

# The 37th RD50 Workshop (Zagreb – online Workshop)

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## Book of Abstracts



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**Welcome / 1****Workshop opening**

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Welcome of the participants; general information regarding this Workshop

**LGADs / 2****Timing resolution on a 3D silicon pixel detector**

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We report on the measurements of time resolution for double-sided 3D pixel sensors with a single cell of  $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$  and thickness of  $285\text{ }\mu\text{m}$ , fabricated at IMB-CNM and irradiated with reactor neutrons to  $8\text{e}14\text{ MeV n}_{eq}/\text{cm}^2$  and then to  $2.3\text{e}15\text{ MeV n}_{eq}/\text{cm}^2$ . Measurements were conducted using a radioactive source at a temperature of  $-20$  and  $20\text{ }^\circ\text{C}$  in a bias voltage range of  $50\text{--}300\text{ V}$ . The reference time was provided by an LGAD detector produced by Hamamatsu. In order to reduce the effect on jitter a detector has been produced and tested with the same technology but with a thickness of  $235\text{ }\mu\text{m}$ . The results obtained are compared to measurements conducted prior to irradiation.

**Defect Characterization / 3****The boron-oxygen (BiOi) defect complex induced by irradiation with 23 GeV protons in p-type epitaxial silicon diodes**

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In this work the Thermally Stimulated Current (TSC) technique has been used to investigate the properties of the radiation induced BiOi defect complex by 23 GeV protons, including activation energy, capture cross section, defect concentration as well as the annealing behavior. At first isothermal annealing (at 80 °C for 0 to 180 minutes) followed by isochronal annealing (for 15 minutes between 100 °C and 180 °C in steps of 10 °C ) studies had been performed in order to get information about the thermal stability of the BiOi defect in 50  $\Omega$  cm material after irradiation with 23 GeV protons to a fluence of  $6.91 \times 10^{13}$  p/cm<sup>2</sup>. The results will be presented and discussed. Furthermore, the extracted data from TSC measurements are compared with the macroscopic properties derived from current-voltage (I-V) and capacitance-voltage (C-V) characteristics. In addition the introduction rate of BiOi as function of the initial doping concentration was determined by exposing diodes with different resistivity (10  $\Omega$ cm, 50  $\Omega$ cm, 250  $\Omega$ cm, and 2 k $\Omega$ cm) to 23 GeV protons. These results will be compared with data from DLTS measurements achieved by the team of the RD50 “Acceptor removal project”

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## The “1 micron” project

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Resistive readout allows designing thin sensors with a small material budget and excellent spatial resolution. In this contribution, I will present how exploiting the properties of AC-LGAD is it possible to reach a spatial precision of 1  $\mu$ m with large pixels (150-200  $\mu$ m), keeping the material budget low enough to meet the stringent requirement of the future e<sup>+</sup>e<sup>-</sup> experiments.

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## Irradiation study with passive CMOS pixel detector structures on RD50-MPW2 chips

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RD50-MPW2 is pixel detector prototype fabricated in 150 nm High Voltage CMOS technology at LFoundry. It is a successor of RD50-MPW1 chip developed within RD50 collaboration to study this technology for future experiments. Chips were manufactured on p-type silicon with different initial resistivities and irradiated with neutrons in reactor in Ljubljana. E-TCT and I-V measurements were made with passive pixel test structures. Depletion depth was measured as a function of bias voltage with E-TCT to extract information about effective space charge concentration. Dependence of Neff and detector current was studied as a function of neutron fluence. Measurements were repeated after several annealing steps at 60 °C.

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## Preliminary USTC-1 LGAD Results and Large Array Characterization for HGTD

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We will present the preliminary test results of the USTC first batch LGAD, which is designed by USTC focusing on **deep implantation** and **carbon diffusion** techniques to improve the irradiation hardness. The design follows the ATLAS-HGTD specifications with 50 um active thickness and 8-inch wafers are used. In the first prototyping run, 6 wafer splits with different gain layer dose and depth have been fabricated. The test results include I-V, C-V, and TCT with both laser and the beta source. USTC group also focuses on the **large array characterization** with the self-designed readout system and probe-cards for the coming application's QA requirement on ATLAS. We have achieved stable and low noise measurement on the 5x5 and 15x15 HPK prototype arrays for HGTD.

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## A summary of the radiation resistance of carbonated gain implants

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A new Ultra Fast Silicon Detectors production (UFSD3.2) has been produced by Fondazione Bruno Kessler (FBK) in Trento, in collaboration with University of Trento and National Institute of Nuclear Physics in Turin (INFN); this production aims to improve the radiation resistance of the multiplication layer (gain layer).

Previous FBK-UFSD productions (UFSD2 and UFSD3) demonstrated that the co-implantation of carbon into the gain layer mitigates the acceptor removal mechanism. In UFSD2 and UFSD3, the gain implant has been enriched

with carbon in a range of dose 1C-10C [a.u.]. The carbon enrichment showed unexpected effects: the active fraction of boron into the gain implant decreases with increasing carbon dose (carbon-boron capture); the intrinsic radiation resistance of carbonated gain layers is better for carbon dose 1C than higher doses.

In UFSD3.2, a carbon dose in a range 0.4C-1C has been implanted, in the order to identify the optimal carbon dose that maximizes the radiation resistance and minimizes the carbon-boron capture.

In this contribution: we will report a mapping of carbon-boron capture in a range of carbon dose 0.4C-10C; we will show the acceptor removal coefficients measured on gain implants enriched with carbon doses 0.4C, 0.6C, 0.8C and 1C, irradiated with neutrons up to fluence of  $2.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ . Our studies show a link between the dose where carbon-boron capture starts and that that makes the most radiation resistant gain implant

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## Radiation tolerant small-pixel passive CMOS sensors with RD53A readout

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With the HL-LHC upgrade of the ATLAS detector, the surface of the ATLAS pixel detector will increase from  $2 \text{ m}^2$  to approximately  $13 \text{ m}^2$ . Therefore, commercial CMOS processing lines offering high production throughput at comparatively low costs, represent an attractive option for such large-area detectors. Further benefits originate from multiple metal layers, metal-insulator-metal capacitors, and polysilicon layers which offer enhanced sensor designs through additional routing options.

Thinned, small-pixel passive CMOS sensors in 150 nm technology offered by LFoundry were manufactured and assembled into hybrid pixel modules using the RD53A readout chip.

The sensors were characterized, before and after irradiation to fluences of  $5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$  and  $1 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ , in the laboratory and also using a minimum ionising electron beam. Their performance in terms of noise and hit-detection efficiency equals that of conventional planar pixel sensors. Special emphasis will be put on the results after a fluence of  $1 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$  yielding a hit-detection efficiency of approximately 99 %.

Detector Characterization and Simulation / 9

## Irradiation of gate-controlled diodes and MOS capacitors with <sup>60</sup>Co-gamma photons

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During the era of the High-Luminosity (HL) LHC the experimental devices will be subjected to enhanced radiation levels with fluxes of neutrons and charged hadrons in the inner detectors up to  $\sim 2.3 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$  and total ionization doses up to  $\sim 1.2 \text{ Grad}$ . A systematic program of irradiation tests with neutrons and charged hadrons is being run by LHC collaborations in view of the upgrade of the experiment, in order to cope with the higher luminosity of HL-LHC and the associated increase in pile-up events and radiation fluxes. While most related studies focus on irradiation with neutrons, hadrons or X-rays, in this work, a complementary radiation study with gamma photons from a  $^{60}\text{Co}$  source is presented. The doses are of the orders of tens of kGy. The irradiated test structures contain among others gate-controlled diodes (GCD). Surface and bulk components of the electric current can be separated through IV measurements on a GCD, and the interface recombination velocity and interface state density can be determined from the surface current. Here, the alterations in the GCD current components after irradiation are investigated. MOS capacitors are also located on the test structures and the CV measurements on them are compared with the output of a TCAD simulation. The devices under test are made of oxygen enriched float zone p-type silicon.

## LGADs / 10

### First results from thin silicon sensors for extreme fluences

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The first production of thin LGAD sensors from FBK has been completed.

The preliminary electrical characterization of sensors before irradiation will be presented and discussed.

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### Status of CNM LGAD Runs

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In this contribution, we will present our latest LGAD developments. We have completed the fabrication of two LGAD runs and another two are currently being fabricated. The 1st run, AIDA2020 v2, has already been presented at the 35th RD50 workshop, which is a repetition of the previous AIDA2020 run. We have since performed more measurements which show improved results, and these will be presented. The 2nd run is devoted to calibrating our 6-inch technology in 50  $\mu\text{m}$  epitaxial wafers. In this run, pad diodes were fabricated with a variety of boron implantation doses, calibrated with the previous 6-inch runs. Preliminary results of the electrical characterization will be presented. The performance of this run is crucial to select the best technological parameters for the new ATLAS-CMS Common Run. We will base our technological parameters on the 6-inch runs in SOI and epitaxial wafers. Lastly, we are developing a new AC-LGAD run in 6-inch wafers.

## LGADs / 12

### Preliminary test results on LGAD devices

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First batch of LGAD devices, developed by RAL, University of Oxford, University of Birmingham and Open University in collaboration with T2ev semiconductor foundry, have been designed and fabricated for fast timing applications and potential use in HGTD for ATLAS.

Up to eight different LGAD device flavours, differing in energy and dose of the implanted gain layer, have been fabricated on 6" wafers.

On each wafer, both LGAD and PiN diodes of same layout are available for comparison of performances.

Preliminary test results on the first batch of LGAD structures, including description and details of simulations of the devices, will be presented.

Description of coming tests and plans for next fabrication iteration will also be given.

## Detector Characterization and Simulation / 13

### Gamma, neutron, proton irradiated p-type silicon MOS capacitors with aluminium oxide.

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We report on the study of response of the MOS capacitor with atomic layer deposited (ALD) Al<sub>2</sub>O<sub>3</sub> layer on p-type silicon substrate to neutron, proton, and gamma irradiation. Alumina films are prominent for use as passivation layers in silicon radiation detectors instead of surface electron accumulation termination structures as alumina forms negative oxide charge on the silicon-oxide interface. In order to investigate the interface charges and surface damage after irradiation with different particles electric characterization of MOS capacitors were conducted by capacitance-voltage measurements. The results are described in correlation with the changes in effective oxide charge. TCAD simulations accompanied the study. The flat band and hysteresis of C-V curves after gamma irradiation showed development of mobile charges in dielectric film. Proton and neutron irradiated samples demonstrated decrease of capacitance in the accumulation region which can be explained by displacement damage. At the same time, the observed shift of effective oxide charge with increase of irradiation indicates the surface charge accumulation. The findings of bulk damage were described by a creation of BiOi level.

## CMOS / 14

### Characterization of passive CMOS strip detectors

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An increasing trend towards full silicon trackers in future high energy physics experiments provokes the need to cover increasingly large areas with silicon detectors. As a consequence, detector designs that utilize cost-effective production processes are becoming more important. Employing CMOS production lines for sensors allows large and high-resistive wafers at low cost, making them a prime candidate.

In this talk we will present the first laboratory measurements of novel passive CMOS silicon strip sensors developed by the ATLAS Collaboration.

The study contains three different strip flavors fabricated on a 150 µm wafer by LFoundry on a 150 nm process. The strip sensors have a length of up to 4 cm, formed by stitching of individual elements.

The initial characterization of the sensors includes current-voltage, capacitance-voltage and inter-strip capacitance measurements. Further measurements on the sensor performance include source measurements and characterization with different laser techniques.

A main focus of the study were position dependent measurements to achieve the main goal of understanding the impact of the stitching process employed on the functionality of the sensors.

LGADs / 15

## Simulation and testing results of the low gain avalanche diodes developed by IHEP and IME in China

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The ATLAS experiment High Granularity Timing Detector (HGTD) project has been approved as a part of the Large Hadrons Collider Phase-II Upgrade (HL-LHC). The Low- Gain Avalanche Detector (LGAD) with time resolution better than 50ps is the key technology to separate collisions in limited space which has been studied and researched by many institutes. This talk will present the simulation and testing results about 50um thick LGAD sensors designed by the Institute of High Energy Physics (IHEP) and fabricated by Institute of Micro Electronics (IME) of Chinese Academy of Sciences. Testing results show that the IHEP-IME sensors with different doping profiles have different breakdown voltages(VBD) and capacitance-voltage properties, which are consistent with the simulation results. Beta testing results show that the time resolution of IHEP-IME sensors are better than 40ps and the collected charges of IHEP-IME sensors are larger than 20fC before irradiation.

CMOS / 16

## Active pixel matrix measurements of irradiated RD50 HV-CMOS prototypes

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The active matrix of the RD50 HV-CMOS MPW2 prototype consists of 8x8 pixels with analogue front-end only. While former measurements on irradiated sensors have been performed only at passive test-structures, first results of the irradiated active matrix are discussed in this presentation. The test structures do have a similar layout than the active matrix, but only one pixel at a time can be measured by contacting it with probe needles. Each pixel of the active matrix can be readout one after the other. A slow control using a shift-register allows to automatize readout. A DAQ system has been developed already and has been successfully verified on non-irradiated chips. Details about the DAQ system have been reported in the last workshop as well. The same system is used for reading out the irradiated sensor samples. A setup for using a radioactive source together with the MPW2 is established as well.

Moreover, preparations for a first test beam at MedAustron, a clinical proton beam facility close to Vienna, are ongoing. This needs a new trigger setup and a slightly adapted readout system, which is currently under development.

In this contribution, we will show results from measurements of the irradiated matrix and compare them with the unirradiated sensors. A beta source is used to generate signals in the sensor for comparison. Finally, first thoughts about a setup and an outlook for a first test beam using the active matrix of MPW2 are given.

**Defect Characterization / 17****Structural, compositional and defect studies on hadron irradiated B-doped silicon diodes**

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**Co-authors:** Eckhart Fretwurst<sup>3</sup>; Joern Schwandt<sup>3</sup>; Gregor Kramberger<sup>4</sup>; Michael Moll<sup>5</sup>

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HRTEM, LA-ICP-MS and DLTS techniques were employed to characterize several types of B-doped silicon diodes after irradiation with hadrons. The HRTEM results on LGAD samples irradiated with 1019cm<sup>-2</sup> show that there is a preferential grouping of defects along tracks normal to the film surface. We will present the LA-ICP-MS technique, recently installed in NIMP, with which we could estimate the Boron concentration not only in the moderate doped LGADs gain layer but also in high resistivity EPI and FZ silicon. The DLTS results on samples of different resistivity and impurity content are presented and discussed in relation with the acceptor removal process.

**RD50 Beta source measurement systems (Friday) / 18****Sr90-Beta Setup at CERN SSD: Hardware and Data Analysis**

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**Co-authors:** Marcos Fernandez Garcia<sup>2</sup>; Michael Moll<sup>3</sup>; Esteban Curras Rivera<sup>3</sup>

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A Sr-90 based beta- particle setup was developed and commissioned at CERN-SSD for measuring silicon sensors, specifically their timing properties. Herein, we detail what hardware is thereby deployed, how the setup is operated, as well as data processing and analysis of measurements, for which the open-source programs TRICS and ROOT are used.

**LGADs / 19****LGAD measurements from different producers**

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The performance of latest LGAD sensor prototypes from different producers were studied before and after irradiations with neutrons. The charge collection, timing and gain layer depletion voltages were compared.

**RD50 Beta source measurement systems (Friday) / 20**

## JSI charge collection/timing setup

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The hardware, DAQ and analysis software of the JSI setup will be presented.

**Transient Current Techniques (Thursday) / 21**

## Characterization of advanced detector and electronic devices performed at RBI

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The PaRaDeSEC project “Particle and Radiation Detectors, Sensors and Electronics in Croatia” is an ERA Chair Horizon 2020 in the EU Framework Programme for Research and Innovation. A national center for development of radiation particle detectors, sensors and their associated electronics was successfully established as a result of the PaRaDeSEC project. The new Center for Detectors, Sensors & Electronics –CDSE is an independent RBI unit with a focal point of all activities related to the development, testing and construction of devices for the Nuclear, Particle and Astro-Particle, as well as Medical Physics Experiments and applications.

Advanced detector and electronic device testing activities are performed at the RBI’s irradiation facility and the accelerator center (the largest experimental complex in Croatia).

The Radiation Chemistry and Dosimetry Laboratory at RBI has a high intensity gamma radiation source of Co-60 (2 PBq radioactivity) that is capable of delivering a large range of dose rates and can provide an excellent environment for radiation hardness studies. The facility is equipped with a specially designed and constructed setup with a temperature regulated environment accompanied by actively monitored dosimetric measurements. In this work we demonstrate that this setup is ideal for irradiation tests of both detector structures and integrated circuits.

The Ion Beam facility at RBI is equipped with a microprobe system that can deliver a variety of ions (from H to Au) into a 1 µm spot size at their respective energies (maximal energy between 8 MeV for protons and 25 MeV for heavy ions). The focused IBIC technique produces a spatially resolved

Charge Collection Efficiency 2D map of different pad and pixelated detector structures. Moreover, the versatile capabilities of the microprobe at RBI is capable of evaluating the behaviour under ion irradiation of specific areas and elements inside sensors and electronic circuits. This makes it the ideal tool for SEE mapping on microscopic scale and finding the sensitive circuit elements responsible for the failure of the device. The facility is able to provide a Si and Cl ion beam with energy of 25 MeV that correspond to LET of 14.5 and 17.9 MeV-cm<sup>2</sup>/mg (respectively) inside Si substrate devices. The dependence of LET with depth was observed and presented in this work.

The techniques presented here are specially relevant for HVCMOS because they need CCE, TID and pinpoint accuracy SEE analysis due to their monolithic integration of detector and read out electronics in the same dye.

## LGADs / 22

### Electrical and timing performance of AC-LGADs

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Low Gain Avalanche Diodes (LGADs) are characterised by a low to moderate gain (2 - 100), short rise time, high signal-to-noise ratio and exhibit excellent timing performance (30-40 ps), however fine pixelization of LGADs is difficult to achieve. To provide fine spatial resolution the AC-coupled LGAD (AC-LGAD) approach was introduced. In this type of device, the signal is capacitively induced on fine-pitched electrodes placed over an insulator. AC-LGAD prototypes are designed and fabricated at Brookhaven National Laboratory (BNL) and segmented in both pixel matrices and strips with different configurations. These prototypes are characterized by IV, CV and TCT scans, and their time resolution is measured by studying the time coincidence between signals generated in two sensors by beta particles from a <sup>90</sup>Sr source. Test results of AC-LGADs fabricated at BNL are compared to those obtained at a test-beam at FNAL with 120 GeV protons and those of LGADs fabricated at BNL and HPK. Simulations are used to get insight on the generation of the signal induced on the hit pixels/strips and their neighbours.

## Defect Characterization / 23

### An increase of the quantum yield in highly irradiated Si.

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**Co-authors:** Vilius Vertelis<sup>2</sup>; Vaidotas Kazukauskas<sup>2</sup>; Juozas Vysniauskas<sup>2</sup>

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The measurement of spectral dependence of photoconductivity permits to investigate the deep level spectrum, recombination at the surface and photoelectric quantum yield. This presentation deals with observation of an increase of quantum yield at lower photon energy in highly irradiated Si in comparison with less or non-irradiated Si. The effect was observed in neutron irradiated Si to the fluence 1e16 cm<sup>-2</sup> and higher. It is attributed to the impact ionization via deep levels.

**Defect Characterization / 24****Defect investigations of electron irradiated p-type Si sensors**

**Authors:** Anja Himmerlich<sup>1</sup>; Yana Gurinskaya<sup>1</sup>; Isidre Mateu<sup>None</sup>; Ana Ventura Barroso<sup>2</sup>; Vendula Maulerova<sup>3</sup>; Esteban Curras Rivera<sup>1</sup>; Michael Moll<sup>1</sup>; Ioana Pintilie<sup>4</sup>; Chuan Liao<sup>3</sup>; Eckhart Fretwurst<sup>3</sup>; Joern Schwandt<sup>3</sup>; Leonid Makarenko<sup>5</sup>

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P-type silicon exposed to high radiation environment undergoes an apparent deactivation of the boron dopant –known as the so-called Acceptor Removal Effect (ARE). To investigate the impact of high energy electrons of different fluences on the ARE, p-type Si diodes, irradiated at the CLEAR facility at CERN with 200 MeV electrons as well as sensors irradiated with 5.5 MeV electrons at Belarusian State University in Minsk were characterized.

In this talk radiation induced changes in the macroscopic device properties extracted from C(V) and I(V) measurements will be presented. Furthermore, an overview of the microscopic radiation induced defects, investigated by TSC (Thermally Stimulated Current technique) as well as DLTS (Deep Level Transient Spectroscopy) measurements will be given. Both techniques provide information about defect characteristics such as activation energy, capture cross section or defect concentrations, and enable to calculate the defect generation rates for the electron irradiated sensors.

**Defect Characterization / 25****Alpha irradiation induced stability studies in single crystal diamond radiation detectors**

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**Co-authors:** Mohapatra Sarthak<sup>2</sup>; Sahu P K<sup>3</sup>; Vala Sudhir Sinh<sup>4</sup>; Abhangi Mithul R<sup>5</sup>

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The time stability of a single crystal diamond radiation detector in response to alpha particle irradiation is studied in this work. A diamond detector is fabricated from a free-standing single crystal diamond plate and is packaged for the alpha irradiation studies. The detector under the bias voltage of +70 V is kept under constant alpha irradiation from a mixed  $\alpha$ -source having major activity from <sup>239</sup>Pu and minor activity from <sup>238</sup>Pu. The diamond detector is found to be stable for the tested period of 4 hours, in consistent with the work carried out by Girolami et al. [1]. To further test the stability of the detector against alpha irradiation for increasing time duration and at the same time avoiding any avalanche related multiplication effects, the irradiation is again carried out for nearly 12 hours without the application of the bias voltage. It is found that the performance of the detector is degraded severely after the irradiation and this can be attributed to the alpha irradiation induced

polarization effects in the diamond detector [1,2]. This phenomenon is found to be reversible and after subsequent room temperature annealing with and without bias, the detectors are functioning as expected.

#### References:

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## Detector Characterization and Simulation / 26

### Analysis of I-V characteristics as a method in the study of radiation degradation of Si detectors

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Generation of the current by radiation-induced defects in Si p-n junction detectors is one of the processes responsible for their radiation degradation. In the study, analysis of the I-V characteristics is performed for the profiling of radiation defects acting as current generation centers. The experimental results are obtained for the Si p+-n-n+ diodes with a nonuniform defect distribution induced by radiation with Ar ions that form heavily damaged cluster-rich region produced by silicon recoils in the track end. Processing of the I-V characteristics showed that the current generation rate distribution along the track is nonmonotonous and its maximum is shifted from the track end towards the p+ contact. This evidences that formation of radiation defects related to the impact of recoils significantly suppresses the current generation.

## Transient Current Techniques (Thursday) / 27

### Investigation of the amplitude decrease in subsequent pulse detection in irradiated silicon sensors

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During edge- and Top-TCT measurements using subsequent laser pulses with a pulse repetition time of several microseconds, a significant decrease in the measured signal amplitude has been observed. The charge created during the pulses has severe effects on the electrical configuration of the sensor. This can be explained by either trapping of charge carriers which alter the charge distribution and in turn the electric field profile –known as the polarization, or in case of non-depleted bulk as a consequence of dielectric relaxation, when the almost-intrinsic irradiated bulk restoration after the charge perturbation of the steady state electrical configuration is relatively slow –often described with time dependent weighting field.

This study investigates different dependencies of the decrease on voltage, fluence, laser intensity, type of created carrier and time between pulses. It includes simulations of the electric field change

and a fit model for trying to discriminate between trapping induced polarization and relaxation effects.

## Defect Characterization / 28

### Electron, neutron and proton irradiation effects on four-quadrant SiC radiation detectors

**Authors:** Joan Marc Rafi<sup>1</sup>; Giulio Pellegrini<sup>1</sup>; Philippe Godignon<sup>1</sup>; Sofia Otero Ugobono<sup>1</sup>; Gemma Rius<sup>1</sup>; Vainius Dauderys<sup>1</sup>; Isao Tsunoda<sup>2</sup>; Masashi Yoneoka<sup>2</sup>; Kenichiro Takakura<sup>2</sup>; Gregor Kramberger<sup>3</sup>; Michael Moll<sup>4</sup>

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Owing to their low dark current, high transparency, high thermal conductivity and potential radiation hardness, there is a special interest in silicon carbide devices for radiation monitoring in radiation harsh environments or operation at elevated temperatures.

In this work, segmented four-quadrant pn junction diodes produced on epitaxied 4H-SiC substrates are studied. The impact of 2-MeV electron, neutron and 24-GeV/c proton irradiations (up to fluences of  $1 \times 10^{16} e/cm^2$ ,  $3 \times 10^{17} n/cm^2$  and  $2.5 \times 10^{15} p/cm^2$ , respectively) on the electrical characteristics is studied by means of current-voltage (I-V) and capacitance-voltage (C-V) techniques. Relevantly, similar low reverse currents for irradiated SiC devices are obtained regardless of particle type and applied fluences, which are at least about four orders of magnitude lower than comparable Si devices. Electrical rectification character of the diodes is lost for the highest fluences. The effects of irradiation on interquadrant resistance and charge build-up in the interquadrant isolation are also assessed. Additionally, device performance as a detector is investigated under irradiation with a collimated  $^{239}\text{Pu}$ - $^{241}\text{Am}$ - $^{244}\text{Cm}$  tri-alpha source. As a validation for sensing applications, SiC device performance as a radiation detector is preserved at room temperature, at least up to  $2 \times 10^{15} n/cm^2$  as well as all other reached electron and proton fluences.

Summarizing, advantages of using SiC devices in alpha particle detection in harsh environments can be envisaged. This study contributes to the milestones in fabrication and radiation hardness assessment of new radiation detectors based on wide bandgap materials, and it is in alignment with the new materials research line objectives in the current RD50 5-years work program.

## Detector Characterization and Simulation / 29

### Determination of proton hardness factors with commercial PiN diodes

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The radiation hardness of detectors is of paramount importance for the success of the scheduled High Luminosity upgrade of the CERN Large Hadron Collider. This has driven a global campaign

for sensor characterisation and irradiation testing facility qualification. The effect of radiation damage from various particle species and energies are conventionally communicated in term of the equivalent 1 MeV neutron fluence, related by a hardness factor. The University of Birmingham, in collaboration with CERN and Karlsruhe Institute of Technology, have performed a campaign of measurements to determine the proton hardness factor at several irradiation facilities, using commercial BPW34F PiN diodes. Recently, Bonn University has commissioned a proton irradiation facility at Bonn Isochronous Cyclotron of Helmholtz Institut für Strahlen- und Kernphysik (HISKP) and utilised the same technique to estimate the corresponding hardness factor. The diodes used in this study have now been measured at the University of Birmingham, following an identical procedure to the earlier studies. A summary of the measurement campaigns will be given and the results of recent measurements of these diodes will be reported.

## RD50 Beta source measurement systems (Friday) / 30

### Characterization with a $\beta$ -source setup of the FBK UFSD 3.2 & HPK2 LGAD productions

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In this contribution, I will present the characterization of the latest LGAD productions manufactured at FBK (UFSD3.2) and HPK (HPK2), performed with the  $\beta$ -source (Sr90) setup of the Torino Silicon Lab (INFN – University of Torino). In particular, I will focus on temporal resolution and gain measurements of either irradiated (up to a fluence of  $2.5 \times 10^{15}$  neq/cm<sup>2</sup>) and non-irradiated devices. Results on sensors with different gain layer depths and carbon implantation doses will be shown.

In addition, I will compare the performances of FBK UFSD3.2 sensors with four different active thicknesses (25, 35, 45, 55  $\mu$ m).

I will also discuss the issues faced during the development of a dry and cold (-30°C) setup and provide some informations on the Torino  $\beta$ -setup, both on the hardware and software side.

## Transient Current Techniques (Thursday) / 31

## Capabilities of testing detectors for high energy physics by MeV energy ions

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By shrinking the sizes of detectors used in high energy physics experimental setups, techniques that can characterise detectors at the micrometer size levels are getting more and more attention. This may be one of the reasons why the Ruđer Bošković Institute (RBI) and its microprobe based IBIC (ion beam induced charge) system, attracted more than 20 users from the high energy physics community during the course of the AIDA2020 project. Several important developments and improvements, initiated by users, have been in the meantime accomplished and as such the IBIC setup is now much more suitable for testing of different detectors, from simple basic structures to complex monolithic prototypes and devices.

In this presentation we will show the main characteristics of the present setup for IBIC and ion beam induced TCT, that are an integral part of the ion microprobe end station. Ion beams of the MeV energy range (0.1 to 25 MeV, depending on the ion mass), with respective ranges in silicon between 1 and 500  $\mu\text{m}$ , are provided by one of the two electrostatic accelerators (1.0 and 6.0 MV tandems). Experiments are generally performed in vacuum chamber. However new in-air setup can be used for larger detector structures, which can be exposed to proton beams with still small enough spot sizes (3-10  $\mu\text{m}$ ). Several characteristic applications of the system within the AIDA2020 will be presented together with a foresight to new future projects that may be beneficial to high energy physics community.

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## Double Sided LGADs for 5D Measurements

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We describe and simulate a concept which combines small pixels enabled by 3D sensor-electronics integration with gain produced by a Low Gain Avalanche Diode (LGAD) layer (inverted LGAD). The detector is double-sided, with electrons collected by the cathode, which provides timing information, and an anode with small pixels to provide position and angle information. The cathode can be coarse grained, providing timing with fewer fast amplifiers to limit power consumption. The anode layer benefits from the gain of the LGAD, with larger signals that also limit the power needed. Position can be reconstructed by measuring the pattern of total charge deposited on the anode. Angle and depth of charge deposit can be measured by the shapes of the anode pulses. We describe a fabrication option based on buried layers. We also describe a possible assembly technology based on 3D integration.

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## Radiation effects in the CMS phase 1 pixel detector

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Radiation defects induced by the harsh radiation environment in the CMS experiment heavily impact the operation of the upgraded silicon pixel detector, that has been installed in the beginning of 2017. During the data taking period of 2017-2018, the phase 1 CMS pixel detector, composed of 4 barrel layers and 3 endcap disks, has experienced up to  $1 \times 10^{15} n_{eq}/cm^2$ . In this presentation we will discuss the evolution of the detector properties, such as leakage current and depletion voltage under irradiation. We present the simulation of evolution of these quantities in 2017-2018 for barrel and 2 endcap regions, and compare it with the data.

## Transient Current Techniques (Thursday) / 35

### Charge collection characterization of irradiated diode using a novel edge-on electron beam technique

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The charge collection of two  $n^+p^+p^+$  pad diodes has been measured using a 5 GeV electron beam (at DESY) entering from the 150  $\mu m$  thick side edge side of diodes. Using the EUDAQ telescope it is possible to precisely reconstruct the beam position. The collected charge as a function of the beam position along the diode thickness is investigated.

This measurement technology is novel and comparable to the better-known edge-TCT. The alignment of the beam direction with respect to the diode surface was done online during the data taking. The diodes have an area of 25  $mm^2$  and a p-doping concentration of  $4 \times 10^{12} cm^{-3}$ . The measurements were performed at  $-20^\circ C$  for bias voltages up to  $V_{bias} = 800 V$ . One diode was irradiated with 23 MeV protons to a 1 MeV neutron equivalent fluence of  $\Phi_{eq} = 2 \times 10^{15} cm^{-2}$ . The second diode was not irradiated. For the non-irradiated diode, the charge profile is uniform as a function of the beam position. For the irradiated diode, the charge profile is non-uniform and the changes as the applied bias voltage.

This work presents the procedure of measurement and the online alignment along with the results obtained for two diodes.

## Detector Characterization and Simulation / 36

### Update on radiation damage investigation of epitaxial p-type silicon using Schottky and pn-junction diodes

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This project focuses on the investigation of trap energy levels introduced by radiation damage in epitaxial p-type silicon. Using 6-inch wafers of various boron doping concentrations ( $1e13$ ,  $1e14$ ,  $1e15$ ,  $1e16$ , and  $1e17 \text{ cm}^{-3}$ ) with a  $50 \text{ }\mu\text{m}$  epitaxial layer, multiple iterations of test structures consisting of Schottky and pn-junction diodes of different sizes and flavours are being fabricated at RAL and Carleton University.

Updates and details on the initial fabrication phase of devices on high resistivity wafers will be given. IV and CV scans of fabricated test structures have been performed and cross-checked between institutes, the results of which will be presented.

In collaboration with Semetrol LLC (USA) and the National Institute of Material Physics, Bucharest-Magurele, Romania, samples of both Schottky and pn-junction diodes have been further investigated using Deep-Level Transient Spectroscopy (DLTS) and Thermal Admittance Spectroscopy (TAS) to characterise trap energy levels in unirradiated devices.

The findings as well as plans for measurements of samples irradiated at the University of Birmingham and the Jožef Stefan Institute, Ljubljana, will be discussed.

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## Inter-pixel resistance measurements of irradiated pixel sensors with different isolation structures

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So-called “passive CMOS” pixel and strip sensors using commercial CMOS chip fabrication lines have become an interesting alternative to standard planar sensors. An important question is how the resistance between electrodes changes as a function of irradiation fluence for various implant geometry. We present preliminary results on the measurements of the inter-pixel resistance of passive CMOS sensor test-structures fabricated in the LFoundry 150 nm CMOS technology. The inter-pixel resistance of two types of test-structures, namely with and without equipping p-stop isolation between pixel implants, were evaluated by fitting the current-voltage behavior between a single pixel and the surrounding pixels. Unirradiated samples of both types deliver a resistance of  $\sim 10^{14} \Omega$ . Results from the samples after 14 MeV proton irradiation ( $5 \times 10^{14} \text{ neq cm}^{-2} - 1 \times 10^{16} \text{ neq cm}^{-2}$ ) reveal a drop of the resistance by approximately 3 orders of magnitude for the structures with p-stop and approximately 6 orders of magnitude for the ones without p-stop. From the data, no clear dependence of inter-pixel resistance on the proton irradiation fluence is observed.

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## Discussion: Defect and Material Characterization

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**Detector Characterization and Simulation / 39**

**Discussion: Detector Characterization and Simulation**

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**RD50 Beta source measurement systems (Friday) / 40**

**Comprehensive mip particle measurement and analyses system**

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**RD50 Beta source measurement systems (Friday) / 41**

**Beta setup in Zurich**

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**RD50 Beta source measurement systems (Friday) / 42**

**Discussion on Beta Setup**

**RD50 Beta source measurement systems (Friday) / 43**

**Coffee Break**

**LGADs / 44**

**Efficiency estimation on irradiated LGAD with respect to sensor stability**

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## Characterization of CMS-ETL HPK2 LGAD samples before irradiation

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## Preliminary results from mortality studies conducted on the LGADs using the ELI fs-laser beam

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We report on the first results of a mortality campaign on the Low Gain Avalanche Detectors (LGAD) produced by Hamamatsu (HPK) as prototypes for the High-Granularity Timing Detector (HGTD) in ATLAS. The study was conducted at the ELI Beamlines site during the ELI RD50 campaign as part of the ELI User Experiment that has been recently selected from the ELI User Call proposals. The HPK-P2 (WF25) sensors from the most recent run production were irradiated with neutrons in the JSI research reactor of TRIGA type in Ljubljana on the four fluences, (4, 8, 15, 25) x 10<sup>14</sup> neq cm<sup>-2</sup>, and subjected upon the carefully designed fs-laser based mortality study. The research strategies and applied methodology will be explained, and the results discussed. The preliminary results will be opened to conversation and feedback from the RD50 collaboration. The plans will be discussed too.

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## Discussion on LGADs

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## Discussion: CMOS sensors

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Transient Current Techniques (Thursday) / 49

## An update report on the upgrade of the TCT - TPA/SPA experimental station at the ELI Beamlines facility

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The already approved concepts of TCT-TPA and TCT-SPA (both developed within the RD50 Collaboration) have been brought by the RD50 Montenegro team to the pan-European Research Infrastructure and laser facility ELI Beamlines in March 2020. RD50 Montenegro team partnered with RD50 teams from Slovenia, Italy, and the Czech Republic. The idea was to build an additional research TCT infrastructure for RD50 and a powerful and comprehensive research tool for wider community of users. The uniqueness will be the opportunity to use both, TCT-SPA and TCT-TPA techniques, with the possibility for the wavelength, power, and repetition of the fs- laser beam to be varied and tuned. Beside the TCT technique, a new research line such as the mortality study with high pulses is under development and the protocol may be standardized in the future. By exposing technology to a field that it has not been previously used for, new use cases for the technology may potentially emerge.

Within the ELI Beamlines department for Structural Dynamics the Ultrafast spectroscopy group possesses unique know-how and expertise, as well as cutting-edge laser technologies that are continuously being developed and refined. To the project they contribute state-of-the-art knowledge and technology transfer related to ultra-short pulse lasers, advanced spectroscopy methods and instrumentation. Experimental time at the ELI Beamlines facility is provided as part of the normal user operations (within the framework of the ELI access policies) and as part of in-house science and development projects. The know-how and the expertise potential of ELI is enhanced locally by the logistic help of the RD50 Czech collaborators. The sensors and readout boards, as well as expertise support are provided by INFN and JSI.

In June 2020, the first initial steps and the jitter study on LGAD using the fs- laser beam have been shown on the 36th RD50 Workshop. In the meantime, the significant investment in the experimental station was done by ELI RP4: Applications in Molecular, Bio medical and Materials Science. An access to ELI through an application by Montenegro team to ELI Open User Call was gained in September and after the application by Montenegro Rd50 team was selected Eli gave priority to the applied project. In this presentation we will give an update report on the upgraded TCT-TPA/SPA set up and discuss the plans towards future upgrades.

**Transient Current Techniques (Thursday) / 50****Discussion on TCT/IBIC techniques****Detector Characterization and Simulation / 51****Measurements of Sensor Radiation Damage in the ATLAS Inner Detector using Leakage Currents**

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Non-ionizing energy loss causes bulk damage to the silicon sensors of the ATLAS pixel and strip detectors. This damage has important implications for data-taking operations, charged-particle track reconstruction, detector simulations, and physics analysis. This talk presents simulations and measurements of the leakage current for the ATLAS pixel detector as a function of location in the detector and time, using data collected in Run 1 (2010-2012) and Run 2 (2015-2018) of the Large Hadron Collider. The extracted fluence shows a much stronger  $|z|$ -dependence in the innermost layers compared to calculations. Furthermore, the overall fluence is significantly higher on the second innermost layer with an increasing agreement with calculations at higher radii. These measurements are an important validation of the simulation models and can be used in part to justify safety factors for future detector designs and interventions.

**Transient Current Techniques (Thursday) / 52****The first TPA signal in LGAD (HPK-P2/HGTD and FBK-W1/UFSD) and PIN using the ELI fs-laser**

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The first TPA signal in LGAD at the TPA/SPA experimental research station, that is under development at the premises of the research infrastructure and laser facility ELI Beamlines, is presented. The RD50 campaign at ELI's site for the ELI fs- beam profile study and TPA signature was conducted in Oct/Nov 2020 and performed under the ELI User Call Framework after an application by Montenegro team was submitted to the ELI User Call on the behalf of the RD50 Collaboration and accepted as the user experiment with priority. The study was performed on LGADs (HPK-P2 (HGTD):WF25, FBK (UFSD):W1) and their reference PIN sensors. Active thickness of INFN LGAD is 55  $\mu\text{m}$  and support wafer is 570  $\mu\text{m}$ , while active thickness of HPK-P2 is 50  $\mu\text{m}$  and support wafer is 200  $\mu\text{m}$ . The TPA signal is obtained by focusing fs-1550 nm beam by X100 NIR APO objective. The sensor samples

were illuminated in the centre of PAD. The TPA control pots, the spatial beam profile characterisation and sensor (LGAD& PIN) characterisation (gain layer depletion and full depletion voltage) will be presented. This program will continue at ELI in future.

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### **Proposal: Passive CMOS submission for sensors and test structures**

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