in reverse
  - Trap filling by forward current

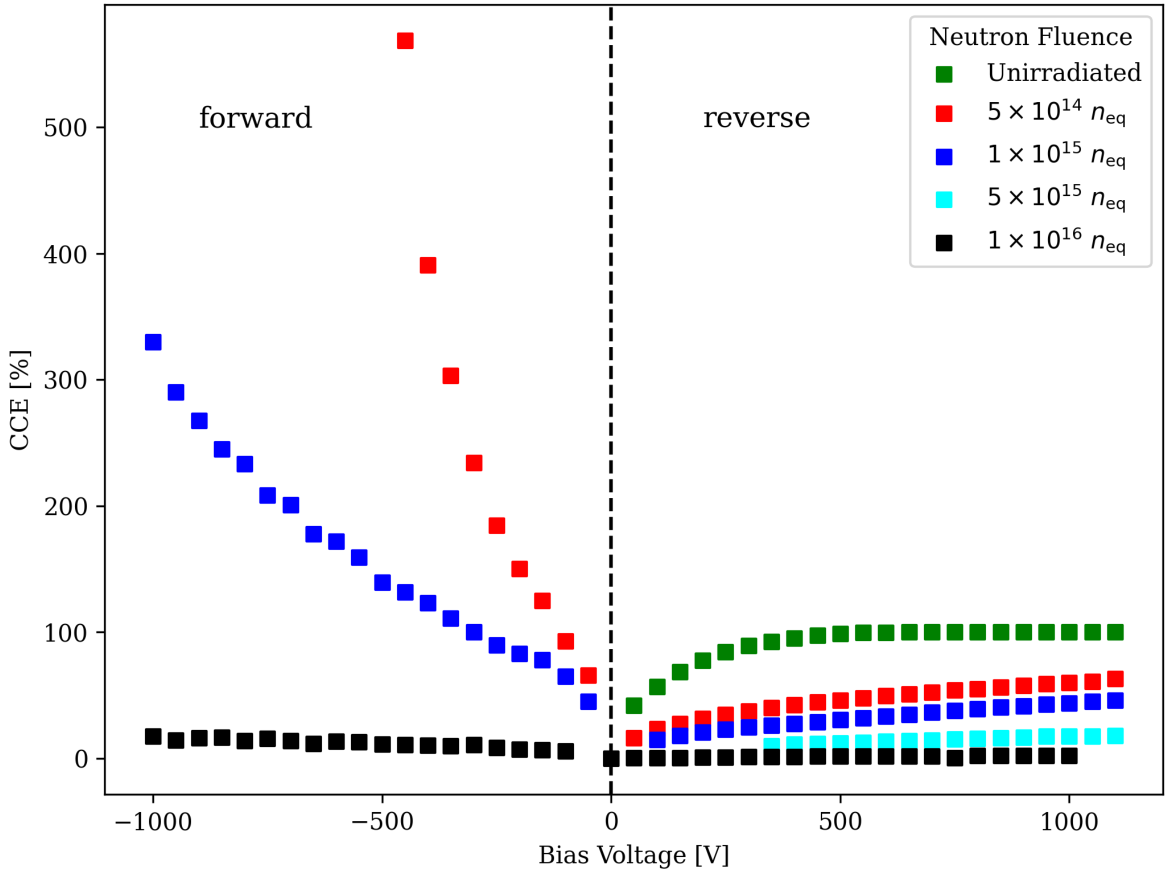


material from HEPHY

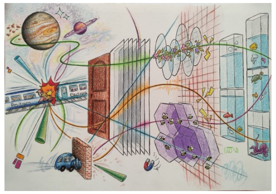
Silicon Carbide: CCE characterisation

UV Laser

- 370nm LASER, < 100 ps pulse length
- High charge deposition (~ 10 MeV) and waveform averaging → very good SNR
- Results in reverse bias agree well with p+
- Charge gain observed in forward bias
- Also observed in TPA-TCT [13], likely related to the very high charge deposition



material from HEPHY

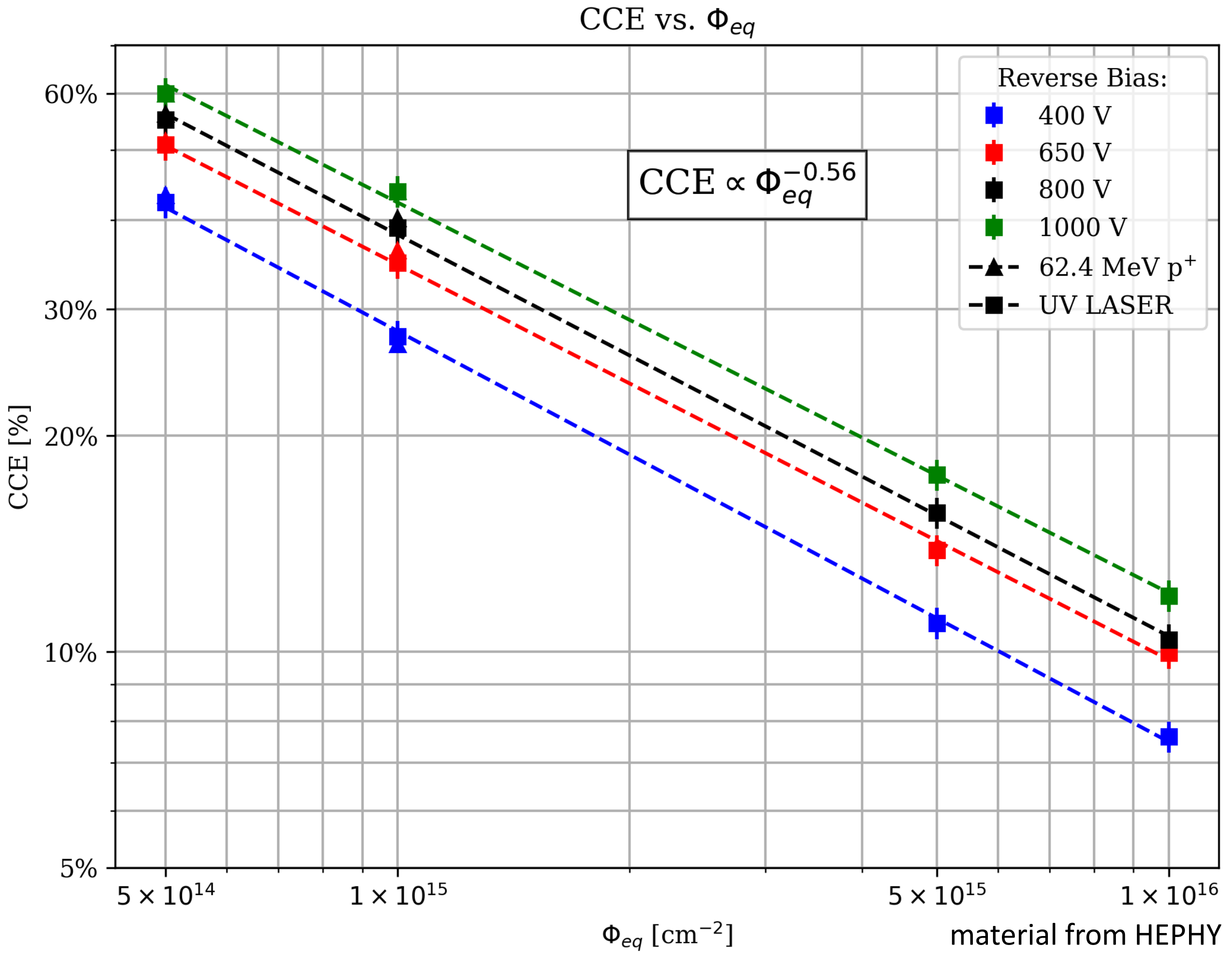


Silicon Carbide: CCE characterisation

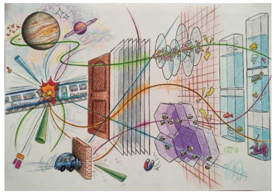
CCE vs irradiation fluence

- CCE follows a power law ($\propto \Phi^{-0.56}$), even for different bias voltages
- CCE > 10% for $1 \cdot 10^{16}\ n_{eq}/cm^2$

- More work needed to increase radiation hardness of SiC:
  - Annealing [12]
  - Defect engineering

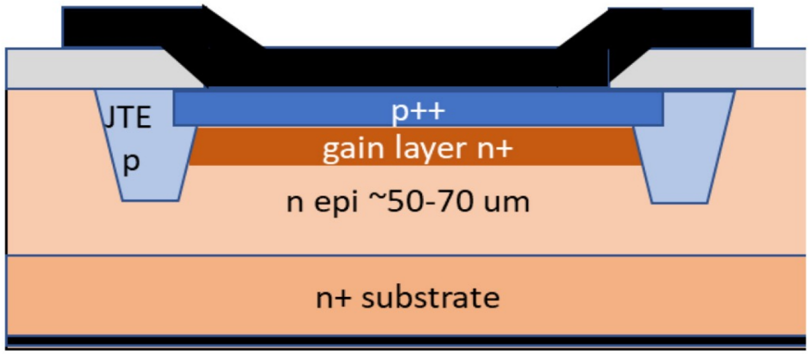


material from HEPHY

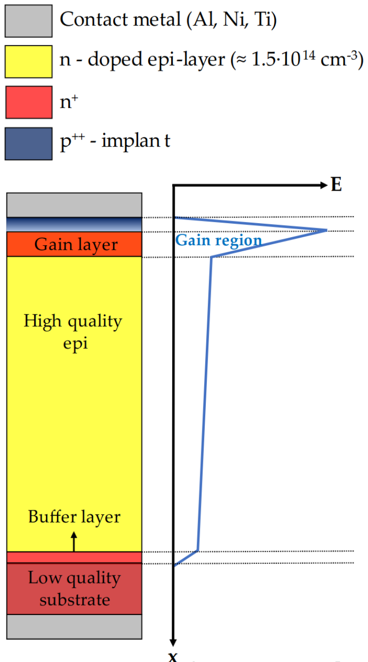


Silicon Carbide: LGAD

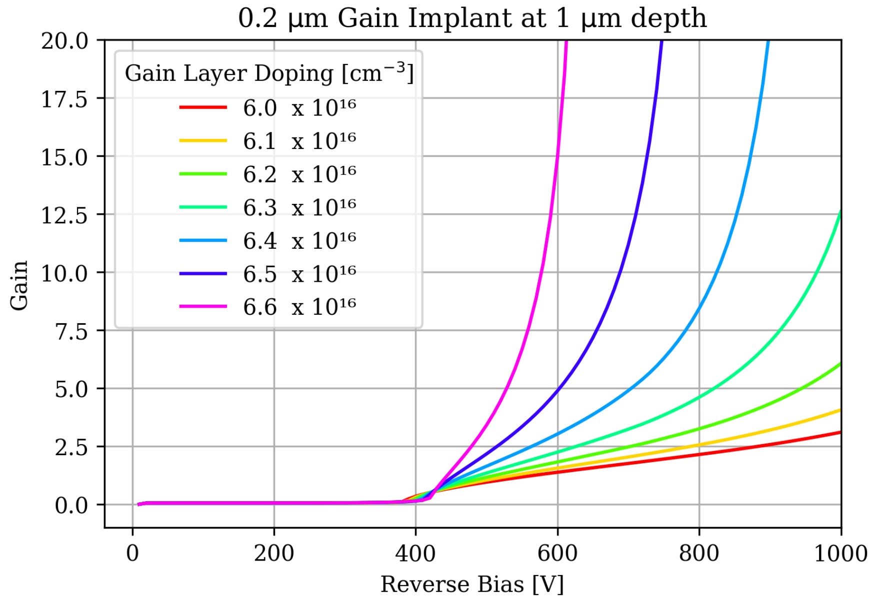
- LGAD : Low Gain Avalanche Diode [16], wide-spread usage for Si
- Attractive for SiC (large signal from thin detectors, timing)
- RD50 common project [17], ongoing work at IHEP / NJU [18-20]
- TCAD studies to optimize design



Idealized 4H-SiC LGAD structure [20]

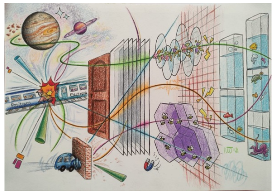


Cross section of SiC LGAD [17]



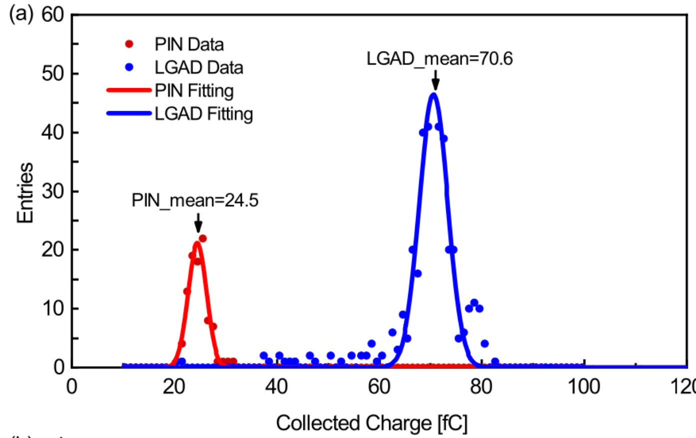
TCAD Simulation of 4H-SiC LGADs with different gain doping

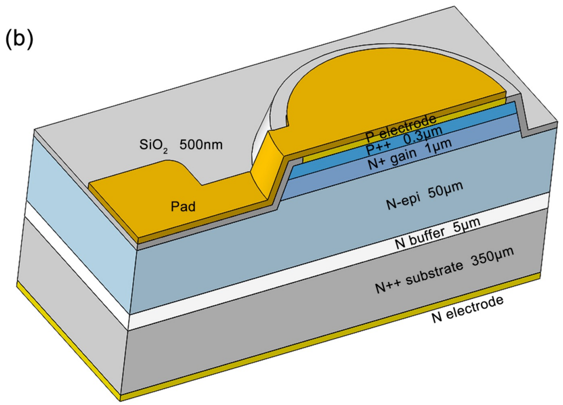
material from HEPHY

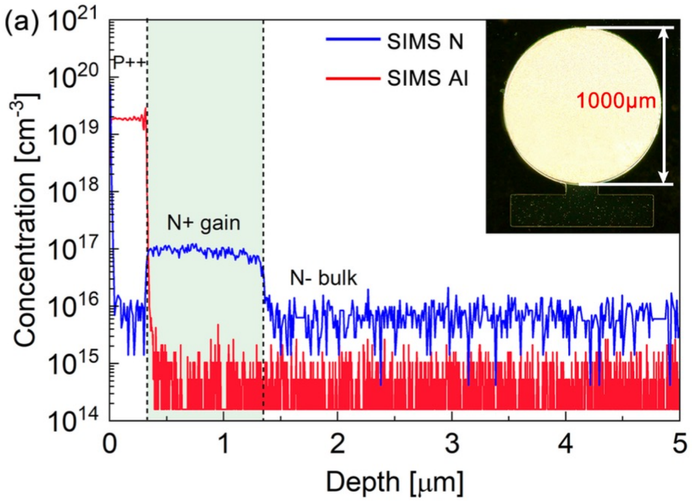


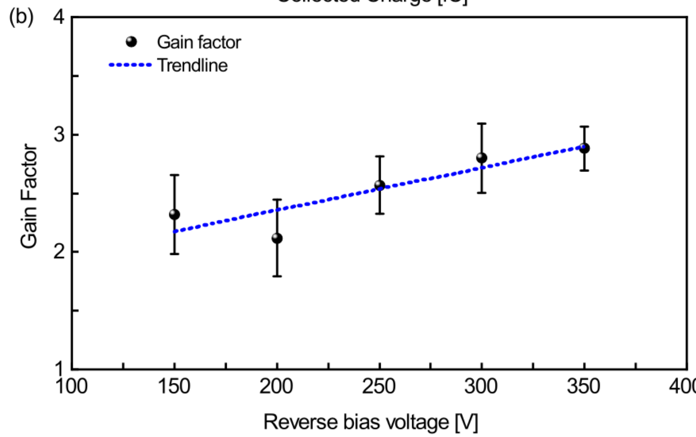
Silicon Carbide: LGAD

- First LGAD realised in the SICAR project [23].
- Low leakage current 2.4nA at 400V.
- Gain observed with alpha particles of about 3 at 350V.
- Next steps improve design to reach gains of factor 10.

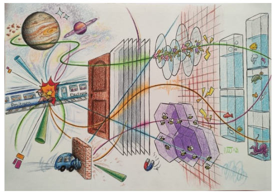






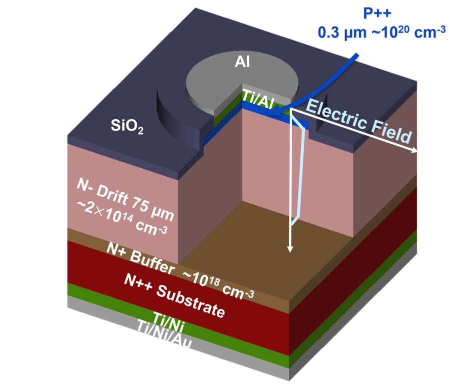


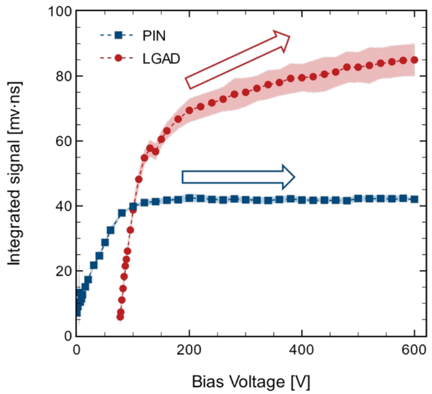
material from IHEP

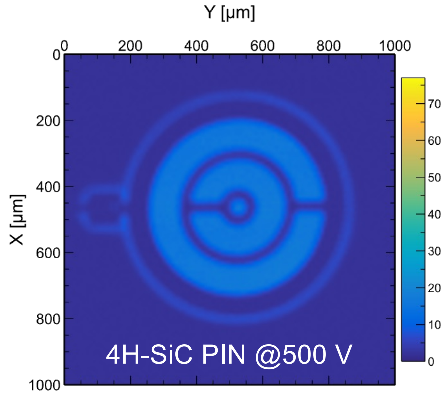


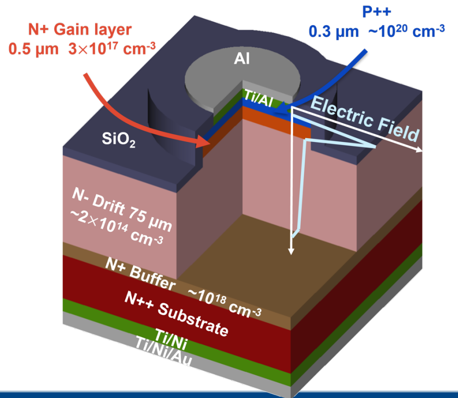
Silicon Carbide: LGAD

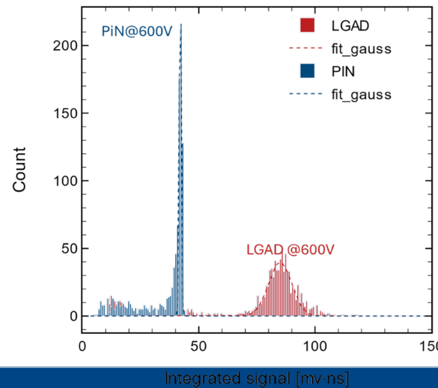
Lawrence Berkeley National Laboratory / North Carolina State Univ/ Brookhaven National Laboratory have a collaboration aimed at developing 4H-SiC LGADs

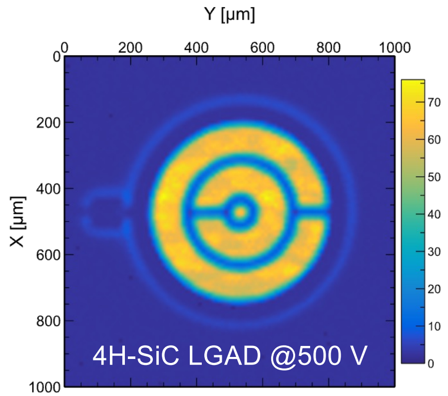










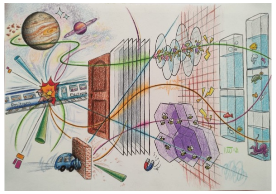


The latest progress at CPAD 2024 , 20th Nov
https://indico.phy.ornl.gov/event/510/contributions/2261/

Status

- Have developed models and simulations which give us design insight.
- Have fabricated devices which demonstrate charge gain and good time resolution.
- Have fabricated AC coupled multi-segment devices which show good position resolution.

material from LBNL/NCSU/BNL



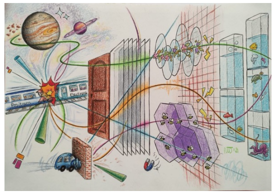
Silicon Carbide: Summary

- 4H-SiC features extremely low leakage currents even after irradiation up to $1 \cdot 10^{16}\ n_{eq}/cm^2$
- CCE scales with fluence $\propto \Phi_{eq}^{-0.56}$
- Unirradiated devices can be accurately simulated using TCAD
- Ongoing work on SiC LGAD, promising for timing applications
- New wafer production in the pipeline.

This work was supported by the Austrian research promotion agency FFG, project number 883652.

Production and development of the 4H-SiC samples was supported by the European Union’s ERDF program “A way of making Europe”, grant references: PID2021-124660OB-C22

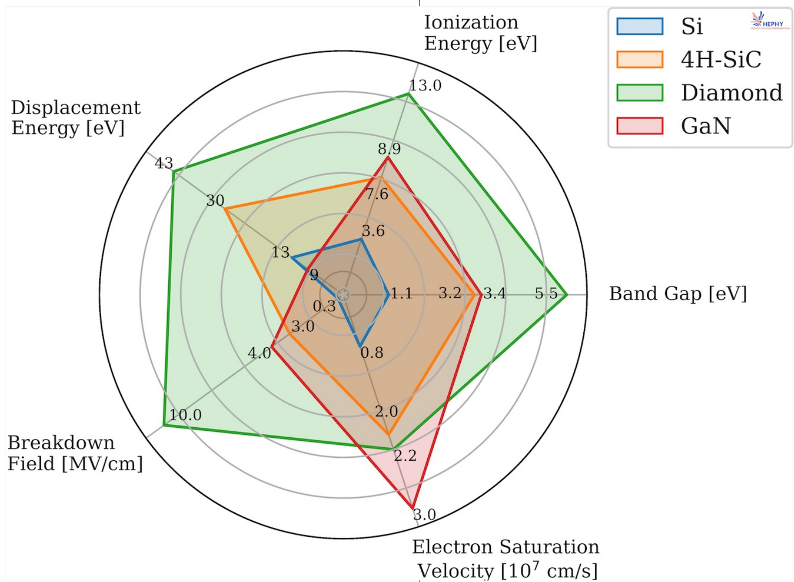
material from HEPHY



Diamond

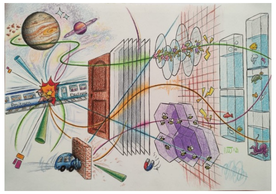
DRD3

Property	Diamond	Silicon
band gap	5.47	1.12
mass density [g/cm³]	3.5	2.33
dielectric constant	5.7	11.9
resistivity [Ωcm]	$>10^{11}$	2.3e5
breakdown [kV/cm]	1e3...20e3	300
e mobility [cm²/Vs]	2150	1350
h mobility [cm²/Vs]	1700	480
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

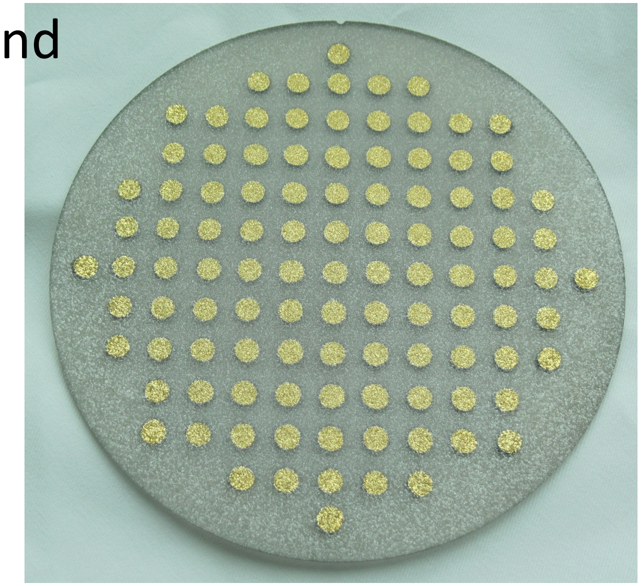


– Low dielectric constant ➔ low capacitance
– Low leakage current ➔ low noise
– Room temperature operation
– Fast signal collection time

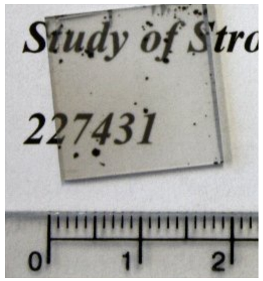
–MIP signal ~2 smaller at same X_0
–Efficiency < 100% (pCVD)

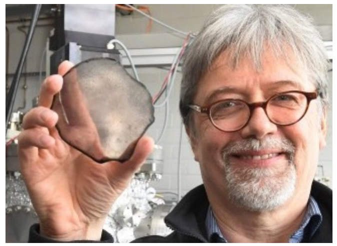


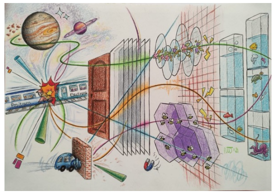
Diamond



- Today two <u>main manufacturers</u> of detector grade diamond
  - **ElementSix Ltd**
    - large **polycrystalline** wafers
    - **single crystal** diamonds
  - **II-VI Semiconductors**
    - large **polycrystalline** wafers
    - relatively recent entry
- <u>Alternative sources</u>
  - Diamond on Iridium (DoI) (Audiatec, Germany)
  - Hetero-epitaxially grown -> **large area**
  - **Highly oriented crystallites**.



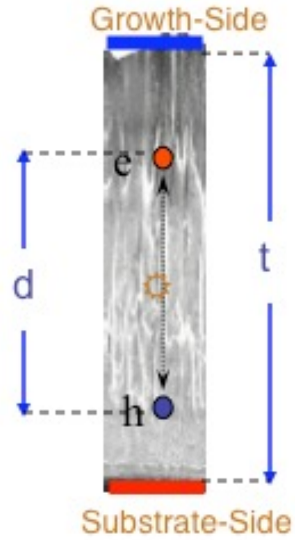


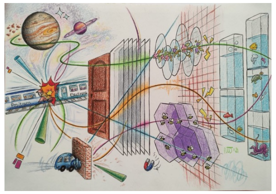


Diamond

- Impressive progress over the last 25 years.
- Current state of the art for **polycrystalline** CVD diamond **δ ~ 320 μm in 500um thickness**
  - **(~11500 e/MIP)**
  - **commercially available.**

  - 1995: δ ~ 50 μm
  - 2000: δ ~ 180 μm
  - 2020: δ ~ 320 μm





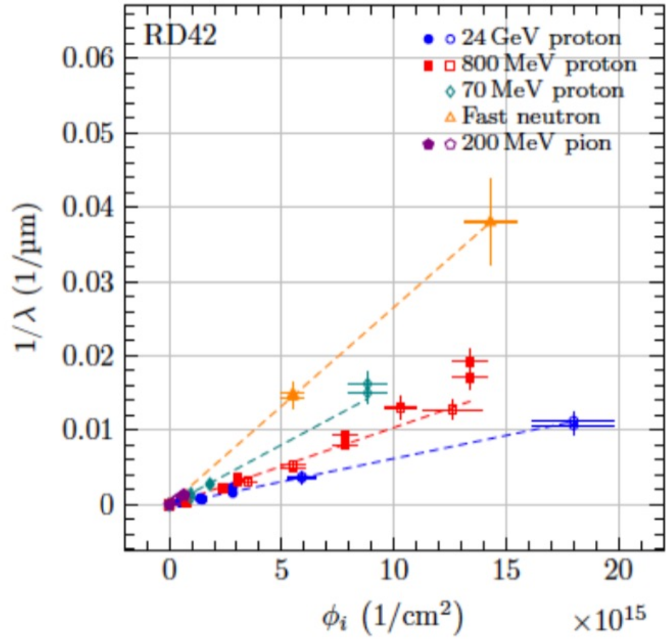
Diamond

scCVD pCVD

3

- Summary of RD42 irradiation results:

Irradiation Species	k_i
200 MeV pions	3.2 ±0.8
Fast neutrons	4.27 ± 0.33
70 MeV protons	2.60 ± 0.27
800 MeV protons	1.67 ± 0.09
24 GeV protons	1



Radiation damage is fitted with simple damage model:

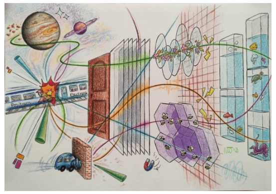
$$\frac{1}{\lambda} = \frac{1}{\lambda_0} + k_\lambda \Phi$$

damage constant

particle fluence

”Back-of-an-envelope calculation, expect Schubweg of:
$\lambda \sim 16\mu m$ at 10^{17} cm^{-2} protons_24 GeV_eq

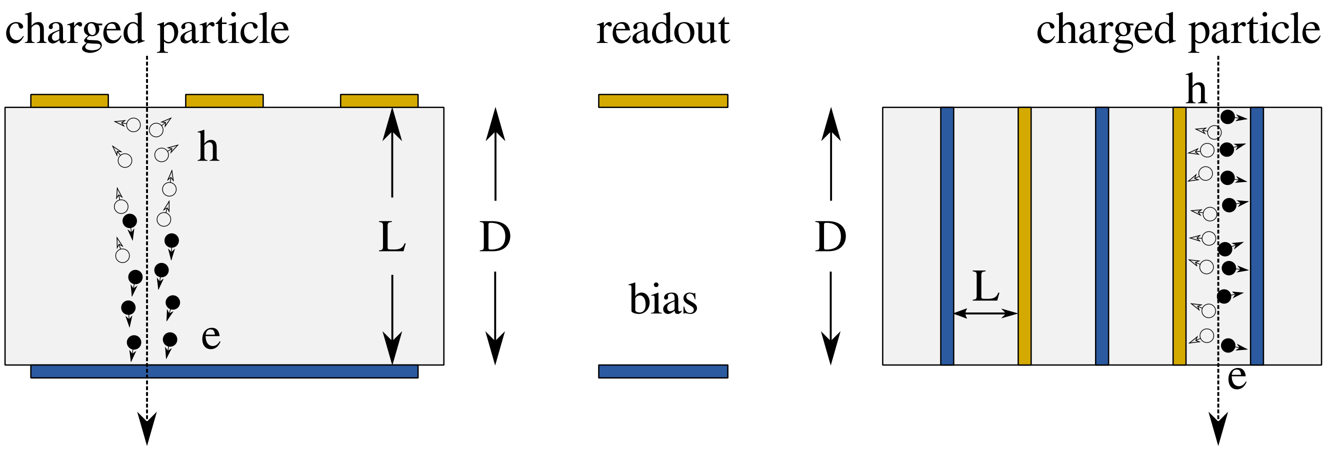
*normalized to 24GeV protons

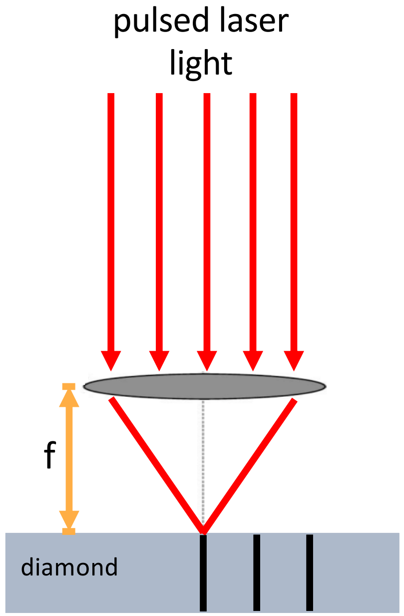


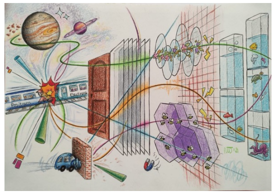
Carrier lifetime challenge – 3D diamond detectors

DRD3

- 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)
- Build **3D detectors** to reduce transit time.
- Huge progress made in fabrication of 3D diamond detectors in the last 10 years.

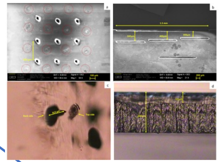




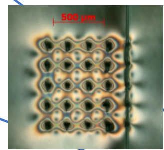


3D diamond? (2008)

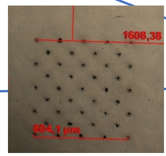
Lasered graphitic structures in pCVD ('10)



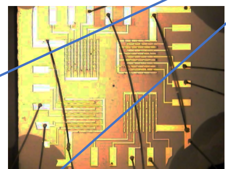
Single crystal with column structure ('11) [30]



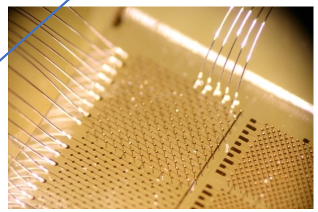
Pico second laser for improved graphitic electrodes ('12)



Femto second laser processing and **TCAD simulation ('13,'14)**



Phase modulated laser processing ('15,'16)



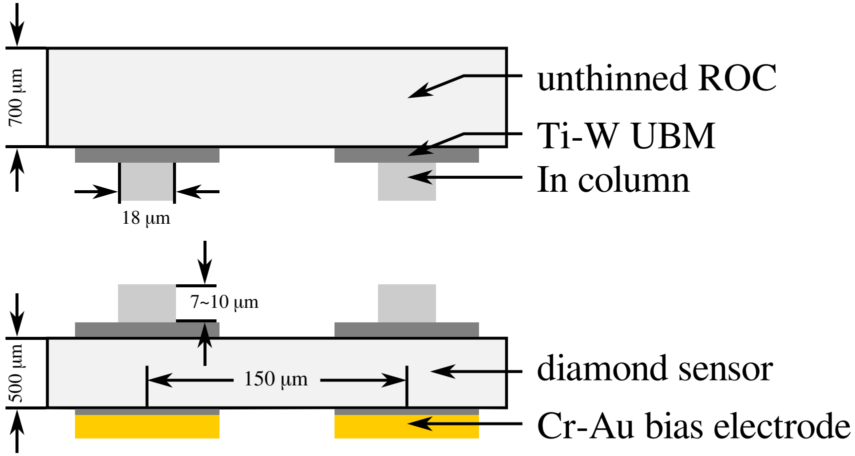
Polarised & Phase modulated laser processing ('17,'18)

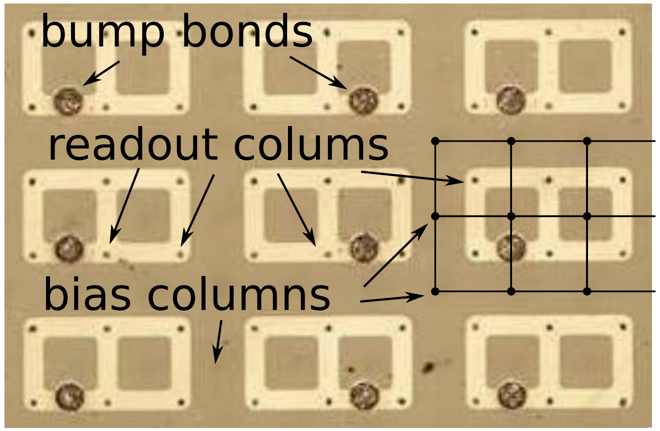
Prototypes with poly and single crystal diamond (2019 ++.

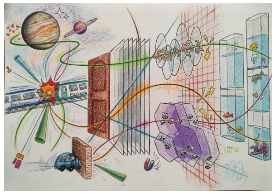
Several Prototypes tested at
Diamond Light Source [30]
CERN test beam [31]
RBI proton beam [32]
Clinical Photon beam [33]

3D Diamond prototypes

- CMS and ATLAS pixel prototypes tested:

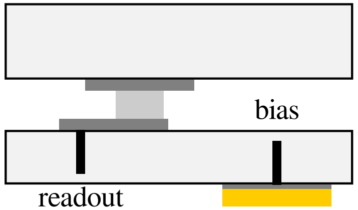


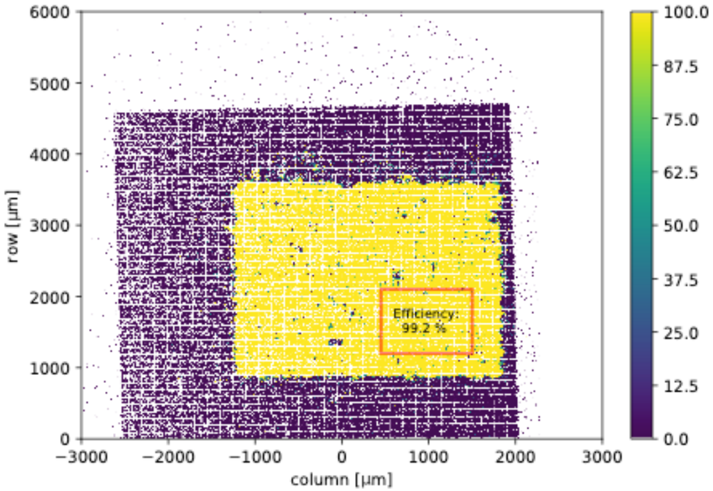


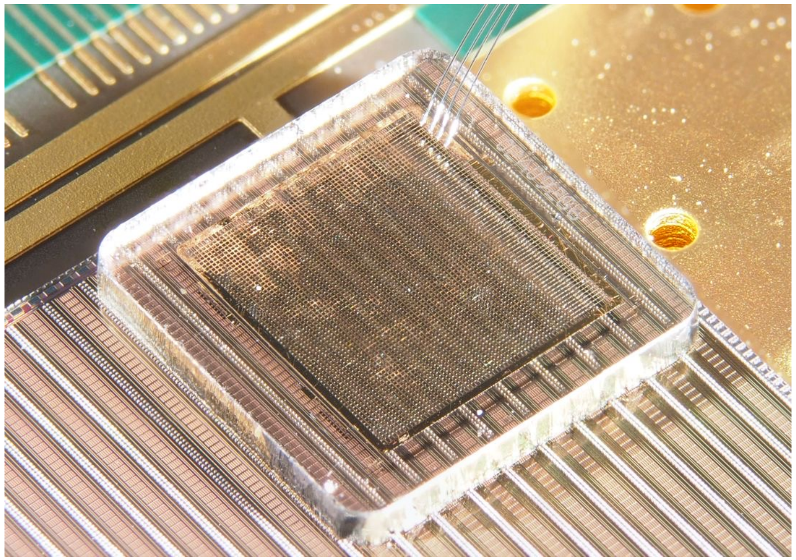


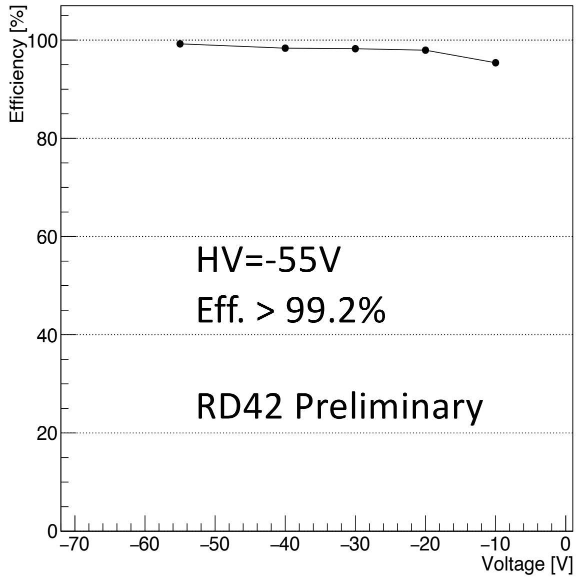
3D Diamond prototypes

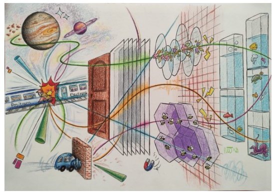
- CMS and ATLAS pixel prototypes tested:









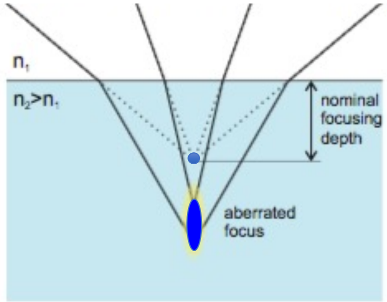


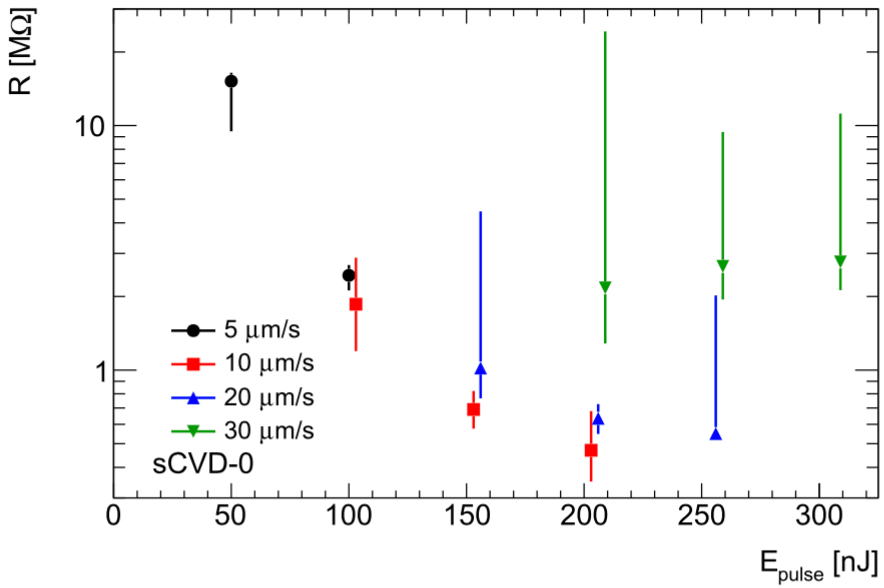
3D Diamond challenges

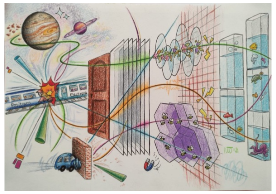
- **Optimise graphitisation process for 3D diamond production in terms of:**
  - **Resistivity**: currently at (1 - 0.1Ωcm) aim for <0.1Ωcm.
  - **Processing speed**: currently O(10um/s), aim to speed up and/or parallel processing of wires.
  - **Wire thickness / uniformity**: Little data available, needs more research effort.
- **Optimization of internal electric field**
  - **Geometry**: Recently internal cage structure optimise E field.
  - Will explore the full potential (see later slides).
  - Characterise timing performance.
- **Radiation hardness**:
  - Need to check predictions with latest devices.
  - 25um cells in 3D.

3D Diamond challenges

- Laser wave front shaping helps to decrease resistivity.
- Dependence on processing parameters being studied [34].
- **More research needed to lower resistivity.**

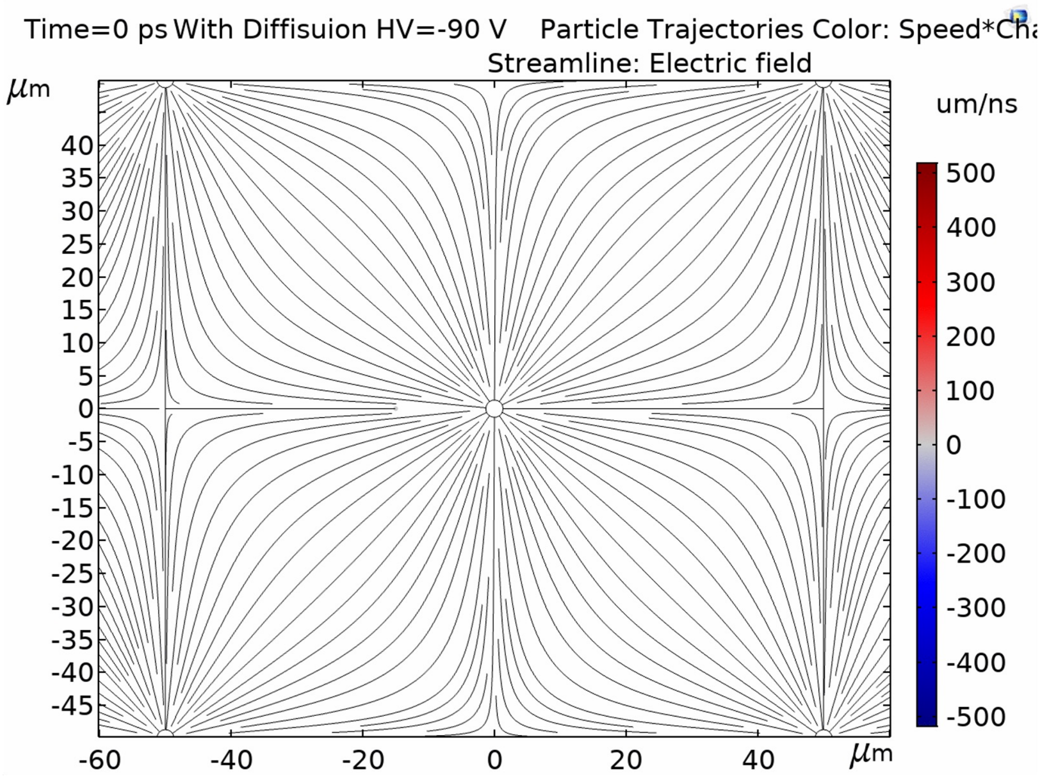






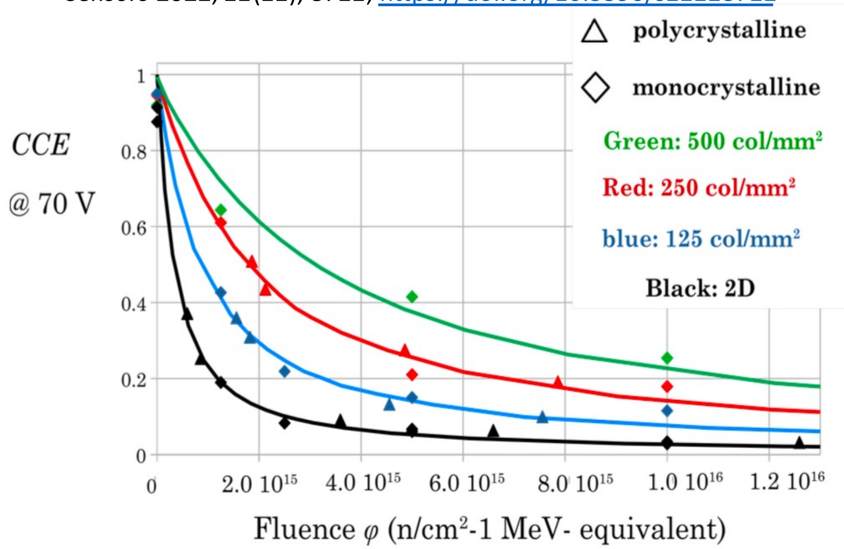
3D Diamond challenges

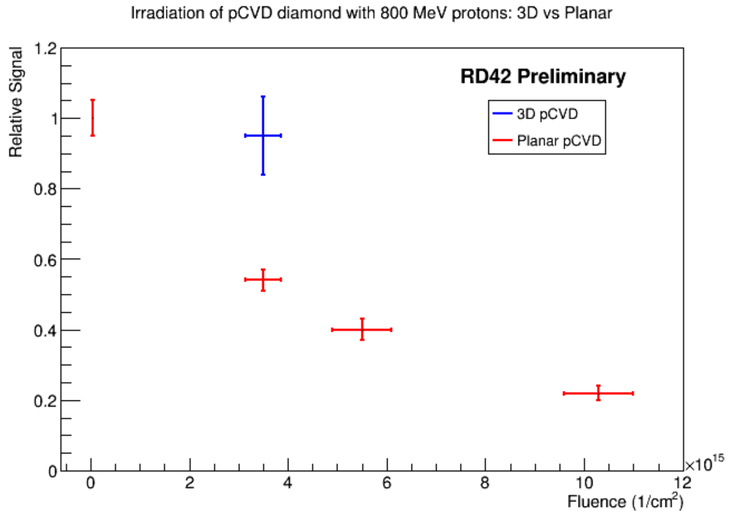
- Low field regions might effect transit time.
- Preliminary simulations show not a concern due to diffusion.
- More work needed to quantify impact of radiation damage.



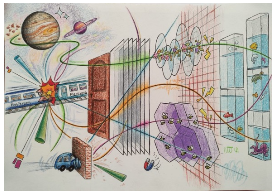
3D Diamond challenges

Sensors **2022**, *22*(22), 8722; https://doi.org/10.3390/s22228722





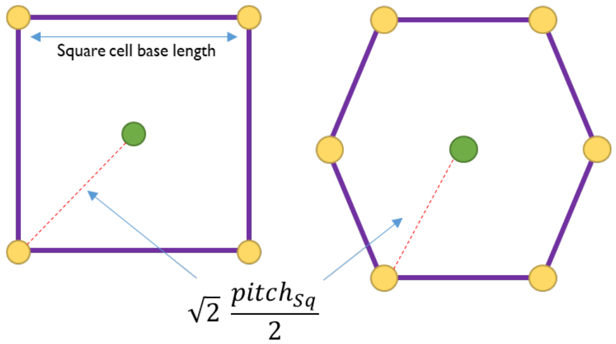
- Few radiation hardness data available, but promising:
  - Compare signal loss in 3D pixels to published results from planar
  - **3D sensors collect twice as much charge when unirradiated**
  - **3D sensors see 5±10 % reduction** in signal at 3.5 $x10^{15}$
  - **Planar sensors see 45±5 % reduction** for 3.5 $x10^{15}$

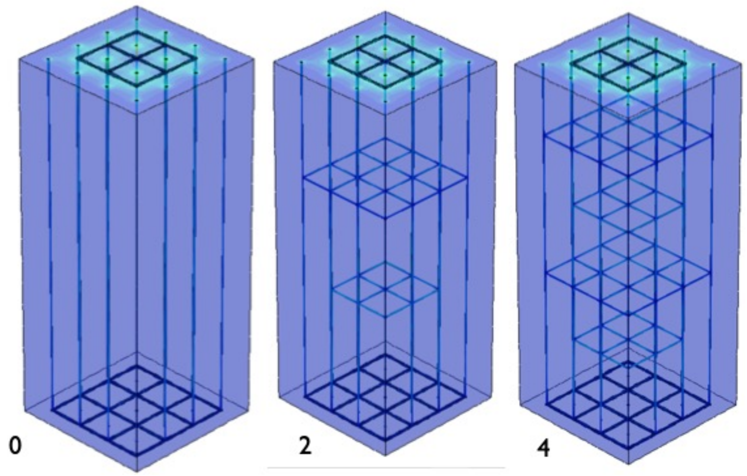


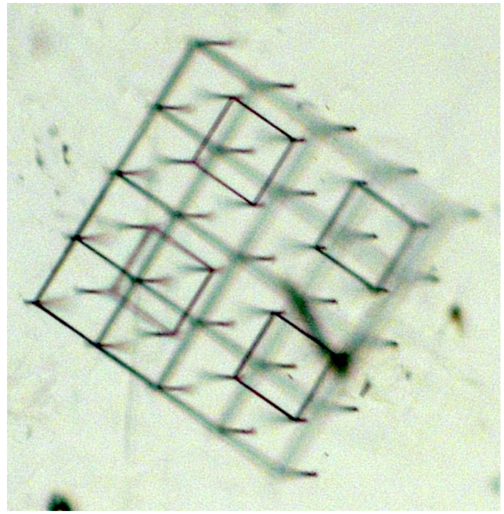
3D Diamond challenges

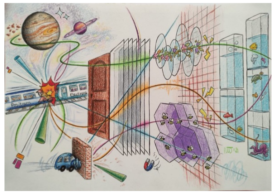
DRD3

- Laser processing allows any geometry, including horizontal wires.
  - Exiting possibility to optimise the electric and weighting field.
  - Small cell sizes realizable, wire diameter at abut 1μm.
  - Simulation studies currently ongoing.
- Future research in this area:
  - Optimise geometry
  - Wire processing
  - cell sizes <(25μm)^2
  - Simulation – Prototyping – Characterization.









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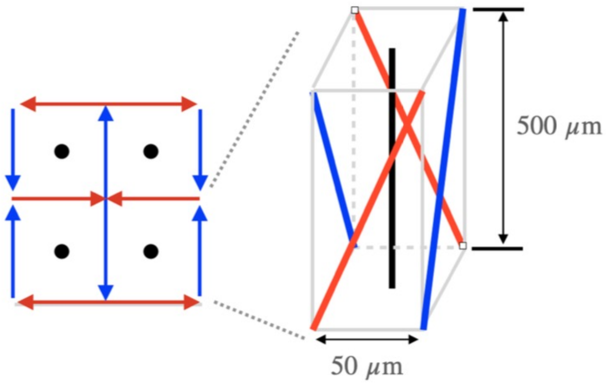
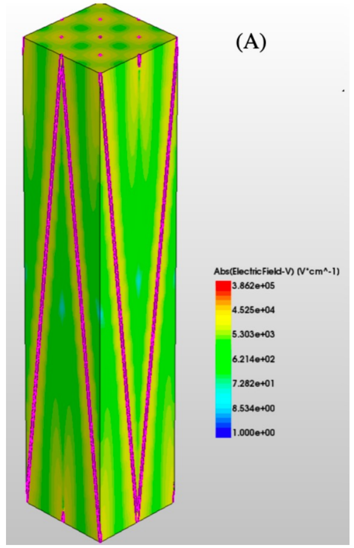
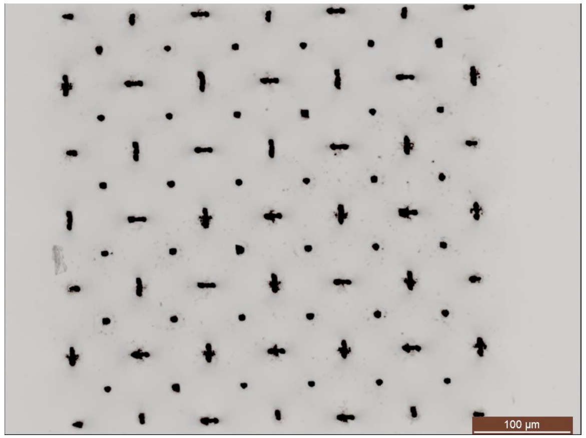
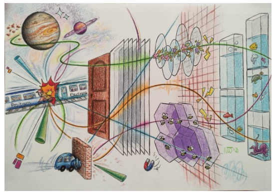


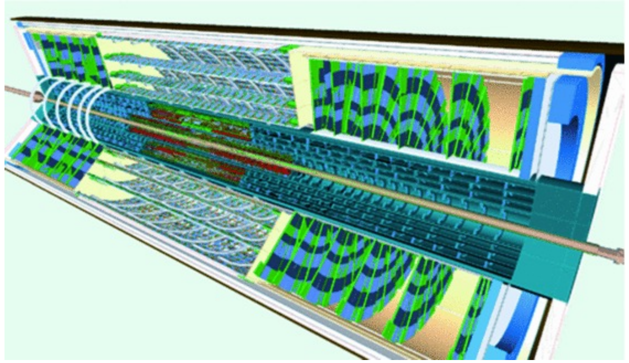


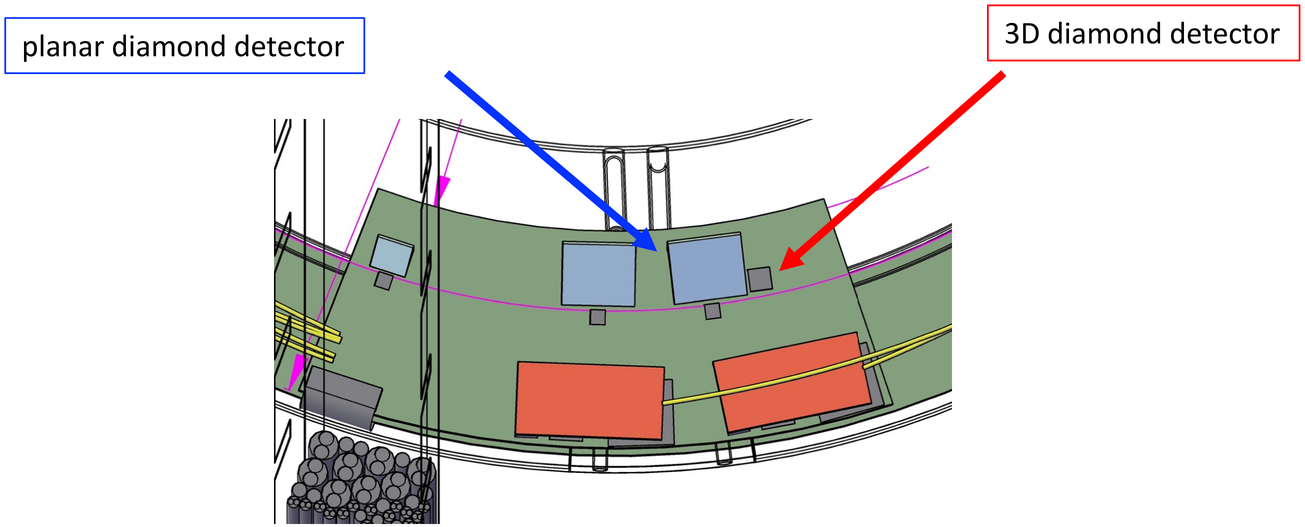


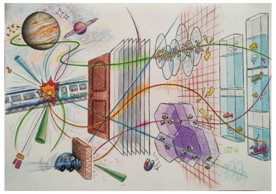


3D Diamond for future experiements

- The BCM’ phase-2 project of ATLAS will feature small area **3D diamond detectors**.
  - Prove technology readiness for small cells.
  - Stepping stone for larger area application.

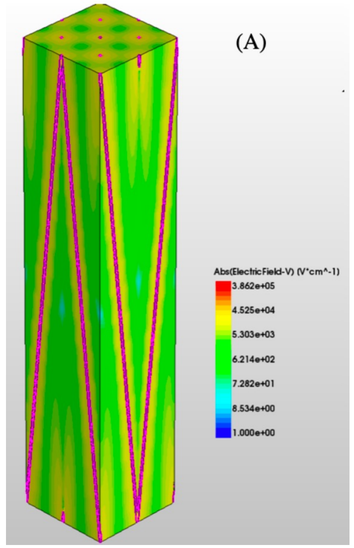


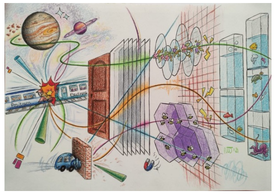




Diamond Summary

- Diamond is established in HEP as a radiation tolerant detector.
  - Primarily Beam monitor at experiments and LHC.
- Synthetic diamond has improved in quality.
  - Profit from interest in other fields, e.g. quantum computing.
- 3D Diamonds promising to master the FCC-hh radiation challenge.
- Next steps for 3D diamond
  - Production of final planar and 3D sensors for ITk BCM' (ATLAS)
  - Move to 25x25 μm^2 cell sizes and characterise rad hardness
  - Investigate scaling of column production
  - Investigate gain structures





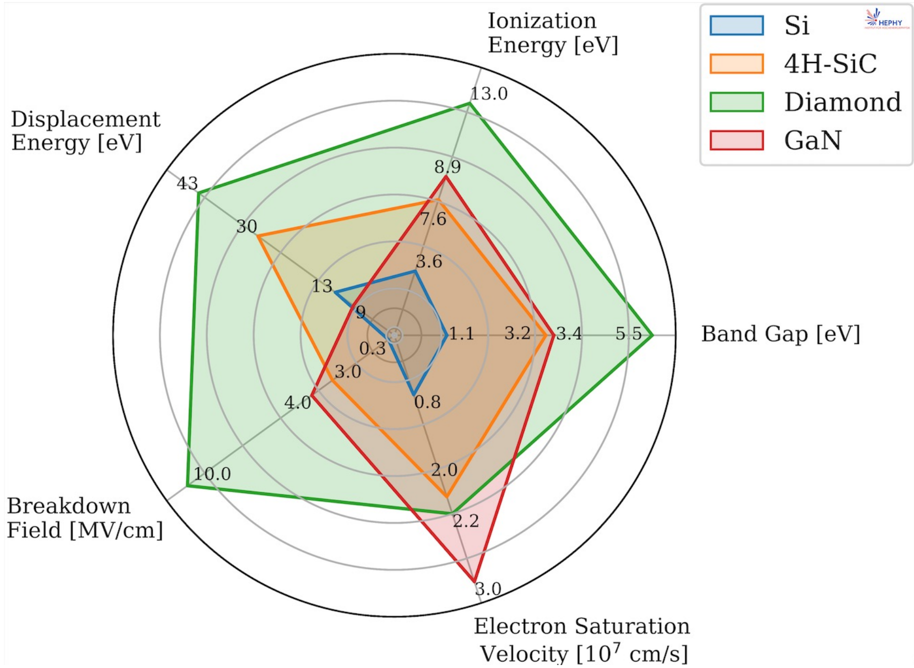
Summary & Outlook

Wide bandgap materials are promising to address the challenges of future particle physics experiments.

Common properties are superior displacement energy and charge carrier velocities, translating to radiation hardness and speed.

Synergy with industry trends allows particle physics to profit from exciting new developments in this field.

Exciting time to explore the possibilities of wide-bandgap materials!



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