16th (Virtual) "Trento" Workshop on Advanced Silicon Radiation Detectors

Tuesday, 16 February 2021 - Thursday, 18 February 2021

FBK, Trento

Book of Abstracts

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Prospects for 3D integration in future pixel detectors and readout chips

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3D integration technologies have generated a wide interest in the pixel sensors and front-end electronics communities. They have the potential to lead to the fabrication of multilayer high performance devices with no dead area, where each layer is optimized for its function (particle sensing, analog signal amplification and filtering, digital memory and readout, silicon photonics,..). Recent developments associated with industrial and scientific applications of CMOS image sensors have reinvigorated the interest of the community, showing the potential of advanced interconnection technologies in the design of high performance detectors. This paper will review the experience that the high energy physics community gained so far, and assess the current status of R&D work on 3D integration applied to particle detection systems. Finally, the prospects of 3D integration for the future generation of pixel detectors (either hybrid or monolithic) will be discussed, along with the critical features of the technology in view of different applications.

Session 5: 3D Integration 1 / 137

Photon/Particle to Digital Converter

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The Photon to Digital Converter configuration was introduced by the universite de Sherbrooke (EC, Canada) to label their single photon detector composed of an array of Single Photon Avalanche Diode (SPAD) array and a CMOS electronics chip assembled in 3D. In this talk we show an extension of the PDC concept to the detection of charged particles as well as single photons relying on a backside illuminated avalanche diode array. The thickness of the diode array and avalanche gain are tailored to the detection of the particle of interest: single Ultra-violet to infra-red photons, keV scale electrons, minimum ionizing particles, or even heavy ionizing particles. The central element of the concept is the molecular bonding used to fuse the sensor and electronics chips enabling processing of the sensor backside post bonding. In this conceptual talk, we will argue that the development of 3D integrated digital SPAD array and Low Gain Avalanche Diodes can strongly benefit from cross-development.

Session 11: 3D Sensors / 138

Time resolution of an irradiated 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 μm $\times$ 50 μm and thickness of 285 μm, fabricated at IMB-CNM and irradiated with reactor neutrons to 8e14 MeV n_{eq}/cm^2 and then to 2.3e15 MeV n_{eq}/cm^2. Measurements were conducted using a radioactive source at a temperature of -20 and 20 \textdegree C in a bias voltage range of 50-300 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 μm. The results obtained are compared to measurements conducted prior to irradiation.

Session 4: Simulations / 139

Parametric process optimization for Indium, Gallium and Boron dopants using TCAD simulation modeling

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Radiation tolerance for fluences exceeding 2-3 × 10^{15} n_{eq}/cm^2 in current Low Gain Avalanche Diodes (LGAD) and other intrinsic gain silicon devices, is highly compromised due to gain layer de-activation. Previous studies using Carbon co-implantation or Gallium at the gain layer, have already demonstrated a 20 % improvement and a 20 % degradation respectively. Use of Indium, an implant demonstrated to increase tolerance at solar cell applications, can be considered as an alternative to the above. In this study, a process optimization is performed to evaluate the feasibility of a production yielding same doping characteristics for Indium, Gallium and Boron dopants. The reference profile, against which optimization is performed, is extracted though SiMS measurements on Gallium implanted LGAD gain layer. Using preliminary SRIM calculations, generic parameters are extracted and subsequently translated into multiple process scenarios, simulated thought TCAD Synopsys. With a multi-dimensional fit approach, doping profiles characteristics are evaluated (dose integral, depth, profile shape) and the appropriate process parameters, allowing a uniform profile across all implants, are extracted.

Session 8: LGAD 1 / 140

Optimization of gain layer doping, profile and carbon levels on HPK and FBK sensors

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Low Gain Avalanche Detectors (LGADs) are thin silicon detectors (ranging from 20 to 50 um in thickness) with moderate internal signal amplification (up to a gain of ˜50) [1]. LGADs are capable

of providing measurements of minimum-ionizing particles with time resolution as good as 17 picoseconds [2]. In addition, the fast rise time (˜500ps) and short full charge collection time (˜1ns) of LGADs are suitable for high repetition rate measurements in photon science and other fields.
The first implementation of this technology will be with the High-Granularity Timing Detector (HGTD) in ATLAS and the Endcap Timing Layer (ETL) in CMS for the high luminosity upgrade at the Large Hadron Collider (HL-LHC). The addition of precise timing information from LGADs will help mitigate the increase of pile-up and improve the detector performance and physics sensitivity.
Past publications [3-4] have proven the vast improvement in term of radiation hardness of deep gain layer and carbon implantation in LGAD designs. In this contribution a study will be shown on the tuning of the doping concentration in the deep gain layer of HPK sensors to optimize the performance before and after radiation damage. Furthermore the effect of the combination of a deep gain layer and carbon implantation in FBK sensors will be shown alongside an optimization of the carbon concentration level.
Results on electrical properties and charge collection will be shown on pre and post irradiation. Sensors were irradiated at JSI (Ljubljana, Slovenia) with neutrons and at CYRIC (KEK, Japan) with protons, then tested using the beta-scope setup and probe stations at UCSC.

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Session 9: LGAD 2 / 141

A Data-Driven of Test beam related LGAD mortality

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Using test-beam data on 80-120 GeV pion beams, a study of LGAD mortality is presented for neutron and proton irradiated samples for fluences up to 6e15n_{eq}/cm^2. An empirical model is established for estimating maximum safe operating voltage point and a link is demonstrated between bias voltage and beam-related damage. Comparisons are performed with similar operating points at laboratory conditions and a link with incoming particle rate is debated. Macroscopic and microscopic inspection of damaged devices is also presented with an emphasis on non-handling related incidents.

Session 8: LGAD 1 / 142

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 implant).

Previous FBK-UFSD productions (UFSD2 and UFSD3) demonstrated that the carbon infusion into the gain implant slows down the removal of acceptors. 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 inactivation); the intrinsic radiation resistance of carbonated gain implants 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 inactivation.

In this contribution: we will report a mapping of carbon-boron inactivation 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 2.5E15n_eq/cmˆ2. Our study identified the more intrinsic radiation resistant gain implant.

Session 11: 3D Sensors / 143

Performance of irradiated FBK 3D sensors for the ATLAS ITk pixel detector

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3D pixel sensors will be used for the innermost layer (L0) of the ATLAS ITk detector at High Luminosity LHC. The pixel size will be either 25 µm x 100 µm (barrel, central part of L0) or 50 µm x 50 µm (endcap, lateral rings). Sensor wafers with 150 µm active thickness have been produced by FBK in

collaboration with INFN. Several sensors were bump bonded to RD53A read-out chips at Leonardo and tested in laboratory and at DESY beam line. In this talk, we report on the test beam characterization in terms of hit efficiency and charge collection of two modules (25µ µm x 100 µm and 50 µm x 50 µm) irradiated with 27 MeV protons up to a fluence of 1.0e16 1 MeV n_{eq} cm^{-2}. Moreover, leakage current and power dissipation of 3D diodes after 1.0 and 1.5e16 1 MeV n_{eq} cm^{-2} irradiaton with neutrons is shown. Finally, the preparation work for the assembly of endcap L0 modules in INFN Genoa is presented.

Session 4: Simulations / 145

Predicting the Response of p-type Silicon Sensors to Radiation Environments: a Hamburg Model Simulation

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An overview of the response of p-type silicon sensors to non-ionizing energy loss, accompanied by a new simulation of these effects, is presented. Silicon detection is a mature technology for registering the passage of charged particles. At the same time it continues to evolve toward increasing radiation tolerance as well as precision and adaptability. For these reasons it is likely to remain a critical element of detection systems associated with high energy particle physics experiments. Silicon sensor leakage current and depletion voltage depend upon the integrated fluence received by the sensor, and upon its thermal history during and after the irradiation process. The high energy physics community has gradually shifted to the use of p-type silicon sensors in place of n-type. This will help reduce manufacturing costs and increase radiation tolerance. The Hamburg Model simulation code developed for the prediction of n-type silicon sensors in the experiments at the LHC is being adapted for p-type silicon sensors. The alterations of the model and code base will be discussed.

Session 11: 3D Sensors / 146

Test Beam Results of FBK pixel sensors for the Phase-2 CMS Tracker with the RD53A readout chip

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The High Luminosity upgrade of the CERN Large Hadron Collider (HL-LHC) will require new high-radiation tolerant silicon pixel sensors for the innermost layers of the CMS experiment tracking detectors, capable of withstanding fluences up to 2.3E16 neq/cm2 (1MeV equivalent neutrons). Results obtained in beam test experiments with FBK planar and 3D pixel sensors interconnected with the RD53A readout chip are reported. RD53A is the prototype in 65nm technology issued from RD53 collaboration for the future readout chip to be used in the upgraded pixel detectors. The interconnected modules have been tested on an electron beam at DESY, before and after irradiation, up to an equivalent fluence of 1E16 neq/cm2. The sensors were made in the FBK foundry in Trento, Italy, and their development was done in collaboration with INFN (Istituto Nazionale di Fisica Nucleare, Italy). Analysis of collected data shows hit detection efficiencies around 99% measured after irradiation. All results are obtained in the framework of the CMS experiment R&D activities.

Session 2: Planar Sensors / 147

Investigation of subsequent pulse detection in irradiated silicon sensors

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During investigations of the signal composition in silicon strip sensors, that were irradiated and annealed until the occurrence of charge multiplication, it was observed that charge carriers created previously have effects on the subsequent signal. This lead to the conclusion that drifting charge left the sensor in a meta-stable state.
Using the Edge- and Top- Transient Current technique the influence of subsequent laser pulses was investigated, where a significant decrease of measured charge amplitude was observed. This decrease turned out to be dependent on the laser intensity, the time delay between pulses, the measurement temperature, the applied voltage and the irradiation fluence.
In this study it is investigated how trapping (or charge accumulation) and de-trapping (relaxation) can explain the observed decrease. This includes simulations of the electric field change and a fit model to describe the decrease.

Session 7: Electronics / 148

RD53 pixel chip developments for the ATLAS and CMS High Luminosity LHC

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The Phase-II upgrades of ATLAS and CMS will require a new tracker with readout electronics operating in extremely harsh radiation environment and high data rate readout.
The RD53 collaboration is a joint effort between the ATLAS and CMS experiments facing the challenges of developing hybrid pixel readout chips for the upgrades of the pixel detectors of both experiments.
A large size demonstrator, called RD53A, was produced in 2017 to qualify the chosen 65nm CMOS technology and compare different analog front-ends and digital architectures for the development of the final production ASICs (Integrated Circuit). The chip has been extensively used for sensor characterization and the design, test and verification of the system architectures of ATLAS and CMS.
The final chips for the two experiments are being designed based on these results, having as a reference a common virtual baseline chip, called RD53B, which is adapted to the needs of each experiment (e.g. chip size, analog front-end, triggering features). The RD53B-ATLAS version was submitted in March 2020 and it has been extensively tested, providing valuable results for the implementation of the RD53B-CMS version, which is being finalized in these days and planned to be submitted in March 2021.
A general overview of the chip architecture will be presented, as well as the first preliminary test results

Session 2: Planar Sensors / 149

Testing HPK Planar Pixel Sensors for the CMS Phase 2 Upgrade

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With the High Luminosity upgrade of the Large Hadron Collider (HL-LHC), the Compact Muon Solenoid (CMS) experiment is foreseen to collect an integrated luminosity of 3000 or even 4000 fb^{-1}. This comes with up to 200 proton-proton collisions per bunch crossing and correspondingly a high multiplicity of particle tracks. For 3000 fb^{-1}, the upgraded CMS Inner Tracker will have to withstand 1 MeV neutron equivalent fluences ϕ_{eq} of up to 2.3×10^{16} cm^{-2} at a distance of 2.8 cm from the beam, whilst maintaining its track and vertex finding capabilities.

Planar n^{+}-p pixel sensor prototypes with pixel sizes of 50×50 $\mu\mathrm{m}^2$ or 25×100 $\mu\mathrm{m}^2$ and an active thickness of 150 μm were produced 2017 by Hamamatsu Photonics (HPK) and characterized in the DESY II test beam facility. A second set of revised prototypes was produced 2019, incorporating improvements of the sensor design based on findings from the 2017 production. The sensors were bump bonded to ROC4SENS or RD53A readout chips. The former is dedicated to sensor studies and the latter is a common ATLAS and CMS prototype for the HL-LHC. The sensor chip assemblies were irradiated with protons to fluences ϕ_{eq} of up to 2×10^{16} cm^{-2} before characterization in the test beam. The irradiations took place at PS-IRRAD Proton Facility at CERN, the Irradiation Center Karlsruhe and the Birmingham Irradiation Facility.

Even at the highest fluences hit efficiencies of 99 % are reached at bias voltages close to 650 V, thus a key requirement for sensors in the upgraded CMS Inner Tracker is fulfilled. At the given voltage the leakage current per pixel was about 5 nA at a temperature of about -32 °C. In addition, the presented results show the impact of the sensor choice on the hit efficiency, spatial resolution and crosstalk.

Session 3: CMOS Sensors / 150

Active pixel matrix measurements of RD50 MPW2 HV-CMOS chip

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The RD50-CMOS groups aims to design and study High Voltage CMOS (HV-CMOS) chips for use in a high radiation environment. Currently, measurements are performed on the RD50-MPW2 chip, the second prototype developed by the RD50-CMOS group. Those measurements are discussed in this talk.
The active matrix of the RD50 HV-CMOS MPW2 prototype consists of 8x8 pixels with analogue frontend only. While former measurements on irradiated and non-irradiated sensors have been performed only at passive test-structures, first results of the (irradiated) active matrix are discussed in this presentation. Each pixel of the active matrix can be readout one after the other. A slow control using a shift-register allows to automatize readout.
The analog behavior of the active matrix has been studied with eTCT measurements while the digital readout is tested with injection pulses, a radioactive source and a proton beam. This talk will cover the most relevant aspects of all of these measurements, focusing on a future implementation in a telescope-like setup in a proton beam.

Session 5: 3D Integration 1 / 151

Pixel detector hybridization and integration with Anisotropic Conductive Films

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An alternative pixel-detector hybridization technology based on Anisotropic Conductive Films (ACF) is under development to replace the conventional fine-pitch flip-chip bump bonding. The new process takes advantage of the recent progress in industrial applications of ACF and is suitable for time- and cost-effective in-house processing of single devices. This new bonding technique developed can also be used for the integration of hybrid or monolithic detectors in modules, replacing wire bonding or solder bumping techniques. This contribution introduces the new ACF hybridization and integration technique, and shows the first test results from Timepix3 hybrid pixel assemblies and from the integration of ALPIDE monolithic pixel sensors to flex circuits.

Session 7: Electronics / 152

Timespot1: A 28-nm CMOS ASIC for pixel read-out with time resolution below 20 ps

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We present a prototype ASIC solution for vertex detectors of the next generation of colliders, where high resolution in both space and time measurements will be mandatory requirements in order to cope with the huge number of tracks per event to be detected and processed. The ASIC, named Timespot1, designed in CMOS 28-nm technology and featuring a 32x32 pixel matrix with a 55 µm pitch, is conceived as the first prototype in a series, capable to read-out pixels with timing capabilities in the range of 30 ps and below. Each pixel is endowed with a charge amplifier, a discriminator and a Time-to-Digital-Converter, capable of time resolutions below 20 ps and read-out rates (per pixel) around 3 MHz. The timing performance are obtained respecting a power budget of about 50 µW per pixel, corresponding to a power density of approximately 2 W/cm2. The ASIC has been submitted for production in December 2020 and the dies are expected to arrive soon. Along with the ASIC characteristics and performance, obtained from post-layout simulations, we present an overview of the demonstrator presently under development to test the system in a small real environment.

Session 11: 3D Sensors / 153

Performance of 3D sensors produced at CNM and uniformly irradiated up to 2e16 n_{eq}/cm^2

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The inner detector of the ATLAS experiment will be replaced by a completely new Inner Tracker (ITk) to exploit the performance of the High Luminosity upgrade of the LHC accelerator (HL-LHC). The new tracker will have to operate in an unprecedented radiation environment. In particular, the hybrid pixel detectors of the innermost layer of the ITk will need to survive a particle fluence of about 2e16 n_{eq}/cm^2 before being replaced.
A novel 3D pixel sensor technology featuring thin active substrate and small pixel cells has been selected to instrument the innermost barrel layer and rings of the ITk. The performance in terms of hit efficiency and power consumption of 3D pixel sensors produced at CNM and uniformly irradiated up to 2e16 n_{eq}/cm^2 have been investigated. Results obtained from the characterisation of 3D pixelated test structures as well as half-size sensors coupled to the RD53A prototype chip are presented.

Session 10: Technologies and Applications / 154

Radiation damage on FBK Silicon Photomultipliers

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Silicon Photomultipliers are array of many single-photon avalanche diodes (SPAD) connected in parallel to common anode and cathode, each with an integrated quenching resistor. Each pixel is sensitive to a single photon, working in Geiger-mode, with high internal electric fields to trigger self-sustaining avalanche multiplication processes. They are emerging as detector of choice in many applications ranging from quantum physics, nuclear medicine and high-energy physics experiments, because of their versatility and their high dynamic range. In particular, when used for space applications or in high energy physics experiments, like the CMS-HCAL, SiPMs are often exposed to a significant dose of radiations. Typical values are in the order of 109 - 1010 neq/cm2 for space applications, or up 1014 neq/cm2 for calorimetry applications in experiments of HEP.
To be able to properly work up to the end of the experiment, a good radiation tolerance (or radiation hardness) is required and the SiPMs have to be properly optimized to be able to survive such radiation doses or to minimize the effects of the damage as much as possible, thus reducing their performance worsening.
In FBK (Trento, Italy) we have been developing different SiPM technologies over last years, optimized for different applications in terms of detection efficiency (for example with peak sensitivity

in the blue-wavelength region, or in the green-wavelength region) and performance characteristics in specific application conditions (e.g. working in liquid nitrogen). It is therefore also interesting to be able to characterize and compare the main performance-parameters degradation, of these different technologies.
Generally, as for the majority of silicon-based photodetectors, the radiation damage can affect both the surface region and the bulk through ionizing energy loss (IEL) and non-ionizing energy loss (NIEL) respectively, introducing defects and recombination centers. Depending on the energy and the particle type, either one type of damage or the other one is more relevant and likely to happen. However, differently from other type of radiation sensors, SiPMs work in Geiger mode, with high electric field in the active volume, being possibly more sensitive to even small defects, particularly in the bulk. As a consequence of the damage the SiPMs show an increase of both leakage current (i.e. not multiplied one) and dark current (i.e. the multiplied current, generating the dark count rate, DCR, of the SiPM) resulting in an increase of the noise and possibly also a decrease of the signal amplitude, leading to a dominance of the noise events (i.e. dark counts) over the signal (photon counts). This is reflected in a decrease of the signal-to-noise ratio which is an important parameter for the performance of a SiPM.
In our investigation, protons have been chosen for their property of being heavy charged particles doing both ionizing and non-ionizing interactions. Their damage effect has been converted into 1 MeV neutron equivalent damage. We present and compare the characterization results of several SiPMs from different technologies. We irradiated the SiPMs with protons, with energy of 62MeV at INFN-LNS facility (Catania, Italy). The SiPM have been properly characterized after irradiation shown an important increase of the primary noise with some saturation effects. However, the main electrical characteristic, like breakdown voltage are not affected, as well as the correlated noise. We investigated also the activation energy of dark counts, showing a reduction as well as the sensitivity. Furthermore, we performed Emission Microscopy (EMMI) tests identifying the main failure position inside the micro-cell active area.

Session 1: System Issues / 155

Ionizing and Non-Ionizing Energy Loss irradiation studies with 70-230 MeV protons at the Trento Proton Therapy Center

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Proton induced Ionizing and Non-Ionizing energy loss campaigns are required studies for silicon sensors and electronic devices qualification when designed for medical, space and high energy physics applications.
The Experimental Area of the Trento Proton Therapy Center offers the possibility to perform these studies using a 70-230 MeV proton beam designed for medical treatment of oncological patients. This area, used only for non medical applications, is equipped with two beamlines reserved for biological experiments, silicon sensor tests and electronic device qualifications. One of these lines is also equipped with a unique passive beam modulator system, called double ring, where large area proton irradiation on silicon sensors and electronic devices can be performed.
In this talk a description of the beam parameters and irradiation regime possibilities will be given, and also the description of a new set-up used in September 2020 for single event upset rate measurement on a electronic device.

Session 11: 3D Sensors / 156

Sub-pixel characterization of innovative 3D trench-design silicon pixel sensors using ultra-fast laser-based testing equipment

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For the operations during the High Luminosity phase of LHC, dedicated studies have shown that new vertex detectors with single-hit time resolutions in the range from 10 to 50 picoseconds will allow to recover the current tracking and vertexing capabilities. The TimeSPOT project has developed 3D trench-based silicon pixel sensors with a time resolution in the range of 20 ps. To carefully study their performances and optimize their design, it is important to precisely measure the time response of the sensors at a sub-pixel level. Such a characterization, performed at the INFN Cagliari laboratory, is obtained using a custom laser-based setup, able to deposit a known energy in a specific region of the pixel and perform a detailed scan of the sensor sensitive volume. The detailed characterization of a TimeSPOT 3D pixel sensor will be presented at the conference.

Session 11: 3D Sensors / 157

Laboratory characterization of 3D-trench silicon pixel sensors with a 90Sr radioactive source

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In order to cope with the high luminosity phase conditions at the LHC experiments, the development of detectors with enhanced time resolution and radiation hardness is required. TimeSPOT, an INFN-funded project, has developed 3D-trench silicon pixel sensors able to achieve a very good time resolution for minimum ionizing particles. In 2019, these sensors were tested for the first time on a high-energy charged-particle beam at the Paul Scherrer Institut (PSI) and a time resolution of 20 ps was measured. In order to perform accurate time resolution measurements in our laboratory, a beam test like setup using a ^{90}Sr beta emitter was built. The results obtained are in agreement with PSI beam test measurements, implying that such a setup is, at least for sensor time characterization, a valid alternative to high-energy charged-particles beam tests. This setup, together with the characterization of a TimeSPOT 3D pixel sensor, will be presented at the conference.

Session 10: Technologies and Applications / 158

Epitaxial growth and characterization of 4H-SiC for detection applications

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Silicon Carbide (SiC) is a compound semiconductor, which is considered as a possible alternative to silicon for particles and photon detection. Its characteristics make it very promising for the next generation of nuclear and particle physics experiments at high beam luminosity.
Silicon carbide shows a large variation in crystal lattices according to the stacking sequence of the atoms in the crystalline lattice. Among all the SiC polytypes, 4H-SiC is considered to be the most

appropriate for high-power, high-frequency, and high-temperature applications in microelectronics, and also it has the widest bandgap and an almost isotropic electronic mobility [1]. Moreover, SiC based detectors are more resistant to the ionizing radiations than Si ones. Then, they can be used in high level radioactive ambient where the temperature and the radiation environment preclude the use of conventional microelectronic semiconductors [2-3].
Some studies based on the effects of neutron, proton and heavy ions irradiation on SiC diodes evidenced the high radiation hardness of this devices [4], that maintain their performances after irradiation at doses as high as 20 MGy [5-6]. Therefore, for all these characteristics the use of these detectors is particularly interesting for all those activities where high particles flux must be detected.
The high-quality material used for device application is typically grown epitaxially by a Chemical Vapor Deposition (CVD) process. Epitaxy allows a highly precise control of thickness, doping and homogeneity of crystal films. The epitaxial growth of SiC films is typically realized in horizontal hot-wall reactors in a low-pressure regime and, for 4H SiC polytype, temperatures ranging from 1550 to 1650℃ [7]. Nowadays 4H-SiC can be growth on relatively large area (150 mm wafers) with thickness until 250 µm and a low density of defects.
A new field of application of the solid state detectors is a neutron detection in harsh environment such as thermonuclear fusion. The Single-Crystal Diamond (SCD) detectors are used on this field, but high cost, the small dimensions of the wafers and a low availability of commercial monocrystalline diamond allow the use of alternative materials like SiC. From a previous paper [8] it has been observed that the resolution of SCD detectors 150 micron thick is better than the resolution of 100 micron thick SiC detector. Furthermore, the resolution of the SCD detectors increases increasing the thickness. Then to increase the resolution of the SiC detectors is necessary to increase considerably the thickness of the epitaxial layer.
The purpose of this work is to grow a 250-micron epitaxial layer of 4H-SiC material through a CVD process and a Chemical Mechanical Polishing (CMP) process at the end of growth. We have characterized our sample optically through Photoluminescence (PL) and Raman (i-LOPC) spectroscopy for defects distribution and carrier lifetime evaluation. We obtained a PL map and his relatives signal of 4H-SiC with 250 µm of epitaxial layer. At this step our sample presents some defects, but most of them are located on the edges of the wafer. This effect is connected to the presence of the off-axis of the substrate towards the [11-20] directions. We compared the 250 µm thick epy layer with two other samples having an epitaxial layer thickness of 100 µm which we obtained with two different growth rates, 60 and 90 µm/h respectively. Furthermore, we started with the manufacturing process, then we want to study its behavior under working conditions through simulations and irradiation under neutron beam of 14 MeV.
We have been measured the carrier lifetimes through the Raman shift of the LO phonon-plasmon-coupled mode (LOPC) [9]. Given that the LO phonon-plasmon coupling is obtained thanks to the free carriers generated by the high injection level induced by the laser, this technique is named induced-LOPC (i-LOPC). Moreover, there are some processes to increment the carrier lifetime and, as a consequence, the diffusion length for 4H-SiC. These post growth processes, such as oxidation and passivation processes, could increase these values thanks to the decrement of carbon vacancies [10]. Hence a possible increase of lifetime and diffusion length after a high temperature oxidation process will be evaluated.
We also compared the influence of different types of stacking faults (SF) defects on the carrier lifetime values and how, following the LO shift in Raman analysis, the decrease in laser power shows a gradual decrease in the difference in LO shift ON-SF and OUT-SF, until the peaks overlap, obtaining the same duration values for both areas. The analysis of the thick epitaxial layer is necessary to understand if this epitaxial material could be used in order to fabricate devices for neutron detection. A considerable effect of the growth process and of the laser power on the carrier lifetime is observed and will be explained at the conference.

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Session 9: LGAD 2 / 159

Technology Developments on Thin iLGAD Sensors for Pixelated Timing Detectors

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In this contribution, we will present the status of the technological developments at IMB-CNM to fabricate 50 µm thick Inverse Low Gain Avalanche Detectors (iLGAD) for pixelated timing detectors.

The iLGAD sensor concept is one of the most promising technologies for enabling the future 4D tracking paradigm that requires both precise position and timing resolution. In the iLGAD concept, based on the LGAD technology, the readout is done at the ohmic contacts, allowing for a continuous unsegmented multiplication junction. This architecture provides a uniform gain over all the active sensor area (100% fill factor).

The soundness of this detection concept was successfully demonstrated in a first generation of 300 µm thick iLGAD sensors. Currently, we are developing 50 µm thick pixelated iLGADs optimized for timing with an periphery design able to sustain higher electric fields and a simpler single-side manufacturing process.

This activity is carried out in the context of the RD50 and AIDAInnova projects with the participation of the CERN-SSD, IFAE, IFCA, IMB-CNM, NIKHEF, University of Hamburg, University of Santiago de Compostela and University of Zurich.

Session 9: LGAD 2 / 160

Performance of the USTC first batch LGADs

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We present the performance of the USTC-1 LGADs which are designed by the USTC and fabricated at the IME (Institute of Microelectronics ,CAS). The LGADs are made with five 8-inch wafers with 1x1, 2x2, 5x5, and 15x15 arrays with 50 µm active thickness according to the specification of the ATLAS HGTD project. Different peripheral region designs are attempted and the gain layer energy and dose are varied to optimize the radiation hardness. The ultra-deep gain layer and carbon diffusion strategy are also tried with two wafers. The I-V and C-V results show good uniformity on the VBD, VGL. The transient signal measured with beta-scope and laser is used to evaluate the timing resolution and collected charge.

Session 9: LGAD 2 / 161

Characterization with a β-source setup of the UFSD3.2 production manufactured at FBK

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In this contribution, I will present the characterization of the latest LGAD production manufactured at FBK (UFSD3.2), performed with the β-source (Sr90) setup of the Torino Silicon Lab (INFN –University of Torino).

The UFSD3.2 production features a wide range of designs: the tested sensors have four different active thicknesses (25, 35, 45, 55 µm), different splits of Gain Layer dopings and Carbon implantation doses, and either standard and innovative "deep"gain implants.

I will present measurements of time resolution, gain and collected charge, and provide a thorough comparison between the tested sensors, in order to highlight their strengths and weaknesses. Such measurements also include results on sensors irradiated at the JSI TRIGA reactor (Ljubljana) up to a fluence of 2.5E15 neq/cm2, which allow comparing the performances after irradiation of the different designs.

Session 2: Planar Sensors / 162

Edge-on technique using a high energy electron beam for characterisation of irradiated pad diodes

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The charge collection of three $150\ \mu$m thick n^+pp^+ pad diodes has been scanned along the diode thickness using a 4.2 GeV electron beam at the DESY II beam test facility. The electron beam enters from the sensor edge and its position along the edge was reconstructed by three planes of a EUDET-type telescope. Compared to the conventional edge-TCT with laser light, the main advantages of using electron beam are: I. The method can be used for pad diodes, II. The results of the measurements can be normalised to an absolute value.

The diodes have an area of 25 mm^2 and a p-doping concentration of 4×10^{12} cm^{-3}. The measurements were performed at $-20\,°$C for bias voltages up to $V_{bias} = 800$ V. One diode was not irradiated while the other two were irradiated with 23 MeV protons to a 1 MeV neutron equivalent fluence of $\Phi_{eq} = 2 \times 10^{15}$ cm^{-2} and 4×10^{15} cm^{-2}, respectively. The result of these measurements is the charge profile as a function of depth for each diode. For the non-irradiated diode, the charge profile is uniform as a function of the depth and independent of the applied bias voltage. For the irradiated diodes, the charge profiles are non-uniform and it changes with the applied bias voltage. The Charge Collection Efficiency (CCE) of irradiated diodes at 800 V was estimated using these measurements to be 0.88 and 0.78 for the lower and higher irradiation fluence, respectively.

In this work, the online alignment and the measurement procedures, as well as charge profiles of three diodes are presented. The results are used for tuning simulation models of charge collection in irradiated diodes and segmented silicon sensors.

Session 4: Simulations / 163

TCAD numerical simulation of irradiated Low-Gain Avalanche Diodes

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In this work the results of several device-level simulations, carried out with the state-of-the-art Synopsys Sentaurus Technology CAD (TCAD) tool, of non-irradiated and irradiated Low-Gain Avalanche Diode (LGAD) detectors will be presented. Thanks to the intrinsic multiplication of the charge within these silicon sensors, it is possible to improve the signal to noise ratio thus limiting its drastic reduction with fluence, as it happens instead for the standard silicon detectors. In order to have a predictive insight into the electrical behaviour and the charge collection properties of the LGAD detectors up to the highest particle fluences expected in the future HEP experiments, a radiation damage model (called "New University of Perugia TCAD model") has been fully implemented within the simulation environment. By coupling this numerical model, which allows to consider the comprehensive bulk and surface damage effects induced by radiation on silicon sensors, with an empirical model that describes the mechanism of acceptor removal in the multiplication layer, it has been possible to reproduce experimental data with high accuracy, demonstrating the reliability of the simulation framework.

Note: This work has been supported by the Italian PRIN MIUR 2017 "4DInSiDe"research project

Session 7: Electronics / 164

Optimization of the 65 nm CMOS Linear front-end circuit for the CMS pixel readout at the HL-LHC

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A prototype chip integrating a matrix of 16 × 16 readout channels has been designed and tested in the framework of the RD53 developments for pixel detectors at the High-Luminosity LHC. The matrix is divided in two regions featuring different flavours of the front-end stage, or Linear front-end, that have been tested and compared. The front-end channels include a low-noise charge sensitive amplifier with detector leakage compensation circuit, a free-running comparator, and a current-mode DAC for threshold tuning. The front-end circuits were developed in a 65 nm CMOS technology and feature an overall area of 35 μm × 35 μm with a current consumption close to 5 μA. The prototype has been tested before and after exposure to total ionizing doses up to 1 Grad(SiO_2) of X-rays. A comprehensive discussion of the design and of the characterization of the readout channels will be provided in the conference paper.

Session 8: LGAD 1 / 165

Status report on the radiation tolerance assessment of CNM AIDA2020v2 and HPK-P2 LGADs.

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The forward region of the CMS MIP Timing Detector, proposed for the HL-LHC upgrade, will be instrumented with timing detectors based on LGAD technology. Devices from two different producers, Hamamatsu Photonics (HPK2 campaign) and CNM-IMB (within the framework of AIDA 2020), tested by 3 different institutes (CERN, IFCA-CSIC and UZH) are presented in this talk. Electrical IV/CV characterizations of irradiated HPK2 (4e14, 8e14, 1.5e15 and 2.5e15 neq/cm2) and AIDA2020(1.5e15, 2.5e15 neq/cm2) devices are presented. Timing measurements of these devices with laser and/or radiactive source are planned and will be, temptatively, included in this talk.

Session 2: Planar Sensors / 166

Laboratory Measurements of Stiched Passive CMOS Strip Sensors

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Upgrades to existing particle physics detectors as well as future experiments in high-energy physics will continue to employ silicon sensors as central tracking elements, with an ever larger area covered by the silicon sensors. Already now, the sensors are a main cost driver. In addition, they are available from only a very small number of manufacturers in the quantities required. Therefore, detector technologies and designs that are cost-effective and can be realised through established commercial industrial production processes are becoming more and more relevant. One important group of candidates are sensors realised in CMOS technology. Typically, CMOS foundries are equipped for producing die sizes that are much smaller than the full size strip sensors in production e.g. for LHC experiments today. In order to obtain large sensors, several neighbouring reticles have to be connected in a process known as stitching.

For this contribution, passive strip sensors were designed and developed in a p-CMOS technology including stitching and produced by a European manufacturer. Following initial electrical characterisation on a probe station, the sensors were tested in the laboratory with Sr-90 sources and IR-lasers. The sensors comprise three different flavours of strip sensors fabricated on a 150 ⊠m thick wafer with the passive p-CMOS 150 nm process. Our sensors have a strip length of up to 4 cm, formed by stitching of up to five individual reticles. One key area of results to be presented is position-dependent measurements to understand the performance of the sensors.
In this context, we also evaluate the impact of stitching on the functionality of the sensors. Based on our results, we are able to demonstrate that the stitching does not show any negative effect on the sensor performance, and, hence, the stitching can be considered successful.

Session 3: CMOS Sensors / 167

ARCADIA: sensor development and chip design of innovative low-power, large area MAPS

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The ARCADIA collaboration is developing Monolithic Active Pixel Sensors (MAPS) with an innovative sensor design, that uses a proprietary processing of the back side to improve the charge collection efficiency and timing over a wide range of operational and environmental conditions. The sensor design targets very low power consumption, of the order of 20 mW cm^{-2} at 100 MHz cm^{-2} hit flux, to enable air-cooled operations of the sensors. Another key design parameter is the ability to further reduce the power regime of the sensor, down to 5 mW cm^{-2} or better, for low hit rates like e.g. at space applications. The MAPS architecture, initially embodied in a 512 $\times$ 512 pixel matrix, should enable the scalability of the sensor up to matrix sizes of 2048 $\times$ 2048 pixels. Maximising the active area of the single sensor (10 cm^2 or bigger) simplifies and reduces the costs of detector construction, and enables applications where no support material over the entire sensor area can be tolerated (e.g. medical scanners). The ARCADIA collaboration has established innovative architectures to deal with large pixel matrices, where the typical pixel column can reach many centimetres in length, with many thousands of pixels to read out.
In 2020 the ARCADIA collaboration has finalised a first design of a prototype of 1.3 $\times$ 1.3 cm^2 active area consisting of 512×512 pixels with 25 μm pitch. This prototype is currently being produced in a first engineering run with integrated digital electronics. Additional test structures of pixel and strip matrices with pitches ranging from 10 to 50 μm and total thicknesses of 50 to 200 μm will become available for detailed testing within first quarter of 2021.
In this contribution, we will present the current status of the project, the validation of the sensor concept by comparing measurements with TCAD simulation, and discuss the comprehensive simulation studies that lead to the design of the sensor test-structures which are currently in production.

Session 3: CMOS Sensors / 168

Bi-layered CMOS SPADs with coincidence-based DCR rejection for charged particle detection

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The features of SPADs, mainly used for the detection of faint optical signals in applications such as optical ranging, fluorescence lifetime imaging, position emission tomography and Raman spectroscopy, can be exploited also for charged particle detection. SPADs can leverage their huge internal gain to make charge pre-amplification unnecessary and reduce power dissipation. Moreover, on account of the very thin sensitive volume around the SPAD junction, the amount of sensor material can be minimized, therefore complying with the severe material budget requirements for future linear collider experiments. Use of CMOS processes in SPAD development offers the advantage of integrating the readout and processing electronics in a common substrate, resulting in a monolithic detector structure. This lends itself to improving the mechanical robustness of the system, simplifying the assembly of large detectors and optimizing the front-end circuits in terms of signal integrity and timing performance. On the other hand, noise performance of SPADs, usually represented through the dark count rate (DCR) parameter, can jeopardize their capabilities as charged particle detectors. This work presents the characterization of arrays of SPADs, targeting charged particle detection, fabricated in a 150 nm CMOS technology. The devices under test (DUTs) include both single layer and vertically interconnected, bi-layered SPAD arrays with coincidence readout, the latter approach being proposed as a DCR mitigation strategy. The results presented in this work are mainly focused on the study of the breakdown voltage and its uniformity in the single layer arrays and of the dark count rate, measured in different working conditions, in both single- and dual-layer structures. In particular, the DCR in dual-layer SPAD assemblies is proved to comply with the statistical model accounting for the coincidence between random avalanche signals, with median DCR values well below 1 kHz/mmˆ2. The comparison between the DCR performance of the two configurations emphasizes the advantage of the coincidence readout over the standard, single-tier architecture. Preliminary results from cross-talk characterization of the DUTs will also be introduced and discussed.

Session 3: CMOS Sensors / 169

Comparative study of MALTA pixel detectors on epitaxial and Czochralski silicon

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The High Luminosity upgrade of the LHC necessitates extensive upgrades to its four major experiments. Specifically for ATLAS, the installation of the Inner Tracker (ITK) requires the development of new radiation hard silicon pixel sensors. Depleted Active Monolithic Pixel Sensors (DMAPS) produced in standard CMOS processes are a cost effective and lightweight alternative to state-of-the-art hybrid detectors if they can fulfill the given requirements for radiation hardness, signal response time and hit rate capability. The MALTA and Mini-MALTA sensors were shown to maintain sufficient detection efficiency after irradiation to the life time dose expected at the outer layers of the ITK. These sensors feature a small symmetric pixel pitch of only 36.4\textmu m, a low capacitance of <5fF/pixel of the collection electrode, low noise of roughly ENC\approx10e^{-} and low power consumption of roughly 1\textmu W/pixel. Further improvements to detector efficiency are explored by changing the starting material for these sensors and using Czochralski instead of epitaxial silicon. The depleted region in the sensor can then be extended further by increasing the bias voltage. In turn, this increases the amount of collected charge and thus the signal in the sensor. This talk will discuss laboratory IV measurements, analogue signal studies and beam test results obtained with this new type of the MALTA detector and show comparisons to detectors on epitaxial silicon before and after irradiation.

Session 10: Technologies and Applications / 170

New multichannel modular detection system based on Silicon Drift Detectors

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We present a detection system with high sensitivity and efficiency specially designed to exploit the potentials of X-ray absorption spectroscopy in fluorescence mode. It consists of 8 monolithic multi-pixel arrays, each with 8 (SDD) cells with a total area of 570 mm^2. Optimized to work in an energy range of 3-30 keV, this 64 channels integrated detection system includes ultra-low noise front-end electronics, dedicated acquisition system, digital filtering, temperature control and stabilization. Room temperature characterization tests at Elettra Sincrotrone Trieste demonstrated very interesting results; they include an energy resolution at the Ka line of Mn 5.9 keV below 170 eV FWHM. The system is now installed and operating at the XRF-XAFS beam line of the SESAME Synchrotron light source in Jordan.

Session 1: System Issues / 171

The Upstream Tracker: the silicon strip detector for the LHCb upgrade

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The Upstream Tracker is a four-layer silicon strip detector positioned upstream of the dipole magnet. It is a key sub-detector for charged particle tracking, capable to provide fast track momentum information, essential for the software based trigger. We will discuss the detector design, based on silicon strip sensors, which features embedded pitch adapters and top-side biasing. The sensors are readout by a novel front-end ASIC mounted on hybrid circuits in the active area. The status of the construction will be presented.

Session 8: LGAD 1 / 172

Gain suppression mechanism observed in Low Gain Avalanche Detectors

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Low Gain Avalanche Detectors (LGADs) is one of the most promising sensing technologies for future 4D-tracking applications and recently it has been qualified to be used in the ATLAS and CMS timing detectors for the HL-LCH upgrade. LGADs are able to achieve an excellent timing performance by the presence of an internal gain that improves the signal-to-noise ratio leading to a better time resolution.

These detectors are designed to exhibit a moderate gain with an increase of the reverse voltage. Also, the value of the gain strongly depends on the temperature. Thus, these two values must be kept under control in the experiments to maintain the gain within the required values. A reduction in the reverse bias or an increase in the temperature will reduce the gain significantly.

In this talk, we present a new mechanism of gain suppression observed in LGADs. It was observed that the gain measured in these devices highly depends on the charge density generated by a laser or particle in the bulk. Measurements performed with different detectors under different conditions showed that ionizing processes that induce less charger density in the detector bulk lead to an increase in the detector's measured gain.
Therefore, measurements conducted with IR-laser and Sr-90 in the lab confirm this mechanism and will be presented in this talk.

Session 3: CMOS Sensors / 173

Charge collection efficiency of a thinned, backside biased, neutron irradiated High Voltage-CMOS active matrix

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Monolithic High Voltage-CMOS (HV-CMOS) sensors are emerging as a prime candidate for tracking systems in future physics experiments. They are designed to be suitable for these challenging environments by integrating the sensing diode and readout ASIC in a single layer of silicon allowing for high bias voltages and using high resistivity substrates. This results in thin detectors with fast charge collection and high radiation tolerance.

The H35DEMO is a demonstrator sensor ASIC in the 0.35 µm HV-CMOS process from AMS and manufactured in a few substrate resistivities between 20 Ω·cm and 1 kΩ·cm. It features four active matrices with 50 µm × 250 µm pixels and different readout electronics flavours. We have thinned a 1 kΩ·cm wafer of H35DEMOs to 100 µm and processed it to allow backside biasing. We have irradiated several of these samples with neutrons up to fluences of 2E16 neq/cm2 to study their radiation tolerance.

In this work, we report initial Charge Collection Efficiency (CCE) measurements of thinned and backside biased H35DEMOs before and after neutron irradiation. For this study, we have used one active matrix of pixels with in-pixel amplification and a Strontium 90 radioactive source.

Session 3: CMOS Sensors / 174

E-TCT characterisation of neutron irradiated 180 nm HV-CMOS pixel test structures

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MuPix8/ATLASPix1 are two large area monolithic pixel detectors for the Mu3e experiment at PSI and the ATLAS ITk upgrade respectively. They were manufactured together in the ams AG 180 nm HV-CMOS process (aH18) as part of the same engineering run (˜ 2 cm x 2 cm total area). This engineering run also includes a few passive pixel test structures.

Presented in this work are I-V characteristic curve and edge-Transient Current Technique (e-TCT) measurements of two sets of such passive pixel test structures. The first set are 80 Ω·cm nominal substrate resistivity samples, that are topside biased. The second set are 200 Ω·cm nominal substrate resistivity samples that have been thinned to 300 µm and backside processed to allow backside biasing. In both cases, measurements include samples irradiated with neutrons to fluences up to 1E16 1 MeV neutron equivalent fluence and up to 2E16 1 MeV neutron equivalent fluence for the thinned, backside biased samples.

Measurements of the depletion depths of both sets of samples made using e-TCT are used to estimate the effective doping concentration. The evolution of effective doping concentration is then studied as it changes with neutron equivalent fluence.

Session 9: LGAD 2 / 175

TCT-TPA/SPA studies of single event effects in thin LGADs at ELI Beamline

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The Single Event Effects (SEE) at large energy deposits in LGADs and PINs operated at extreme electric fields are studied at ELI Beamlines. The outcomes of conducted studies based on fs-laser TCT-SPA/TPA will be presented.
Fluences covered are the ones of interest for ATLAS and CMS: 4e14, 8e14, 1.5e15, 2.5e15 cm-2.
The future steps will be discussed too,

Session 6: 3D Integration 2 / **176**

3D integration technologies at FBK for Radiation and Optical Sensors

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In the last decade, 3D integration technologies have been driving important developments in CMOS microelectronics like memories and CMOS image sensors. They allowed an increase in the integration level of electronics components as well as the implementation of new functionalities.
In the framework of the IPCEI project (Important Projects of Common European Interest), Fondazione Bruno Kessler is acquiring new capabilities for the microfabrication of 3d integrated sensors. The aim of the project is to develop innovative radiation and optical sensors by integrating the most recent technologies for 3d integration to the more standard sensor technologies (SiPM, LGAD, pin detectors). The result of this integration would lead to a new generation of radiation sensors with enhanced performance and additional functionalities that cope with the new requirements coming from the HEP and medical imaging communities.
In this contribution, we present the latest results on backside-illuminated SiPM and Through Silicon Vias (TSV) for interconnecting the current analog sensors to digital read-out electronics. The FBK R&D roadmap for the next years on 3D integrated radiation sensors is also presented.

Session 2: Planar Sensors / **179**

Passive CMOS sensors for radiation-tolerant hybrid pixel-detectors

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The hybrid pixel detectors of the ATLAS and CMS experiments will be replaced for the operation at the HL-LHC in 2026. To maintain the tracking performance, the surface area of the future detectors will significantly increase while the pixel pitch decreases.

An attractive option for the production of the pixel sensors in such large area detectors is the utilization of a CMOS processing line. In addition to the cost-effectiveness and high-throughput of commercial CMOS lines, process features can be exploited to further enhance sensor performance. For example, field-plates can replace the common p-stop/p-spray inter-pixel isolation, poly-silicon layers enable biasing structures without a punch-through implementation, and MIM-capacitors allow for AC coupling.

After 5 years of R&D with passive sensors using the LFoundry 150 nm CMOS process, with many prototypes and design iterations, a milestone has been reached. In a dedicated submission full-size sensors have been produced that are compatible with the current RD53 readout chips and match the requirements of the ATLAS and CMS experiments.

This presentation will focus on the full-size sensor submission and depict latest results from irradiated prototypes (up to 1e16 neq/cm²) and inter-pixel isolation structures with field plates. Sensor parameters such as detection efficiency, break down behavior, inter-pixel resistivity, and charge collection properties will be discussed.

Session 8: LGAD 1 / 180

Development of AC-LGADs for large-scale high-precision time and position measurements

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Low Gain Avalanche Detectors (LGADs) are thin silicon detectors (ranging from 20 to 50 um in thickness) with moderate internal signal amplification (up to a gain of ˜50) [1]. LGADs are capable

of providing measurements of minimum-ionizing particles with time resolution as good as 17 picoseconds [2], [3]. In addition, the fast rise time (as low as 150 ps) and short full charge collection time (as low as 1 ns) of LGADs are suitable for high repetition rate measurements in photon science and other fields.
The first implementation of this technology will be with the High-Granularity Timing Detector (HGTD) in ATLAS and the Endcap Timing Layer (ETL) in CMS for the high luminosity upgrade at the Large Hadron Collider (HL-LHC). The addition of precise timing information from LGADs will help mitigate the increase of pile-up and improve the detector performance and physics sensitivity.
The current major limiting factor in granularity is due to structures preventing breakdown caused by high electric fields in near-by segmented implants. As a result, the granularity of LGAD sensors is currently limited to the mm scale.
In this paper, we present measurements on AC-LGADs (also named Resistive Silicon Detectors RSD), a version of LGAD which has shown to provide spatial resolution on the few 10's of micrometer scale [4]. This is achieved by un-segmented (p-type) gain layer and (n-type) N-layer, and a di-electric layer separating the metal readout pads. The high spatial precision is achieved by using the information from multiple pads, exploiting the intrinsic charge sharing capabilities of the AC-LGAD provided by the common N-layer. It depends on the location, and the pitch and size of the pads.
Using a focused IR-Laser scans directed alternatively at the read-out side on the front and the bias side on the back of the AC-LGAD, the following detector parameters have been investigated in RSD produced by FBK [4]: sheet resistance and termination resistance of the n-layer, thickness of the isolation di-electric, doping profile of the gain layer, and pitch and size of the readout pads.
The data are used to recommend a base-line sensor for near-future large-scale application like the Electron-Ion Collider where simultaneous precision timing and position resolution is required in the tracking detectors.

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Session 6: 3D Integration 2 / 181

Interconnection studies for monolithic silicon pixel detector modules using the MALTA CMOS pixel chip

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The material budget in the innermost tracking layers is a critical parameter that strongly influences the impact parameter resolution especially for lower momentum particles. Monolithic silicon pixel detectors can be thinned to typical thicknesses of 100 µm or less, thus providing the possibility to minimize the silicon contribution in the material budget. The MALTA monolithic silicon pixel sensor is a large area radiation hard monolithic CMOS sensor developed in the 0.18 µm CMOS process. It provides the possibility to transfer data and power from chip to chip and first tests using ultrasonic Al-wedge wire bonding have validated this concept to build multi-chip modules. Several interconnection technologies are being studied to provide high quality and mechanically robust direct chip-to-chip connections between different MALTA chips. Transferring data (GHz) and power from chip-to-chip will further contribute to designing a low mass and compact MALTA module. This presentation will present the studies and first findings as well as plans to build a large area module.

Session 6: 3D Integration 2 / 182

3D integration in nanoelectronics: Basic technologies and applications to image sensors

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The Moore's law, which governs the development of microelectronics for 50 years, is nearly ending due do its physical limits at the 2nm or 1nm technology nodes. In order to improve the device performance and for reducing the signal latency and the power consumption, the semiconductor industry has focused its efforts for stacking wafer on wafer, die on wafer, and die on die. This paper will review the basic technologies for achieving 3D chip integration, such as TSV, hybrid bonding, monolithic integration, and the chiplet approach. Applications of some of these technologies to visible and IR sensors will be presented.

Session 5: 3D Integration 1 / 183

Advanced Electronic Packaging Technologies for Hybrid Detectors

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Hybrid pixel detector modules are the basic building blocks of vertex detectors in HEP as well as solid state detector cameras for x-ray imaging. A pixelated sensor chip, made of silicon or III/V semiconductor, is connected to one or more electronic readout chips by thousands of electrically conductive interconnect structures.
The talk will give an introduction in the interconnection and assembly technologies and their specific requirements. The latest results of solder bump bonded hybrid modules for future HEP detector

upgrades will be presented. Furthermore, we will give an overview of alternative bonding technologies, i.e. transient liquid phase bonding, metal-metal direct bonding and metal-oxide hybrid bonding. These technologies can be used for chip to wafer as well as wafer to wafer bonding approaches. Beside the overview of common and advanced assembly technologies, some examples of more complex electronic packaging concepts will be described more in detail. This part will include the 3D packaging technology of electronic readout chips with through silicon vias (TSV). Assembly and test results of hybrid pixel detector modules using TSV readout chips will be presented in this talk.

Session 7: Electronics / 184

Readout architecture for the HEPD-02 tracker

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The adoption of monolithic active pixel particle detectors in space missions is obstructed by a number of technical challenges involving power dissipation, mechanics and material budget.
This work presents a sparse readout architecture for the 3-layers particle tracker, based of the ALPIDE MAPS chip, under development for the HEPD-02 instrument.
With a total of 150 APIDE chips and the stringent constrains imposed by a space mission, the deployment and readout of such detector requires careful optimizations to limit the power consumption but at the same time maintain useful performances.
Such task is approached with a custom parallel readout architecture, implemented on a single low-power FPGA chip managing the entire tracker.
The envisaged solution can be scaled up to detectors of size and complexity larger than HEPD-02, constituting a viable option for future mid-sized space missions.

Session 4: Simulations / 185

TCAD simulation studies of Fully Depleted Monolithic Active Microstrip Sensors (FD-MAMS) for the ARCADIA project

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Monolithic silicon sensors have become increasingly popular in the particle and applied physics community as a viable alternative to hybrid sensors for charged particle detection. In the framework of the INFN ARCADIA project, we have developed 10 um pitch Fully Depleted Monolithic Active Microstrip Sensors (FD-MAMS) to transfer the monolithic approach to microstrip detectors, with the aim of providing an innovative and cost-effective solution for tracking and timing applications. The FD-MAMS that we studied are fully compliant with commercial CMOS fabrication processes. The properties of monolithic microstrips were investigated by means of a TCAD simulation campaign, which was also aimed at identifying the most promising layouts to be included in the first ARCADIA production run. Special attention was given to the enhancement of the sensor performance in terms

of reduced capacitance and fast charge collection in low-power operation. The fine pitch of 10 um enables high spatial resolution and still allows the monolithic integration of distributed readout electronics in the inter-strip region. A surface radiation damage model was included in the TCAD simulations to estimate the effects of 10 to 10^5 krad total ionizing dose on the sensors'electrical characteristics. In the presentation, the sensor concept, the layout choices and the results of the simulation campaign will be presented, and their implication will be discussed in view of the possible applications. The strategies adopted to boost the charge collection speed in the sensor also under heavily ionising particles will be reported. The first tape-out, which includes 1.1 cm long FD-MAMS, has been submitted to the foundry at the end of 2020. Experimental measurements on the test structures will be performed in the next months.

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Conference Closing

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Welcome

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Session 5: 3D Integration 1 / 188

Introduction

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Session 1: System Issues / 189

Pixel sensor development for the ATLAS ITk upgrade

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An upgrade of the ATLAS detector system is foreseen for the High Luminosity phase of the LHC accelerator (HL-LHC) which will start operations in 2027. The present inner detector will be replaced by a new full-silicon Inner Tracker (ITk) designed to face the challenges posed by the large particle multiplicity and the extreme radiation environment at HL-LHC. The innermost part of the ITk, the pixel detector, will consists of five barrel layers and novel ring-shaped structure optimised to cover a pseudo-rapidity of $|\eta| < 4$. A great effort is presently ongoing within the ATLAS Collaboration for the qualification of the final sensor technologies and the pixel modules which will instrument the ITk.
In this contribution, designs and recent results of 3D and planar silicon pixel sensors will be presented, together with the module concepts developed for the future ATLAS pixel system.

Session 1: System Issues / 190

Results of evaluation of the multi-module and serial-powering demonstrator for the ITk Pixel Outer Barrel for the Phase-II upgrade of the pixel detector of the ATLAS experiment

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For the high luminosity era of the Large Hadron Collider (HL-LHC) it is foreseen to replace the current inner tracker of the ATLAS experiment with a new detector to cope with the occurring increase in occupancy, bandwidth and radiation damage. It will consist of an inner pixel and outer strip detector aiming to provide tracking coverage up to $|\eta|<4$. The layout of the pixel detector is foreseen to consist of five layers of pixel silicon sensor modules in the central region and several ring-shaped layers in the forward region. It results in up to 14 m^2 of silicon depending on the selected layout. Beside the challenge of radiation hardness and high-rate capable silicon sensors and readout electronics many system aspects have to be considered for a fully functional detector. The modules will be powered serially to reduce the power consumption and both stable and low mass mechanical structures and services are important. An effort was started to prototype a demonstrator with about 40 modules powered in six serial powering chains. The prototype was built with realistic mechanics and services. The test infrastructure includes not only the prototype but all elements of a full system from pixel modules, services, the detector control system and interlock, to power supplies and readout systems. Detail tests have been carried out with the modules based on the front-end chip FE-I4 [1] due to the dedicated shunt-regulators (Shunt-LDO) that can be operated with a constant current as needed for serial powering. In the presentation, the latest results and full evaluation of the electrical prototype are presented. Important qualification steps of the system design and its operation are discussed.

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Announcement