New Structures

New structures based on silicon substrates are, possibly together with materials other than silicon, the most promising options to extend radiation tolerance to the region of 7-8×10^{17} n_{eq}/cm^2.

- Milestones [2018-2022]
  - WP3.1 3D sensors [6 MS]
  - WP 3.2 LGAD [4 MS]
  - WP 3.3 CMOS [6 MS]
  - WP 3.4 New Materials [5 MS]

New Structures

Upcoming milestones

WP 3.1. 3D detectors

- M1: full radiation tolerance study of 3D pixels connected to the RD53A chip (Q3/2019).
- M2: radiation tolerance studies of 25x250 µm2 pixel cell design and feasibility (yield) studies for the 25x100 µm2 pixel cell layout (Q4/2019).
- M3: final radiation tolerance study of 3D pixels connected to the RD53B chip (Q4/2020)
- M4: Understanding the limit of the radiation hardness of the 3D geometry up to 1017n_{eq}/cm^2 (Q2/2021)
- M5: Evaluation of the time performances of new 3D geometries (Q3/2020).
- M6: Design and simulation of new 3D detectors geometries for operation at $8x10^{17}n_{eq}$/cm^2 (Q4/2022).

WP 3.2. Sensors with intrinsic gain

- M1: Understand the effect of Carbon and Gallium on gain after irradiation (Q1/2019)
- M2: Model the acceptor removal effect after irradiation (Q3/2019)
- M3: Produce new LGAD design to increase the fill factor (Q2/2020)
- M4: Design and simulate new LGAD geometries for operation at $1×10^{17}n_{eq}$/cm^2 (Q4/2022)

New Structures

Upcoming milestones

- ## WP 3.3. CMOS and monolithic devices

  - M1: Characterization of the diodes and readout electronics of unirradiated and irradiated RD50-MPW1 samples (Q4/2018).
  - M2: Design and submission for fabrication of RD50-ENGRUN1 (Q4/2018).
  - M3: Characterization of unirradiated and irradiated RD50-ENGRUN1 samples (Q3/2019, Q3/2020).
  - M4: Characterization of irradiated backside biased RD50-ENGRUN1 samples for operation beyond 1016 neq/cm2 (Q4/2020).
  - M5: Studies of stitching process options (Q4/2021).
  - M6: Characterization of unirradiated and irradiated stitched samples (Q4/2022).

- ## WP 3.2. New Materials

  - M1: Fabricate new radiation detectors in different Wide Band Gap (WBG) high quality materials (Q4/2019).
  - M2: Study the radiation hardness of detectors based on WBG materials (Q2/2020).
  - M3: Understand the feasibility of large areas detectors based on WBG materials (Q2/2021)
  - M4: Investigate the fabrication of radiation detectors based on 2D materials (Q3/2021).
  - M5: Explore operations at 8×1017 neq/cm2 (Q4/2022) using innovative materials.

3.3.3 Silicon sensors for extreme fluences environments

Silicon is by far the most studied sensor bulk material at high fluences [Ch3-30], although studies of other materials such as SiC, GaN, and Diamond are also being performed due to the good potential shown so far. The expected behaviour of silicon sensors at high fluences obtained by predictions based on the damage parameters (introduction rate of space charge, trapping probabilities, generations current) measured at low fluences proved to be too pessimistic. Measurements above fluences of a few $\times 10^{15}$ $n_{eq}\,cm^{-2}$ demonstrate that silicon sensors' performance greatly surpass the predictions. The successful operations of thin silicon planar detectors at fluences above 2×10^{16} $n_{eq}\,cm^{-2}$ and silicon 3D detectors above 3×10^{16} $n_{eq}\,cm^{-2}$ have been reported [Ch3-31]. The few measurements available at fluences approaching those at FCC-hh, about 1-2×10^{17} $n_{eq}\,cm^{-2}$ [Ch3-32], point to the possible operation of silicon 3D detector even above these radiation levels, maintaining signals around a few thousands of electrons. Although 3D detectors are the most promising technology for high-radiation environments, signals of around 1000 electrons were also observed in planar sensors of standard thickness (about 300 μm) [Ch3-33], with some indications of charge multiplication found in thin sensors [Ch3-34]. The signals (induced currents) at these fluences are very short, only a few 100 ps, and the losses are dominated by the charge trapping.

The changes of silicon properties at extreme fluences are currently poorly known. Reliable measurements of fundamental semiconductor properties such as carrier mobilities, impact ionisation coefficients, the introduction of charged defects, trapping, and generation centres are therefore prerequisites to any detector design. It is crucial that the properties of silicon sensors above fluences of 5-10×10^{16} $n_{eq}\,cm^{-2}$ are measured and modelled.

The current limitations in exploring the semiconductor properties at extreme fluences are both in terms of the investigation techniques as well as in facilities that would allow the studies and exposure of the sensors to such extreme radiation levels. Any future progress in this field is very closely linked to improvement in both these aspects. The latter particularly depends on access to adequate resources.

The synergies with fusion reactor instrumentation are many and can be fruitfully exploited. The extension of current research lines of the RD50 [Ch3-35] research group and/or the creation of new R&D collaborations is needed to create the necessary resources to explore the extreme fluence frontier. This is particularly true given the associated issue of finding microelectronics solutions able to withstand such an environment, while coping with the heavily reduced signal size and the demands of ever faster timing capabilities (see Chapter 7).

3.3.4 Wide band-gap semiconductors

Wide band-gap (WBG) semiconductors have some attractive properties and also some associated problems. The balance between these benefits and drawbacks will decide how they could be used in future tracking detectors. Whilst a WBG reduces the leakage current, maintaining low noise levels even at high temperatures, it also increases the required electron-hole generation energy. This increase implies that the number of

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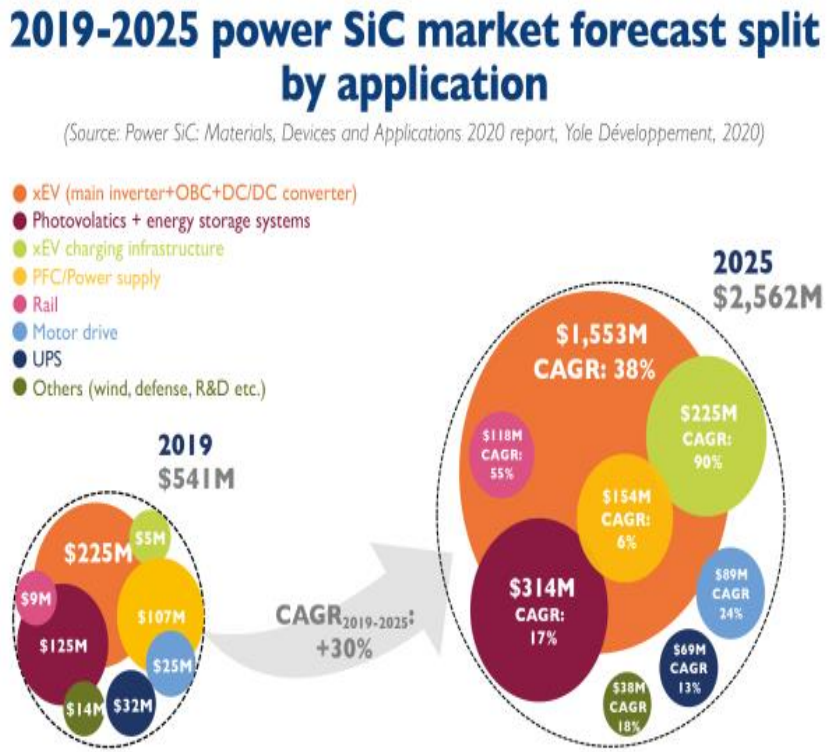
SiC radiation detectors



Silicon carbide is expected to improve energy efficiency in key sectors of the economy. Europe has many **large companies** leading this technology.

Property	Si	4H-SiC	Advantage
Bandgap [eV]	1.12	3.27	Low dark current levels, room temperature
Saturation electron velocity [10^7 cm/s]	1.0	2.0	High intrinsic time resolution
Breakdown field [MV/cm]	0.3	⊥: 4.0; ǁ: 3.0	High operation voltages
Atomic displacement threshold [eV]	13-20	22-35	High radiation resistance
Thermal conductivity [W/cmK]	1.5	5.0	Good cooling properties

Works well in harsh environments.

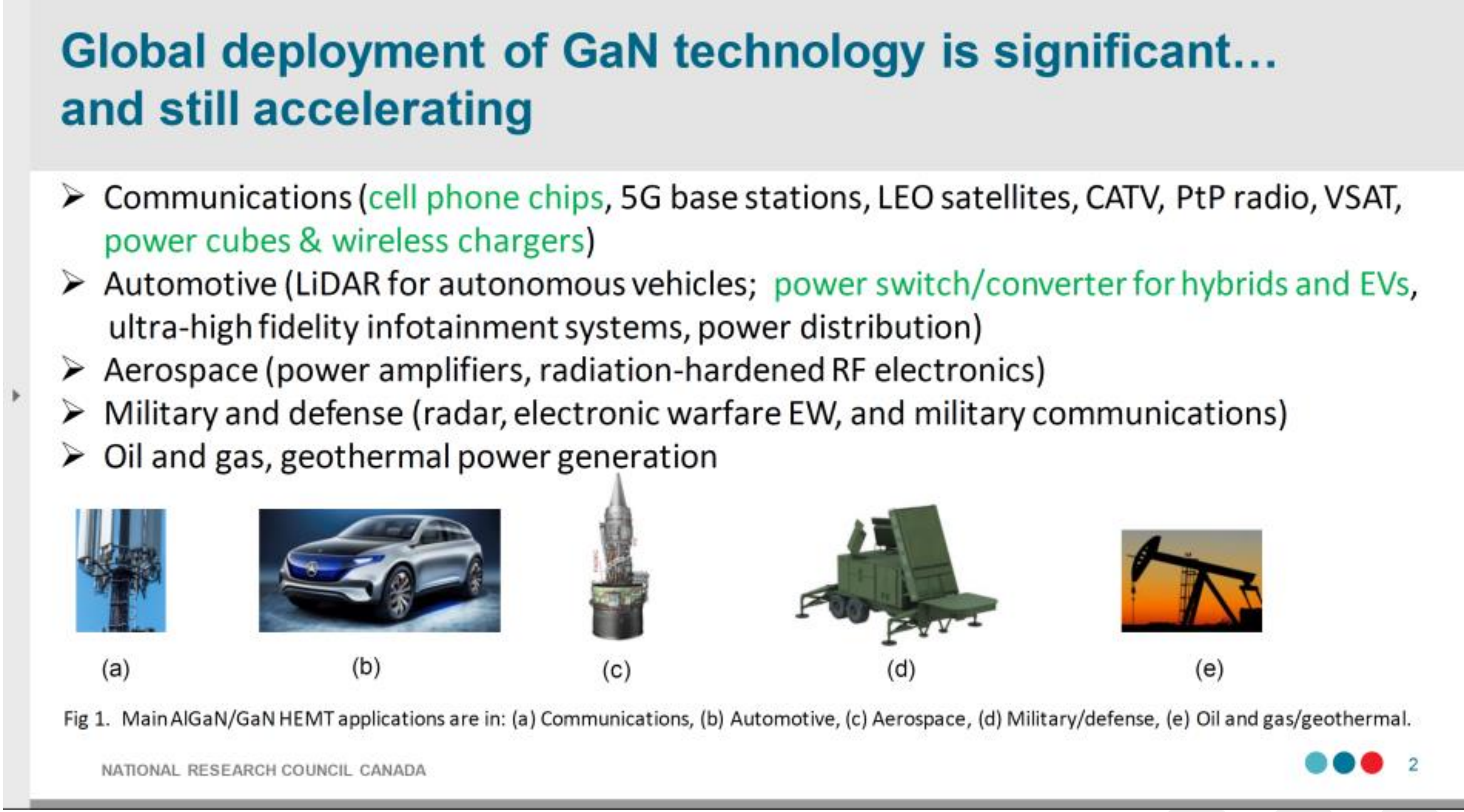
Very recently Silicon-Carbide CMOS technology is available in the **EUROPRACTICE** portfolio, provided by Fraunhofer IISB. -> Monolithic Pixels possible? LGAD? 3D?

- Epitaxial layer thickness is limited by increasing defect density (< 150 µm) -> 3D, LGAD, etc…
- R&D necessary to prove radiation hardness for specific applications.
- Low charge generation per µm and MIP SiC: 57eh; Si: 80 – 90eh -> S/N to be understood.

150mm wafers

F Nava et al 2008 Meas. Sci. Technol. 19 102001

J.M. Rafí et al 2018 JINST 13 C01045



Global deployment of GaN technology is significant… and still accelerating

- Communications (cell phone chips, 5G base stations, LEO satellites, CATV, PtP radio, VSAT, power cubes & wireless chargers)
- Automotive (LiDAR for autonomous vehicles; power switch/converter for hybrids and EVs, ultra-high fidelity infotainment systems, power distribution)
- Aerospace (power amplifiers, radiation-hardened RF electronics)
- Military and defense (radar, electronic warfare EW, and military communications)
- Oil and gas, geothermal power generation

(a) (b) (c) (d) (e)

Fig 1. Main AlGaN/GaN HEMT applications are in: (a) Communications, (b) Automotive, (c) Aerospace, (d) Military/defense, (e) Oil and gas/geothermal.

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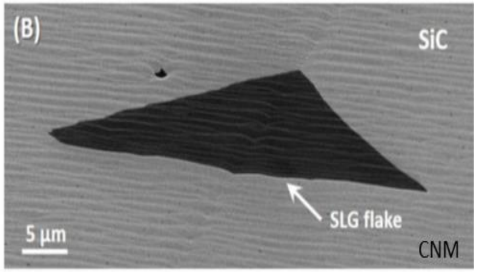
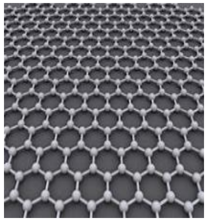
2

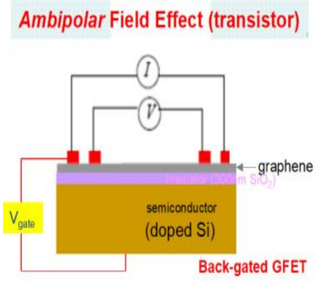
2D materials (Graphene- the perfect atomic lattice)

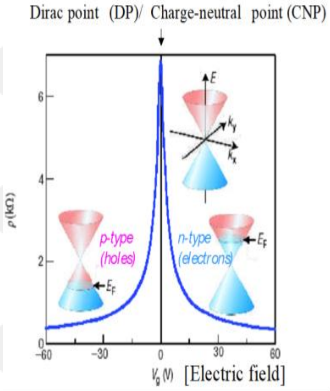
- Incredibly rapid and surprising developments, mainly in photonics. High mobility (x10 Si), ultra thin, good thermal conductor, flexible, gain possible, integrable etc...
- Graphene (or other 2D materials) in radiation detection systems is in its infancy-> mainly based on Gr-FET.
- New ideas for direct detection of radiation are necessary. Rad hard no 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.



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.







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.

-Propose new projects on WBG detectors or 2D materials to accomplish the milestones.

-LGAD can help in SiC but it is difficult to multiply holes.

-Diamond? May be in the near future.

-understand radiation damage (microscopic and macroscopic effects).

-Explore the use of radiation detectors in different fields-> -> Fusion- > export our know how on measurements, simulation etc…

-Long term, integration electronics and sensors in WBG.