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The CMS Pixel System

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Abstract

The CMS hybrid pixel detector is located at the core of the CMS tracker and will contribute significantly to track and vertex reconstruction. The detector is subdivided into a three layer barrel, and two end-cap disks on either side of the interaction region. The system operating in the 25 ns beam crossing time of the LHC must be radiation hard, low mass, and robust. The construction of the barrel modules and the forward disks has started after extensive R&D. The status of the project is reported. © 2005 Elsevier Science. All rights reserved

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1. Introduction

The operation of detectors at the LHC is challenging. At design luminosity the LHC will produce about 20 primary interactions, ~ 1000 particles per beam crossing at a rate of 40 MHz. This particle flux implies an expected a dose of 3×10^{14} neq/cm²/year 1MeV neutron equivalent at 4 cm from the interaction region at a luminosity of 10^{34} cm⁻² s⁻¹.

The CMS pixel detector [1] shown in Fig. 1 covers a pseudorapidity range $-2.5 < \eta < 2.5$, matching the acceptance of the central tracker. The pixel cell size of 150×100 μm^2 has been chosen to provide high-resolution 3D space points close to the interaction point for precise vertex determination and fine granularity for charged track pattern recognition. The pixel detector is essential for the reconstruction of secondary vertices from b and tau decays, and forming seed tracks for the outer track reconstruction and L2/L3 triggering [2]. It consists of three barrel layers (BPix) with two end-cap disks (FPix), on each side as shown in Fig 1. The 53 cm long BPix layers will be located at mean radii of 4.4, 7.3 and 10.2 cm. The FPix disks extending from ~ 6 to 15 cm in radius, will be placed on each side at $z = \pm 34.5$ and $z = \pm 46.5$ cm. Bpix (Fpix) contain 48 million (18 million) pixels covering a total area of 0.78 (0.28) m².

The Lorentz drift of the electrons inside the magnetic field of 4 T leads to charge spreading of the order of 150 μm for unirradiated sensors ~ 300 μm thick. Therefore the charge will be collected in more than one pixel. Charge interpolation leads to an improved spatial resolution. The forward detectors are tilted at 20° in a turbine-like geometry to induce charge sharing so that the drift direction is not parallel to the magnetic field. A position resolution of approximately 10 μm in both directions can be achieved with charge sharing between neighboring pixels. The reduction in the depletion depth or the increase in bias voltage will lead to a reduction of charge sharing and therefore a degradation of the spatial resolution with radiation damage.

Fig. 1 Schematic view of the CMS pixel system

2. Sensor Design

The sensors are “n-on-n” with n⁺ implants on n bulk silicon. Electron collection has the advantage that after irradiation induced space charge sign inversion, the highest electric field is located close to the collecting electrodes. Therefore n-on-n sensors can be operated after type inversion, but require inter-pixel isolation. BPix and FPix have adopted a moderated p-spray [3] and optimized p-stop isolation [4] respectively. The layout is shown in Fig. 2. Due to possible failures in the pixel-readout chip (ROC) contacts biasing is needed. This is

realized by a bias grid and punch-trough structures for the p-spray detectors and by openings in the rings for the p-stop detectors. Guard rings have been implemented on the p-side of the sensor, keeping the edges of the sensor at ground potential. The design of the guard rings has been optimized to reach a breakdown voltage exceeding 600 V.

Fig. 2 Layout of the pixel sensors: p-spray (left), pstop (right)

Beam tests have been performed with irradiated and non-irradiated sensors. Most of the BPix tests were conducted using PSI30, a preliminary version of the ROC with a pitch of $125\mu\text{m} \times 125\mu\text{m}$, while FPix used the final PSI46 chip. The track detection efficiency was measured for both technologies. After a fluence of 8×10^{14} neq/cm², above the goal of the CMS TDR, the detection efficiency is 98.8% and $(97.5 \pm 0.1)\%$ for Bpox and Fpix respectively [5]. The p-spray sensors have been irradiated up to proton fluences of 2.6×10^{15} neq/cm². The total charge collected at a bias of 600 V after 1.2×10^{15} neq/cm² (2.6×10^{15} neq/cm²) was about 60% (28%) compared to an unirradiated sample. At the same bias, the detection efficiency of the sensors is above 95% after a fluence of 1.2×10^{15} neq/cm² using a pixel threshold of 3 k-electrons. These results [5] surpass the CMS goals [1].

3. The readout chip

The readout chip (ROC), described in [6], must detect signals above a threshold, assign them to the correct bunch crossing, and store the information during the $3.2\mu\text{s}$ latency of the CMS trigger. The ROC (PSI46V2) is fabricated in a commercial $0.25\mu\text{m}$ process made radiation tolerant by following modified layout rules [7]. The chip incorporates 1.3 million transistors in an area of $7.9\text{ mm} \times 9.8\text{ mm}$. Its function can be divided into three sections: a control and supply block in the chip periphery, an array of pixel unit cells (PUC) organized in double columns, and the double column periphery which transfers the hit information from the pixels to the storage buffers as soon as possible and performs trigger verification. The total number of pixels is 80×52 with a pixel size of $100\mu\text{m} \times 150\mu\text{m}$. The pixels are organized into 26 double columns of 2×80 pixels.

The chip periphery contains control and supply circuits. The serial programming interface is based on an I²C-like protocol, modified to run at 40 MHz. Low voltage differential signal (LVDS) pairs provide clock and data lines. First level triggers and commands for reset and calibration signal injection are coded into a single LVDS signal. Digital-to-analog converters (DACs) adjust offsets, gains, thresholds, supply voltages, timings, etc. Control registers set the trigger latency, the readout speed, the range for calibration pulses and can enable/disable the ROC. A band-gap voltage reference and programmable voltage regulators lead to a good immunity against power ripple and reduce chip-to-chip cross talk.

The pixel unit cell contains a charge sensitive preamplifier, a shaper, and a comparator. A global threshold can be programmed for the whole chip but each pixel has a 4-bit DAC to trim the threshold to compensate for local

mismatches. When the amplitude of the shaper output signal exceeds the comparator threshold, the periphery of the chip is notified and the amplitude is stored in a sample-and-hold capacitor. The double column periphery then creates a time stamp and initiates a scan which copies the amplitude of all hit pixels into the data buffers. After the trigger latency the buffers are either deleted or readout. In case of a trigger confirmation the double column is reset after the readout.

Data losses can occur at several stages in the readout chain. The data losses are due to a pixel being busy while the charge is transferred to the data buffers, the reset of the double column after each triggered readout, and overflow of the local buffers. At a radius of 4 cm the total data loss is estimated to be about 3.8% at a luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

The performance of the ROC has been evaluated in test beam and the lab. The pulse height response to calibration signal injection is linear between 10 and 20 k-electrons. The response is slightly non-linear at low charges and saturates for charges above about 2 MIPS. The intrinsic noise of the preamp/ shaper has been measured to be ~ 190 and 120 electrons with the p-spray and p-stops detectors respectively. The threshold distribution should be as uniform as possible. The width of a Gaussian fit to the untrimmed threshold distribution of a ROC is around 300 electrons. After trimming, the threshold dispersion is ~ 80 electrons. For an absolute threshold of 2500 electrons the effectively in-time threshold is at ~ 3200 electrons, i.e. the time difference between a signal of 3200 electrons and very high charges above 100K electrons is below 25 ns. The ROC consumes a total of about 120mW which corresponds to only $29 \mu\text{W}$ per pixel. The radiation hardness has been evaluated up to a dose of 13.2 MRad.

4. Bump bonding

The signal charge created by a particle traversing a pixel on the sensor is passed to the ROC by a $\sim 15 \mu\text{m}$ diameter bump. Bump deposition is a process where a metal (In or SnPb) is deposited on wafers through a masks on which small diameter holes are opened by a photolithographic process. The metal enters the holes and sticks to the Al bond pads patterned upon each pixel and read-out channel. In order to have a strong bond, a thin interface, usually Cr or TiW, must be deposited on the Al pad. The underbump metallization is specific to the bumping process. The metal deposition can either happen through vacuum deposition (e.g. indium) or through an electroplating process (e.g. Sn Pb).

A wet lift-off step takes away the polyamide and the In deposited on it, leaving the bumps on the wafer pads. In the electroplating SnPb process, the bumps are reflowed by heating the wafer. This changes the shape of the bumps from cylindrical to spherical. If bumps are reflowed they are deposited only on one wafer (usually the ROC wafer), while on the mating wafer only the underbump metal is deposited. In the In process, bumps are deposited on both sensor and electronics wafers.

Electronics wafers are $500 \mu\text{m}$ thick, but the active volume is confined to few microns close to the surface. The wafers are thinned by backside grinding down to $150 \mu\text{m}$. After the thinning step, parts are diced out of wafers and connections through a flip-chip process which must achieve a precision placement of $\sim 1\text{-}2 \mu\text{m}$. FPix has selected two vendors for bump bonding: RTI (USA) and IZM (Germany). BPix is instead performing In bump-bonding in house [8]. The throughput is about 20 modules/week for BPiX and 40 modules/week for FPiX when both vendors are in production. Preliminary evaluations suggest a bump bonding yield of about 80%. Reworking of the bump bonded modules is already in place at PSI and IZM.

5. Assembly and Testing

BPix consists of about 800 detector modules that are mounted in three layers on a structure of thin-walled aluminum pipes and carbon fiber cross-pieces. Each of the cylindrical layers is formed by two half-shells. While

the majority of the modules are full modules as seen in Fig. 1, the edges of the six half-shells are equipped with 16 half-modules each. A half-module has eight readout chips.

Each module [9] is composed of readout chips bump bonded to sensors supported by a 250 μm thick silicon nitride material base strip. The module is glued to a High-Density Interconnect (HDI) composed of a low mass three layer PCB with a trace thickness of 6 μm . The HDI hosts the Token Bit Manager chip (TBM) which controls the readout of the ROCs. A power cable is soldered to the HDI while a signal cable is glued to the HDI. Electrical connections from the flex print to the TBM and to the signal cable are provided by wirebonding. The assembled HDI are tested for the functionality of the TBM and for shorts or broken traces in power and token passage lines [10].

A completed full module has the dimensions $66.6 \times 26.0 \text{ mm}^2$, weight 2.2 g plus up to 1.3 g for cables, and consumes 2W of power. The completed modules are extensively tested before and after thermo-cycling between room temperature and -20°C . The fully automatic test setup can handle up to four modules in parallel [10]. The module assembly procedure is capable of a constant rate of three modules per working day. In parallel to that four HDIs can be assembled together with the processing of ROCs and sensors for the bump bonding. Production started in June 2006 and about 200 full modules have been completed. We expect that all modules needed for BPix and spares to be produced in about 9 months.

A total of 672 detector modules, called plaquettes, are needed for FPix. A plaquette, as shown in Fig. 3, is comprised of a bump-bonded module, which is a sensor bump-bonded to several ROCs, joined with adhesive and to a Very High Density Interconnect (VHDI) flex circuit on a supporting silicon plate. The joining is made using parallel plate fixtures aligned on linear rails. The alignment of components is inspected using a coordinate measuring machine. A flexible plate is used for fine adjustments on the fixtures resulting in alignments between joined components within 100 μm . The adhesive bond between plaquette components is made in a vacuum at 60°C , to soften the adhesive and prevent air entrapment. An air cylinder applies and controls the mating pressure, which is limited by the compression allowed on the bump-bonds. The effects of thermal cycling and radiation on the assembled plaquettes have been extensively tested. The tests demonstrate that the adhesive and the application method mitigate warpage due to temperature changes, and provide reliable strength and thermal conductivity. Once plaquettes are mechanically joined, they are clamped in cassettes that accommodate all processing steps such as wirebonding which provides electrical connections between the ROCs and the VHDI. Due to the geometrical constraints, five types of plaquettes with different dimensions are needed.

Fig. 3 Sketch of a plaquette (left) and photo of a panel (right)

After assembly, the plaquettes undergo quick testing at room temperature. During this test the quality of the plaquettes is evaluated in terms of the characteristics of the sensor, the readout chip, the number of bad pixels and missing bonds. If few ROCs on the bump-bonded module fail specifications they are removed with a diamond wire and the module is send back to the bump bonding company for rework. The assembly and testing rate is optimized for a rate of six plaquettes per day. Production started in July 2006 and it is expected to be completed in April 2007. We have currently completed about 200 plaquettes.

Several plaquettes (three or four) are placed on top of a panel to provide full acceptance. The panel uses a beryllium substrate for structural support and heat spreading. A 3M bonding tape, and a kapton flex-circuit (HDI) are assembled on the Be substrate. Several passive components (resistors, capacitors, and an RTD) are soldered to pads on the HDI surface. In addition, wires must be attached to the panel for bias voltage and ground. One TBM is glued on the HDI to control the readout of the plaquettes on the panel. The plaquettes are installed onto the HDI with a 7-mil double-sided tape (Chootherm 1680). The thickness of the tape allows it to conform to the uneven surface of the HDI. Precut pieces of Chootherm are located on the HDI with a fixture. Plaquettes are then butted up against pins and positioned onto the tape with vacuum transfer bars.

Before placing the plaquettes on panels extensive testing takes place. These tests include a 2-days burn-in with temperature cycling between -15 and 20°C and characterization of the ROCs, the bumpbond yield and the sensors. Similar test are repeated after the panel are assembled. The construction of the 192 panels needed for FPIX has started at the level of 1 panel/day but we plan to increase the rate to 2 panels/day. Fig. 3 shows an assembled panel.

Panels are mounted to V-shape Aluminum cooling channels, one on each side, to form a blade. A number of 12 blades are needed to construct a half-disk. Plumbing connections between blade cooling channels are made with short union tubes. Half-disks are mounted on carbon-fiber service half-cylinders where cooling, power lines and front end electronics are installed. The detector will have two disks on each side. However, the design allows a future upgrade of the detector to a three disk system.

6. Outlook and Conclusions

After an extensive prototyping phase the CMS pixel detector is now in construction. All electrical and mechanical elements are in hand. We are planning to install two partially instrumented forward disks and half barrel shells during an engineering run at a center of mass energy of 900 GeV planned for the end of 2007. The engineering run will provide a complete test of Fpix and Bpix and the integration of the pixel system with the rest of the CMS tracking.

The installation conceptual design has been developed and it is being refined. The opening of CMS is expected to take about 1 week per side. Platform with rails will be installed to slide BPix and Fpix inside the tracker. A mock-up test of the rail system took place at CERN in June 2006 and it revealed interferences between Fpix and a detector needed to monitor the beam conditions, which has been resolved. We expect the CMS pixel system to be fully installed during the first physics run in 2008. Beam tests lead us to expect that its performance will be superior to the goals set in the CMS TDR [1]. The pixel detector will have a significant impact upon physics discoveries at LHC.

Acknowledgments

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References

- [1] CMS Collaboration, CMS TDR , CERN-LHCC-1998-06, 1998.
- [2] S. Cucciarelli, Nucl. Instr. and Meth. A 549 (2005) 49.
- [3] T. Rohe, et al., Nucl. Instr. and Meth. A 409 (1998) 224; T. Rohe, et al., IEEE-TNS 51-3 (2004).
- [4] K. Arndt, et al., Nucl. Instr. and Meth. A 511, (2003) 106.
- [5] T. Rohe, et al., Nucl. Instr. and Meth. A 552 (2005) 232.
- [6] H. Chr. Kästli, et al., Nucl. Instr. and Meth. A 565 (2006) 188.
- [7] W. Snoeys, et al., Nucl. Instr. and Meth. A 439 (2000) 349.
- [8] Ch. Broennimann, et al., Nucl. Instr. and Meth. A 565 (2006) 303.
- [9] S.König, et al., Nucl. Instr. and Meth. A 565 (2006) 62.
- [10] A. Starodumov, et al., Nucl. Instr. and Meth. A 565 (2006) 67.