A MAPS-based readout of an electromagnetic calorimeter for the ILC

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Abstract. The physics goals of the International Linear Collider (ILC) require a significant improvement in the calorimetric performance relative to previous generations of detectors. Sampling electromagnetic calorimeters (ECAL) using silicon diodes as the active media are widely considered as a suitably performant—but very expensive—solution. A new digital approach to electromagnetic calorimeter design based on 50 µm pitch Monolithic Active Pixel Sensors is presented as an alternative solution which could offer (at least) the same performance at significantly reduced cost.

1. Introduction and physics simulations

A silicon-tungsten sampling electromagnetic calorimeter based on analogue diode pads having transverse dimensions of order 5 × 5 mm² is the baseline technology choice for two of the ILC detector concept studies, SiD and (G)LD. There are substantial R&D efforts ongoing to verify this technology, the largest effort being from the CALICE Collaboration [1], and its main deficiency is the extremely high estimated cost of the approx. 2000m² silicon required. The MAPS ECAL R&D project is itself part of the CALICE Collaboration, and aims is to demonstrate a proof of principle alternative to the analogue silicon pads. By respecting the same mechanical constraints, the MAPS sensors could present a genuine “swap in” alternative to be considered by the detector concept studies. As MAPS is straightforward to implemented by a standard CMOS process it is widely available from many manufacturers worldwide. This makes it not only more readily available than the high purity silicon used in the diode pads, but should enable mass production to be divided among several vendors, reducing both cost and risk to schedule associated with single vendor sourcing.

The digital calorimetry approach assumes that the pixelated detector will have sufficiently fine granularity that even in the core of the highest density electromagnetic shower, there will be rarely more than one particle per pixel per event. Under such conditions, the energy within the detector will be proportional to the number of pixels hit, and therefore a single bit per pixel can be read out, giving a truly digital calorimeter. Initial studies using the full GEANT4 detector simulation, Mokka, indicate that a pixel size of 50 × 50µm² would be suitable, whereas the onset of saturation effects are seen at the highest expected energies for pixels of 100 × 100µm²,
as shown in Figure 1. An important observation is that when examining the distribution of energies per pixel, the most probable value of the Landau observed is stable for all energies that were studied for 50 µm pixel pitch, supporting the notion that the fraction of pixels with multiple occupancy is tolerably small. More detailed studies of the physics response of the sensor are included in several stages, as shown in Figure 2. Initially, energy deposits are accumulated by GEANT4 on a 5 × 5µm² grid (virtual cells). The charge spread (by diffusion) within the sensor is then applied using a parametrisation of device level simulations (Sentaurus TCAD); noise is added with σ = 100 eV, insensitive regions of the detector are removed, and clustering of individual pixels is applied to reduce the effects of charge spread. The figure shows a clear region of optimal resolution, and although this occupies a narrower range of thresholds as more realism is added to the study, it is still significantly above the estimated noise level of 100 eV.

2. Sensor, device simulations and hardware R&D
The MAPS sensors comprise a thin, 12µm epitaxial layer, on a total silicon thickness of 300 µm, with readout integrated into the sensor design. The movement of charge is by diffusion, and n-well diodes are arranged as shown in Figure 3 to optimise the efficiency for charge collection within a single pixel while reducing charge sharing between neighbouring pixels. PMOS transistors within the pixel also attract charge, thus reducing the useful signal collected by the diodes. To remedy this, a novel process (“INMAPS”) was developed, adding a 1µm deep p-well implant directly below the n-well region of the electronics, as in Figure 4.

With the typical 30 layer ECAL considered by GLDC and SiD, the total number of pixels is 10^{12}, therefore noise levels are extremely important to assess, as is maintaining acceptable signal-to-noise. Part of the optimisation of the device layout submitted to the foundry was to model the signal to noise and the total collected charge for MIP-equivalent input charge injected at key positions within a sensor. An example of this optimisation can be seen in Figure 5, comparing diode sizes between 0.9 µm and 3.6 µm.

Studies of the effectiveness of this process are among the first tests planned with the sensors, comparing different configurations of MAPS, with and without this deep p-well process.
Figure 3. Layout of sensor, showing (a) four diode locations, and (b) architecture-specific analogue circuitry.

Figure 4. Schematic of “INMAPS” deep-p well process to reduce loss of signal at diodes due to accumulation by n-well electronics within the pixel.

Figure 5. Simulated signal to noise ratio for three different diode sizes, as a function of distance to diode (arbitrary units, indexed across sensor diagonal). The injected charge was equivalent to one MIP at normal incidence. The diodes fabricated were 1.8 µm to ensure minimum signal to noise of 15.

3. Outlook
The first sensors were received from the foundry in July 2007, and laser-based charge diffusion measurements at RAL will commence in the near future, using a system which can operate at wavelengths of 1064, 532 and 355 nm, focusing to less than 2 µm spot size, pulse duration 4ns, operating at 50 Hz repetition rate. Complementary tests will be carried out using high intensity bench sources and cosmic rays, at Imperial and Birmingham, respectively. A small scale electron beam test at DESY is also in preparation for late 2007.

The evaluation of the physics performance of a MAPS ECAL will continue within the frameworks of both the (G)LDC and SiD detector concepts, to assess the potential benefits of this novel approach.

References
[1] The CALICE Collaboration, CALICE Report to the Calorimeter R&D Review Panel, J-C Brient et. al. http://arxiv.org/abs/0707.1245