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LARGE-AREA SILICON DETECTION IN HADRONIC SAMPLING CALORIMETRY

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Abstract: The usage of a maximum size silicon wafer area was optimized by using a geometry with two trapezoidal detectors, each of 28 cm². In order to enable the use of silicon detectors for hadron calorimeters a mosaic module consisting of 18 trapezoidal detectors was developed and assembled. Laser cutting technique was employed to minimize dead area of the mosaic. In the performed investigations no physical deterioration was observed.

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1. Introduction

Silicon detectors have been used in high-energy physics for many years, particularly in the study of coherent interactions on Si nuclei [1], [2]. Currently their usage as inner vertex detectors and in calorimeters is considered for colliding beam machine experiments. In the latter case very large areas are required but since the active volume can be small, relatively low resistivity, not fully depleted devices can be employed [3]-[6].

The silicon detectors are being made using float-zoned (FZ), high-resistivity (1 - 6 k Ω cm) silicon wafers, which at present have a maximum size of 10 cm diameter.

The size of silicon detectors has been so far a limiting factor in building hadronic calorimeters. For hadrons impinging onto a calorimeter sampling plane, the lateral shower containment requires an active area whose radial extension is about 10 to 15 cm. The longitudinal shower containment, at energies as high as 800 GeV, needs between 10 to 12 interaction lengths which, for uranium as absorber, is about 1.0 to 1.2 m depth. In order to measure the energy with a resolution of the order of (35% - 40%)/ $\sqrt{E}$ [E is the incoming particle energy in GeV], a silicon active sampling plane should be located every 3 - 4 mm of uranium. The Si/U sandwich calorimeter is the most compact among the sandwich calorimeters.

In order to overcome the above mentioned detector size limitation, a mosaic module, consisting of 18 trapezoidal silicon detectors, was developed and assembled. Each trapezoidal detector (28 cm²) is obtained by optimizing the usage of one half of the wafer area and as a result a sampling plane of 504 cm² active area was obtained (fig.1).

In this paper the detectors and the mosaic manufacturing are described. Also some experimental results are presented.

2. Large Area Trapezoidal Silicon Detectors

The trapezoidal radiation detectors are being processed (by ANSALDO) using 10 cm diameter silicon wafers. They are in fact p-i-n diodes, operated either fully or partially depleted by applying a reverse bias voltage. So far, FZ silicon, with typical resistivity of 1 - 2 k Ω cm, seems to be suitable for large area detectors in calorimetric applications.

Another potential material is the Czochralski silicon. Recent Czochralski crystal growth techniques, employ a strong magnetic field around the pulling crucible and promise resistivities higher than 1 k Ω cm. Until now, Czochralski silicon has been used in integrated circuits fabrication, with resistivities lower than 50 Ω cm. As compared to floating zoned silicon, their uniformity was poor and they had a higher content of oxygen and other impurities. The magnetic Czochralski silicon has partially improved characteristics, in particular with regard to uniformity. So far samples of 3" wafers have been produced with resistivities up to 4.5 k Ω cm.

The detectors can be produced with thicknesses in the range of 300 to 1000 μ m.

For the fabrication of a detector, on the silicon wafer surface, a layer of thermal silicon dioxide about 1 μ m thick, is grown. Care is taken to minimize the concentration of oxide charges. In order to pattern the silicon dioxide and to open the windows for the subsequent ion implantation for the p⁺ anode layer, a standard photolithographic process is used. The trapezoidal geometry is with a plain p⁺ well and a field plate metallization structure. When the window for the p⁺ well is opened in the oxide, the boron ion implantation is carried out. The n⁺ cathode layer, made by means of phosphorus ion implantation, ensures a back ohmic contact and acts as a "field stopper" in order to drop to zero the electric field on the cathode side of the p-i-n structure (fig 2), when the diode is reverse biased at voltages corresponding to full depletion.

In order to remove the defects produced in the ion implanted layer, different degrees of annealing are used. Phosphorus gives an amorphous layer and is being returned to the crystalline structure at relatively low temperatures (600° C). Point defects and interstitials produced by boron, tend to cluster and to produce dislocations during low temperature (600° C) annealing and require intermediate temperature (900° - 1000° C) annealing to reconstruct the silicon lattice. When the processes are finished, the

p-i-n structure is completed. The last step, passivation coating, is optional and performed only when full environmental protection of the detector is required. The passivation coating is basically made of a cured layer of polyimide resin, which covers both the silicon dioxide and the metallized surface on the detector front.

As already mentioned, the optimal silicon detector size cut out from a wafer is two trapezoidal detectors. In this work the two detectors cut from a 10cm diameter wafer had an area of 28cm² each. In fig 3, the dependence of the leakage current of the trapezoidal detector as a function of externally applied reverse bias voltage is presented. The detector is 400 μ m thick and has a 28 cm² active area. It is fully depleted at about 100 V, where it has a leakage current of about 64 nA/cm².

The active area is extended laterally beyond the junction region by electrical field lines. This extended active area, A_E , is to a first approximation, proportional to the depleted region X_d [cm]:

$$A_E = \lambda X_d P \quad [\text{cm}^2]$$

where P is the junction perimeter in cm and λ is the ratio between the lateral extension of the active area and the depleted layer width. The detector capacitance is

$$C_D = 1.0359 [(A_j + A_E)/X_d] \quad [\text{pF}] \quad (1)$$

where A_j is the junction area in cm². For n-type bulk silicon the extension of the depleted layer is

$$X_d \approx 0.529 \cdot 10^{-4} \sqrt{[\rho(V + V_B)]} \quad [\text{cm}] \quad (2)$$

where ρ is the detector resistivity in Ωcm , V_B is the built-in voltage and V is the reverse bias voltage. From eqs. (1) and (2) :

$$C_D = 1.958 \cdot 10^4 \{A_j/\sqrt{[\rho(V + V_B)]}\} + 1.0359 P\lambda \quad [\text{pF}] \quad (3)$$

where $1.0359 P\lambda$ is the correction to the standard formula of C_D . This term is, in our case, small (less than 1%).

In fig 4, the detector capacitance, C_D , as a function of the reverse bias voltage V is presented. The continuous line is the best fit to the data

using eq. (3) with $A_j = 27.9 \text{ cm}^2$, $P = 23.1 \text{ cm}$ and ρ , λ , and V_B as free parameters. The fitted values are $\rho = (5729 \pm 42) \text{ } \Omega\text{cm}$, $\lambda = 0.10 \pm 0.06$ and $V_B = (0.57 \pm 0.15)V$.

The number of electron-hole pairs, generated by a relativistic particle, traversing a silicon detector, is large as compared to the charge carriers of other devices used as an active sampling layer in calorimetry. A depleted layer width of 150 to 300 μm is sufficient to yield a good signal-to-noise ratio even for a single non-showering particle, when proper electronics is used. Moreover, in the usual showering condition, many particles are traversing the active layers of the calorimeter.

Relatively low resistivity material is expected to have a better performance than a detector made of a high one [7] and can be used not fully depleted. These devices perform likewise to fully depleted ones when the space charge region width [8] is the same. For fast electronics (shaping time less than 20 ns), the signal is proportional to the number of e-h pairs generated in the space charge region. A long integrating time of the associated electronics provides a signal with a contribution due to charge, which migrates from the field-free region. This charge corresponds to the collection of electron-hole pairs created in 25 to 50 μm inside the field-free zone for a collection time of about 0.5 to 1.0 μs [9].

3. Mosaic Modules

To overcome the problem of the single detector size a mosaic module, consisting of 18 trapezoidal silicon detectors, was developed and assembled. The size of the mosaic module is thus 504 cm^2 .

Standard methods of wafer scribing and cutting, like the diamond saw technique, are suitable for square or rectangular geometries. For the case of trapezoidal detectors, a laser cutting method was developed, using a CO_2 laser. By assembling a silicon detector mosaic, dead areas are necessarily introduced, since the supporting wafer is larger than the junction region. In order to minimize these losses in active area the laser cut should be performed as close as possible to the junction edge. Since the mechanical and physical effects of laser cutting were unknown, investigations of the behaviour of leakage current with the distance of the cut from the metallized edge were carried out (fig 5). In this work the metallized region extends the junction edges by about 500 μm . In fig 5, the value of

5 mm corresponds to the minimum distance of the metallized region from the wafer edge. Thus it represents the uncut detector. The results indicate that the maximum variation is about 1% and for the minimum distance cut (175 μm) it is less than 0.3%. Eventually a neodymium (Nd-Yag) laser might be chosen because of its higher efficiency than the CO_2 laser, which could result in sharper and smoother edges.

For detector modules, two fiberglass sheets (with thicknesses of 0.5 and 1.2 mm respectively) are used to bring the electrical connections to both junction and rear side of detectors. These ones are attached to the fiberglass by silicon rubber and electrically connected to the metal paths by conductive epoxy resin. The contacts are brought to an external fan-out, which can be a standard connector or a flat capton cable. To define and to monitor the energy scale of the device, radioactive α -sources (usually U^{233}) can be deposited on the detector surface by a technique similar in most respects, to vacuum evaporation or sputtering. For full protection against environmental contamination and for sealing of the radiation source, the detectors are being passivated with a polyimide coating. This technique is highly reliable and provides in-situ calibration of silicon detectors placed in an experimental apparatus.

4. Silicon Hadronic Calorimeter Prototype

A hadronic calorimeter prototype is currently under construction by SICAPO collaboration (Genoa- Hamburg- McGill- Milan- Tel Aviv- Trieste) at CERN. It consists of 5 interaction lengths of uranium and 130 silicon sampling planes. Silicon mosaic modules are located every 4 mm of uranium, which is about 3.8% of an interaction length.

The 28 cm^2 active area and 400 μm thick trapezoidal detectors were tested with an Am^{241} α -source. The associated electronics of this laboratory test was an ORTEC-125 charge preamplifier and ORTEC-472 spectroscopy amplifier. The shaping time of the amplifier was 125 ns. The standard deviation of the noise gaussian distribution was found to be (18.6 ± 2.0) keV which is approximately the expected value for an input capacitance of about 750 pF (this is for the fully depleted trapezoidal detector).

The modules are being tested at the t_9 hadron beam at the CERN-PS. All the detectors are under continuous monitoring for the leakage current via a microprocessor system and for capacitance directly to the acquisition

computer.

The tests of the hadronic calorimeter regarding the energy linearity and resolution are going to be performed in the t_s hadron beam.

5. Conclusions

The area of two of the trapezoidal detectors described in this paper is 71% of the wafer area, as compared to about 59% for the maximum squared area detector. If the trapezoidal detectors were designed up to the outer perimeter of the silicon wafer, the relative area could have been increased to about 83%.

Combinations of trapezoidal detectors allow to assemble mosaic modules with very large active areas.

The geometry of the silicon detectors described in this paper was enabled by the laser cutting technique. No physical deterioration was observed in the trapezoidal detectors.

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FIGURE CAPTIONS

FIG 1 : Large-area mosaic consisting of 18 trapezoidal silicon detectors.

FIG 2 : Full p-i-n structure of a silicon detector.

FIG 3 : Leakage current vs reverse bias voltage.

FIG 4 : Detector capacitance vs reverse bias voltage. The continuous line represents the best fit to the data.

FIG 5 : Leakage current variation vs the distance of the metallized region to the edge after the cut.

Fig. 1

- Silicon dioxide
- n⁺ phosphorus ion implanted layer
- p⁺ boron ion implanted layer
- n⁻ high resistivity silicon
- aluminum metallizations

Fig 2

Fig 3

Fig 4

Fig 5