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SILICON DETECTORS IN ELECTROMAGNETIC AND HADRONIC CALORIMETRY

P.G. Rancoita^{*)} and A. Seidman^{**)}

ABSTRACT

A review of investigations performed by the SICAPO collaboration at CERN on Si/W and Si/U sandwich calorimeters employing silicon detectors as active medium, is presented. Experimental results, such as the response of sensed energy versus incoming electron energy and depleted layer width, of the longitudinal and lateral development of electromagnetic showers and of the energy resolution, are given. Mosaic modules of silicon detectors, which enable the construction of silicon sampling hadronic calorimeters, are also described. A comparison of results from SICAPO, Hamburg (Si/Pb), and Tokyo (Si/Pb and Si/W) calorimeters is shown.

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^{*)} INFN, Milan, Italy.

^{**)} Tel Aviv University, Israel, and CERN, Geneva, Switzerland.

1. Introduction

The availability of silicon wafers, with areas up to 100 mm diameter, has lead to the development of large ion-implanted silicon detectors and to investigations of their usage in high-energy physics, especially in calorimetry [1], [2]. Also studies on the possible, not fully depleted, use of relatively inexpensive, low-resistivity detectors were performed [3].

After preliminary studies, which started in 1983, Si/W and Si/U sandwich calorimeters employing silicon detectors as an active medium were developed by the SICAPO (Silicon CALorimeter and POLarimeter) collaboration at CERN. Experimental tests were carried out at CERN-PS and SPS on both low and high resistivity silicon detectors, fully and not fully depleted (Chapter 2).

Also the energy resolution $[\sigma(E)/E]$, the response of sensed energy versus incoming electron energy and depleted layer width X_d , and the longitudinal and lateral development of electromagnetic showers were studied (Chapter 3).

Studies on Si/Pb sandwich calorimeters were performed by a group in Hamburg and on both Si/Pb and Si/W calorimeters by another group in Tokyo. A comparison of results from SICAPO, Hamburg and Tokyo prototype calorimeters is shown in Chapter 4.

Mosaic modules (made of silicon detectors) whose dead area is less than 4%, and which enable the construction of silicon sampling hadronic calorimeters are described in Chapter 5.

2. Silicon detectors of SICAPO electromagnetic calorimeters

The number of electron-hole pairs, generated by a relativistic particle traversing a silicon detector, is large compared with the charge carriers of other devices used as 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.

The SICAPO detectors (with physical thicknesses between 250 and 300 μm) were operated not fully depleted. They perform likewise to fully depleted ones, when the space charge region width is the same [4].

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 [5].

The stability of the depletion layer width (X_d) was found to be about 0.5%. The variation of X_d , ΔX_d , as a function of the position was measured by studying the most probable energy-loss, ϵ_{mp} , of 80 GeV protons traversing the silicon detectors. It was found $\Delta X_d = \pm 6 (\pm 3) \mu\text{m}$ for $X_d = 200 \mu\text{m}$, but no systematic variation. In fig.1 the energy loss spectrum sensed by a detector is shown. The full line is the fit to a Landau distribution convolved by a Gaussian function[6].

The energy scale calibration for each individual device of $5 \times 5 \text{ cm}^2$, was carried out by exposing them to a beam of single relativistic particles (100 GeV protons)[7]. The standard deviation of the Gaussian noise distribution was 26.7 keV on average. This value takes into account the contributions due to electronics, detector and cable.

3. Silicon electromagnetic calorimeters

The first calorimeter investigated by SICAPO[8] consisted of 24 radiation lengths of tungsten, in which a silicon detector was located every two radiation lengths. The overall length of the calorimeter was 12 cm.

The experiment was carried out in the X7 beam at CERN-SPS. The energies of the incoming electrons was between 4 and 49 GeV and the intensity roughly 10^2 to 10^3 electrons/burst (with duration of 2s).

The energy response was found to be linear to better than 1% and the energy resolution $\sigma(E)/E = (17.6 \pm 0.3)\% \sqrt{\tau}/E$, where τ is the number of radiation lengths of the passive material, interspaced between the active samplers. Fig.2 shows the mean energy deposited in the calorimeter as a function of the incoming energy. The full line is a least square fit to the data

$$\epsilon = (5.558 \pm 0.004)E + (-1.3 \pm 1.5) \quad [\text{MeV}]$$

where ϵ is the detected energy in MeV and E the incoming electron energy in GeV. In fig.3 the values of $\sigma(E)/E$ are shown as a function of E .

The longitudinal shower development was studied by reading out each sampler. Fig.4 shows the average energy deposited as a function of the depth, expressed in radiation lengths, t , in the calorimeter.

Another SICAPO calorimeter[9] contained 24 radiation lengths of either uranium or tungsten with a silicon detector located after each two radiation lengths of absorber. The silicon detectors were operated with depletion layers of 200 and 70 μm . The experiment was performed at the t_9 beam at CERN-PS, with E of 2, 4, 6 GeV.

Fig.5 presents the energy response of the calorimeter as a function of E . The data show the linear response of the sensed energy versus E seen at high energies[8]. The linearity is observed for the detectors operated with X_d of 200 and 70 μm and employing both uranium and tungsten as showering media. The energy resolution of the calorimeter was not reduced by more than 10 - 15% when the detectors had depleted layer widths of 70 μm . However, independently of the X_d values, the mean sensed energy is about 11% higher when uranium absorbers are used.

The same calorimeter configuration[10], with tungsten absorbers and the same beam, but detectors operated with depletion depths of 40, 70, 100, 125, 150 and 200 μm (by adjusting the reverse bias voltage) was investigated.

Fig.6 presents the longitudinal shower transition curves for each of the six depletion depths. The peak position is independent of the depletion depths and averages 5.54 ± 0.14 radiation lengths. Fig.7 shows the overall energy response of the calorimeter as a function of depletion depth. The response is linear over the whole range measured. As can be seen, there is a positive energy intercept of the line which is caused by charge diffusion in the silicon (the migration effect [5]). Some charge is always being collected from the field-free region, closest to the junction, even for no externally applied bias voltage, V ; each detector has for $V = 0$ an effective active layer consisting of the charge depletion region due to the built-in voltage V_B and the diffusion field-free zone. From the fitted slope and intercept of the line, representing the sensed energy versus X_d , we find an average effective contribution from the field-free region, X_{FF} , of $(23 \pm 2)\mu\text{m}$ at zero depletion depth. This value has to be compared with that of 25 μm [5] found under non-showering conditions with relativistic β^- particles.

The energy response of the first two detectors in the rise of the shower transition is shown in fig.8. The lines are a least squared fit to the

data. The response of the individual detectors is quite similar to the overall response, i.e., a linear dependence of the deposited energy versus the depleted layer width. It was observed that, as expected, since the slopes are proportional to the number of equivalent minimum ionizing particles traversing the detectors, they increase monotonically up to the shower maximum and decrease monotonically afterwards.

It can thus be concluded that the behaviour of a silicon sampling calorimeter as a function of the depleted layer width is in agreement with the response, expected from a silicon diode junction and electromagnetic shower development, according to the simplest model.

The lateral electromagnetic shower development was studied for 2, 4 and 6 GeV electrons in a silicon sampling calorimeter with tungsten and uranium as absorbers, at various depths of radiation lengths, up to 16[11]. The measurements were performed with a Hamamatsu 1 mm pitch silicon strip detector, 28x28 mm² area and 190 μ m thick. Fig.9 presents the lateral shower distribution at 2 up to 16 (every 2) radiation lengths of tungsten for 6 GeV electrons and fig.10, similarly, for uranium. The energy scale is represented in the left-hand side of each figure.

It was found that the ratio, R , of the sensed energy (in the silicon detector) with uranium to that of tungsten is 1.16 on average, for the three (2, 4 and 6 GeV) electron energies. It is in agreement with the experimentally obtained R [9] and the calculated one[12]. A comparison of R for all measured depths of radiation lengths, at the three energies, with those obtained previously[9] shows that up to about 8 radiation lengths, they are in agreement. Above the 10th radiation length they differ by about 25% on average and depend on energy. The reason for the agreement in the ratio of the total energy seems to be the fact that up to 8 radiation lengths, the largest part of the incoming energy was already deposited. From figs.9 and 10 it can be seen that the 24 mm lateral extension of the detector does not have full lateral shower containment.

The full width half maximum (FWHM) of the summed distribution along X_0 is 6 mm at 2 GeV and 5 mm at 6 GeV for both uranium and tungsten. At 4 GeV it is 6 mm for uranium and 5 mm for tungsten.

The Tokyo group [13] has shown the lateral development (summed along X_0) for electromagnetic showers in a Si/W calorimeter, having 5 mm resolution at 4.5 GeV of the incoming electron energy. The FWHM of the distribution was about 13.3 mm. This is about twice the value of that expected from Monte Carlo calculations[13] and actually found in above described experiment.

4. Comparison of different sampling calorimeters

Experimental results are available from electromagnetic sampling calorimeters consisting of sandwich of Si/W and Si/U (SICAPO collaboration at CERN[14]), Si/Pb (Hamburg[15] and Tokyo[16] groups), and Si/W (Tokyo group[13], preliminary data, with non-homogeneous sampling). The silicon detectors of the Hamburg and Tokyo groups (thickness 190 μm and 1000 μm respectively) were operated fully depleted while those of the SICAPO group (average physical thickness 295 μm) were not fully depleted (depletion depths of 200 and 70 μm).

The calorimeters, although all employ silicon as the active medium, have different effective radiation lengths, critical energies, densities, sampling frequencies and depletion depths. In order to obtain a simple, well defined procedure for comparing the data, the Rossi's approximation B was used. It gives overall results, usually in good agreement with experimental data or median shower position and shower width. It also predicts that the energy resolution in sampling calorimeters will be proportional to $\sqrt{\tau/E}$, where τ is the sampling frequency and E the incident particle energy.

For shower development, Rossi's approximation B assumes (1) asymptotic values of cross-sections for pair production and bremsstrahlung, (2) constant ionization loss per radiation length, which is about equal to the energy, ϵ_{crit} , lost by electrons or positrons in one radiation length, (3) zero opening angles in collision processes, and (4) no Compton scattering etc. The total track length, T , is given by $T = E X_0/\epsilon_{\text{crit}}$ where X_0 is the radiation length. In a sampling calorimeter the critical energy and the radiation length are replaced by the effective critical energy ϵ_{eff} and the effective radiation length X_{eff} . Thus, the energy sensed by the active silicon planes is $E_{\text{Si}} = p_{\text{Si}} T (\epsilon_{\text{Si}}/X_{\text{Si}})$, where p_{Si} is the fraction (by mass) of silicon, X_{Si} is the radiation length and ϵ_{Si} is the critical energy of silicon. From that the ratio η of the sensed energy E_{Si} to the incoming energy E is obtained:

$$\eta = p_{\text{Si}} [(\epsilon_{\text{Si}}/X_{\text{Si}})/(\epsilon_{\text{eff}}/X_{\text{eff}})] \quad (1)$$

where

$$\epsilon_{\text{eff}}/X_{\text{eff}} = \sum_i p_i (\epsilon_i/X_i)$$

To calculate the critical energies of the various materials of the calorimeters, the results of the fit of Dovzhenko and Pomanski were used. They give

$$\epsilon_{\text{crit}} = B(ZX_0/A)^a \quad [\text{MeV}]$$

where Z is the atomic number of the material, X_0 is the radiation length in g/cm^2 , A is the atomic mass, $B = 2.66$ and $a = 1.11$.

As already mentioned, both the Hamburg and Tokyo calorimeters were run with the silicon detectors fully depleted while the SICAPO calorimeters with a thickness of $295 \mu\text{m}$ were depleted to only 200 and $70 \mu\text{m}$. Because of charge diffusion in the field-free region (the migration effect), the energy response of the calorimeter is greater by an amount corresponding to about $23 \mu\text{m}$ increased depletion depth [5]. Accordingly, effective active layers of 223 and $93 \mu\text{m}$ were taken for the comparison.

The predicted ratio η from eq.(1) and the measured one η_m are shown in Table 1.

It is expected that the calorimeters see less than predicted, since approximation B overestimates the track length.

The Tokyo and SICAPO calorimeters, for which p_{Si} varies by more than one order of magnitude, detect about 70% and 80% of the predicted energy respectively.

The Hamburg calorimeter sees about 45% of the predicted value. This low value is explained partially by the longitudinal and lateral losses, both of which are about 10% of the incoming electron energy.

It can be concluded that for full longitudinal and lateral containment there is good agreement for η_m/η and $\sigma(E)/E$ (energy resolution) where for SICAPO it is $17.6\% \sqrt{(\tau/E)}$, for Tokyo it is $17.5\% \sqrt{(\tau/E)}$ for Si/Pb and $17.0\% \sqrt{(\tau/E)}$ for Si/W and for Hamburg it is $20.7\% \sqrt{(\tau/E)}$ (10% longitudinal and 10% lateral loss) for Si/Pb.

5. Silicon detection in hadronic sampling calorimetry

In calorimetry large area silicon detectors are required, but since the active volume can be small, relatively low resistivity, not fully depleted devices can be used[17].

Currently, a Si/U electromagnetic calorimeter is in an advanced stage of development. It will consist of 20 silicon mosaic planes (of about 504 cm^2 active area each), interspaced by about 5 mm U ($1.56 X_0$) and thus its

total length will be about $31X_0$. The Si/U calorimeter is to be followed by a scintillator/U calorimeter (3 scint./U stacks from NA34 group).

The aim of the test (to be carried out by Bologna, Milan and Tennessee group) is to study how the resolution of the hadronic calorimeter is affected by the silicon readout in the electromagnetic section for incoming hadrons and how (possibly) to have a compensating calorimeter.

It is planned by the SICAPO collaboration at CERN (Genoa, Hamburg, McGill, Milan, Tel-Aviv and Trieste) to develop a full Si/U hadronic calorimeter, consisting of 130 silicon sampling planes (about 6.5 m^2) by the end of 1987. Silicon mosaic modules are located every 4 mm of uranium, which is about 3.8% of an interaction length.

A silicon sampling plane (fig.11) is made of 18 trapezoidal silicon detectors of 28 cm^2 each. They are being processed (by Ansaldo), using 100 mm diameter silicon wafers. They are p-i-n diodes, operated either fully or partially depleted by applying a reverse bias voltage. So far, floating zone silicon, with typical resistivity of $1 - 2 \text{ k}\Omega \text{ cm}$, seems to be suitable for large area detectors in calorimetric applications.

For the fabrication of a detector on the silicon wafer surface, a layer of thermal silicon dioxide, about $1 \mu\text{m}$ 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.12), when the diode is reverse biased at voltages corresponding to full depletion.

In fig.13, the dependence of the leakage current of a trapezoidal detector as a function of externally applied reverse bias voltage is presented. The detector is $400 \mu\text{m}$ thick and has a 28 cm^2 active area. It is fully depleted at about 100 V, where it has a leakage current of about 64 nA/cm^2 .

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 $X_D[\text{cm}]$:

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

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

$$C_D = 1.0359 [(A_j + A_E)/X_D] \quad [\text{pF}] \quad (2)$$

where A_j is the junction area in cm^2 . For n-type bulk silicon the extension of the depleted layer is

$$X_D = 0.529 \cdot 10^{-4} \sqrt{\rho(V + V_B)} \quad [\text{cm}] \quad (3)$$

where ρ is the detector resistivity in Ωcm , V_B is the built-in voltage and V is the reverse bias voltage. From C_D and X_D [eqs. (2) and (3)]:

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

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.14, 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 the last equation of C_D 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 $\rho = (5729 \pm 42) \Omega\text{cm}$, $\lambda = 0.10 \pm 0.06$ and $V_B = (0.57 \pm 0.15) \text{ V}$.

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.15). In this work the metallized region extends the junction edges by about $500 \mu\text{m}$. In fig.15, 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 ($175 \mu\text{m}$) 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 were 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 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.

The 28 cm² active area and 400 μ m 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_s hadron beam at the CERN-PS. All the detectors are under continous 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.

6. Conclusions

A silicon sampling calorimeter fulfills the requirements of compactness, granularity, long-time stability and reliability needed in colliding beam machine experiments.

The energy resolution for electromagnetic shower is about $17\% \sqrt{(\tau/E)}$, where τ is the sampling frequency and E is the incoming electron energy in GeV.

The mosaic module made of silicon detectors, whose dead area is less than 4%, enable the construction of silicon sampling hadronic calorimeters.

At present large-area silicon mosaic is under discussion for calorimetric application in SLC and HERA experiments.

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TABLE 1

Calorimeter parameters (comparative)

Group	Sampling type	Phys. thickness (μm)	Active layer (μm)	Active area (cm^2)	Absorber (mm)	$L^{(1)}$	η (%)	η_m (%)	η_m/η (%)	e^- Energies (GeV)
SICAPO	Si/W	295	223	25	7 (2)	24	0.58	0.46	80	2, 4, 6
	Si/W	295	93	25	7 (2)	24	0.25	0.19	77	2, 4, 6
	Si/U	295	223	25	6.3	24	0.67	0.52	78	2, 4, 6
	Si/U	295	93	25	6.3	24	0.28	0.22	78	2, 4, 6
TOKYO	Si/Pb	1000	1000	38	5	10	5.71	3.86 (3)	68 (3)	0.25, 0.375, 0.50, 0.625, 0.75
	Si/W	1000	1000	64	3.5 (4)	18	4.78 (4)	3.67 (3) 3.48	77 (3) 73	0.5, 1.0, 2.0, 3.0, 4.0, 4.5
HAMBURG	Si/Pb	190	190	8	6	12.8	0.98	0.44	45	1.5, 3.0, 5.0

(1) Calorimeter depth (in radiation lengths).

(2) 97% of tungsten and 3% of Fe and Ni.

(3) Includes only first 3 energies.

(4) Up to 9 radiation lengths, assuming homogeneous sampling.

FIGURES CAPTIONS

Fig.1 : Energy-loss spectrum of a relativistic proton traversing a $5 \times 5 \text{ cm}^2$ silicon detector depleted at $200 \mu\text{m}$. The most probable energy-loss is 56 keV and the standard deviation of the Gaussian noise contribution is 20.8 keV .

Fig.2 : Mean energy detected by the Si/W calorimeter vs the incoming electron energy.

Fig.3 : Values of $\sigma(E)/E$ vs the incoming electron energy. The full line is $\sigma(E)/E = 17.6\%V(\tau/E)$, $\tau = 2$.

Fig.4 : Longitudinal shower development vs the depth t in number of radiation lengths for 4, 9, 16, 25 and 49 GeV. The lines are fitted curves.

Fig.5 : Mean energy detected by the calorimeter vs the incoming electron energy for uranium with a silicon depletion layer of $200 \mu\text{m}$ (■); for uranium with a silicon depletion layer of $70 \mu\text{m}$ (□); for tungsten with a silicon depletion layer of $200 \mu\text{m}$ (●); for tungsten with a depletion layer of $70 \mu\text{m}$ (○). The full lines are the least squares fits to the data. The incoming electron energy is 4 GeV .

Fig.6 : The longitudinal shower development in the silicon/tungsten sampling calorimeter for depletion depths, X_d , of 40, 70, 100, 125, 150 and $200 \mu\text{m}$. The incoming electron energy is 4 GeV . The curves superimposed on the figure show the results of a linearized least squares fit to the data. The fitting procedure is described in [8].

Fig.7 : The energy response of the calorimeter a function of the silicon detector depletion depths X_d . The line shown is a least squares fit to the data.

Fig.8 : The energy response of the first two detectors at depths of 2 and 4 radiation lengths in the calorimeter as a function of depletion depths.

Fig.9 : Lateral shower distribution at 2, 4, 6, 8, 10, 12, 14 and 16 radiation lengths (X_0) of tungsten for 6 GeV electrons; S is the 1 mm pitch strip number.

Fig.10: Lateral shower distribution at 2, 4, 6, 8, 10, 12, 14 and 16 radiation lengths (X_0) of uranium for 6 GeV electrons; S is the 1 mm pitch strip number.

Fig.11: Large-area mosaic consisting of 18 trapezoidal silicon detectors. The active area of the silicon sampling module is 504 cm².

Fig.12: Full p-i-n structure of a silicon detector.

Fig.13: Leakage current vs reverse bias voltage for a 28cm² trapezoidal silicon detector.

Fig.14: Detector capacitance vs reverse bias voltage for a 28cm² trapezoidal detector. The continuous line represents the best fit of eq.(4) to the data.

Fig.15: Leakage current variation vs the distance of the metallized region to the edge after the laser cut, for a 28cm² trapezoidal silicon detector.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

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

Fig. 12

Fig. 13

Fig. 14

Fig. 15