The CMS Silicon Pixel Detector for HL-LHC

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for the CMS Collaboration

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Outline

- The CMS Tracking Detector Upgrade for the HL-LHC
- Detector layout
- Status of pixel sensor R&D
  - Planar and 3D silicon
- Serial powering
- Modules
The High Luminosity LHC: Roadmap

- CMS Phase II Pixel Upgrade
  - Tracker TDR (Q2 2017)
  - Installation of phase-1 Pixels (Q1 2017)
  - CMS Technical Proposal & Scope Document (Q2/Q3 2015)
The Phase II Upgrade of the CMS Pixel Detector

High-Luminosity LHC:
- Luminosity of $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$, up to 200 events/ 25 ns bunch crossing
- Maintain occupancy at $\approx %$ level and increase the spatial resolution
  - Pixel size $\sim 25 \times 100$ μm$^2$ or $50 \times 50$ μm$^2$ (currently $100 \times 150$ μm$^2$)

Tilted layout:

辐射水平

Radiation level for the 1$^{\text{st}}$ pixel layer after 3000 fb$^{-1}$:
- $\Phi_{eq} \approx 2 \times 10^{16}$ cm$^{-2}$, dose $\approx 10$ MGy

3D or planar pixel sensors for 1$^{\text{st}}$ layer?
- R&D in parallel. Both options will be described and costed for TDR
Coverage of geometrical acceptance:

- **Barrel:**
  - 4 layers à la phase I: $r_1 = 2.9$ cm, $r_4 = 16.0$ cm
  - but shorter: $z_{\text{max}} = \pm 20$ cm instead of $\pm 27$ cm

- **Forward:**
  - coverage at large $|\eta|$ obtained by increasing the number of discs (11+11) $z_1 = \pm 25$ cm $z_{11} = \pm 265$ cm

**Total: ~4.5 m$^2$ of Si**

- **Simple mechanics:**
  - no turbines/blades in the FPIX discs

- **Step in the pixel envelope**
  - $r=20$ cm $\rightarrow$ $r =30$ cm at $z=160$ cm
  - to allow the installation of the central section with beam pipe in place
Charge collection studied for irradiated 200 µm thick n-in-p pad diodes
- 5k electrons at $\Phi_{\text{eq}} = 1.3 \times 10^{16} \text{ cm}^{-2}$ (900 V bias)

Thin silicon:
- Similar signal in 100 µm epi strip sensors as in 200 µm MCz: 5 k electrons at ~800V
- However: Strong increase of current and noise with voltage at $\Phi_{\text{eq}} = 1.3 \times 10^{16} \text{ cm}^{-2}$: Signs of soft breakdown/charge multiplication

Charge collection measurements need to be redone with pixel sensors: Weighting field
- HPK submission, INFN/FBK submission
CMS Preliminary

25x100 μm²

50x50 μm²

25x100 μm²

50x50 μm²

thicknenss open=100 μm/full=150 μm

threshold 1000e/1500e/2000e

Severe loss of resolution at large η for square pixels for high thresholds
Tasks: Pixel Sensors and Modules

- Technical choice for inner layer: 3D or planar Si
- Sensor bulk material: 6” n⁺-p wafers
- Chose sensor thickness
- Optimize sensor geometry and design
  - Evaluate Radiation hardness
- Sensor periphery
  - Design thin/active edges
- Bump bonding: Fine pitch, thin silicon
  - Find cost effective solution
- Spark protection at sensor edges
  - Choose BCB polymer deposition or parylene coating
Promising candidates for layers with very high radiation damage are:

- 3D pixel sensors
- thin planar pixel sensors ($100 \, \mu m \leq d \leq 200 \, \mu m$, currently $d = 285 \, \mu m$)

**Common advantage:**
- Short drift path
- Higher field at same $V_{bias}$
- Lower operation voltage
- Less power consumption

**Thin planar sensors (n-in-p):**
- Lower total $I_{leak}$ after irradiation
- Less material (multiple scattering)

**Drawbacks:**
- Smaller initial signal (76 e$^{-}$/μm)
- Thinning step required
- Sensor „bow“

**3D sensors:**
- Thicker sensors possible

**Drawbacks:**
- Higher capacitance
- Lower yield
- Higher cost
Thin, small pitch planar pixel sensors

- HPK submission \((n^+\text{-p})\)
  - \((50\times50, 25\times100, 30\times100 \, \mu\text{m}^2)\) sensor design options on thin \((150 \, \mu\text{m})\) n-in-p wafers
- INFN – FBK R&D program, together with ATLAS \((n^+\text{-p})\)
- SINTEF \((n^+\text{-n})\)

First thin small pixel test sensors work well

Next step: Demonstrate radiation hardness

3D silicon

- INFN – FBK R&D program (3D batches)
- CNM Barcelona

Successful production of 3D sensors. Next step: Demonstrate feasibility of small pixels.
ROC Options for R&D

- **PSI46dig** and PROC600
  - IBM 250 nm, 100 x 150 μm², 80 x 52 pixels, rad hard > 5 MGy (PROC600)

- ROC4Sens (PSI)
  - IBM 250 nm, 50 x 50 μm², 155 x 160 pixels, no charge threshold, rad hard > 5 MGy, operated with CMS pixel test board, **staggered BB pattern**, opening 15 μm
  - available since summer 2016 (on PROC600 wafer)

- FCP130 (FNAL)
  - GF 130nm, 30 x 100 μm², 160 x 48 pixels, threshold: ~1000 e⁻, rad hard few MGy, DAQ under development
  - availability foreseen early 2017

- RD53A:
  - 65nm, 50 x 50 μm², 400 x 192 pixels, min. threshold: 600 e⁻, rad hard up to 10 MGy **non-staggered BB pattern**
  - availability 2017

For ROC developments, see also talks on “**RD53 status and plans**” by L. Gaioni and “**Radiation Tolerance of 65nm CMOS**” by M. Menouni (Thu)

- FEI4 (ATLAS) (used for serial powering studies)
  - GF 130 nm, 50 x 250 μm², 336 x 80 pixels, threshold < 2000 e⁻, rad hard > 5 MGy
HPK Submission on 6” n⁺-p wafers

- 35 wafers 6” n⁺-p FZ, 3 materials
  - 150 µm, no handle wafer
  - 150 µm + 50 µm Si-Si direct bond
  - Deep diffused 150 µm + 50 µm
  - P-stop and p-spray isolation (only dir. bond)

Aims of the R&D submission:

- Evaluate pixel geometry: 25x100 vs. 50x50 µm²
- Study and Optimize sensor design
  - Pixel isolation: p-stop vs p-spray (rad-hardness)
  - Bias scheme for small pixels
    - no bias, common punch through, polysilicon bias
  - Metal overhang to mitigate E-field
  - Signal routing

Pixel sensors for these r/o chips:

- PSI46/PROC600, ROC4sens, RD53a, FCP130, CHIPiX65, (FE-I4)

Design with HPK, wafers expected back early 2017
INFIN Planar Submission

- Common ATLAS and CMS pixel R&D at FBK Trento funded by INFN
  - n-in-p pixels on 6”, new 6” production line!

Aims of the R&D submission:

- Study and optimize pixel sensor design
  - P-spray vs P-stop isolation
  - Punch through versus no punch through bias structures
- Evaluate module/ interconnectivity issues
  - Thinning (before/after processing)
  - Explore bump bonding technologies: IZM Berlin, SELEX Rome
  - Spark protection (BCB)
- 2 planar batches (plus 1 more to come)
  - Dec 14: Qualification batch, 100/130 µm thickness
    - 31 modules (PSI46): First results, irradiation and analysis ongoing → Successful 100 µm pixel production!
- Planar Active/Slim Edge batch: Sensors in production, first process steps done
3D Sensors: CNM Run

- 3D pixel sensors fabricated by CNM, Spain
- IBL run, read out with CMS PSI46dig ROC
- 100x150 µm²

Double sided 3D process yields good sensors with "standard" pixel size
3D: Small Pitch Run at CNM

- Joint RD50 project: ATLAS, CMS, LHCb
- 230 µm wafer, n-in-p, double sided
- CMS: Sensor designs for 3 chips
  1) ROC4sens 50x50 µm²
  2) PSI46dig 100x150 µm²
  3) Fermilab FCP130 30x100 µm²
- Aims:
  - Test small pitches (25x100 and 50x50)
  - Aspect ratio: 8 µm holes in 230 µm (1:25)
  - 100 µm and 200 µm slim edges
  - Radiation hardness of different layouts

5 wafers completed December 2015
All diced
Investigating Ni/Au UBM
(electroless and electroplating)
Flip-chip to FE-I4 validation in progress
Status of INFN R&D on 3D Pixel Sensors

- 3D sensors made with single sided DRIE (deep reactive ion etching) process at FBK Trento, Italy

- Si-Si Direct Wafer Bond (DWB) **100 µm and 130 µm active FZ**, 500µm handle CZ

**Aims:**

- Trying "the technology limit" with many small pitch structures

- Production completed, 3D wafer quality overall satisfactory

- Bump bonding to FE-I4 + PSI46dig at Selex in preparation

- Investigations of small pitch 3D pixels to come

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See also talk by G.-F. Dalla Betta on "Small pitch 3D devices" (Thur 9 am)
Pixel Phase II Powering Baseline

- Required power: ~20 kW for 4.5 m²
  - Traditional powering schemes (phase-0: direct from PS, phase-I: DC-DC converter) cannot be used due to material and space issues (aggravated by forward extension) and radiation → investigate serial powering across modules
  - Material gain factor given by # of modules in series
- Serial powering: current driven (voltage drops ~not relevant) and intrinsically low mass; not very efficient and failure modes needs to be carefully evaluated
- Gain experience with setup based on ATLAS FEI4
- Shunt-LDO* circuit is the heart of SP approach
  - Integrated in the ROC itself
  - Developed for FEI4 chip family, being ported in RD53
  - Provides regulated voltage, shunts the excess current (*LDO: Low Dropout Regulator)
Modularity and Modules

- No opto-electronic device able to withstand the radiation environment of the inner layers.
- Solution: “remote” IpGBT placed on the pixel service cylinder and connected to the module (readout and control signals) via e-links cables.
- Modularity defined by matching output rates of modules to e-link and IpGBT specs.

- Minimal number of module types e.g. 2x1 or 2x2 ROCs/module with typical size of a ROC 2x2 cm².
- No wedge shaped modules.
- Possibly small/large pixels in different layers/discs.
Conclusion

- HL-LHC poses high demands on pixel detector
  - Radiation hardness → thin sensors with radiation hard design
  - Efficient and precise tracking at high rates → small pixel pitches
  - Radiation tolerant, fine pitch, low noise readout chips → RD53
  - Fast links

- R&D programs to develop thin, fine pitch sensors and address pixel design issues
  - Planar: HPK submission, INFN/FBK (together with ATLAS), SINTEF
  - 3D: INFN/FBK (together with ATLAS), CNM

- Fine pitch bump bonding of thin sensors/ROCs challenging and a major cost driver

- Serial Powering baseline, R&D ongoing

- Tracker Upgrade TDR due next year!
BACKUP
From n-in-n to n-in-p

- n-in-p single sided process
  - More vendors, cost effective

- Thin sensors: Especially costly for double sided n-in-n

- n-side readout preferred
  - Electrons: Higher mobility than holes, higher lifetime
    → Advantage to collect electrons at high weighting field ($E_W$)
  - Excess noise observed in p-in-n strip sensors for $\Phi > 1 \times 10^{15}$ cm$^{-2}$
  - T-CAD simulations confirm that p-in-n sensors have the tendency to exhibit high electric fields at the strips due to positive oxide charges (likely curable by careful design)

Noise histograms in 80 $\mu$m pitch strip sensor

- n-in-p
- p-in-n
n-in-p mini strip sensors from HPK Outer Tracker campaign in DESY testbeam

5000 e⁻ at ~800 V

Similar collected charge to 200 µm MCZ/FZ!

However: Strong increase of current and noise with voltage at $\Phi_{eq} = 1.3 \times 10^{16} \text{ cm}^{-2}$: Signs of soft breakdown/charge multiplication
Addressing the Sparking Problem

Sparking between ROC and sensor is a concern for single-sided n-on-p pixel modules. Also of concern for OT modules. Possible solutions:

- Parylene coating of entire module after assembly
- BCB polymer deposition during processing (cut lines exposed?)