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Towards a Technological Prototype for a High-granularity Electromagnetic Calorimeter for Future Lepton Colliders

Taikan Suehara[1] on behalf of CALICE SiW-ECAL group[123456]

[1]Department of Physics, Faculty of Science, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, 819-0395 Japan
[2]Laboratoire Leprince-Ringuet, Ecole Polytechnique, 91128 Palaiseau Cedex, France
[3]Laboratoire de Physique Nucleaire et de Hautes Energies, UPMC, Case courrier 200, 4 place Jussieu, 75005 Paris, France
[4]Laboratoire de l'Accelerateur Lineaire, Centre Scientifique d'Orsay, 91898 ORSAY Cedex, France
[5]OMEGA Microelectronics Center, Ecole Polytechnique, 91128 Palaiseau Cedex, France
[6]Department of Physics, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033 Japan

E-mail: suehara@phys.kyushu-u.ac.jp

Abstract. The CALICE collaboration is preparing large scale prototypes for highly granular calorimeters for detectors to be operated at a future lepton collider. Currently a prototype of a silicon-tungsten electromagnetic calorimeter SiW-ECAL will be assembled which in terms of dimensions and layout meets already most of the requirements given by the lepton collider physics programme and hence the detector design. In particular the front end electronics will be embedded into the layer structure of the calorimeter and have to fit within alveolar layers with less than 1 cm in height. In this paper the design of the prototype and the steps towards the realisation are presented. The presented technology plays also a key role in the upgrades of the LHC Experiments CMS and ATLAS.

1. Introduction

Particle flow is considered to be the key concept of calorimetry in future energy-frontier lepton colliders such as International Linear Collider (ILC). Jet energy in the particle flow is measured with momentum of tracks and energy of neutral clusters. Since the momentum resolution of tracks is much better than the energy resolution of clusters in general, this gives better energy resolution of jets.

The particle flow requires a highly granular calorimeter system to separate particles, especially in electromagnetic calorimeter (ECAL). The reference design of ECAL for International Large Detector (ILD), one of two detector concepts for ILC, has 30 layers of tungsten absorbers and sensors with the total depth of 24 radiation lengths, as described in the Detailed Baseline Design report [1]. Silicon sensor technology (SiW-ECAL) is one of the promising options for ILD ECAL, because of the easy implementation of fine segmentation and the good maturity of technology used for various detector applications. One of the big challenges of the SiW-ECAL system is to realize a readout system of a huge number ($\sim 10^8$) of channels with embedded ASICs in between the sensor and absorber layers.

The concept of SiW-ECAL system was first tested with a "Physics Prototype" [2], which proved the concept of particle flow calorimetry in good agreement with the Monte Carlo simulations with several test beam campaigns in 2005-2011.

The goal of the second "Technological Prototype" is to establish a system which is ready to be used as a real detector as ILD ECAL, such as:

- Embedded electronics with dedicated ASICs with 1-3 mm electronics layers
- Smaller cell size of around 5×5 mm^2
- Power pulsing capability (bias currents of front end electronics enabled and shut down in synchronization with the ILC beam structure)
- Buffering up to 15 event frames with self-triggering capability
- Multiple ASICs connected on the bus structure

The first technological prototype was fabricated with one 5×5 mm^2-segmented sensor and four ASICs and tested with an electron beam in DESY in 2012-13 [3]. Based on the experience of physics and technological prototypes, we have developed a new technological prototype which is aimed to be even closer to the to ILD ECAL.

The SiW-ECAL development has been conducted mainly within the framework of CALICE collaboration, which aims to develop highly granular calorimeters to be operated at future colliders in a consistent manner. Strong synergies exist with the recently raised effort of developing high-granular calorimeter to be installed in the CMS for the HL-LHC upgrade [4].

2. Sensor studies

Figure 1 shows a silicon sensor. The biggest technical issue of the sensors is square-shaped events caused by hits on the sensor edge. This is considered to be due to a floating guard-ring that surrounds the sensor. We are investigating sensors without guard rings as well as optimizing the spacing on the edge. Our study with laser photons hitting on the edge showed that the sensors without guard rings do not suffer from the square events.

Figure 2 shows the comparison of the dark current of sensors without guard rings with different edge spacings and thicknesses. The sample with smaller spacing and 500 μm thickness gives significantly lower breakdown voltage than others. Other samples have acceptable leakage current and breakdown voltage.

We also studied the sensors with neutron irradiation. Data were taken at the neutron beamline of up to 7.8 MeV at a tandem accelerator in Kobe university. The increase of the dark current observed after the irradiation shows that the effect scaled to the estimated irradiation of ILC calorimeter is in an acceptable range, as shown in Fig. 3.

3. Electronics and Assembly

SKIROC2 (Silicon Kalorimeter ReadOut Chip 2) is a 64 channel readout ASIC designed for SiW-ECAL. It has self-triggering capability, 15 analog memories, 12-bit ADC and 12 bit counter for bunch tagging of each event in a ILC train. It features further two slow shapers of different gain and power pulsing capability. Performance of the SKIROC2 chip is shown in [5].

Figure 4 shows a schematic of our "short slab". It is equipped with four 256-pad silicon sensors and 16 ASICs packaged in BGA400. (Alternative chip-on-board implementation of the ASICs is also being studied.) It also has a kapton film to apply bias voltage (100-120 V) to sensors, cooling and electric shielding, detector interface (DIF) to send data to the DAQ system, and a big capacitance for power pulsing. The sensors are attached by conductive glue with a auto-dispensing robot to the printed circuit board (PCB). Four slabs have been prepared for the first test beam.

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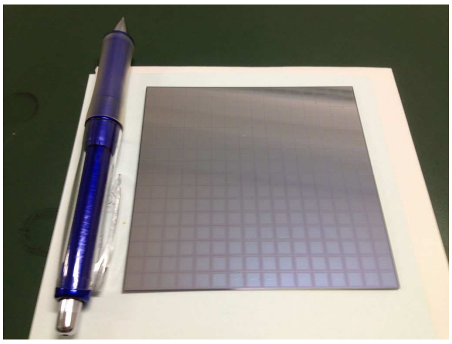

Figure 1. A sample of the silicon sensor for SiW-ECAL.

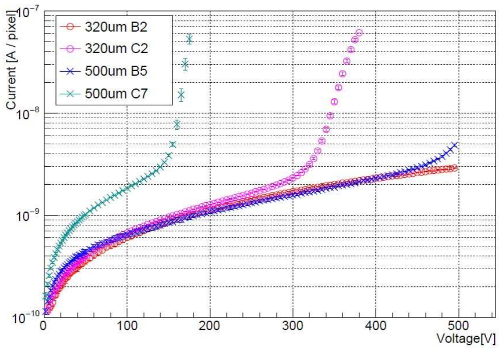

Figure 2. Leakage current of sensors without guard rings.

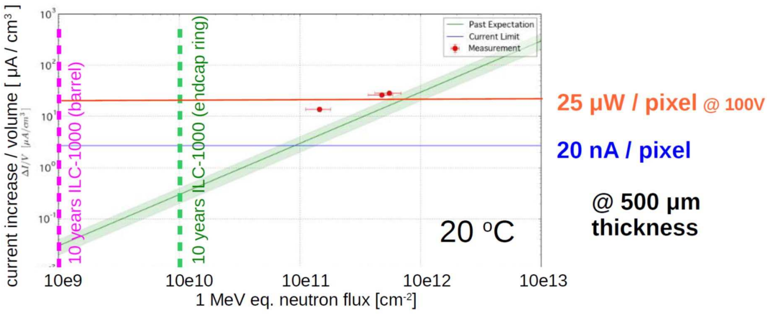

Figure 3. Results of irradiation (red points) with expectation to ILC. The result is nearly consistent with past results of various silicon sensors (inclined line with a band). The dashed lines show the estimated flux of ILC 1 TeV operation. The horizontal lines show our limitation caused by power consumption (upper) and by current electronics (lower).

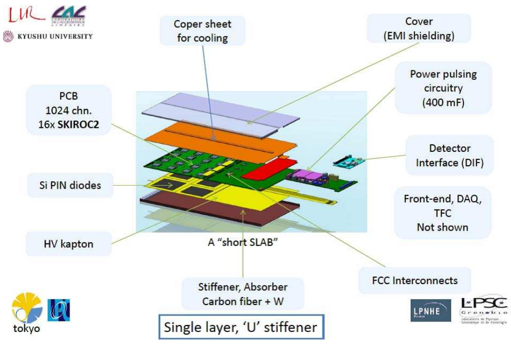

Figure 4. Schematics of the slab designed as the second prototype.

Figure 5. Setup of the test beam at CERN SPS with three active slabs.

4. Test beam at CERN

Beam test was conducted at CERN SPS H2 beam line at November 2015. Three slabs with 12 sensors and 48 ASICs were operated during the test beam. The setup (without shielding outside) is shown in Figure 5. Events with pions, electrons and muons with 10-150 GeV energy were taken.

Figure 6 shows a sample of a hitmap measured by a slab. The beam spot was clearly visible, with some number of channels with hits missing, because they are masked due to larger trigger rate due to higher noise. This is caused by misconfiguration of tuning trigger threshold on each channel, which is planned to be corrected in the next ASIC production (SKIROC2a).

Figure 7 shows distribution of signal-to-noise (S/N) ratio obtained on each channel (except inactive channel) by calculating 60 ADC count divided by root mean square of the pedestal distribution of the channel on several types of muon runs. 60 ADC counts correspond approximately to the maximum probability of minimum ionizing particle (MIP). It shows that S/N ratio of between 15 and 20 is obtained for most of channels, which is big enough to have essentially no accidental noise with 0.5 MIP trigger threshold.

The test beam was operated with a 5 times higher gain of preamplifier than the gain assumed for the real ILC operation to assure dynamic range up to more than 1000 MIPs. (The feedback capacitance of the preamplifier was set to 1.2 pF instead of 6.0 pF.) Reducing gain currently lowers the S/N ratio, but the high S/N ratio at the high gain shows noise level low enough at the preamplifier input, which is the most essential part for the noise.

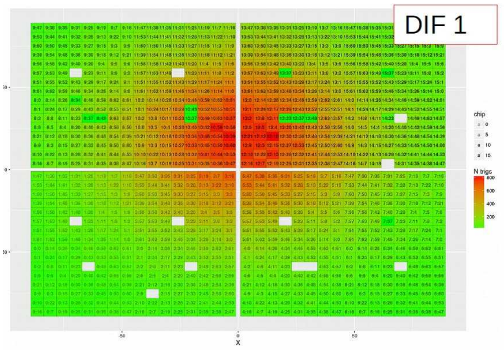

Figure 6. A hitmap of one slab with four sensors.

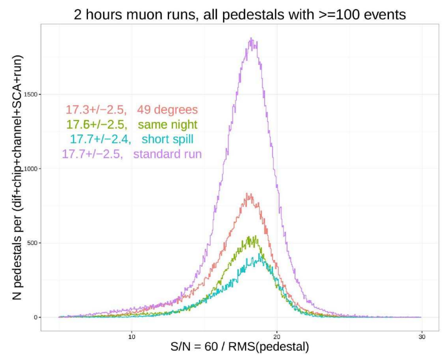

Figure 7. Distribution of signal-to-noise ratio in each channel (preliminary).

5. Summary and Plan

This contribution reports on progress of the CALICE SiW-ECAL prototype with ILC compatible integrated electronics and silicon sensors with $\sim 5 \times 5$ mm^2 pixelization. Sensor studies have shown that the sensor without guard ring is a good candidate for SiW-ECAL. The improved slabs of technological prototype with BGA-packaged SKIROC2 have been fabricated and first test beam has been done in CERN SPS beam line. The preliminary result shows a good signal-to-noise ratio.

We plan to fabricate more layers, including those with sensors without guard rings, and conduct a series of test beam in 2016. The new slabs will be also equipped with the new SKIROC2a for comparison with the previous version. We will also fabricate "long slabs" which are chains of ten slabs to fit the structure of ECAL assembly of the real detectors for future colliders.

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