Development of thin n-in-p pixel modules for the ATLAS upgrade at HL-LHC

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Introduction

- Investigation of the performance of thin n-in-p planar pixel sensors with active edges:
 - Charge collection efficiency measurements before and after irradiation
 - Hit efficiency from beam tests at DESY
- Charge collection efficiency of 200 µm thick n-in-p planar pixel sensors up to a fluence of 1.4x10¹⁶ n_{eq}/cm²
- Development of quad FE-I4 modules with planar sensors for the outer layers of the upgraded ATLAS pixel system

Future planar n-in-p pixel sensors productions

Phase II Pixel System Layout and Requirements



- 2 Outer Barrel Layers / Disks
- Probably planar n-in-p
- **Δ** Sensor thickness 150 μm
- 2x2 (Quad) chip modules

2 Inner Barrel Layers

- Sensors: different materials and technologies possible
- Radiation hardness up to 2x10¹⁶ n_{eq}/cm²
- **□** Thickness: 150 µm or lower
- Pixel pitch of 25x100 µm² or 50x50 µm² → FE-chip in 65 nm CMOS technology

Thin planar pixel sensors for the inner layers

- Reduced material budget
- Higher radiation resistance (see also talk by S. Kuehn "Silicon Sensors for High Luminosity Trackers: RD50 Status Report")

Mean cluster width along η assuming FE-I4 chip pitch along z: 250 μm







n-in-p pixels on FZ and MCZ material

 \Box 100 μ m and 200 μ m thickness \rightarrow together with the active edges makes these sensors very attractive candidates for the inner layers in Phase II

p-spray isolation method transferred from HLL to VTT

Flip-chipping performed at VTT after removal of support wafer

VTT active edge sensors



Δ 125 μm edge implemented In FE-I3 and FE-I4 sensors

5 50 μm implemented only in FE-I3 sensors

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IV of active edge modules before irradiation



Collected charge with ⁹⁰Sr, FE-I₃ module



IV after irradiation



CCE after irradiation



At high fluences (Φ =(5-6)x10¹⁵ n_{eq}/cm²):

- 100 μ m thick sensor is completely depleted at V_{bias}= 200 V
- 200 μm thick sensor still not fully depleted up to V_{bias}=400 V

Beam tests at DESY

- ❑ 4 GeV electrons
- EUDET telescope
- ~(1-1.5) kHz trigger rate
- Perpendicular beam incidence
- Data taking in Nov 2013, Feb 2014







Δp·Δg≥<mark>źż</mark>

Edge efficiency at DESY beam test

VTT FE-I3, 100μm thickness with 50 μm active edge, unirradiated



Efficiency between last pixel implant and edge of module: ~(85±1)%

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Summary of hit efficiency for thin n-in-p modules



125 μm

□ 200 µm thick sensors need higher Vbias for the hit efficiency to saturate with respect to 100 200 µm thick sensors → consistent with CCE results

Comparison of FE-I₃ and FE-I₄ performance



100 µm thickness: FE-I3 modules show a hit efficiency higher than FE-I4 modules at equal fluence and voltage

FE-I₃ module

 $V_{bias}=350 V$

Comparison of FE-I₃ and FE-I₄ performance



Second production of active edge pixels at ADVACAM



Active edge process for all the structures

Wafer layout of the new production at ADVACAM (spin-off VTT)

- In collaboration with Glasgow, Göttingen, LAL, CLIC CERN-LCD,
- Geneva University for medical applications

50, 100, 150 μm sensor thickness: 5 FZ p-type wafers for each thickness

- FE-I4 quad sensor
- FE-I4 single chip sensors different geometries
- Omegapix sensors
- TIMEPIX sensors for CLIC R&D
- CLICpix sensors for CLIC R&D
- Pixel and strip structures for medical applications

Improvement of the punch-through structure design



- Reduced space occupied by this biasing scheme allows for its application to 25x500 µm² pixels, interconnected to FE-I4 chips, used to study resolution at the pitch foreseen for inner pixel layers at HL-LHC



n-in-p FE-I4 sensors at CiS on 4" Wafers

- Production on 200 and 300 μm thick 4" wafers
- Single chip and double chip modules
- Spark protection with 3 µm layer of patterned
 BCB deposited on the sensor surface at IZM





- Guard ring structure with 450 μ m inactive edge
- Production with very good yield of 95% both for single and double chip sensors (following IBL prescriptions)

Irradiations of 200 μm thick FE-I4 sensors

- n-in-p sensor 200 µm thick produced at CiS, bump-bonded to FE-I4 chips at IZM
- Irradiated up to 1.4x10¹⁶ n_{eq}/cm² in Los Alamos with 800 MeV protons (as measured in 1 cm x 1 cm Al foil centered on the beam)
- beam spot structure observable in many scans during the tuning





Φ=1.4×10¹⁶

Charge collection of 200 μm thick FE-I4 sensors



Larger uncertainties at high fluence:

- Higher uncertainty in the charge calibration at lower ToT
- Effect of the not uniform irradiation
- Bias introduced by the threshold at low value of the collected charge

- ⁹⁰Sr beta electrons (Cd and Am sources used as reference)
- Threshold: 1600 e
- Only region of central beam-spot retained in the analysis
- 45% CCE at 800 V after 7x10¹⁵ neq/cm²
- 28% CCE at 800 V after 14x10¹⁵ neq/cm²



Hit Efficiency of 200 μ m thick FE-I4 sensors



Hit Efficiency of 200 μm thick FE-I4 sensors



Quad modules development

Quad FE-I4 modules are the baseline option in the LOI for the two outer pixel layers





- CIS 4" n-in-p wafers: 1600 μm distance between two FE-I4 Double Chip sensors diced as a quad module (~4x4 cm²)
- Read-out systems: RCE and USBPix system with Burn-in card
- In collaboration with:



GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN



Test-beam results with the FE-I4 quad module



Efficiency

n-in-p FE-I₄ sensors on 6" wafers at CIS





- Quad module: 4+4 ganged pixel rows in the center of the sensors between two chips in the y direction
 - $1450 \ \mu m$ long pixels in the x direction

Production on 6" wafers help to cover the large pixel surface foreseen for HL-LHC in a cost-effective way

- □ First 6" production at CIS
- 6" wafers on p-type FZ material,
 16 kΩ cm, 270 μm thick
- The sensors will be interconnected to the FE-I4 chips at IZM
- 3 μm BCB layer deposited as isolation against sparks between sensor and chip

Future quad module developments

- Processing of thin (~150 μm) n-in-p quad sensors on 6" wafers at CIS and ADVACAM
- Optimization of bump bonding process for thin sensors and chips (use of a glass substrate for the chip, same procedure as for IBL)



- Use of a quad flex (designed in the University of Bonn)
- Systematic irradiation program
- Study of system aspects as sensor-chip isolation: parylene coating, BCB deposition on sensor surface

In collaboration with:



GEORG-AUGUST-UNIVERSITÄT





- Excellent performance of thin pixels with active edge sensors demonstrated before and after irradiation up to a fluence of 5x10¹⁵ n_{eq} / cm²
- Charge collection studies performed with 200 μm thick n-in-p sensors up to a fluence of 1.4x10¹⁶ n_{eq} / cm²
- Development of quad modules with sensors of the same production to investigate system aspects for the upgrade of the outer pixel layers in ATLAS at HL-LHC
- $\hfill\square$ New planar pixel productions foreseen at ADVACAM and CIS with sensor thickness in the range 50-150 μm

Additional material

 $\int \Delta p \cdot \Delta g \ge \frac{1}{2}$

Active edges with planar n-in-p sensors - 100 μm thick





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Charge collection efficiency after irradiation

FE-I3 100 µm thick sensor with 125 µm slim edge, threshold 1500 e- → 87% CCE at 300 V for both all and edge pixels after irradiation at KIT (1x10¹⁵ n_{eq}/cm²)



J p-type MCZ FE-I4, 100 µm thick sensor, with 125 µm slim edge, threshold 1100 e-→ compatible charge collection properties between edge and internal pixels



Charge collection efficiency after irradiation

FE-I3 100 µm thick sensor with 125 µm slim edge, threshold 1500 e- → 87% CCE at 300 V for both all and edge pixels after irradiation at KIT (1x10¹⁵ n_{eq}/cm²) and in Ljubljana (5x10¹⁵ n_{eq}/cm²)



p-type MCZ FE-I4, 100 μm thick sensor, with 125 μm slim edge, threshold 1100 e → compatible charge collection properties between edge and internal pixels



FE-I₄ Single Chip Modules



FE-I4 with 100 µm edge, Bias Ring + Guard Ring, punch-through structures



FE-I4 with 50 µm edge, one GR, no punch-through structures

FE-I4 with 100 µm edge, Bias Ring, punch-through structures





Planar pixel sensors for fine pitches

- Timepix sensor designed in n-in-p technology for CLIC R&D \rightarrow possible example of geometry a sensor to be attached to future chip with 50x50 μ m²
- Sensor of a previous production with this bump-structure already interconnected at ADVACAM



Timepix active edge sensor for CLIC R&D: 55×55 μm², edge = 50 μm

Implant 30 μm Aluminum 40 μm UBM 25 μm Passivation 20 μm

Characterization of the quad modules

Module tuning with RCE read-out system



Charge collection for pixels of different thickness

ATLAS Upgrade Thin n-in-p pixel modules for the



Charge collection for pixels of different thickness





Performance of the 200 um thick batch



Yield following IBL prescriptions on 200 um thick wafers:

Double FE-I4 sensors I(VdepI+30V)<2 uA = 97% Single FE-I4 sensors I(VdepI+30V)<1 uA = 95%

Resolution at the DESY test-beam

$\langle \Delta_{f} \Delta_{g} \rangle \geq for not irradiated sensors$



Residual along short pixel side (50 μ m length)



Set-up for irradiated sensors



Residual along short pixel side



Test-beam measurements of the quad module

- Data from PPS beam test in November at DESY with 4 GeV electrons
- RCE for module readout
- 1 Quad (4 FE-I4B chips) & 1 FE-I4A single chip module as reference plane





The output of the 4 FE chips is encoded in a bigger device and treated as a single module for the rest of reconstruction steps

Test-beam results with the FE-I4 quad module



Possible future technologies for thin 6" wafers





- TAIKO (DISCO, Japan) process on 6" wafers
 - Leaves a thicker frame at the outer circumference
 - Lowers wafer warpage
- CIS backside-cavities
- Etching of cavities on the backside (<100> material) as alternative to the use of an handle wafer
- Technology well known from pressure sensors
- Guarantees stability on wafer level by thick frames at the sensors edges
- Sensitive area is located at the ,membrane': thickness down to 50 um should be feasible
- Dicing on the thick frames or within the cavity







High eta collected charge

- Overflow peak due to the calibration (10ToT (a) 10 ke) at the edge of the ToT range (1-14) for a particle crossing 250 μm (~20 ke)
- ToT distribution inside clusters of width X=7 along the wide pixel side



- Higher charge collected directly below the n-implant
- Study to be repeated with an optimized ToT tuning when CERN-SPS will be again available for beam-tests

Charge Collection of 200 μ m thick FE-I4 sensors

Map of the average ToT at Φ= 14x10¹⁵ n_{eq}/cm²

- Map of average ToT clearly shows different levels of irradiation over area of the module
- Tuning:

Threshold 1600e

6 ToT to 4 ke





