The Compact Muon Solenoid Experiment

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Sensors for the CMS High Granularity Calorimeter

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Abstract

The CMS experiment is currently developing high granularity calorimeter endcaps for its HL-LHC upgrade. The design foresees silicon sensors as the active material for the high radiation region close to the beampipe. Regions of lower radiation are additionally equipped with plastic scintillator tiles. This technology is similar to the calorimeter prototypes developed in the framework of the Linear Collider by the CALICE collaboration. The current status of the silicon sensor development is presented. Results of single diode measurements are shown as well as tests of full 6-inch hexagonal sensor wafers. A short summary of test beam results concludes the article.

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Sensors for the CMS High Granularity Calorimeter

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ABSTRACT: The CMS experiment is currently developing high granularity calorimeter endcaps for its HL-LHC upgrade. The design foresees silicon sensors as the active material for the high radiation region in the electromagnetic section and the forward region of the hadronic part. Regions of lower radiation are equipped with plastic scintillator tiles. This technology is similar to the calorimeter prototypes developed in the framework of the Linear Collider by the CALICE collaboration. The current status of the silicon sensor development is presented. Results of single diode measurements are shown as well as tests of full 6-inch hexagonal sensor wafers. A short summary of test beam results concludes the report.

KEYWORDS: Calorimeters, Particle tracking detectors, Timing detectors, Radiation-hard detectors, Si microstrip and pad detectors

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1 Introduction

The High-Luminosity LHC (HL-LHC) upgrade planned for 2026 will yield significantly increased instantaneous luminosity of up to $7 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$. After the estimated time of operation of 10 years, the total integrated luminosity seen by the Compact Muon Solenoid (CMS) detector [1] will amount to about 3000fb^{-1} . The current calorimeters have been designed for nominal LHC conditions and will be replaced by new High Granularity Calorimeters (HGCAL).

The HGCAL is planned as a sampling calorimeter consisting of 600 m^2 of segmented silicon sensors in high radiation regions. In regions of lower radiation, additional 500 m^2 of plastic scintillators readout by SiPMs (Silicon PhotoMultiplier) will be installed. The expected fluences at the end of the HL-LHC operation in the endcap region are shown in Figure 1. Close to the beampipe at the location of the electromagnetic shower maximum, the fluence is highest with about $10^{16} n_{\text{eq}}/\text{cm}^2$, with n_{eq} being the 1 MeV neutron equivalent. The integrated ionizing radiation dose is expected to amount to about 1.5 MGy (150 Mrads). The HGCAL is designed with a pseudo-rapidity coverage as the current endcap calorimeters of $1.47 < |\eta| < 3.0$ [2]. It will be able to cope with the high background from collisions occurring in the same bunch crossing (pile-up) and reliably identify and measure photons, electrons and jets.

This conference contribution summarizes the current status of the HGCAL silicon sensor development. Results of single diode measurements are shown as well as tests of full 6-inch hexagonal sensor wafers with 135 cells.

2 Design

The choice for a high granularity silicon-based calorimeter follows the considerable experience of silicon detectors in high energy physics and, especially, that obtained from the CMS tracker,

Figure 1. Cross-section of the endcap calorimeter region with the expected fluences for HL-LHC [2].

the RD50¹ and CALICE² [3] collaborations. The coverage of a 600 m² area with silicon is made possible by the drastic reduction in silicon production cost, resulting from improvements in silicon processing technology. The HGCal is subdivided into three components, as shown in Figure 2. The Electromagnetic Endcap (EE) calorimeter is situated closest to the Interaction Point (IP). It consists of 28 layers of silicon sensors with copper, copper-tungsten and lead absorbers with a total depth of 25 radiation lengths (X_0) and 1.3 interaction lengths (λ). The Front Hadronic calorimeter (FH) consists of 12 layers of silicon sensors and scintillators with steel absorbers for a total of 3.5 λ . The Back Hadronic calorimeter (BH) is farthest away from the IP and has 12 layers similar to the FH but with thicker absorber layers, amounting to a total depth of 5.5 λ . The power consumption of one endcap calorimeter will be about 60 kW at the end of the calorimeter lifetime. The entire calorimeter will be operated at -30°C cooled by bi-phase CO₂ to reduce the silicon leakage current and, consequently, maintain good signal-to-noise ratio after irradiation.

2.1 Silicon Modules

The silicon module designs currently consider hexagonal sensors of 6" or 8" in diameter. In addition to the sensor, the single modules consist of elements for mechanical handling and readout electronics. For the results reported below, only 6" sensors have been used. The hexagonal shape of the sensors has been chosen to maximize the active detector area that can be obtained from a single wafer. The sensor area is subdivided into hexagonal cells with an area of 0.5 to 1 cm² each, thus amounting to about 128, 256 or 512 cells, depending on the wafer size. The cell size is chosen to limit the cell capacitance to 60 pF, for all employed sensor thicknesses. Figure 3 shows a bare sensor on a copper-tungsten (25, 75%) baseplate. At the sensor edges, the gold-plated KAPTONTM foil between the sensor and the baseplate is visible, insulating the sensor from the baseplate and

¹RD50 Radiation hard semiconductor devices for very high luminosity colliders. <http://rd50.web.cern.ch/rd50>

²A high granularity calorimeter system optimised for the particle flow measurement of multi-jet final states at the ILC, running with centre-of-mass energy between 90 GeV and 1 TeV. <https://twiki.cern.ch/twiki/bin/view/CALICE>

Figure 2. Cross-section of one of the two HGCALs highlighting the design [2].

providing bias contact with the back plane of the sensor. The baseplate provides mechanical

Figure 3. A hexagonal silicon sensor during assembly in a module [4]. The baseplate and the KAPTON™ foil are visible.

stability, serves as heat sink and as calorimeter absorber. Its thermal expansion coefficient is close to that of silicon. Each of the sensor cells is wire-bonded through a hole in a hexagonally shaped PCB (Printed Circuit Board) and connected to the front-end readout ASICs (Application-Specific Integrated Circuit). A cross-section of a module is shown in Figure 4.

2.2 Cassettes

For the deployment in the detector, modules are mounted on both sides of 6 mm-thick wedge-shaped copper cooling planes with embedded pipes for CO₂ circulation. The 30-degree wedges are closed on both sides by steel-clad lead plates that act as the main absorbers and also provide mechanical rigidity and protection. Each of these ‘cassettes’ integrates its own front-end electronics and all services.

Figure 4. Cross-section of a sensor module [2], showing the main design elements.

3 Performance tests of Silicon sensors

A series of tests with diodes and sensors from Hamamatsu Photonics (HPK) has been performed to determine the optimal design for the sensors. In the following, a selection of results is shown from electrical tests of single diodes, full wafers and beam tests.

3.1 Single diode tests

The effect of irradiation on different layouts of silicon sensors has been studied, using single diodes. While the high-fluence regions close to the beampipe require thin sensors to mitigate the effects of radiation damage, the outer regions can be equipped with thicker sensors. Figure 5 shows the collected signal for different sensor thicknesses and types as a function of the fluence. In this investigation, n-type sensors consistently yield a slightly higher signal than p-type sensors. The sensors of about 300 μm thickness yield the highest signal at low irradiation, but their performance drops drastically with higher irradiation. For highest fluences, a small sensor thickness of 120 μm is necessary to maintain a reasonably high signal. The data points of the 300 and 200 μm thick sensors are linearly extrapolated (dashed lines) to allow the direct comparison to the respective thinner sensor in the region of higher radiation. The effects of radiation damage can be partially mitigated by a higher bias voltage. Consequently, the sensors are designed to withstand a bias voltage of up to 1000 V. At the maximum fluence of $1 \times 10^{16} n_{\text{eq}}/\text{cm}^2$ the diodes still show good signal and are capable of resolving a single MIP (Minimum Ionizing Particle) from the background noise with suitable electronics.

The HGCal is also aiming at a precise timing resolution of about 50 ps to improve the pileup rejection [2]. Beam tests demonstrated that an intrinsic resolution of about 20 ps is achievable for a signal of 20 MIPs [5].

3.2 Full wafer tests

The hexagonal sensors are produced from a single wafer and, before being assembled into modules, a quality assessment is performed. Sensor testing setups based on probe stations are used to perform semiautomatic IV and CV measurements of all cells on the sensor. The sensor is held by vacuum on the chuck of a probe station and each cell's contact pad is contacted simultaneously with a spring-loaded needle (pogo pin) fixed on a specially produced probe card. The probe card routes

Figure 5. Effect of neutron fluence on the collected signal for different sensor thicknesses [2].

the signal to an external switching matrix, which is connected to the measurement devices. To cope with a large number of channels (> 128), a special switch card has been produced at CERN. It carries 64 primary multiplexers (MUX) with 8 channels each and is therefore capable of switching between up to 512 channels. An exchangeable probe card with pogo pins has been designed and can be plugged into the switch card. This two-card solution allows a quick adaptation of the setup to new sensor geometries. Temperature and humidity are monitored with sensors on each card.

First tests show an excellent quality of the sensors. None of the cells on any of the sensors tested showed a breakdown voltage below 1000 V and the total current of one full sensor is in the low μA and often even 100 nA range. The cell capacitance values at full depletion for 300 μm sensors are in the expected range and the depletion voltage is about 180 V. Figure 6 shows the recorded leakage current values for all cells at a bias voltage of 1000 V. The cells in the edge regions show a higher leakage current, which is most likely due to lower crystal quality in the periphery during wafer growth. Figure 7 shows the recorded cell capacitances at a bias voltage of 300 V, well above the depletion voltage. As expected, cells with smaller surface area show smaller capacitances than full cells.

3.3 Beam tests

A prototype setup of a part of the HGCal using the aforementioned sensors has been tested in beam tests at FNAL [6] and CERN in 2016, using a flexible mechanical support structure to allow the testing of multiple detector configurations. The detector at FNAL consisted of 16 sampling layers of silicon sensors interspersed with tungsten plates, amounting to a total thickness of up to $15 X_0$. The detector at CERN consisted of 8 layers with tungsten and lead absorbers in two configurations, with sensors at thicknesses of 6 to 15 and 5 to 27 X_0 . The FNAL test beam facility can provide protons at energies of 120 GeV and electrons at 4 to 32 GeV. The test beam at CERN offers higher energies of 20 to 250 GeV for electrons. For particular studies, also 125 GeV pions and muons

Figure 6. Cell leakage current for a 6" sensor with 135 cells at 1000 V.

Figure 7. Cell capacitance for a 6" sensor with 135 cells at 300 V.

were used. In both cases, the analog signals were readout using the 64-channel SKIROC2 ASIC, developed for the CALICE collaboration [7]. The data were recorded with a custom DAQ (Data Acquisition) system, designed to be scalable using commercially available components mounted on custom PCBs [8]. The data were collected and stored in FPGAs (Field-Programmable Gate Array). They were then routed to an Avnet ZedBoard³ connected to a PC via ethernet.

The sensors tested at FNAL had a thickness of 200 μm and 128 cells. The test beam analysis showed that the signal-to-noise ratio for a single MIP is around 7 for all sensors and cells. Summing the signals in all cells above a threshold of two MIPs, the distribution of the deposited energy in each silicon sensor was determined. Using a Gaussian fit to the distribution of the weighted sum of the energy of all layers, the detector response was determined. It is shown as a function of the beam energy in Figure 8 and compared to a simulation based on Geant4 [9]. The data agree with the simulation within uncertainties. The analysis of the test beam data recorded at CERN is ongoing.

Figure 8. Energy response observed as a function of the beam energy. Data are shown in red, the simulation is shown in blue [4].

4 Conclusion

The endcap calorimeters of the CMS detector will be replaced for HL-LHC by a High Granularity Calorimeter (HGCAL). The new HGCAL uses silicon sensor technology to achieve high granularity, a timing resolution of less than 50 ps to suppress the large background from pile-up events and sustain the expected radiation level. Single sensor tests demonstrate the excellent electrical properties of the sensor prototypes. A series of beam tests is being performed to demonstrate the detector performance. Based on the results of these tests, the main design decisions will be taken and a Technical Design Report (TDR) is planned for the end of 2017.

References

- [1] S. Chatrchyan et al., *The CMS experiment at the CERN LHC*, *JINST* **3** (2008) S08004.

³<http://zedboard.org>

- [2] The CMS Collaboration, *Technical Proposal for the Phase-II Upgrade 298 of the CMS Detector*, 2015, CERN-LHCC-2015-010.
- [3] J. Repond et al., *Design and Electronics Commissioning of the Physics Prototype of a Si-W Electromagnetic Calorimeter for the International Linear Collider*, *JINST* **3** (2008) P08001. arXiv:0805.4833v1.
- [4] R. Rusack, *High Granularity Calorimeter for the CMS Endcap at HL-LHC*, 2016, CMS-CR-2016-444.
- [5] E. Curras et al., *Radiation hardness and precision timing study of silicon detectors for the CMS High Granularity Calorimeter (HGC)*, *Nucl. Instr. Meth.* **845** (2016) A60.
- [6] R. Chatterjee, *First results from a beam test of a high-granularity silicon-based calorimeter for CMS at HL-LHC*, 2016, CMS-CR-2016-338.
- [7] S. Callier et al., *SKIROC2, front end chip designed to readout the Electromagnetic Calorimeter at the ILC*, *JINST* **6** (2011) C12040.
- [8] P. Rubinov, *Development of a Flexible, Scalable, Low Cost Readout for Beam Tests of the High Granularity Calorimeter for the CMS Endcap*, 2016, poster presentation at the IEEE NSS/MIC Conference 2016.
- [9] S. Agostinelli et al., *GEANT4: A simulation toolkit*, *Nucl. Instr. Meth.* **506** (2003) A250.