Last (43rd) RD50 Workshop on Radiation Hard Semiconductor Devices for Very High Luminosity Colliders (CERN)

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Book of Abstracts

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SiC / 63

Thermal Annealing of Electron, Neutron and Proton Irradiation Effects on SiC Radiation Detectors

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Silicon carbide (SiC) is a wide bandgap semiconductor with physical properties that make it especially appropriate for radiation monitoring in radiation-harsh environments and for elevated temperature operation. In this work, the radiation effects in electron, neutron and proton irradiated 4H-SiC pn junction diodes have been investigated by means of electrical characterization in both, reverse and forward polarizations, including current-voltage characteristics measured in the temperature range from -50℃ to +200℃. It is found that the observed radiation-induced conduction resistance is exponentially dependent with the measuring temperature. The generation of acceptor-like defects is thought to be responsible for the resistivity increase of the material, eventually leading to the formation of a semi-insulating layer, with loss of diode rectification character.
The stability of the radiation-induced effects has been evaluated by applying series of thermal treatments up to 400℃. Interestingly for applications, partial recovery of diode rectification functionality is observed for electron irradiated devices, with a diode conduction recovery of more than four orders of magnitude. Furthermore, partial recovery of detectors charge collection efficiency (CCE) in alpha particle detection is registered on all cases, electron, neutron or proton irradiated devices, once subjected to the applied thermal treatments.
Additionally, it is observed that the limited conduction registered under forward bias for highly irradiated SiC diodes actually allows their application as radiation detectors when operated in forward polarization. Although some lower CCE is found for SiC detectors under forward bias, better energy resolution is obtained under this operation regime, particularly at low absolute bias voltages. It is thought that filled radiation-induced traps under forward bias condition decrease charge trapping of electron-hole pairs generated upon exposure to an alpha particles source.
Briefing, some superior characteristics of SiC devices, such as those involving operation at high temperature values, may enable their use beyond the intrinsic limitations of silicon devices. Furthermore, they may help simplify some current radiation detectors experiments implemented with silicon devices, in which cooling is needed to keep functional operation after high irradiation fluences or exposure to visible light must be prevented.

SiC / 64

Four-quadrant Si and SiC Photodiodes for Beam Position and Monitor Applications

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Single and four-quadrant (4Q) photodiodes are very common beam intensity and position diagnostic devices for hard X-ray synchrotron beamlines, and they are also of interest for real time monitoring and dosimetry in particle therapy medical applications. Ultrathin Si devices are advantageous in terms of cost and sensing area compared to diamond standard. X-ray beam position monitors, are to be thinner than 10 µm when made of silicon to achieve X-ray transmission higher than 90% for photon energies above 10 keV. Owing to their lower dark current, lower susceptibility to temperature and visible light conditions, and potential radiation hardness, there is also interest in silicon carbide (SiC) for some of these applications.
In this work, an extensive study involving physical and electrical characterization, as well as radiation effects, is carried out on single and 4Q photodiodes fabricated on ultrathin (10 µm, 5 µm and 3 µm) Si films from Silicon-on-Insulator (SOI) substrates, as well as on 1-2 µm-thick Si membranes obtained by chemical back-etching of high resistivity (HR) Float Zone (FZ) bulk Si substrates. Furthermore, 4Q devices fabricated on 5 µm-thick semi-insulating SiC epitaxial layers on bulk 4H-SiC substrates are also studied. Finally, the performance of the devices as radiation detectors is investigated by means of laser beam scanning transient current technique (TCT) and X-ray test beam at XALOC beamline of ALBA Synchrotron in Cerdanyola del Vallès (Barcelona).

Radiation damage general / 65

A lightweight algorithm to model Radiation Damage Effects in Monte Carlo Events for High-Luminosity LHC experiments

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Radiation damage significantly impacts the performance of silicon tracking detectors in Large Hadron Collider (LHC) experiments such as ATLAS and CMS, with signal reduction being the most critical effect. While adjusting sensor bias voltage and detection thresholds can help mitigate these effects, generating simulated data that accurately mirrors the performance evolution with the accumulation of luminosity, hence fluence, is crucial.

The ATLAS and CMS collaborations have developed and implemented algorithms to correct simulated Monte Carlo (MC) events for radiation damage effects, achieving impressive agreement between collision data and simulated events.
In preparation for the high-luminosity phase (HL-LHC), the demand for a faster ATLAS MC production algorithm becomes imperative due to escalating collision rates, events, tracks, and hits, imposing strict constraints on available computing resources. This talk outlines the philosophy behind the new algorithm, its implementation strategy, and the essential components involved. The presentation also includes results from closure tests.

LGAD / 66

MAPS devices with internal gain for timing applications: state of the art and future developments

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In this contribution we present an update about the development of Monolithic Active Pixel Sensors (MAPS) at INFN in the framework of the ARCADIA project. Thanks to the first two engineering runs, manufactured in 2020 and 2021 with a 110 nm CMOS process, the device concept has been well assessed and tested, both through extensive laboratory characterizations and the comparison between experimental measurements and numerical simulations. In view of timing applications, a multiplication layer has been added to the design of our third run, delivered in early 2023. Here we present the first electrical and dynamic characterization campaigns performed on the passive test structures, which proved that the sensors (*i*) can be depleted and (*ii*) properly operate in the charge multiplication regime. Finally, also a few key aspects of the sensor optimization in perspective of the incoming productions will be considered through the discussion of combined TCAD-Montecarlo numerical analyses.

LGAD / 67

18 MeV Proton Irradiation of Low Gain Avalanche Detectors

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The LGAD technology is of great interest for high-energy physics (HEPs) as a 4-D tracking device and has been qualified for use in the timing detectors of the CMS and ATLAS experiments for the high luminosity upgrade of the LHC (HL-LHC). During the operation in strong radiation fields, the radiation damage progressively leads to performance degradation of LGADs, which therefore need a more profound theoretical understanding and further design optimizations.
The following study presents the results of 18 MeV proton irradiation conducted at the cyclotron of the Bern University Hospital. The investigation of radiation-induced degradation produced by low energy protons is of special interest since it demonstrates the limits of the Non-Ionizing Energy Loss (NIEL) scaling. LGADs produced by Hamamatsu Photonics (HPK) as well as devices with differently carbonated gain layers produced by Centro Nacional de Microelectrónica (CNM)-IMB are included in the study.
Electrical characterization, radiation-induced acceptor removal and gain reduction as well as timing measurements of a a selected subset of samples will be presented. In addition, an outlook with comparison to similar devices irradiated at CERN with 23 GeV protons will be discussed.

Radiation damage general / 68

Hunting for Sharks with TCAD (Simulation of TPA-TCT measurements on LGAD Gain Suppression)

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We present TCAD simulations on the gain suppression in LGAD sensors as measured with TPA-TCT.

Radiation damage general / 69

Two Photon Absorption –Transient Current Technique: TCAD Simulation of a PIN & Influence of Radiation Damage on the TPA-TCT

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The Two Photon Absorption –Transient Current Technique (TPA-TCT) is a tool for the characterisation of particle detectors. Contrary to present state of the art TCT, TPA-TCT enables characterisation measurements with three dimensional spatial resolution. A tabletop setup for the investigation of silicon based detectors was commissioned at CERN to pioneer the technique. A 430 fs pulse fiber laser with a wavelength of 1550 nm is used, to generate excess charge by Two Photon Absorption in silicon. The laser light is focused so that excess charge is generated in a small volume (approximately 1µm × 1µm × 20µm) around the focal point. This talk presents the TPA-TCT setup at CERN SSD and shows recent investigation of radiation damage in 150 µm thick planar sensors fabricated by CIS. The beam depletion due to linear absorption and the influence on the refractive index are investigated. Furthermore, TCAD simulation are used to study TPA-TCT measurements in a PIN diode.

SiC / 70

Defect Spectroscopy on Proton Irradiated 4H Silicon Carbide Devices

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New radiation hard materials are investigated for future high energy particle physics experiments. Silicon carbide is one of the materials currently considered, due to it's interesting properties, e.g. a larger bandgap and a higher breakdown field compared to silicon. The larger bandgap leads to low leakage currents even after high fluences of irradiation, allowing for non-cooled operation.
This study focuses on investigating intrinsic and radiation-induced defects in n-type 4H-SiC devices by subjecting them to 23 GeV protons at various fluences. The sensors studied were manufactured by IMB-CNM, with a 5 µm or 50 µm thick epitaxial layer on top of a 350 µm thick 4H-SiC substrate. The samples were irradiated at IRRAD to 1E+11, 1E+12, 1E+13, 1E+14 and 1E+15 p/cm^2. TSC and DLTS measurements were performed in the temperature range of 20 K to 350 K. The presented results include IV and CV measurements taken before and after irradiation, as well as the defect parameters obtained from TSC and DLTS measurements.

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Characterisation of the FBK EXFLU1 thin sensors with gain in a high fluence environment

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The EXFLU1 batch of LGAD sensors on substrates of thickness between 15 and 45 μm were exposed to various radiation grades between 1×10^{-14} and 5×10^{-15} $\mathrm{n_{eq}cm^{-2}}$ using the neutron reactor at JSI. The sensor designs themselves, manufactured at FBK, are optimised to preserve characteristics at high fluences. The latest studies of the effects of radiation have been performed, with the impact on thin sensors of varying design considered for their characterisation pre- and post-irradiation, and are presented.

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Spatial resolution of RSD2 array of pixels measured at a beamtest

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This contribution presents the first study of the spatial resolution of an array of RSD2 450 um pitch pixels. The results have been obtained in the latest test beam at the DESY 6 GeV/c electron line. The readout board is based on the FAST2 ASIC, a 16-channel fast amplifier chip developed in Torino. The results demonstrate that resistive readout yields a spatial resolution smaller than 5% of the pixel size and a 100% fill factor over an area covered by multiple pixels.

Monolithic devices / 73

Time resolution of the RD50 HV CMOS MPW2

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The CERN RD50 collaboration develops depleted monolithic active pixel CMOS sensors for future colliders with the aim of high radiation tolerance, good time resolution, and high granularity pixel detectors. We will show that one prototype in 150 nm high voltage CMOS from LFoundry, the RD50-MPW2, featuring 64 active pixels of 60 μm pitch has a time resolution of 220 ps for an injected charge of 12 ke-.

Charge in the sensor was generated with laser pulses from the backside (back-TCT), where for each pixel the time of arrival and time over threshold were measured with a fast oscilloscope to evaluate the time resolution of the entire pixel circuit including in-pixel amplification and discrimination. This is compared to the timing performance of the analog circuitry through charge injection. This is the first time this measurement was performed for the entire pixel matrix. With a first two-dimensional in-pixel measurement in the pixel matrix plane, we give insight into the electric field in the sensor.

LGAD / 74

USTC-IME LGAD pre-production for HGTD

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The Low Gain Avalanche Detector (LGAD) technology is proposed for the ATLAS High Granularity Timing Detector (HGTD) towards the High-Luminosity Large Hadron Collider (HL-LHC). USTC-IME LGADs are designed by the University of Science and Technology of China (USTC) and fabricated by the Institute of Microelectronics of Chinese Academy of Science (IME, CAS). The prototypes of the USTC-ME LGAD are shown to meet the specifications of the HGTD project. The

pre-production was launched in February 2023. The measurements of early series of this run will be presented.

LGAD / 75

Investigation of low gain avalanche detectors exposed to proton fluences beyond 1015 neq/cm2

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The High Luminosity Large Hadron Collider upgrade will increase the luminosity of the LHC by a factor of 10. Low gain avalanche detectors (LGADs) promise excellent timing resolution, which can mitigate the pileup associated with high luminosity. The most highly irradiated LGADs will be subject to 2.5 × 10ˆ15neq /cm2 of hadron fluence during Run 4; their timing performance must tolerate this. Hamamatsu Photonics K.K. (HPK) and Fondazione Bruno Kessler (FBK) LGADs have been irradiated with 400 and 500 MeV protons respectively up to the Run 4 hadron equivalent fluence. Measurements of the irradiated LGADs' leakage current, capacitance, charge collection, and timing performance are presented. A timing resolution better than 70 ps is observed for all fluences. Charge collection is below 10 fC for the HPK sensors after (0.9±0.5)·10ˆ15neq/cm2, and for the FBK sensors after (1.7±1.0)·10ˆ15neq/cm2 for all operating voltages below 600 V. 2x2 arrays of both the FBK and HPK LGADs were produced to study the inter-pad characteristics. The inter-pad resistance for the HPK LGADs stayed slightly above 10 MΩ for 5·10ˆ14neq /cm2, and the inter-pad resistance of the FBK LGADs fell slightly below 1 MΩ after 10ˆ15neq/cm2. Observations of the punch-through voltage and inter-pad isolation for fast signals are reported.

LGAD / 76

Radiation hardness studies of Half-Activated-Boron LGADs

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HPK has produced LGADs where boron was not fully activated after the implantation. This was an attempt to reduce acceptor removal in the gain layer by formation of defect complexes of non-activated interstitial boron atoms with radiation induced interstitial silicon atoms and other impurities. In this was the replacement of activated boron by interstitial silicon in the lattice position would be mitigated. A set of such sensors with different fraction of activated boron was irradiated by reactor neutrons and studied with CV-IV and charge collection/timing measurements.

Facilities / 77

Proton Hardness Factor at the Bonn Cyclotron Irradiation Site

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The proton irradiation site at the Bonn Isochronous Cyclotron is in operation since 2021.
The accelerator typically provides a 14 MeV (˜12.5 MeV on DUT) proton beam with a few mm width and currents of 1 μA and to the site.
DUTs are irradiated in a cooling box at < -20 ℃, mounted on a XY-motorstage, which is moved row-wise through the beam on a grid-like pattern.
Dedicated diagnostics enable online beam monitoring with relative uncertainties of a few $\%$, allowing beam-driven irradiations,
resulting in highly-precise and uniform fluence distributions.
Cross-check measurements of the beam-based fluence determination method used in Bonn are compared to the typical (metallic) foil activation,
yielding consistent results while the beam-based method has an uncertainty of a few $\%$.
Recent measurements of the proton hardness factor, using 150 μm thin, passive LFoundry sensors, yield a hardness factor of $\kappa = 3.74 \pm 0.12$,
agreeing with the previous value with significantly lower uncertainty. Implications of the low-energy protons on the measured hardness factor and
limitations for DUT irradiations in Bonn are discussed.

Radiation damage general / 78

Effect of annealing on charge collection with n-on p type silicon strip detectors irradiated with 24 GeV/c protons

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Extensive studies of effects of annealing at 60C on charge collection efficiency were made with miniature n in p type silicon strip detectors during development and production of sensors for ATLAS ITk strip detector. Measurements were made with Alibava system with electrons from Sr90 source with detectors irradiated with reactor neutrons and low energy protons. At not too high bias voltages typical annealing behavior was measured: beneficial effects of short term annealing was followed by a drop of charge collection efficiency at longer annealing times.
Recent measurements with detectors irradiated with 24 GeV protons in CERN IRRAD facility showed somewhat different behavior in which a drop of collected charge was observed after short term annealing. In this contribution first results of studies of this effect with charge collection and E-TCT measurements will be presented.

SiC / 79

Charge Collection Study of SiC-LGAD - SICAR1

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Silicon carbide (SiC) has potential to be used for fast particle detection in radiation environment because of its wider band gap and high electron mobility. To improve the SiC PIN detection for small signal generated by minimum ionizing particles (MIPs), a 4H-SiC Low Gain Avalanche Diode has been proposed –SICAR. The first version (SICAR1) has been fabricated with initial electrical test shows that the dark current is around 5.6uA under full depletion voltage at 350V. The charge collection efficiency is up to 98%@ 150V. These findings offer promising possibilities for fast particle detection in future radiation environments.

LGAD / 80

Single Event Burnout in thin silicon sensors

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The Single Event Burnout (SEB) was observed for the first time in 50µm-thick LGAD, and studied by ATLAS and CMS collaborations during the R&D activity on LGAD sensors for their respective timing detector.
The experimental results observed on particle beam showed that, in 50µm-thick silicon sensors, the SEB occurs at bulk electric fields of 11.5-12 V/µm.
In this contribution, we report SEB results recently obtained on silicon sensors with active thickness between 15µm and 55µm. Beam tests at DESY and CERN facilities, performed during the last year, showed a relationship between the active thickness of the sensor and the burnout electric field.

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Radiation resistance of Carbon-shield LGADs and comparison with standard carbonated LGADs

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LGAD sensors with a carbon-enriched multiplication layer are the state-of-the-art in terms of radiation resistance, concerning this specific sensor technology. The presence of carbon allows LGADs to operate, while maintaining unchanged temporal resolution, even after irradiation fluences of 1-2x10^15 neq/cm^2.

Carbonated LGADs have been successfully produced by FBK, CNM and IHEP-IEM. FBK, in EXFLU1 production, has recently produced LGADs with a carbon shield implanted below the gain layer, with the aim to protect the gain layer from bulk defect migration and to further improving their radiation resistance.

In this contribution, the first results obtained on Irradiated Carbon-shield LGADs are presented and compared with those of standard Carbonated LGADs.

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Measurements on last IMB-CNM LGADs production

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In this contribution we will present measurements on LGADs corresponding to our CNM's second production run based on 6-inch, 50μm active layer thick, Si-Si wafers (6LG2-v2 technology). The wafers were carbon enriched using five different implantation doses and one implantation energy. For the gain layer, samples were fabricated using a single boron implantation dose and energy. Measurements and analysis of the electrical characterization and radiation hardness were carried out on these LGADs.

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Sensor design, guard ring, breakdown

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Silicon pixel sensors manufactured using commercial CMOS processes are promising instruments for high-energy particle physics experiments due to their high yield and proven radiation hardness. As one of the essential factors for the operation of detectors, the breakdown performance of pixel sensors constitutes the upper limit of the operating voltage.

In the first part, we present a comparative study of six types of passive CMOS test structures fabricated on high-resistivity wafers, and each of them features a combination of different inter-pixel designs and sets of floating guard rings, which differ in the geometrical layout, implantation type, and overhang structure. The study based on the leakage current measurements of unirradiated samples and TCAD simulations was carried out to identify correlations between the guard ring designs and the breakdown voltages. This ultimately provide design features targeting higher breakdown voltages.

In the second part, we present the simulation study for improving the breakdown performance in the design of RD50-MPW4 monolithic CMOS detector prototype.

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Precision determination of the tracking resolution of beam telescopes

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Beam tests are the standard method for determining the position resolution of detectors. This requires the precise knowledge of the beam-position resolution at the detector to be tested. A method is proposed which achieves this. It uses a segmented silicon detector with normally incident beam. It is found that for normal incidence events with cluster-size 2 have a position accuracy well below 1 µm. The method is first demonstrated with simulated events, which are also used to investigate how to deal with cross-talk, electronics noise, energetic ⊠-electrons, and incident beams with a few degrees off the normal to the sensor plane. Finally, using CMS Phase-2 prototype pixel sensors before and after hadron irradiation, the accuracy of the beam tracks reconstructed by the EUDET beam telescopes of the DESYII test beam facility and extrapolated to the pixel sensor, is determined.

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Characterisation of the MC40 cyclotron irradiation line at the University of Birmingham

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The MC40 cyclotron at the University of Birmingham is routinely involved with proton irradiations for several detector R&D projects. For the majority of these irradiations, a 27 MeV proton beam is delivered at a current of 200 nA, being able to supply fluences of a few 10^{15} n_{eq}/cm^2 in one day. The proton energy at the target and the corresponding hardness factor have been previously determined to be 24 MeV and 2.2, respectively. Following several maintenance works, a revision of the MC40 R&D irradiation line is important to assess the consistency in the performance since the last evaluation.

The two major focuses of the ongoing characterisation of the cyclotron is the dosimetry and an updated measure of the hardness factor. The proton dosimetry is performed using nickel foil and the beam energy incident on the foil is an important parameter given the energy dependant cross-section. To estimate this, a Geant4 simulation of the cyclotron irradiation line was established with the ability to profile the beam energy as it traverses the setup. Beam profile simulations is compared to measurements at the facility with gafchromic film. The hardness factor is determined via measurements of the leakage current in post-irradiated silicon diode structures.

Aside from understanding recent performance, these tests of the cyclotron also serve to better understand a recurring feature in ATLAS inner tracker (ITk) strip sensor test chips irradiated using the cyclotron. Specifically, the interstrip resistance of the interdigitated structures has consistently fallen under the quality assurance specifications. An investigation has been performed with test chips irradiated to fluence points in the range 1 x 10^{14} n_{eq}/cm^2 to 2 x 10^{15} n_{eq}/cm^2 at beam energies of 27 MeV and 20 MeV. The difference in beam energies provides a different TID per unit of proton fluence and the overall ratio of ionising to non-ionising damage delivered to the samples should differ significantly. The measurements of these interdigitated structures allows the interplay between ionising and non-ionising damage to be investigated.

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Charge carrier mobility evaluation in Silicon Microstrips detectors exploiting photoconductivity phenomena

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Silicon Microstrips (STRIP) detectors were evaluated after 1MeV neutron irradiation in the fluence range from 1E+15 to 1E+17 /cm2. Photoconductivity spectral measurements were performed in range from 0.45 eV to 3.5 eV of excitation energy with different applied electric potential. The spectral shape variation with the applied electric potential raised the idea of the model with changing quantum efficiency and the presence of the another mobility layer inside the samples. This is the extended research of the samples previously characterized by magnetoresistivity (MR) technique. The proposed model complements and better explains the MR results.

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Beam test characterization of RD50-MPW3

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The RD50-MPW3 is a HV-CMOS sensor developed by the HV-CMOS working group manufactured in the LFoundry 150nm process.
In this talk, I will present the most recent testbeam results.
Following up on the results of the test beam in 2022 at the CERN-SPS facility, presented in earlier workshops, this talk focuses on the successful test beam campaign at DESY in Jul. 2023.
I will highlight the changes to the DAQ system, which led to improved results this year compared to earlier campaigns.
Furthermore, I will discuss the results gathered at the medical facility MedAustron in Austria.
At the end, an outlook to planned beam test campaigns in 2024 for the successor chip, the RD50-MPW4, will be presented.

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Electric field measument in LGAD

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We propose a novel methodology to measure the electric field of LGAD. This method introduces the estimation of the elongation of the carrier cluster caused by diffusion and the divergence of the electric field force during its drift along the detector. The maximum of time derivative tested from edge-TCT is extracted to quantify the dispersion of the light-induced carriers. Both RASER simulation and experimental results have shown that the diffusion profile method could be applied to certain edge-TCT facilities as an alternative of electric field measurement.

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The numerous configurations of „interstitial boron"and their involvement in ARP of LGADs

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Abstract: Defects in silicon are known to occur in numerous different configurations each exhibiting different properties e.g. related to the interaction with charge carriers. In this contribution recent results of density functional theory calculations of the so-called "boron interstitial (B_i)"defect in silicon are shown and compared to an already existing model of that defect. The "boron interstitial" defect means that a boron and a silicon atom share one lattice position. Configurations of that defect where the silicon interstitial atom is one or more lattice constants away from the boron atom are not considered. The acceptor removal phenomenon (ARP) which impacts low gain avalanche detectors (LGAD) is discussed on the basis of these recent results.

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Timing Characterization of LGADs for Space Based Applications

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In modern astroparticle physics experiments, it is crucial to feature a tracker and a calorimeter to measure and identify primary charged cosmic rays; at the same time, it is necessary to distinguish those from the back scattered particles entering the tracker from the calorimeter.Time-of-flight measurements are also used for particle identification. In recent years, Low Gain Avalanche Detectors (LGADs) have emerged as a technological solution for precise timing measurements in the tens of ps range for High Energy Physics and other applications. In this field, the typical LGAD channel size is O(1 mm2), whereas a silicon sensor for strip geometry in space application is 50-60 cm in length with 100-200 µm pitch, resulting in a channel area of about 1 cm2. This work presents the timing characterization of pad sensors with dimensions up to 1 cm× 1 cm (with and without gain) using a picosecond infrared laser. Different sensor thicknesses are characterized to reduce the effect of capacitance on the timing performances. In addition to that, several gain structures are compared to find the best performing gain layer.

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TCAD simulation of 4H silicon carbide LGADs

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Silicon carbide (SiC) has several advantageous material properties, making it an appealing detector material: its high charge carrier saturation velocity and breakdown voltage allow for an intrinsically higher time resolution than for silicon (Si). The larger bandgap suppresses dark current, even for highly irradiated material, reducing power consumption and thus omitting the need for cooling.
However, current limitations in the manufacturing of epitaxial layers of sufficiently high resistivity and thickness, as well as its large ionization energy compared to Si, mitigate the number of generated charge carriers and therefore reduce the signal output. The realization of a 4H-SiC low gain avalanche diode (LGAD), utilizing a controlled charge multiplication, could overcome this drawback while simultaneously boosting time resolution.

This talk presents our progress in simulating and designing such 4H-SiC LGADs. It will review SYNOPSYS-TCAD simulations of simplified LGAD structures to benchmark and characterize crucial design parameters and impact ionization models. In addition, a simplified analytical model to expedite the search for viable designs will be introduced.
New Alpha and UV-TCT measurements of neutron-irradiated planar 4H-SiC diodes that indicate signal-enhancing properties when operated in forward bias will be shown and possible origins of this behavior will be discussed.
Finally, a status report of the previously presented 4H-SiC wafer run in collaboration with CNM will be given.

Radiation damage general / 92

Test beam analysis of irradiated passive CMOS strip sensors

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A significant challenge in producing the larger structures typical for silicon strip sensors is the limited reticle size of the CMOS process. This problem can be solved through the so called stitching of the reticles.
The sensors that are the subject of this talk are passive CMOS strip sensors, containing three different strip variants, designed by the University of Bonn. They were produced by LFoundry in a 150 nm process on a 3-5 kΩ cm float zone wafer, with additional backside processing by IZM Berlin.
To examine the radiation hardness of the stitches, samples have been irradiated with reactor neutrons to various fluences up to $1 \cdot 10^{16}$ n_eq / cm². Possible effects of the stitching on spatial resolution, detection efficiency or charge collection efficiency and the general performance of the three designs have been studied in detail in several test beam campaigns at the DESY II test beam facility, where unirradiated as well as a number of irradiated CMOS strip sensors were thoroughly examined. In summary, we are able to demonstrate on a large number of samples that multiple stitching can be performed without any degradation of the sensor performance both before and after irradiation.

Monolithic devices / 93

Development and characterisation of depleted monolithic active pixel sensors (DMAPS) in 150 nm and 180 nm CMOS technology

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Monolithic active pixel sensors featuring depleted substrates (DMAPS) present a promising alternative for pixel tracker detectors operating in high-radiation and high-rate environments. The utilization of high-resistivity silicon substrates and high-voltage capabilities within commercial CMOS

technologies holds the potential to significantly enhance radiation tolerance with respect to MAPS. TJ-Monopix2 and LF-Monopix2 chips are the most recent large-scale prototype chips in their respective development line with a column-drain readout architecture.

Designed in 150 nm LFoundry technology, LF-Monopix2 uses a large charge collection electrode with pixel electronics embedded in it. Benefits of this design are short drift paths and a homogeneous electric field across the sensor that increase the radiation tolerance. Optimization of
the pixel layout minimizes potential coupling from the digital circuitry into the sensor node while reducing the pixel size to 50 x 150 um² compared to its predecessor.

TJ-Monopix2 is designed in 180 nm Tower Semiconductor technology. Featuring a small charge collection electrode design with separate readout electronics, the pixel pitch of this sensor could be reduced to 33 x 33 um². A small detector capacitance allows for a large signal-to-noise ratio while an additional n-type layer across the pixel ensures full depletion of the sensitive volume.

In this talk, an overview of both DMAPS developments including results from tests in laboratory and using a minimum ionising particle beam is given. For TJ-Monopix2, timing studies and charge collection measurements are highlighted. For LF-Monopix2, the performance after irradiation to fluences of up to 2e15 neq/cm² is shown.

LGAD / 94

2D pixelated BNL AC-LGADs: From laser TCT to Test Beam characterization

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AC-LGAD (AC coupled Low-Gain Avalanche Detector) sensors have emerged as a highly promising technology for precision particle detection in collider experiments. These sensors offer exceptional capabilities, delivering remarkable time and spatial resolutions on the order of tens of micrometers and picoseconds, all while achieving a 100% fill factor. We present results obtained with AC-LGAD sensors developed by Brookhaven National Laboratory (BNL), showcasing their performance through measurements using infrared laser TCT and high energy particles at the CERN SPS test beam. We analyze and compare different machine learning algorithms, as well as the charge imbalance method, for the hit position reconstruction. In this study, square pixel sensor arrays with 500 μm pitch are presented, paving the way to study smaller pitch sensors in the near future for increased spatial resolution.

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First characterization of TI-LGAD technology in a test beam setup

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The Trench Isolated LGAD (TI-LGAD) technology offers a promising solution to LGAD's fill factor limitations, enabling small segmentation of fast timing silicon sensors for collider experiments. Previous laboratory studies with this technology have already shown similar timing performance and radiation hardness as for the LGAD technology, with a drastic improvement of the fill factor (reduction of inter-pixel no-gain distance). In this presentation we show the first results obtained with the TI-LGAD technology in a test beam setup with high energy particles. The evaluation of the inter-pixel distance in this regime will be presented, as well as the detection efficiency and time resolution. The new results are compared with previous laboratory measurements.

Radiation damage general / 96

Radiation damage investigation of epitaxial p-type silicon for particle detectors 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 cm−3) with a 50 µm 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.

In this talk, updates on the diode fabrication and electrical measurements of the structures will be given. The focus of this talk will be on the characterisation of trap parameters obtained from Deep-Level Transient Spectroscopy (DLTS) and supplemented by Thermally Stimulated Current (TSC) measurements. Spectra for unirradiated and neutron-irradiated diode samples will be shown and their details collected from Arrhenius analyses will be listed. Lastly, DLTS and Charge Collection Efficiency (CCE) measurements conducted on samples before and after neutron irradiation will be evaluated and their results compared.

Radiation damage general / 97

Radiation tolerance of 8-inch silicon sensors for CMS HGCAL

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The High-Luminosity LHC will challenge the detectors with a nearly 10-fold increase in integrated luminosity compared to the previous LHC runs combined, thus the CMS detector will be upgraded to face the higher levels of radiation and the larger amounts of data collected. The High-Granularity Calorimeter (HGCAL) will replace the current endcap calorimeters of the CMS detector. It will facilitate the use of particle-flow calorimetry with its unprecedented transverse and longitudinal readout/trigger segmentation, with more than 6M readout channels. The electromagnetic section as well as the high-radiation regions of the hadronic section of the HGCAL (fluences above 10ˆ14 neq/cm2) will be equipped with silicon pad sensors, covering a total area of 620 m2. Fluences up to 10ˆ16 neq/cm2 and doses up to 1.5 MGy are expected. The sensors are processed on novel 8-inch p-type wafers with an active thickness of 300 µm, 200 µm and 120 µm and cut into hexagonal shapes for optimal use of the wafer area and tiling. Each sensor contains several hundred individually read out cells of two sizes (around 0.5 cm2 or 1.2 cm2). With each main sensor several small sized test structures are hosted on the wafers, used for quality assurance and radiation hardness tests. In order to investigate the radiation-induced bulk damage, the main sensors and single diodes from the test structures have been irradiated with neutrons at RINSC (Rhode Island Nuclear Science Centre, US) and JSI (Jožef Stefan Institute, Ljubljana, Slovenia) to fluences between 6.5·10ˆ14 neq/cm2 and 1.5·10ˆ16 neq/cm2. In this talk, the electrical characterisation and charge collection measurements of the irradiated silicon sensors will be presented. This includes first measurements with so-called partial sensors cut from multi-geometry wafers with internal dicing lines on the HV potential left in the active sensor area, the isothermal annealing behaviour of the bulk material and the CV-frequency and measurement-method dependence present in depletion voltage measurements in irradiated sensors. The observed behaviour of the electrical properties and charge collection efficiency is in agreement with the HGCAL specifications. The results are being used to optimize the HGCAL layout and to establish an operating and annealing scenario for HGCAL.

LGAD / 98

Impact of environmental stresses on Low Gain Avalanche Diodes

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Devices with internal gain, such as Low Gain Avalanche Diodes (LGADs) can have O(30) ps timing resolution. They play a crucial role in High Energy Physics (HEP) experiments. Similarly, resistive

silicon devices, such as AC-coupled LGADs (AC-LGADs) sensors, achieve a fine spatial resolution while maintaining the LGAD's timing resolution. Devices of both types, with varying gain-layer width and doping characteristics, are produced at Brookhaven National Laboratory (BNL). However, their performance is strongly affected by environmental factors such as temperature, humidity, rapid changes in bias voltage settings, and storage conditions. For example, phonon scattering, which is strongly affected by temperature, plays a central role in avalanche multiplication at higher temperatures, where phonon scattering becomes prominent due to the temperature dependence of the phonon population. As such, the operating conditions, such as noise, gain and breakdown voltage, depend on these variables. In view of applications beyond the controlled environment of HEP experiments, these devices are stress-tested against varying environmental conditions. For example, the challenging operating conditions in outer space impose constraints on the operation performance, against temperature fluctuations. We study how different devices with different depletion layers and implantation characteristics respond to these changing climatic conditions. A systematic evaluation of the response of LGAD sensors as a function of these environmental parameters is therefore of essential importance when accounting for any application. This allows us to map the device performance back to the sensor's characteristics. In turn, this will allow the tailored fabrication of devices resilient to harsh conditions at no cost to the operational performance in controlled environments.

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Revealing distinct signals in inter-pad region of Ti-LGAD

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In this presentation, we continue our investigation of charge-space profiles in segmented LGADs with a focus on double-trenched LGADs (2Tr LGAD). We compare the signal behavior of the Ti-LGAD sample with double trenches in the interpad (IP) region to that of LGADs with 2p-stops and bias rings used as isolation structures (both types produced in the Ti-LGAD RD50 batch with difference that LGADs with 2p-stops and bias ring was used as reference prototype and only produced for comparison reasons).

Our experimental results revealed two distinct types of transient current signals in IP region of TI-LGAD: "normal" or "expected" signals resembling the pad signal, and "strong" signals with broadened waveforms and higher amplitudes. We analyze the occurrence of these signals in 2Tr LGADs through extensive acquisition.

We also identify "ghost" signals that randomly appear without laser illumination. The talk explores the dependence of signal characteristics on bias voltage and laser power at different temperatures and discusses potential explanations for the observed behavior.

Only results from study on double trenched prototype from wafer W11 are presented.

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Hunting for the ghost signals in Ti-LGADs

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We present the continuation of our research on IP signals in Ti-LGAD (Wafer 11). Our experimental examination on Ti-LGAD, from the wafer 11, revealed exceptionally high signals within the IP region, which was significantly higher than the signals measured in previously conducted experiments [1] on the segmented LGAD sample with two p-stops and a bias ring in the center of the IP region with the IPD=49 microns (from the same wafer: W11).

This time we show results from our extended research on larger pool of Ti-LGAD prototypes: from wafers W16 and W7. All sensors have 2 trenches in IP region, but the depths of trenches are different.

Tree types of signal in IP region: "expected" and "strong", both induced by laser, and a few types of ghosts (wafer type correlated) are discussed. Special attention is given to the study of the rate of ghosts occurrences in all three samples from three different wafers. We studied also the occurrence rate ratio between the "strong" IP and the "normal" IP signal in pulse to pulse analysis in 10 000 single shot run experiment. Results are discussed.

[1] Gordana Laštovička-Medin, Mateusz Rebarz, Jovana Doknic, Ivona Bozovic, Gregor Kramberger, Tomáš Laštovička, and Jakob Andreasson. "Exploring the Interpad Gap Region in Ultra-Fast Silicon Detectors: Insights into Isolation Structure and Electric Field Effects on Charge Multiplication." Sensors 23, no. 15 (2023): 6746.

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Test beam results from DMAPS produced in LF110 and TSI 180

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The PSI HEP group has designed and produced test devices of DMAPS in two different technologies: Motic in LF 110 and TSI-R4S in TSI 180. The talk reports on the status of these projects including results from test beam campaigns at DESY.

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Time resolution and field uniformity study of single cell 3D pixel structures neutron and proton irradiated up to 1e17 n_{eq}/cm^{2} at 120 GeV SPS beams

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The proven radiation hardness of silicon 3D devices up to fluences of $1 \times 10^{17}\, n_{eq}/cm^2$ makes them an excellent choice for next generation trackers, providing $< 10\, \mu m$ position resolution at a high multiplicity environment. The anticipated pile-up increase at HL-LHC conditions and beyond, requires the addition of < 50 ps per hit timing information to successfully resolve displaced and primary vertices. In this study, the timing performance, uniformity, and efficiency of neutron and proton irradiated single pixel 3D devices is investigated. Three different geometrical implementations are evaluated for fluences up to $1 \times 10^{17}\, n_{eq}/cm^2$ at 120 GeV SPS pion beams. The question of electronic bandwidth is also addressed, with respect to achievable time resolution, efficiency and collected charge. In such a tri-dimensional phase-space, an appropriate operating point is selected depending on the application requirements. A MIMOSA26 type telescope is used to provide detailed tracking information with a ˜$5\, \mu m$ position resolution. Productions with single- and double-sided processes, yielding active thickness of 130 and 230 μm respectively, are studied, with pixel sizes that vary from $55 \times 55\, \mu m^2$ to $25 \times 100\, \mu m^2$. A comparison of field uniformity with respect to electrode geometry is presented, as well as a time resolution study for incidence angles up to 12°.

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TCAD simulations of the ATLAS ITk-Strip sensors for the HL-LHC

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The ATLAS ITk Strip detector is a planned tracker upgrade for the High-Luminosity LHC which utilizes n^+-in-p silicon sensors fabricated by Hamamatsu Photonics with 300 μm signal-generation thickness and approximately 75 μm strip pitch. Measurements and simulations are presented for silicon strip sensors and test devices, including after irradiation to fluences up to $1.4*10^{15}$ 1-MeV neq/cm^2. Two-dimensional sensor simulations are developed with Sentaurus TCAD, informed using detailed optical and electrical measurements, and interfaced to AllPix^2 for detector simulations. Charge traps from the manufacturing process and from radiation-induced defects are studied, both through a parameterization of traps in the surface and bulk and by the direct measurement of traps using deep-level transient spectroscopy.

SiC / 104

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History of the RD50 collaboration and Main Achievements

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RD50 from Experiment perspective

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RD50 collaboration - Beyond scientific achievments

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Radiation Tolerance Study of CNM-IMB Run15973

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We present the results of the Radiation Tolerance Study (Electrical and Radioactive Source characterization) performed at the IFCA on Carbonated-Enriched Gain-Layer small devices (single diode) from the Run #15973 production of CNM-IMB.

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Synchrotron light source X-ray detection with Low-Gain Avalanche Diodes

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Low Gain Avalanche Diodes (LGADs) represent the state-of-art technology in fast timing measurement for charged minimum ionizing particles (MIPs). LGADs are initially developed for future Timing Detectors in the ATLAS and CMS experiments at the High-Luminosity LHC. One of LGADs' key features is the gradient-doped multiplication layer providing intrinsic gain. The intrinsic gain enables the detection of low energy X-rays with good energy resolution and precise timing capabilities. We extensively tested LGADs from HPK and BNL with varying thicknesses ranging from 20μm to 50μm at room temperature. These tests utilized X-ray energies from 5 keV to 70 keV at the Stanford Synchrotron Radiation Lightsource (SSRL) with 10ps pulsed X-ray bunches separated by 2ns interval. In this contribution, we will show that LGADs has better energy sensitivity and timing resolution for low energy X-ray than PiN devices under finely-tuned operational conditions. Moreover, we will demonstrate the high frame-rate capability of LGADs (with at least 500MHz). Additionally, we investigated the gain suppression effect resulting from point-like large charge deposition along with the aid of TCAD simulation. Lastly, we made a crude attempt to assess the feasibility of reliable Compton scattering detection with LGADs, which aim to employ LGADs as pass-through beam monitoring device for high-energy X-ray beams using Compton interaction.

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Gain suppression studies at the CENPA tandem accellerator

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PIONEER is a next-generation experiment proposed at the Paul Scherrer Institute to perform high precision measurements of rare pion decays. By improving the precision by an order of magnitude on the charged-pion branching ratio to electrons vs. muons and the pion beta decay, PIONEER will provide a pristine test of Lepton Flavour Universality and the Cabbibo angle anomaly. At the centre of the experiment, a high-granularity active target (ATAR) will stop the pion and characterise its decay. The ATAR is being designed to provide detailed 5D tracking information, allowing the separation of the energy deposits of the pion decay products in both position and time. The chosen technology is Low Gain Avalanche Detectors (LGAD). These are thin silicon detectors with moderate internal signal amplification. Several types of LGADs still under development are being evaluated to achieve a ˜100% active region, such as AC-coupled LGADs (AC-LGADs) and Trench Insulated LGADs (TI-LGADs). Since a range of deposited charge from Minimum Ionizing Particle (MIP, few 10s of KeV) from positrons to several MeV from the stopping pions/muons is expected, the detection and separation of close-by hits in such a wide dynamic range will be the main challenge.

Using the CENPA Tandem accelerator at the University of Washington,we studied the LGADs response of MeV-range deposits from a proton beam. This contribution will introduce the PIONEER experiment conceptual design and its physics case. The results of the test-beam study will also be presented.

Monolithic devices / 120

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Discussion: Radiation damage

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Welcome to the 43rd RD50 Workshop

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Towards the DRD3 collaboration

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Learning HISPANoS, a new neutron beam facility at CNA

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We present the first detectors and Single Event Effects experiments in the new Hispanos neutron facility, located at the National Centre of Accelerators, Sevilla, Spain. The detector experiment tests commercial photodiodes, with special emphasis in how to avoid electromagnetic interference. The SEE experiment starts to characterize vulnerabilities of a Intel MAX10 FPGA under fast neutrons. Both tests and the lessons learned open way to more evolved experiments for particle detectors and SEE experiments using neutron beams.

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Developments of GaN Schottky devices at NRC

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Wide-bandgap semiconductors such as gallium nitride (GaN) have inherent advantages based on their material properties such as high critical field, high electron mobility and most importantly, high bond energies that lead to lower displacement damage, all of which imply a high radiation hardness. This material system should therefore be considered as an alternative to silicon-based detectors for next-generation colliders. Here, we report on preliminary results of Schottky devices composed of 8 µm thick GaN epitaxially grown with no intentional doping on n+ GaN substrates using Hydride Vapor Phase Epitaxy (supplied by Kyma) and fabricated at NRC Canada. Capacitance measurements reveal low background carrier concentrations ˜1E15 cm-3 and average pixel capacitance of 3 nF/cm2. Dark currents of devices with various areas, including guard rings, provide evidence of bulk dominated leakage currents. After rapid thermal anneal treatment dark currents of ≤ 5 nA/cm2 for reverse bias of -1 V were observed. The barrier height of the Schottky contact was extracted using forward biased conditions at room temperature and estimated to be 0.7-0.75 eV, in reasonable agreement with literature data of Ni/GaN barriers although with some inhomogeneity. Devices were also subjected to reverse biases of 200 V with no breakdown behaviour. Preliminary light injection measurements were performed using a focused laser at 355 nm with a spot size of 10 µm adjacent to a 1 mm diameter device. Although carrier collection was observed, it is too early to quantitatively assess the carrier collection efficiency. Furthermore, no strong dependency on bias was observed. Further processing development is planned using NTT's GaN epi on GaN substrates grown by MOCVD.

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Greetings from special guests via zoom

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Special greetings

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Goodbye

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