28th RD50 Workshop (Torino)

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Book of Abstracts

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Sensors with Internal Gain I / 1

Progress in Ultra-Fast Silicon Detectors

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We report on the status of the development of Ultra-Fast Silicon Detectors (UFSD). UFSD are novel silicon sensors based on the Low-Gain Avalanche Diodes (LGAD) design and, due to internal gain, exhibit a signal which is a factor of ~ 10 larger than standard silicon detectors. The internal gain allows obtaining fast and large signals, a pre-requisite for time applications, and thus they are poised to extend the use of silicon sensors characterized by excellent position resolution into the precision time domain.

UFSD with the desired gain are being manufactured routinely in a variety of sizes and have been tested in several beam tests-. We will concentrate the discussion on thin LGADs with thickness < 100um, we expect the best time resolution with them, due to the high slew-rate and the small contribution of Landau fluctuations.
The results of timing measurements on 75 μm thick LGAD produced by CNM using a beta source will be presented.

Present and Future Experiments / 2

The GigaTracker

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The GigaTracker (GTK) hybrid pixel detector has been designed to provide hits timed to better than 200ps RMS.

I will give an introduction to the detector architecture and talk about the special techniques used to achieve this demanding requirement. I will also describe the factor that we think ultimately limit the time resolution achievable with such an architecture.

Simulation and HV CMOS / 3

Radiation damage models: comparison between Silvaco and Synopsys

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In this talk we will present a comparison between Silvaco and Synopsys predictions when it comes to radiation damage models; the focus will nbe on the recent Perugia model.
Leakage current increase, depletion voltage and trapping time will be extracted and compared.
The simulated structures will include standard and LGAD n-on-p diodes.

Simulation and HV CMOS / 4

Phase II planar pixel sensors: Simulation study of interpixel isolation and surface passivation by a thin-film ALD-layer

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Interpixel isolation and charge sharing before and after irradiation in the proposed Phase II planar pixel n-on-p detectors was studied by TCAD simulations. Both p-spray and p-stop isolated devices with varied isolation doping concentration and depth as well as interface charge density were investigated. The results show that the acceptors in the isolation implantation are compensating the radiation induced surface traps leading to a local minimum of the interpixel resistance as a function of p-spray doping.
Effect of Atomic Layer Deposition (ALD) passivation-layer materials with different dielectric constants and thicknesses on breakdown voltage in 25x100 pixels was also investigated. The negative oxide charge in thin-film ALD-oxide provides strip isolation without any additional isolation structures, thus avoiding their higher processing complexity. The results were also compared to corresponding breakdown voltages of pixels with conventional isolation implantations.

Summary:

Interpixel isolation and charge sharing before and after irradiation in the proposed Phase II planar pixel detectors was studied by TCAD simulations. Effect of different ALD passivation-layer materials on breakdown voltage in 25x100 pixels was also investigated and compared with the results from pixels with isolation implantations.

Radiation Damage I / 5

Neutron Irradiated doping profile evaluation

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The creation of deep level defects after irradiation lowers the efficiency of a detector while increasing its operational voltage. The case of acceptor removal, observed in irradiated LGAD and other types of detectors suggests the presence of a secondary effect in addition to deep acceptor level generation. Estimation of the active dopant profile demonstrates a decrease in the acceptor concentration, proportional to the original doping concentration. Initial evidence from SiMS measurements indicated a marginal reduction on the total doping profile for proton irradiated samples, implanted with boron. A study is repeated with LGAD and boron-phosphorus samples, irradiated with thermal neutrons to fluencies of 2•10^15 neq/cm2 to 10^16 neq/cm2. Post irradiation SiMS measurements are performed and results are compared the non-irradiated and simulated doping profiles. Estimation of the boron neutron capture reactions are additionally evaluated.

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The Birmingham Irradiation Facility

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The Particle Physics and Nuclear Physics Groups at the University of Birmingham have been operating the MC40 cyclotron with UK colleagues from Sheffield and Liverpool since 2013 as an irradiation facility for nuclear, medical and particle physics collaborations, such as RD50, ATLAS and LHCb. This facility offers a proton beam with energy up to 40MeV and currents as high as 2uA, allowing to reach a fluence in the order of 10^15 1MeV neq/cm2 in minutes. Irradiations are typically performed with 27MeV protons and currents in the range of 100-500nA. Irradiations of silicon sensors are carried out in a temperature controlled cold box that can be scanned through the beam. The sensors are cooled to -25C during irradiation. Beam fluence is determined online using a Faraday Cup and offline by measuring the activity of nickel foils. Results from recent sensors irradiated at Birmingham show to be in good agreement with results from other facilities. Currently the facility is extensively used for the ATLAS ITK strips ASICs irradiation program, and it is serving a number of AIDA users. The talk will give an overview of the facility, its commissioning and recent results.

Radiation Damage I / 7

Possibilities of large fluence irradiation dosimetry using multi-crystalline Si

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It had been shown that measurements of carrier recombination lifetime can be employed for contactless and fast evaluation of large fluences of the hadron irradiations. The same calibration function for fluence evaluations derived using electron-grade crystalline silicon wafer fragments fits well the absolute values of carrier recombination lifetime related to the densities of radiation defects introduced by penetrative protons, neutrons and pions. For wide area dosimetry, the cheaper silicon material for fabrication of dosimetry sensors would be desirable. In this presentation, possibilities to exploit the multi-crystalline (mc) Si material for fabrication of such sensors will be discussed. The characteristics of the fluence dependent carrier lifetime measured on 8 MeV proton irradiated mc-Si sensors made of solar-cell standard p-Si substrates will be presented.

Sensor Design / 8

Status of the RD50-Project "NitroStrip"

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The aim of the "NitroStrip" project is to extent the "NitroSil" project by preforming charge collection measurements on strip sensors, which are not included in "NitroSil". Both projects evaluate the radiation resistance of nitrogen enriched silicon.
We will present the finally approved project plan and the current status of the project.

Sensor Design / 9

Performance of thin n-in-p planar pixel modules with and without active edge

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New productions of thin n-in-p pixel sensors designed at MPP will be presented. Sensors of thicknesses of 100 and 150 um have been produced at ADVACAM and CiS and interconnected to FE-I4 chips. At ADVACAM SOI wafers were employed, while at CiS anisotropic KOH etching was carried out to create backside cavities in the wafer leaving thicker frames around each single structure.
To maximize the active area of the thin sensors, slim and active edges were implemented in the sensors of the ADVACAM production. The evaluation assemblies have been measured by means of radioactive source scans and beam tests and the results on charge collection - and edge efficiency will be discussed. The power dissipation for thin sensors irradiated at a fluence of 1e16 will be evaluated and the performance after irradiation up to 1e16 in terms of hit efficiency of different sensor thicknesses in the range of 100 to 270 um will be discussed.
Previous investigations of different punch-through designs have led to the optimization of the pixel biasing structure to limit the related loss of efficiency at high levels of irradiation. This is particularly important for the sensors to be interconnected to the new RD53 chip, given the reduced cell size of 25x100 or 50x50 um2. A pixel sensor production at HLL on SOI wafers where these changes were implemented has been recently completed and the preliminary electrical characterization of the RD53 sensors will be discussed.

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Characterization of NitroSil diodes at KIT

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Diodes made from three different wafer materials (FZ, N-rich FZ, O-rich FZ) have been irradiated with protons (5e13 to 5e15neq/cm^2) and are being characterized (IV, CV, TCT).
Here we present the first results of these measurements.

Present and Future Experiments / 11

Radiation hardness and precision timing study of Silicon Detectors for the CMS High Granularity Calorimeter (HGC)

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The high luminosity LHC (HL-LHC or Phase-II) is expected to increase the instantaneous luminosity of the LHC by a factor of about five, delivering about 250 fb−1 per year between 2025 and 2035. Under these conditions the performance degradation of detectors due to integrated radiation dose/fluence will need to be addressed. The CMS collaboration is planning to upgrade many components, including the forward calorimeters. The replacement for the existing endcap preshower, electromagnetic and hadronic calorimeters is called the High Granularity Calorimeter (HGCAL) and it will be realized as a sampling calorimeter, including 30 layers of silicon detectors totalling 600m^2. The sensors will be realized as pad detectors with cell sizes of between 0.5-1.0 cm^2 and an active thickness between 100 µm and 300 µm depending on their location in the endcaps: the thinner sensors will be used in the highest radiation environment. For an integrated luminosity of 3000 fb−1, the electromagnetic calorimetry will sustain integrated doses of 1.5 MGy (150 Mrads) and neutron fluences of 10x16 n/cm^2 in the worst case. A tolerance study after neutron irradiation of 300 µm, 200 µm and 100 µm n-on-p and p-on-n silicon pads irradiated to fluences up to 1.6x10 16 n/cm^2 is presented. The main properties of these diodes have been studied before and after irradiation: leakage current, capacitance, charge collection efficiency, annealing effects, timing capability. As expected, the results show a good performance even after the most extreme irradiation.

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Experimental determination of the NIEL hardness factor for the new CERN proton irradiation facility.

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A new 24GEv/c proton irradiation facility replaced the old CERN facility in 2014. An experimental determination of the hardness factor of the new facility is ongoing. Results on the scaling of the leakage current with increasing fluence for several irradiations performed in 2015 and 2016 will be presented.

Sensor Design / 13

The influence of edge effects on the determination of doping profiles using silicon pad diodes

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Edge effects for square p+n pad diodes with guard rings, fabricated on high-ohmic silicon, are investigated. Using capacitance-voltage measurements of two pad p+n diodes with different areas, the planar and the edge contributions to the diode capacitance are determined separately. Different methods of extracting the doping concentration are compared. In practically all cases it is found that the results with and without edge corrections differ significantly. After edge corrections, the bulk doping determined is uniform within ± 1.5 %. The voltage dependence of the edge capacitance is compared to the predictions of two simple models. It is recommended that pad diodes of different dimensions, ideally both circular and square, should be implemented as standard test structures for sensor submissions.

Simulation and HV CMOS / 14

E-TCT measurements of irradiated HV-CMOS test structures

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E-TCT measurements with HVCMOS detectors produced by different foundries on substrates with different resistivities will be presented. Samples were irradiated with reactor neutrons in Ljubljana and with protons at CERN PS. Measurements were made with passive detector structures in which current pulses induced on charge collecting electrode could be directly observed. In reverse biased HVCMOS sensors investigated in this work the depleted region is formed in the p-type substrate. With Edge-TCT method the thickness of this layer could be estimated and it was studied as the function of irradiation fluence. It was observed that in some substrates the thickness of depleted layer increased with irradiation in certain range of fluences. The increase of depleted layer was attributed to initial acceptor removal.

Radiation Damage II / 15

Study of surface radiation damage of segmented Si sensors at Hamburg University: Results, status and next steps

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Studies of surface radiation damage and the impact of the charge distribution on the outer surface of segmented silicon sensors are ongoing at Hamburg University since 2007. In this talk, selected results obtained from measurements on test structures and strips sensors will be presented:
- dose and electric field dependence of the effective oxide charge density, Nox,
- dose and electric field dependence of the surface-current density, Jsurf,
- attempts to determine the energy distribution of the interface trap density, Dit, as function of radiation dose,
- study of the charging and discharging of radiation-induced border traps when changing the biasing conditions,
- influence of Nox on the breakdown characteristics of segmented p+n sensors,

- influence of Nox on the electric field and the charge collection of strip sensors,
- time and humidity dependence of the resistivity of the outer surface (passivation layer) of strip sensors and its influence on the charge collection.

It is concluded that the number of parameters which influence surface radiation damage depends is so large, that a complete systematic study is practically impossible and certainly beyond the capabilities of a single group. However, based on the studies presented, extreme values of parameters like Nox, Dit, and Jsurf for maximal electric fields typical for segmented silicon sensors are available. They can be implemented into TCAD simulations in order to study the joint effects of surface and bulk radiation damage for the radiation fields, which are relevant for the HL-LHC (and also the European XFEL). In addition, the importance of verifying by TCAD simulations

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CiS Planar Sensor Technologies for Future High-Luminosity-LHC Upgrades

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Planar hybrid silicon sensors are a well proven technology for past and current particle tracking detectors in HEP experiments. However, the future high-luminosity upgrades of the inner trackers at the LHC experiments pose big challenges to the detectors. The first challenge is an expected radiation damage level of 2E16 n_eq cm^-2. The second challenge is the large detector areas which have to be built as cost efficient as possible, i.e. it is aimed for low-cost and large-sized sensor material.

Various new wafer processing, electroplating or mask-less & electro-less Under-Bump-Metallization and bump deposition and mounting technologies are currently developed at CiS.
Our focus is to coordinate the technologies in order to cope with the application challenges on the one side and the cost efficiency on the other side. The target costs have to match with the full value chain of hybrid modules for inner tracker upgrades and industrial use.

The CiS research institute has accomplished a proof-of-principle run with n-in-p ATLAS-Pixel sensors where cavities are etched to the sensors back side to reduce its thickness. The membranes with areas of up to ~4x4cm² and target thicknesses of 100 and 150µm feature a sufficiently good homogeneity across the whole wafer area. Various technological approaches to realize edge-less sensor layouts, especially using active edges are developed.
For Pixel sensors different new concepts for "removable"bias grids will be investigated.
It will also presented our new opportunities to realize under-bump-metallization, cupper pillars, bump deposition using Lift-off mask or stencil printing or mask-less & electro-less processes.

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Detector Irradiation at CNA

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CNA (Centro Nacional de Aceleradores) is a spanish users facility dedicated to multidisciplinary applications of particle accelerators. The recent activities at CNA associated to irradiation of radiation detectors will be presented.

Radiation Damage II / 18

Generation shallow radiation damages at the strip surface with low energy protons.

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The aim of the shallow radiation damage generation study is the creation of a multiplication layer close to the silicon sensor surface. This is done by irradiating the sensor with low energy protons at the Birmingham cyclotron, which should stop within approximately 20µm. Geant4 simulations have been used to find the best settings for the irradiation. First sensors have been irradiated with 12 MeV protons and the results will be shown.
After the proton irradiation the whole sensors have been irradiated with neutrons at Ljubljana to fluences of 1E15 neq/cm2 and 5E15 neq/cm2. A comparison with standard sensors will be presented.

Sensors with Internal Gain I / 19

Technological Developments on iLGAD Detectors for Tracking and Timing Applications

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This presentation introduces the latest technological development on the Inverse Low Gain Avalanche Detector iLGAD as well as the first characterization results. This structure is based on the standard Avalanche Photo Diodes (APD) concept that includes an internal multiplication of the charge generated by radiation. The multiplication is inherent to the basic n++-p+-p structure, where the doping profile of the p+ layer is optimized to achieve high field and high impact ionization at the junction. In order to ensure a uniform electric field distribution along the device, the iLGAD is a pad-like LGAD with P-type multiplication layer below the N+ implant, in which we change the P+ implantation, by several P-type strips in order to segment the readout electrode, like a P-on-P microStrip detector. In this structure, we move the multiplication layer to the back-side of the chip, and define the ohmic readout elements, strips & pixels, in the front-side. That means the collecting current is dominated by holes instead of electrons.

Sensors with Internal Gain II / 20

First LGAD fabrication on 50um SOI wafers at CNM for the HGTD

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This presentation introduces the simulation and experimental results of the first Low Gain Avalanche Detector on 50um SOI Wafers fabricated at CNM for the High Granularity Timing Detector (HGTD) located in front of the forward calorimeter (FCAL).

Silicon with Internal Gain III / 21

Status of LGAD RD50 projects at CNM

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I will report the first measurements of detectors fabricated with Ga implant and the new proposal for a project to increase the radiation hardness of LGAD sensors using Carbon. In LGAD the gain decreases with irradiation, which can be attributed to effective acceptor removal in the multiplication layer. The relative decrease of measured charge is much more pronounced for LGAD than for standard devices at fluences below 1E15 n/cm2. The reason must therefore be related to the decrease of the multiplication gain rather than trapping of the drifting charge. The gain decrease can be attributed to the reduction of effective doping in multiplication layer, which leads to smaller electric field strengths.

Sensors with Internal Gain II / 22

TCT measurements and analyses of proton irradiated LGADs

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Results from the study of LGADs from CNM Run 7859 will be presented. Some of these sensors have been subjected to proton irradiation at CERN. The fluences to which these were exposed are 1E12, 1E13, 1E14 and 1E15 neq/cm^2. TCT measurements were performed before and after irradiation. These TCT studies were particularly focused on analysing: charge collection, spatial homogeneity, gain, and double junction effects. The results obtained will be shown in this presentation.

Sensors with Internal Gain I / 23

Silicon sensors with internal gain: Optimizing for charged particle fast timing

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Internal Gain in Si timing sensors is needed to overcome the ~100 picosecond lower limit encountered by NA62 GTK and the CMS HGCal projects. We focus on 2 techniques, currently available for achieving internal gain- 1) "reachthrough"in which a high field region is limited to a superficial few micron thick layer and 2) "deep-depleted AD's where it is deep and the distribution between "drift" and "gain"regions is less distinct.

We have studied deep-depleted avalanche detectors using SILVACO simulations and device characterization and report on the results.

Sensor Design / 24

Test beam and clean room studies of ATLAS PPS modules with alternative bias rail geometries

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It is known that for the current design of planar pixel sensors, there is a drop of efficiency at the punch-through structure of the biasing system at the edge of pixels. Various geometries, as part of the ATLAS Inner Tracker (ITK) upgrade, are being investigated to reduce this inefficiency.

Planar pixel sensors with multiple alternative bias rail geometries have been tested at the SPS beam test facility at CERN, with results focusing on the efficiency within the pixel. Measurements of the

pixel detectors in a clean room before and after irradiation were performed to study the noise for the varied designs. Some sensors after irradiation experienced disconnected bump-bonds. Studies into the origin of this will be presented. Future plans for further investigations are also discussed.

Sensors with Internal Gain II / 25

Design considerations on thin LGAD sensors

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In this contribution I will review the progresses made towards the design of segemented, thin LGAD for timing measurements.

Simulation and HV CMOS / 26

TCT studies on AMS H35 CMOS devices for application in the ATLAS tracker upgrade

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H35Demo chips are High-Voltage CMOS (HV-CMOS) devices produced in the 350nm AMS technology (H35) on wafers with four different substrate resistivity, the standard one of 20 Ω ·cm and 80, 200 and 1000 Ω ·cm. The aim of this HV-CMOS production is to study the radiation hardness of such detectors and investigate the possibility to introduce this technology in the next ATLAS tracker upgrade for the high luminosity
LHC.
Having the same sensor production on several resistivities will show whether resistivity higher than the standard one for HV-CMOS would bring a beneficial effect in terms of depletion depth and charge collection efficiency.
Each chip includes four different pixel matrices. Two of them are designed to be interconnected to readout chips only, whilst the other two are completely monolithic.
In addition to the pixel matrices the chips include three test structures to characterize the sensor properties.
The characterisation of test structures with different substrate resistivity has been carried out at IFAE using the Transient Current Technique (TCT). The test structure taken under examination consists of a single diode with eight neighbours that do not include additional electronics allowing to directly sample the signal waveform.
The results of TCT and edge-TCT studies on samples from all the available substrate resistivities will be shown.

Summary:

TCT and edge-TCT on H35Demo chip test structure

Radiation Damage II / **27**

Electric field, mobility and trapping in Si detectors irradiated with neutrons and protons up to 1e17 n_eq/cm^2

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Electric field in silicon irradiated with neutrons up to 1e17 n_eq/cm^2 and PS protons up to 3e16 p/cm^2 was investigated by edge-TCT. From the v(E) dependence under FW bias mobility degradation with fluence was extracted. From a comparison of concurrently measured FW and reverse velocity profiles absolute electric field profiles in the silicon bulk were obtained. A 1/sqrt(Phi) dependence of mobility on fluence was obseved for both irradiations with protons provoking ~20 % more degradation at equal NIEL. The observed mobility degradation and the values of electric field indicate substantial reduction of trapping from linear extrapolation of low fluence values. An attempt is made to extract information on trapping from the measured waveforms.

Radiation Damage II / **28**

TCT measurements of n-type MCz diodes after irradiation with 70 MeV protons and 300 MeV pions

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n-type Magnetic Czochralski (MCz) was found in earlier studies to exhibit a peculiar behaviour with irradiation, in particular not exhibiting space-charge sign inversion (SCSI) after irradiation with high-energetic hadrons such as 24 GeV protons at CERN PS or 800 MeV protons at Los Alamos while the material behaved as expected after irradiation with neutrons or low-energy 23 MeV protons at Karlsruhe.

We have investigated n-type MCz diodes irradiated with 70 MeV protons at CYRIC and 300 MeV pions at PSI by means of the transient current technique (TCT). The presentation will briefly outline the state of knowledge followed by our new results that partially include also annealing studies.

Present and Future Experiments / **30**

Timing information in HEP

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Steering Committee

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3D Pixel Detectors for AFP and HL-LHC

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Radiation Damage I / 35

HRTEM investigations of different clusters produced in Si by electron and neutron irradiation.

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Radiation Damage I / 36

ESR of point defects in pure and 17O/13C doped Si-FZ irradiated with 3.5 and 27 MeV electrons. Correlation with TSC data.

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Sensors with Internal Gain II / 38

Results from the first 300-micron thick LGAD production at FBK

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Sensors with Internal Gain I / 39

Performance of thin LGADs after irradiation

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Sensors with Internal Gain II / 40

Reasons for gain degradation with irradiation in LGADs

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Radiation Damage II / 41

Characterization of neutron irradiated pad detectors using a Transient Current Technique based on the Two Photon Absorption process (TPA-TCT)

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High-resolution three-dimensional imaging of a depleted CMOS sensor using an edge Transient Current Technique based on the Two Photon Absorption process (TPA-eTCT)

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Signal Amplification in strip-LGAD and I-LGADs

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Silicon with Internal Gain III / 45

TCAD Radiation Damage analysis of CNM-LGAD Detectors

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