Semiconductor sensors for the CALICE SiW EMC and study of the cross-talk between guard rings and pixels in the CALICE SiW prototype

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Abstract. The CALICE collaboration is studying high granularity and compact calorimeters for the future International Linear Collider. The electromagnetic calorimeter is made up of tungsten as absorber and silicon detectors implementing PIN diodes arrays. Calibration tests of a first prototype are describe first. Data taken in test beam environment have shown an unexpected behavior of the sensors found to be related to a crosstalk. This crosstalk is suspected to generate the so called "square events" seen in the test beam data where all bordering pixels of the sensor are illuminated. An analytic model is proposed to describe the crosstalk couplings within the sensors. Analytic results are compared with electrical simulation with the aim to understand forthcoming measurements on real hardware. A new design of guard rings is then discussed according to its impact on square events.

1. Introduction
The Calorimeter for the Linear Collider Experiment (CALICE) collaboration [1] is involved in the study and the development of prototypes of calorimeters targeting the needs of the future International Linear Collider experiments.

With the aim to be compliant with Particle Flow Algorithm method, the electromagnetic calorimeter is made to provide a high granularity and density [2]. A prototype intended to test Physics performance has been made up of tungsten as absorber and silicon as sensitive material to implement 6×6 pixels sensors. In a first part, the prototype design is described together with calibration and commissioning results highlighting on uniformity and stability of this 10000 channels detector [3]. In a second part of this article, the silicon sensors will be discussed about the crosstalk point of view. Indeed, the analysis of the data taken during test beam have pointed out an unexpected behaviour of the sensors. It consists in seeing all the bordering pixels to be illuminated. Three kind of models are proposed, compared and discussed to explain this phenomenon. A new way to design the sensors is then proposed being compliant with the constraint of the low cost of the overall sensors production.

2. The prototype of the electromagnetic calorimeter
Designing a sampling calorimeter, the absorber was chosen to allow to separate particles within a jet as well as to build a compact apparatus. Tungsten has appeared to be a good candidate for
the absorber with both a small Molière radius of 9 mm and a small radiation length of 3.5 mm. The sensors are burned on high resistivity 500 $\mu$m thick silicon wafers thanks to microelectronics manufacturing technologies. It supports compactness and granularity as the pixel size is about 1 cm $\times$ 1 cm, close to the Molière radius. The prototype has $24X_0$ split on 30 absorber layers interleaved with sensitive layers. It ensure that 99.5% of the energy for 5 GeV electron showers is enclosed within the detector.

2.1. Structure and instrumentation of the detector

A good energy resolution is achieved for a wide range variating the absorber plates thickness according to three areas of 10 layers each which are respectively made up of tungsten plates of 1.4 mm, 2.8 mm and 4.2 mm.

The sensitive layers are all the same and are made up of modules of nine sensors providing a detection area of 18 cm $\times$ 18 cm (pads are 1 cm$^2$ wide) together with the readout electronics. The electromagnetic calorimeter thus includes 9720 channels. The figure 1 shows a schematics of the architecture of the detector with its 3 independent alveolar structures made up of carbon fiber and epoxy supporting the tungsten plates. The figure 2 a picture of the detector on test beam with the sensitive layers slided into the alveola.

![Figure 1. 3D view of the prototype.](image1)

![Figure 2. Picture of the prototype taken at DESY in 2006.](image2)

2.2. Calibration with cosmic rays

The modules have been calibrated thanks cosmic rays right after their assembly. The assembly process require a lot of different steps, in particular the gluing of the sensors on the printed circuit board where are located the FLC_PHY3 front-end chips designed at LAL [4]. The chips are set to have a dynamic range from 0.1 MIP to 600 MIP on 13 bits (it could be incr eased to 15 bits).

As shown on figure 3 and 4 the MIP calibration (precision of about 5%) as well as the noise level are measured for each channel. The signal-to-noise ratio is 9.1±0.2 with a standard deviation of 1.0±0.1. This result is close to the final goal to have a S/N ratio of 10 and is therefore encouraging for further test in beam conditions. With only 0.1% dead channels, modules assembled from September 2004 do not show performance degradation over the time.
3. Performance in Beam conditions

Many test beam campaigns at DESY and CERN during year 2006 have allowed to quantify the detector performance as well as to validate the simulations models. A total of 300 million of event have been recorded for an energy range going from 1 to 6 GeV at DESY and 6 to 50 GeV at CERN. A run was structured to start with 500 pedestal events, 500 events with internal charge injection at the level of the chips and few tens of thousands data events. A part of the pedestal and calibration events have been taken without beam thanks to a random trigger.

Hardware performance have also been characterized and the main aspects are summarized in the following.

3.1. Pedestal and MIP

The pedestal is defined as the mean value of the signal without beam. The first 500 events of a run are taken. The figure 5 shows the pedestals of one front-end board as a function of time. The shift is due to a bad decoupling of the power supply due to a bad isolation of the PCB traces resulting in changes in the front-end chips working points. It will be corrected in the next version of the front-end electronics. For the data analysis the pedestal are corrected on an event by event basis to compensate the shifts. As shown on figure 6, once corrected, the residual pedestal with respect to the channel is -0.03±0.01 with a standard deviation of 1.05±0.01 ADC counts (a MIP is 46 ADC counts).

The MIP calibration of the ECAL prototype have been performed for each channel thanks to the energy distribution of muon events as shown in figure 7 with a residual pedestal of 0.2% MIP. A fit with a convolution of a Landau and a Gaussian gives the MIP with a statistical uncertainty of 0.5% and a systematic uncertainty of 0.4%. The uniformity over the detector is shown on figure 8. The colors correspond to various sensors batches and MIP values between 44 and 48 ADC counts according to the batch.

3.2. Noise

The noise is evaluated using the same runs as for the pedestals. It is extracted from the standard deviation of the ADC counts distribution on a channel per channel basis. Noise is found to be
Figure 5. Pedestals as a function of time for 216 channels (muon run taken at CERN in 2006).

Figure 6. Uniformity of the residual pedestals $R_G$ as a function of the pad index, for a 45 GeV electron run taken at CERN in August 2006.

Figure 7. Energy distribution of hits in muon events for a particular channel. The fit function is a convolution of a Gaussian and a Landau. Normalisation, $G_L$ and $\sigma_L$ refers to the constant, most probable value and width of the Landau function, and $\sigma_G$ to the width of the Gaussian function.

Figure 8. Equivalent ADC value $G_L$ for a MIP according to the channels number (muon events). Colors correspond to channels respectively from different sensor batches. The group of 36 channels at 23.5 ADC counts corresponds to a non-fully depleted module.

at the level of $5.919 \pm 0.004$ ADC counts with a standard deviation of $0.345 \pm 0.003$ ADC counts. The channel to channel dependence is about 9% of the mean noise but run to run variations are less than 1%.

The pedestal shift effect has an influence on the noise due to the resulting offset with respect to the initial pedestal correction. The noise appears to be larger than expected. The pedestal shift occurs at the level of the PCB, thus the apparent noise is correlated between all channels. An off-line correction procedure have been defined. It is base on successive iterations conditioned by the RMS deviation from the mean pedestal over the channels until the effective noise is compatible with the mean expected noise. The remaining correlation is $-0.0017 \pm 0.0003$ thus validating the correction procedure done event by event.

For sensors exposed to a high level of signal, the signal induced pedestal shift results in an increase of the apparent noise for all the 36 channels of the sensor. This effect is not systematic according to the PCB or to the time. It is identified by a strong correlation between the signal and the pedestal shift of all the channels of the corresponding sensor. It can be interpreted as coupling by a common impedance on the bias voltage line. It can hopefully be corrected
(similar iterative method at the scope of the sensor) and the remaining mean correlation is 0.0058±0.0001 to be compared to 0.019±0.001 before correction performed on a event by event basis.

3.3. Stability
Stability in time can be checked comparing the calibration constants for various test periods. The figure 9 shows a correlation coefficient of 93.2% between the calibration constants for two datasets taken with a 3 months delay. The mean difference for all channels is found to be −0.76 ± 0.01 with a spread of 0.67±0.01 ADC counts. At a front-end chip level, a stable and reliable behaviour is confirmed.

Similar comparisons of datasets do not show clear correlations as function of time, temperature or beam energy for the residual pedestal as well as for the noise.

3.4. Conclusion on the hardware performance
Targeting a signal over the noise ratio of 10, the detector expressed an actual S/N ratio of 7.63±0.01 during test beam operations. This 10 thousand channels detector has shown a good behaviour in time and a satisfactory uniformity with 1.7±0.1% MIP variation over the channels (0.4% with muon runs) and 1.1±0.1% MIP variation over the runs. Building technologies and assembly methods allows to provide a reliable detector to achieve the granularity and compactness requirements of a particle data flow approach for an ILC experiment.

Figure 9. Correlation of the calibration constant between August and October runs showing a good time stability.

Figure 10. Event display including a ”square event”.

4. The silicon sensors
The sensors are made from float zone silicon wafers providing a resistivity greater than 5 kΩ·cm. It is necessary to ensure a full depletion with a reasonable bias voltage, and to obtain low bulk leakage currents. A wafer thickness of 525 mm was chosen, to obtain a signal-to-noise ratio of about 10 at the end of the whole readout electronics chain. A minimum ionising particle (MIP) produces about 80 electronhole pairs per mm of silicon, hence 42,000 electrons are obtained for the 525 mm thickness, giving an allowable noise range for the readout electronics of up to 4000 electrons.

Each wafer is used to make a sensor, consisting of a matrix of 6 × 6 PIN diodes (pixels) of 1 cm² surrounded by a guard ring structure [5], as shown in figures 11 and 12. In order to keep the price and the rate of rejected processed sensors low, the manufacturing process must be as simple as possible, with a minimum number of steps during processing. The final detector will
need about $3000\text{m}^2$ of such detectors. This explains the stringent requirements about the low cost.

![Figure 11](image1.png) **Figure 11.** Picture of a sensor (pixel side). The pixel size is $1\text{ cm}^2$.

![Figure 12](image2.png) **Figure 12.** Details of the matrix dimensions in a module (cathode side). The area shaded in grey corresponds to the guard ring.

The edge termination is made using the guard rings (various number according to the manufacturer). The guard rings are made in the same way as for the pixels. The major advantage is that it does not require any extra step in the fabrication process of modules, helping to reduce the overall cost.

Before gluing, the modules are characterized one-by-one by measuring the leakage current as a function of bias voltage (I-V curve), the full depletion voltage (extracted from C-V curve) and the stability in time (leakage current versus time at a nominal bias). The test bench was used to characterize 550 modules, with an overall yield of 54%.

### 5. Study of the crosstalk

A characterization step in test beam conditions have shown an unexpected behaviour of the sensors (see figure 10). A look at the data reveals illuminated pixels arranged in a square shape corresponding to the silicon wafer border where the floating guardrings structure is located.

A crosstalk phenomenon between this guardrings structure and the nearest pixels to this structure (pixels at the border of the wafer) is suspected to generate the square shape called "square event". The understanding of square event is crucial for the detector development. Prior to direct measurements on real sensors, a simulation step can help to understand the couplings between pixels and guardrings. Simulation models can then be used to evaluate various guardrings designs without the need to manufacture and test expensive real sensors samples.

### 6. Wafer structure and crosstalk models

From the point of view of crosstalk, the wafer can be seen as a capacitance network. This network is defined by the internal structure of the wafer and its geometry in particular the capacitances within the matrix of square pixels and the guardrings.

To overcome signal propagation along the guardrings, the idea is to "cut" the guardrings which took the shape of a dashed line instead of a continuous one. In such topology, the internal capacitances which produce crosstalk are put into series and are divided lowering the crosstalk.
Many design parameters can vary: number of guardrings, distances, segment length, etc. Keeping in mind future measurements on small relatively cheap devices including 3×3 pixels, models and simulation runs have been limited to this low number of pixels. Nevertheless, it is sufficient to evaluate the crosstalk coupling. In future developments of the sensors, the number of guardrings should be limited to 4 to avoid a too large dead area around the sensor. This is also the case in this study. Three different topologies have been simulated, the options are described below:

- 4 continuous guardrings.
- 4 segmented guardrings with segment length equivalent to the pixel size.
- 4 segmented guardrings with segment length lower than the pixel size (factor 3).

The figure 13 shows a matrix of 3×3 pixels and the nearest guardring with internal coupling impedances for a given topology (here, the segment length is equal to the pixel width).

![Figure 13](Image)

**Figure 13.** Wafer model with internal coupling impedances only, to be added to the external coupling model for electrical simulation of the complete sensor.

![Figure 14](Image)

**Figure 14.** Wafer external coupling due to the guardring for the analytic model. Only one guardring is drawn in the case of segments length similar to the pixel dimensions.

With the point of view of square events, a signal is induced on the guardrings by a high energy particle. Charges are collected as for a pixel by the guardrings. The signal can propagate itself through the guardrings or through the pixel matrix due to internal crosstalk. In the followings it is assumed that these two kind of propagation modes are independent.

### 6.1. Analytic model of the crosstalk

This model can be fitted to many geometrical configurations without the need to rewrite an electrical simulation netlist and can then help to evaluate various design options prior to manufacturing and complementary to electrical simulations. It models the crosstalk related to the guardrings only.
The whole measurement chain is modeled in order to take into account the effects of the electronics (bandpass filter).

The figure 14 shows the coupling within the sensor taken into account for the analytic model. Capacitances to ground and coupling of bordering pixels to the guardring are modeled.

The transfer function $H(s)$ can be computed from the equivalent quadripole transfer matrix $T$:

$$H(s) = \frac{\det(T)}{T_{2,2}}$$

where

$$T = T_{elec} \times T_{wafer,p} \times T_{inj}$$

With $T_{elec}$ the transfer matrix of the measurement electronics (amplifier), $T_{wafer,p}$ the transfer matrix of the device under test (wafer or copper-epoxy model) associated to pixel number $p$ and $T_{inj}$ the transfer matrix of the signal injection electronics. With $T_{pix}$ the transfer matrix of the pixel, $T_{seg}$ the transfer matrix of the segment and $T_{ss}$ the transfer matrix of the gap between two segments, the transfer matrix of the whole measurement chain can be written as:

$$T = T_{elec} \times T_{pix} \times (T_{seg} \times T_{ss})^{N_{seg}} \times T_{seg} \times T_{inj}$$

$N_{seg}$ is the number of segment along the signal path following the guardring. This approach neglects the crosstalk between pixels themselves and is limited to the 3 first pixel in a column close to the guardrings. A decrease of the signal amplitude of respectively 21 dB and 75 dB are expected for the second pixel in the cases of 1 cm and 3 mm segment length.

### Table 1. Analytic model response for options 1, 2 and 3 showing a decrease in the signal amplitude (dB) for pixel (A2 and A3) located far from the injection point in the case of segmented guardrings

| Pixel | Continuous | 1 cm  | 3 mm |
|-------|------------|-------|------|
| A1 (ref) | 0 | 0 | -14.5 |
| A2 | -6 | -21.6 | -75 |
| A3 | 0 | -34.6 | -138 |

#### 6.2. Electrical simulation

The capacitances network can be described as an input netlist to an electrical simulator such as SPICE. The internal crosstalk coupling between pixels and guardring can then be simulated with less limitations than the analytical model (as far as the coupling impedances are put into the simulation netlist). The table 2 sums up the simulation results. The bold numbers corresponds to pixels simulated thanks to the analytic model.

Similar results are found compared to the analytic model except for the 3 mm option. In this case the internal crosstalk (coupling shown on figure 13) seems to be dominant.

#### 6.3. Printed circuit models

As a first step for measurements, some models of the sensors have been made in copper and epoxy (printed circuit boards). Various topologies of guardrings are then measured (figures 15, 16, 17). Measurements are compared to theoretic models and electrical simulation. The measurement electronics is made up of a waveform generator injecting signal through a capacitor, the device
Table 2. Electrical simulation results (3×3 matrix of pixels) for options 1, 2 and 3 of the guardrings design. The signal amplitude in db is given with respect to a reference signal taken on the closest pixel from the injection point in the case of continuous guardring.

|               | Continuous | 1 cm     | 3 mm     |
|---------------|------------|----------|----------|
| 0             | -4.4       | 0        | -18.3    |
| -4.4          | -14.1      | -4.4     | -18.3    |
| 0             | -4.4       | -35.6    | -51.2    |
|                |            | -34.2    | -51.2    |
|                |            | -36.0    | -49.0    |
|                |            | -49.8    | -71.1    |
|                |            | -71.1    | -85.7    |

Figure 15. Picture of a test PCB.

Figure 16. Layout for the 1 cm long segments.

Figure 17. Layout for the 1 cm long segments.

under test (wafer or hardware model) and a amplifier to output reasonably high signal to a scope (modeled in the analytic model).

The measurements on copper hardware model have been performed at LPC (Laboratoire de Physique Corpusculaire), Clermont-Ferrand with the contribution of F. Morisseau and M. Benyamna.

The figure 18 shows the analytic model response (curves) for the various design options (Continuous: red, 1 cm: blue, 3 mm: green) and measurements (marks) made on the copper-epoxy hardware model. The measurements errors are comprised within the mark thickness. The measurements fit well with the predicted results (continuous guardring data have been used to fit some model parameters). Slight differences are due to effects not taken into account and the coarse method used to fit some model parameters.

The measurements below 50 dB are imprecise due to the noise level near 55 dB. The test bench should be upgraded for the next measurements steps.

For continuous guardrings, models and measurements are in accordance (20% precision). The analytic model of guardring crosstalk explains the measurements as well as electrical simulation including internal crosstalk.

For 1 cm segmented guardrings, this is still the case but for A2 analytic response is close to the internal crosstalk level. Nevertheless, measurements shows an higher level close to the sum of this two effects. It is confirmed by electrical simulation. For A3, the dominant effect is still the crosstalk related to the guardrings.

For 3 mm segmented guardrings, the full electrical model explains the measurements and its response is close to electrical model of pure internal crosstalk while the analytic model gives extremely low level of guardring crosstalk (A3 not seen). Segment length smaller than the pixel size are then expected to make the guardring crosstalk as secondary effect compared to pixel to pixel crosstalk.
Figure 18. Model response (lines) and measurements (marks) made on hardware model: signal amplitude in dB for the 3 first pixels in a column close to the guardring structure according to the frequency of incoming signal injected on the guardring.

7. Conclusion
A ten thousands channels prototype was build and successfully tested achieving compactness and granularity requirements for a detector compatible with an ILC. The data accumulated from various test beam campaigns at CERN and DESY have allowed to characterize the detector. The signal over the noise ratio was found to be 7.6. This value is close to the goal of 10 and is therefore encouraging for the next development step. With the cost issue in mind, further work is needed about the sensors in order to understand and fix the guard rings related crosstalk. The use of advanced design techniques do not comply with the requirements on the overall cost which has to remain low (less than 10 euros/cm²). Floating guard rings are used as they are manufactured with the same processing steps as for the other parts of the sensors. A segmented layout of the rings have been investigated thanks to analytical and electrical models as well as with measurements on small printed circuits. Results are showing that the crosstalk decreases by about 20 dB on the second pixel from the injection point when using segmented floating guardrings. Measurements on real sensors should confirm that point.

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