A digital ECAL based on MAPS

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Progress is reported on the development and testing of Monolithic Active Pixel Sensors (MAPS) for a Si-W ECAL for the ILC. Using laser and source setups, a first version of the sensor has been characterised through measurements of the absolute gain calibration, noise and pedestal. The pixel-to-pixel gain spread is 10%. Charge diffusion has been measured and found to be compatible with simulation results. The charge collected by a single pixel varies from 50% to 20% depending on where it is generated. After adding detector effects to the Geant4 simulation of an ILC-like ECAL, using the measured parameters, the energy resolution is found to be 35% higher than the ideal resolution, but is still lower than the resolution obtained for an equivalent analogue ECAL.

1   Motivation

In a sampling electromagnetic calorimeter (ECAL), the energy deposited is proportional to the number of charged particles created in the shower, itself proportional to the incident energy of the particle. Two approaches are hence possible to measure the incident energy: by measuring the number of charged particles (digital approach) or by measuring the energy deposited (analogue approach). The motivation for using digital over analogue lies in the fluctuations occurring in the measured quantity. Only fluctuations in the development of the shower are expected if we are able to truely count charged particles. The energy deposited is however subject to additional fluctuations [1], among which the dominant one is due to the Landau spread. The ideal energy resolution for both approaches, obtained with a Geant4 [2] simulation of an ILC-like ECAL (20 layers at $0.6\,X_0$ followed by 10 layers at $1.2\,X_0$, and $500\,\mu$m silicon thickness per layer) [3], is shown in Figure 1. The digital approach is indeed about 30% lower in energy resolution than the analogue approach. From ideal to real conditions, the analogue resolution is however expected to change very little, whereas in the digital case, it is subject to charge diffusion and more importantly depends on the degree to which the number of charged particles can be measured. The following question needs to be answered: how close can we approach the ideal resolution for the digital case?
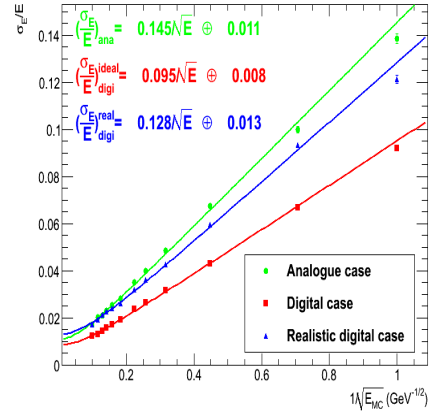

Figure 1: Energy resolution as a function of the incident energy for single electrons, for both analogue and digital approaches (see Section 3 for more details). The three formulae given correspond to the fitted functions displayed.

2 Sensor testing

A prototype sensor of $1 \times 1\,\mathrm{cm}^2$ with a pixel size of $50 \times 50\,\mu\mathrm{m}^2$ was fabricated in 2007, with four different pixel alternatives. The one found to have the best performance (preShape architecture [4]) is described in this section. Each pixel is made of four diodes, situated near the four corners, connected to a charge preamplifier and CR-RC shaper, and a two-stage comparator with individual threshold settings. When a particle generates a signal above the configured threshold, the spatial coordinates and time-stamp are recorded in a 13-bit word. Due to the timing expected at the ILC [3], the data must be stored on the sensor for the entire bunch train ($\simeq 1\,\mathrm{ms}$ or 2600 bunch crossings), and then read out during the $200\,\mathrm{ms}$ available between bunch trains. To reduce the impact of the dead area needed for memory and logic, these have been placed in columns 5 pixels wide ($250\,\mu\mathrm{m}$) every 42 active pixels.

To increase the charge collection efficiency, a deep p-well implant has been added (IN-MAPS process) to the standard $0.18\,\mu\mathrm{m}$ process used, to shield the epitaxial layer from the electronics n-wells. Its performance is reported in Section 2.3 and more details can be found in [4].

The characterisation of the sensor has been made through three main measurements. For each, the general method involves threshold scans, in "Threshold Units" (TU), as the readout is binary. Each time a threshold scan is recorded with an input signal (source/laser), a corresponding noise-only threshold scan needs to be taken systematically for comparison.

2.1 Absolute signal calibration

The absolute signal calibration is studied using a ^{55}Fe source. The emitted photons deposit all their energy, $5.9\,\mathrm{keV}$ or $\simeq 1620$ electrons, within $1\,\mu\mathrm{m}^3$ of silicon. By differentiating the threshold scan spectrum obtained per pixel, a peak can be observed whose central value should correspond to the total charge of 1620 electrons or $5.9\,\mathrm{keV}$. The results for all studied pixels are shown in Figure 2. The gains of the pixels are found to be uniform within 10%. The conversion factors obtained are $1\,\mathrm{TU} \simeq 10\,\mathrm{e}^- \simeq 36\,\mathrm{eV}$.
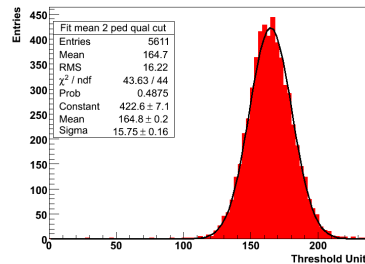

Figure 2: Gain measurement from a ^{55}Fe source for all pixels studied.

2.2 Pedestal and noise measurements

Noise and pedestal are defined by the mean and RMS in single-pixel noise-only threshold scans. By enabling only one pixel at a time, crosstalk effects are avoided. On average, the noise is $6\,\mathrm{TU}$ ($60\,\mathrm{e}^-$ or $220\,\mathrm{eV}$), with a minimum value of $4\,\mathrm{TU}$ ($40\,\mathrm{e}^-$ or $140\,\mathrm{eV}$) as shown in Figure 3, and no correlation is found with the position on the sensor. If no trimming is applied on the individual pixels, the distribution of pedestals for all pixels studied shows a spread of about four times the single-pixel noise. By trimming each pixel using the 4-bit adjustable settings, the spread can be reduced to the size of the single-pixel noise.
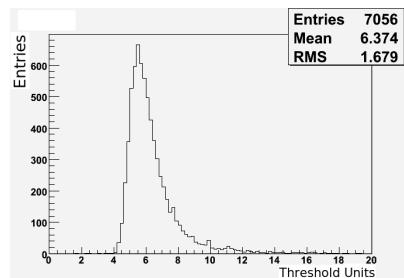

Figure 3: Noise distribution for all studied pixels.

2.3 Charge sharing measurement

A laser was scanned across the pixel to measure the variation in charge collected. The laser spot-size is about $2\,\mu$m, and its wavelength is $1064\,$nm. Silicon is transparent at this wavelength so the laser is fired at the back plane and focused on the epitaxial layer.

A pixel is scanned in $5\,\mu$m steps, and threshold scans are recorded for each step. The charge deposited is found by fitting the falling edge of each spectrum. In order to demonstrate the effect of the deep p-well implant, two sensors are compared, one produced with the INMAPS process and the other without. Results for real data are shown in Figure 4(a) and 4(b).

A simulation is performed in similar conditions using the Sentaurus TCAD software [5]. Results are shown in Figure 4(c) and 4(d). The simulation reproduces the data quite well, with similar level of maximum and minimum charge collected for each sensor. The effect of the deep p-well implant is also confirmed, with a factor 2 to 4 increase in the charge collected. The maximum charge is measured as expected for deposits near the diodes, at 50% of the input charge. The minimum charge, for a deposit inside the pixel, is measured at the four corners and in the middle part of the four sides, at 20% of the input charge. Note, the maximum charge collected from a corner would be 25%, from symmetry.
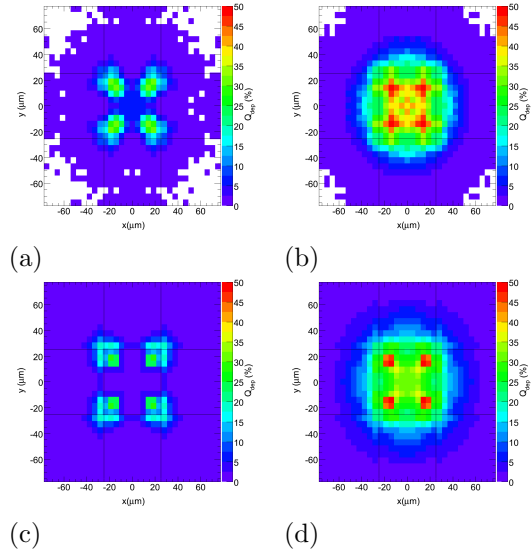

(a) (b)

(c) (d)

Figure 4: Percentage of charge recorded in a pixel as a function of the laser input position, for real data (top) and simulation (bottom), without (left) and with (right) deep p-well implant.

3 Physics expectations

Now that the charge spread simulation has been validated, and the noise measured, more realism can be added to the Geant4 [2] Monte Carlo simulation of a real-size detector. Starting from an energy deposit in $5 \times 5\,\mu\text{m}^2$ cells, charge sharing is applied according to the simulation results described in Section 2.3. The energy is then summed in $50 \times 50\,\mu\text{m}^2$ cells. Noise is added to signal hits by smearing the energy by $120\,$eV ($32\,\text{e}^-$), the target for future versions of the sensor. Hits above threshold are recorded. Noise-only hits are added according to the threshold value. The influence of each effect is studied on the energy resolution as a function of the threshold, for $10\,$GeV electrons. Results are summarised in Table 1.

Effect	Degradation
Noise $\times 2$	5%
Dead area 11%	6%
+ Sensor edges 5%	2%
Charge diffusion	5%
MIP counting	20%

Table 1: Percentage of degradation in energy resolution (σ_E/E) for $10\,$GeV electrons when varying parameters in the digitisation procedure.

The main effect is due to confusion in counting the true number of MIPs. A simple MIP-finder algorithm has been developed based on closest neighbours. The result is shown in Figure 5: even after MIP clustering, the resolution is significantly higher than the ideal case of counting true MIPs. The MIP-finder algorithm is hence crucial, and needs to be optimised. However, the Geant4 simulation at such a small pixel size has never been cross-checked with real data, and beam tests are required to confirm its validity before any optimisation can be meaningful.
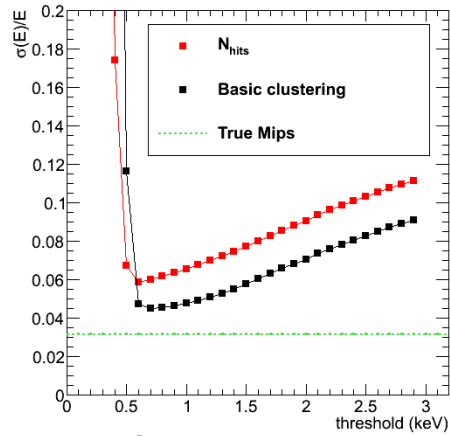
The energy resolution for a range of energies between 1 and 200 GeV is shown in Figure 1 after digitisation. The overall degradation compared to the ideal case is around 35%.

10 GeV electrons

Figure 5: Effect of a MIP-finder algorithm on the energy resolution as a function of threshold.

4 Conclusion

A first version of a sensor dedicated to study digital electromagnetic calorimetry has been developed and characterised using source and laser setups. The pixel-to-pixel gain spread is 10%, and the average noise is $60\,e^-$ with an RMS of about $20\,e^-$. Trimming is required and more trim bits have been added in the second version of the chip to decrease the pedestal spread below the noise level. Charge sharing has been measured and simulation is found to reproduce the real data. The INMAPS process is found to be crucial, doubling (quadrupling) the maximum (minimum) charge collected. These results have been applied to a Geant4 simulation of a real-size detector, and the energy resolution is found to be degraded by about 35% after digitisation compared to a true MIP-counting configuration, but still lower than the corresponding analogue design. The main effect is hit confusion, but real data are needed to validate the simulation at such a small pixel size, before MIP-clustering algorithms can be optimised.

References

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[5] *Sentaurus TCAD, available from* `http://www.synopsys.com/products/tcad/tcad.html`