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 $1\times10^{17} n_{eq}/cm^2$ (Q4/2022)

New Structures

Upcoming milestones

RD50

- 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 $2\times 10^{16}\,n_{eq}\,cm^{-2}$ and silicon 3D detectors above $3\times 10^{16}\,n_{eq}\,cm^{-2}$ have been reported [Ch3-31]. The few measurements available at fluences approaching those at FCC-hh, about $1\text{-}2\times 10^{17}\,n_{eq}\,cm^{-2}$ [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 $300\,\mu m$) [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 $5\text{-}10\times 10^{16}\,n_{eq}\,cm^{-2}$ 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

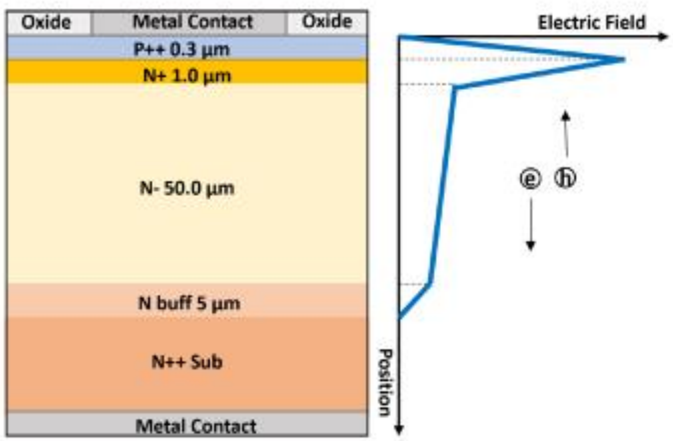
Wide band-gap (WBG) semiconductors have some attractive properties and also some associated problems. The balance between these benefits and drawbacks will decide how they could be used in future tracking detectors. Whilst a WBG reduces the leakage current, maintaining low noise levels even at high temperatures,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

- First SiC with Epitaxial graphene fabricated and tested-> more work to do (Ivan Lopez)
- Good agreement between measurement and DEVSIM simulation (Xiyuan Zhang), no good models are available in Sentaurus TCAD. Work in progress
- SiC for Proton Beam Monitor, efficiency to be obtimized (Ye He), medical applications are being explored by different groups (Thomas Bergauer).
- TPA measurements show the degradation with neutron irradiation of the charge collected (Cristian Quintana)-> Gain would be a obvious solution to use SiC for tracking and timing applications.
- After irradiation charge collected higher in forward bias (C.Q)

Introduction of SICAR— 4H-SiC LGAD for MIP

◆ **SICAR (SIlicon CARbide): 4H-SiC device for MIPs**

- Improve low gain issue of NJU
- Independent designed by RASER team [1]
- Fabricate the 4H-SiC LGAD
- Prototype of SICAR1



Structure of SICAR1

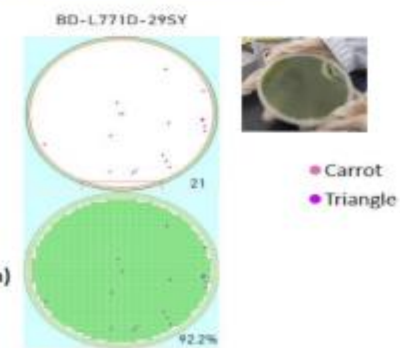
Design of SICAR1

Epi structure	Thickness [um] (Design)	Doping [cm^{-3}] (Design)
P++	0.3	2e19
N+ (gain layer)	1.0	1e17
N- (active layer)	50.0	1e14
N buff	5.0	1e18

Distribution of defects

Surface defects

DIE (2mm*2mm)



[1] RASER -

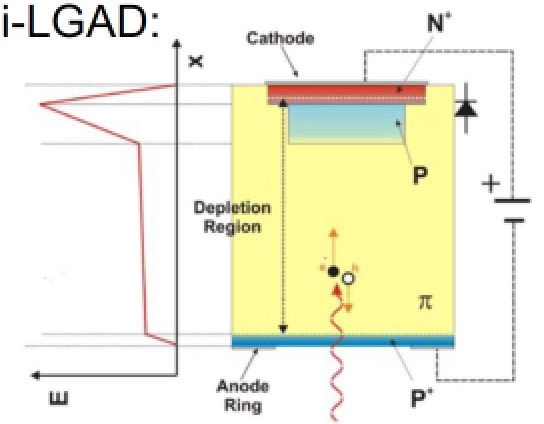
SiC-LGAD: The Idea

- Silicon carbide well suited already for
  - Spectrometric measurements of alpha radiation
  - Beam monitor for O(MeV) ions due to higher signals
- Applications in HEP
  - Signal very small due to limited thickness of epi growth process

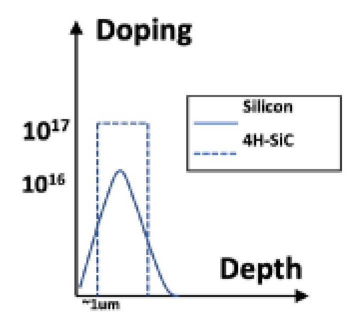
➢ **Implement a gain layer into Silicon Carbide to mitigate the small signals**

Challenges:
- Only n-type substrates available, which implies N-LGAD structure (see also Jairo's talk tomorrow on Si-N-LGAD)
- Creation of deep gain layer not achievable by "normal" ion implantation (as usually done for Si-LGAD) due to high displacement energy and thermal conductivity of SiC
- Gain layer could be implemented during epitaxial growth
  - involvement of wafer supplier necessary in formation of gain layer
  - We know that wafer supplier can grow sandwich of N-/P layers.
  - Alternative: high-energy implantation and high-energy annealing

Si-LGAD:

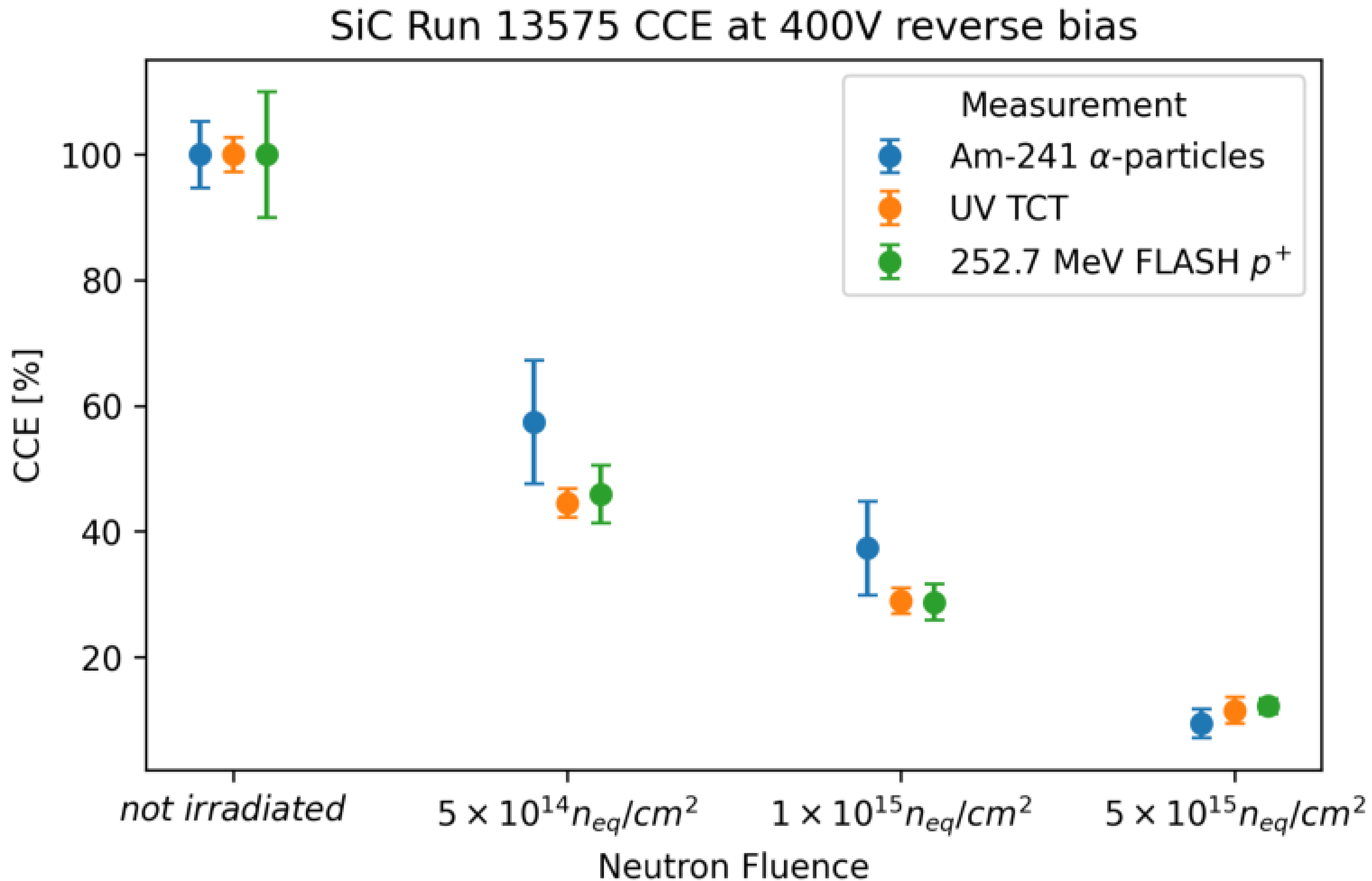


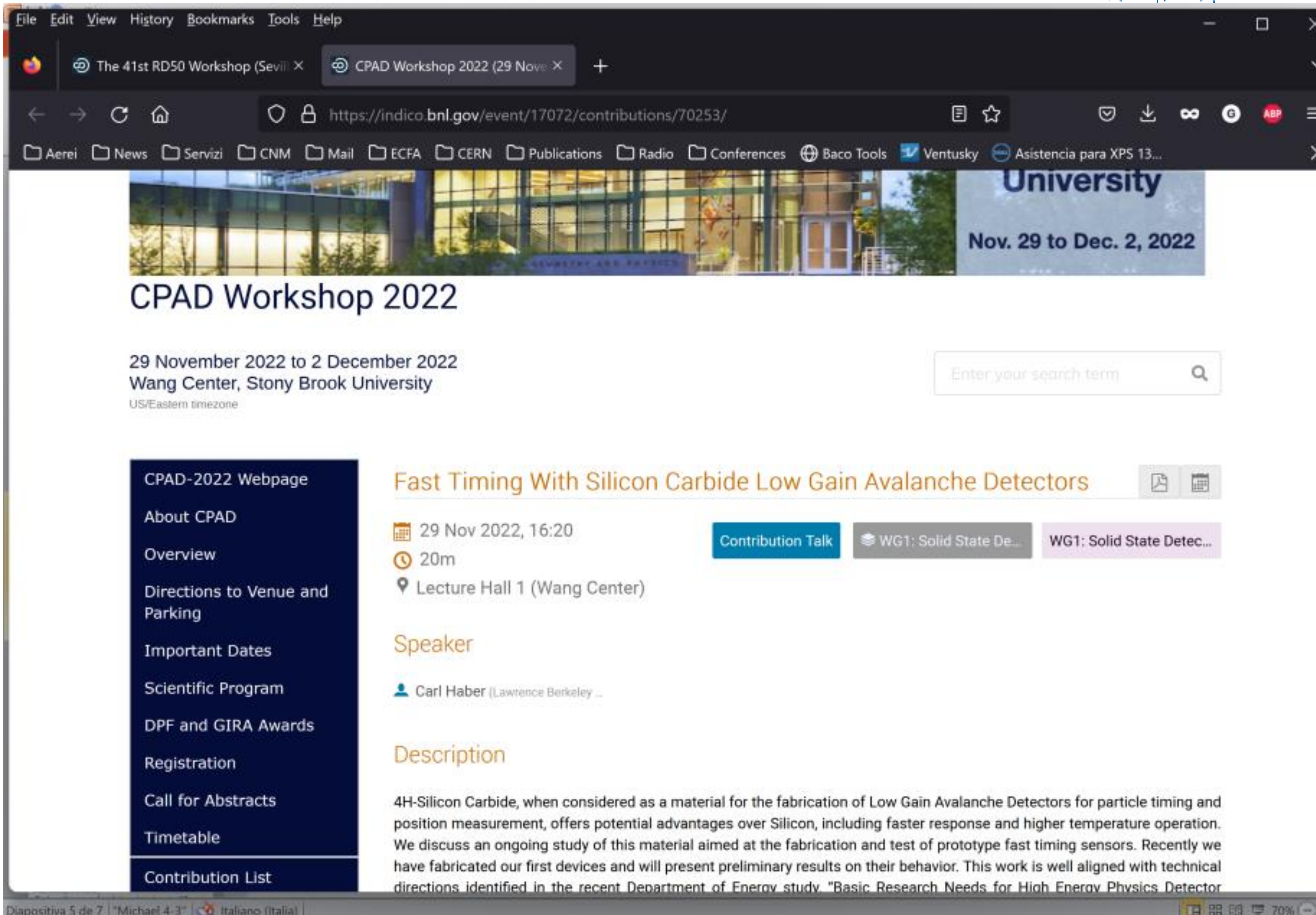
N. Cartiglia



Yang Tao, 39th RD50 workshop

Final CCE comparison

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Contribution List
Fast Timing With Silicon Carbide Low Gain Avalanche Detectors
29 Nov 2022, 16:20
20m
Lecture Hall 1 (Wang Center)
Contribution Talk
WG1: Solid State De...
WG1: Solid State Detec...
Speaker
Carl Haber (Lawrence Berkeley ...
Description
4H-Silicon Carbide, when considered as a material for the fabrication of Low Gain Avalanche Detectors for particle timing and position measurement, offers potential advantages over Silicon, including faster response and higher temperature operation. We discuss an ongoing study of this material aimed at the fabrication and test of prototype fast timing sensors. Recently we have fabricated our first devices and will present preliminary results on their behavior. This work is well aligned with technical directions identified in the recent Department of Energy study "Basic Research Needs for High Energy Physics Detector
Diapositiva 5 de 7 "Michael 4-3" Italiano (Italia) 70%