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PERFORMANCE AND APPLICATIONS OF PASSIVATED ION-IMPLANTED SILICON DETECTORS

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Summary

Planar process has been applied to the fabrication of nuclear radiation detectors. Combining techniques of oxide passivation, photoengraving and ion implantation any desired detector shape can be made with small tolerances in geometrical and electrical properties. Extremely low reverse currents are obtained (less than 1 nA cm^{-2}/100 μm at room temperature) and therefore excellent energy resolutions : 10.6 keV for 5.486 MeV alphas, 1.55 keV for 122 keV gamma-rays with 25 mm^2 area detectors, 300 μm thick. The detectors are capable to be backed at 200° C under vacuum.

Due to the fact that arrangements of many detectors on one wafer can be made, new possibilities open up, especially for particle localization in high energy physics. Planar versions of 200, 50 and 20 μm pitch parallel microstrip detectors have been realized. Results obtained using a beam of 10 GeV/c pions are presented.

Close mounting of several detectors allows the construction of telescopes used as live target in high energy physics experiments.

Introduction

Solid state detectors based on high purity silicon crystals are widely used for the spectroscopy of charged particles. Various types have been realized[1]: diffused pn-junctions, surface barrier devices, ion-implanted detectors. At room temperature, the best performance in terms of energy resolution is generally obtained with the surface barrier detectors. The technology used avoids any high temperature treatment in order to not reduce the lifetime of the charge carriers and therefore to obtain small generation currents. However, despite the use of an epoxy mounting for edge protection, the reverse current is still mainly due to its surface leakage components. Other drawbacks of this technology are :

- the much time consuming fabrication cycle ;
- the inability of the surface barrier detectors to withstand high temperature ;
- the difficulty to make close-mounting of such detectors.

A new method for manufacturing silicon detectors[2] has been developped, based on the so called "planar" process which combines oxide passivation with ion-implantation, resulting in devices overcoming the above mentionned inconvenients of surface barrier detectors. Oxide passivation of the surface is a useful method for the reduction of leakage current[3], whereas ion-implantation, by proper choice of the parameters, allows the tailoring of asymmetric nearly abrupt pn-junctions, with thin dead layers. The photo engraving technique allows easy changes of the shape of the devices by using different masks, making possible for instance the manufacturing of microstrip detectors.

After a description of the fabrication process of passivated ion-implanted silicon detectors (IP detectors) and report on the performance obtained for charged particles and X-ray spectroscopy, some results and applications in high energy physics are presented.

Method of fabrication

Standard polished (111) orientation n-type silicon wafers of two inches diameter are used as the starting material. The available resistivities lie in the range 500-5000 ohm-cm and the usual thicknesses are 300, 400, 500 microns. The charge carrier lifetime is about 1-3 m·sec.

The successive steps of the manufacturing process are illustrated in Fig. 1. They were performed under clean room conditions using laminar flux boxes.

- Oxide passivation was achieved at 1030°C with a mixture of dry oxygen and hydrogen chloride.

- Photographic masks having the desired openings were used for the photoengraving technique. For example, for 5 x 5 mm2 area detectors, the total size of the chips were 8 x 8 mm2 resulting in 21 chips per wafer of 2 inches diameter.

- The doping was performed at room temperature using ion implantation so that nearly abrupt junctions with thin dead layers were obtained. In order to avoid channeling effects, the wafers were implanted at a small angle to the (111) direction. Boron was used for the p-type junction at an energy of 10-15 keV and a dose of 5 x 10^{14} ions.cm^{-2}. The rear contact was also implanted using arsenic at an energy of 30 keV and a dose of 5 x 10^{15} ions.cm^{-2}.

- After implantation the wafers were thermally annealed at 600°C during 30 min, in a dry nitrogen atmosphere.

- The wafers were then metallized on both sides with aluminium, to avoid any problem related to the

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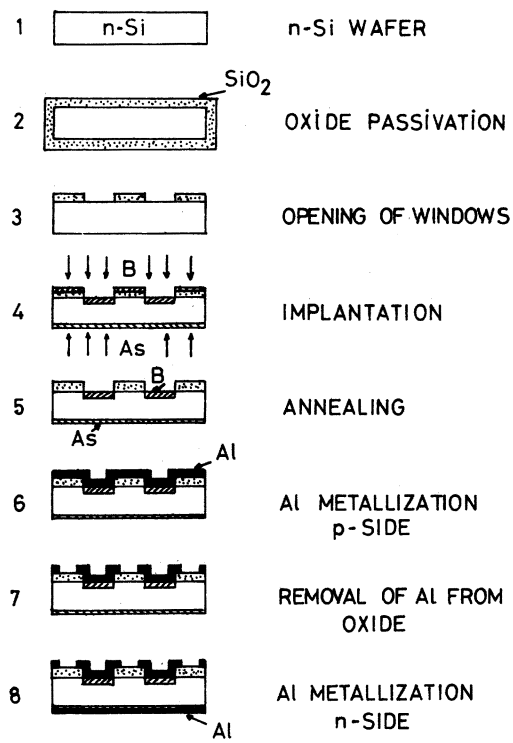

Fig. 1 : Successive steps of the manufacturing process of passivated ion-implanted silicon detectors

sheet resistance of the implanted layers and to facilitate external electrical contacting.

- Aluminium between adjacent chips on the p-side was removed by using an appropriate mask.

- The chips were finally cut with a diamand saw.

Depending on the intended application the electrical connections were performed by pressure contacts on the metal layers, silver epoxy or ultrasonic bonding.

Detectors properties

Current - and capacity - voltage characteristics

Fig. 2 shows the current-voltage characteristic for a 25 mm2 chip, 300 µm thick : the leakage current is less than 1 nA at room temperature for a bias voltage of 200 V (depletion voltage is 130 V).

This value is at least an order of magnitude less than the best values obtained with surface barrier diodes. An estimation of the bulk lifetime of the minority charge carriers from such leakage current gives a lower limit of 15 m sec, which is much higher than that of the starting material (1-3 m sec). Not only the high temperature oxidation process does not adversily affect the lifetime, but on the contrary an improvement occurs, due probably to gettering effects. Furthermore, the protective action of the passivating SiO_2 layer at the edge around the junction appears very effective.

Some dispersion in these characteristics is observed either among chips from the same wafer, or among chips from different wafers. On the average, the current values range between 1 and 10 $nA.cm^{-2}/100\ \mu m$, the highest currents beeing usually obtained with high resistivity silicon wafers (5 k.ohm.cm).

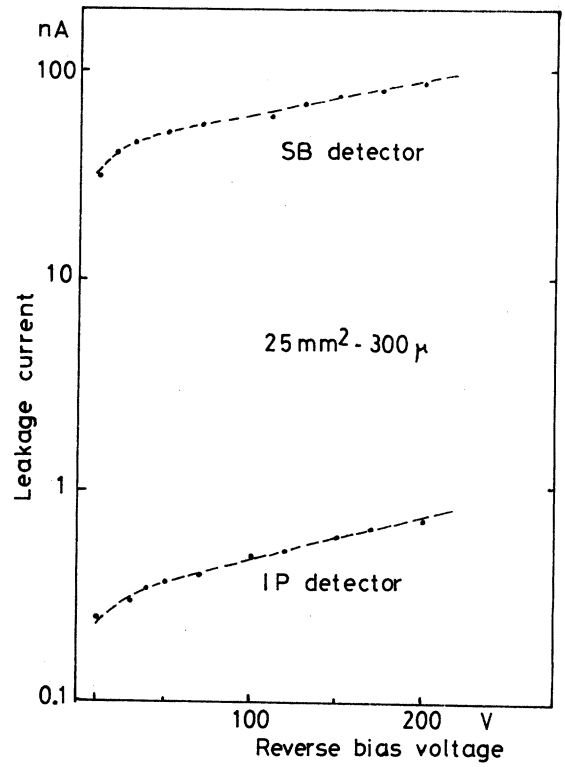

Fig. 2 : Comparison between reverse currents of a surface barrier and a passivated ion-implanted silicon detector of the same size (25 mm2 area, 300 µm thickness)

The dependance of the capacity of the chips on the bias voltage[2] ($C \propto V^{-0.45}$) appears to be near that of an abrupt pn-junction ($C \propto V^{-0.5}$). This result indicates that both channeling effects during the implantation of boron and diffusion effects during the annealing procedure are not restrictions to this method.

Long term stability

The reverse currents remain stable over long periods of time. This has been checked on a 25 mm2 area IP detector, 500 µm thick over a continuous run of 6 months. The current at 120 V remained between 5 and 6 nA during the whole period, the small variations observed beeing attributed to room temperature variations.

Charged-particle spectroscopy

The energy resolution capability of a 25 mm2 area, 300 µm thick IP detector is demonstrated in Fig. 3 for a ^{241}Am alpha-spectrum. The different peaks between 5389 and 5545 keV are clearly seen, the resolution at 5486 keV beeing 10.6 keV.

The dead layer thickness determined by observing the alpha particle pulse height shift with the beam respectively normal to the detector surface and at an angle of 45° is about 0.2 µm. For special applications this dead layer can be reduced below 0.1 µm by lowering the implantation energy.[4]

Experiments with heavy ions[5] (70MeV oxygen) were done using 100 mm2 area IP detectors (220 to 300 µm thick). The measured resolution was about 200 keV which corresponds to the FWHM of the beam (200 ± 20 keV).

Typical values of the pulse rise-times were between 1.2 and 1.6 nsec per 100 μm thickness of the depletion layer, showing the adaptibility of IP detectors for fast timing experiments.

Position sensitive detectors can also be manufactured using the same process, by reducing the implantation dosis of boron to 10^{13} ions.cm^{-2} in order to produce a resistive layer and therefore to provide for measurement of impact position through charge division.

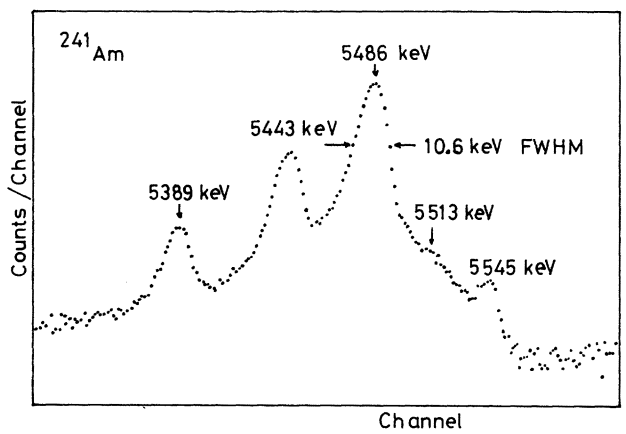

Fig. 3 : Spectrum of a ^{241}Am alpha-particle source (log scale) measured with an IP detector (25 mm2 area, 300 μm thick) at room temperature. Resolution at 5.486 MeV is 10.6 keV (FWHM)

X- and γ-ray spectroscopy

By selecting the chips having the lowest leakage current and optimizing the electronic

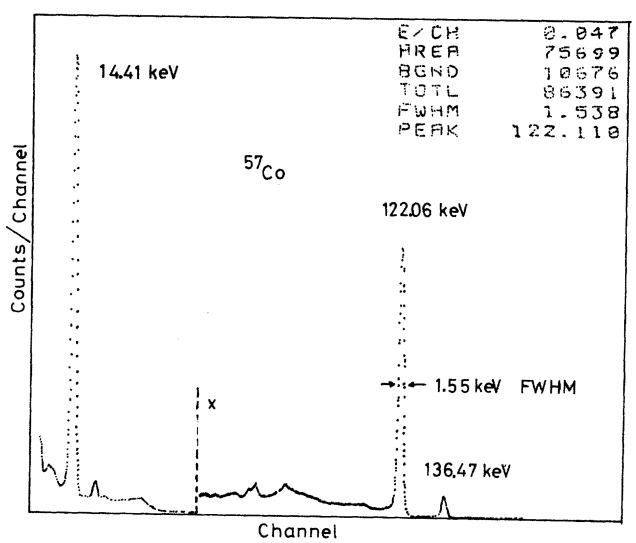

Fig. 4 : Energy spectrum for ^{57}Co-gamma and X-radiation measured with an IP detector (25 mm2 area, 300 μm thick) at room temperature. Resolution at 122 keV is 1.55 keV (FWHM)

components, a noise level of 1.5 keV was achieved at room temperature for 25 mm2 area IP detectors. Therefore, new possibilities are opened in the field of X- and γ-ray detectors at room temperature. Fig. 4 shows an energy spectrum for ^{57}Co gamma rays. The resolution (1.55 keV at 122 keV) is determined mainly by the electronic noise and therefore remains practically constant in the energy range from some keV to 150 keV.

Baking and annealing

Ion implanted pn-junction detectors are able to withstand moderately high temperatures. Using pressure contacts to assure the electrical connection, a 100 mm2 IP detector was used for tests at 200°C. Baking was done under vacuum (10^{-6} Torr) during 15 hours at 200°C. The results are shown in Fig. 5 : the current - voltage characteristic remains essentially unchanged. Similar results have been reported by Hyder.[6]

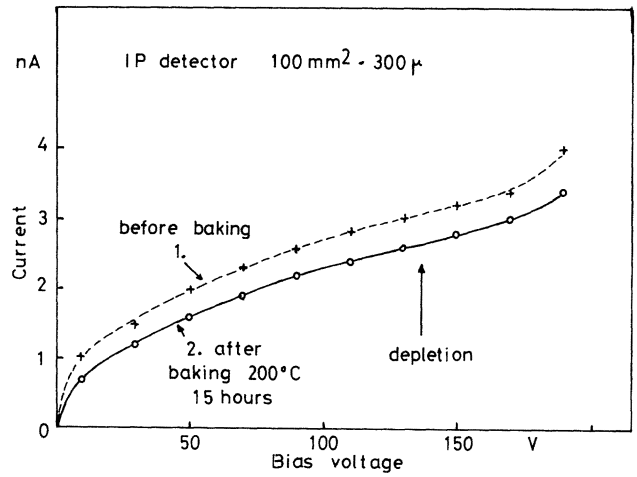

Fig. 5 : Current-voltage characteristics of an IP detector (100 mm2 area, 300 μm thick) before (curve 1) and after baking 15 hours at 200°C (curve 2).

The possibility of heating IP detectors at 200°C is not only attractive for use in high vacuum systems that have to be thermally cycled but offers another interesting application, namely annealing of radiation damage. Experiments were done by Kemmer and Wagner[3] with heavy ions. After an irradiation of a 100 mm2 area detector with about 10^7 oxygen ions, the reverse current increased from 3nA at 150 V to 50nA, as a result of the introduction of crystal defects. An annealing cycle at 200°C during 30 min was tried : the result was a decrease of the post irradiation current to 15nA at 150 V, i.e. a factor 3 reduction. Further improvements seem possible either by higher temperature annealing or by longer times at 200°C, which may be important for some applications.

High Energy Physics Applications

Until recently, solid state detectors have been used very little for high energy physics experiments. Two different kinds of experimental arrangements are beginning to change this situation : one is the use as live targets[7,8] of telescopes made up of thin silicon detectors, the other is the availability of position sensitive microstrip detectors.[9]

Silicon telescopes

The possibility to avoid any epoxy rings for the

mounting of ion-implanted pn-junction detectors allows the construction of target telescopes made up by a stack of silicon slices crossed by the beam. The clearance between adjacent detectors can be made very small, down to 100 μm. Different telescopes have already been realized. For the beauty test experiment[8] (CERN proposal P 137), two telescopes were manufactured following a design supplied by the Genova-Milan physicists : the first consists of 5 silicon sheets 100 μm thick, 1 cm2 area, 130 μm apart each other, the second of 10 silicon sheets 200 μm thick, 5 cm2 of surface, 200 μm apart each other. Every detector is related to an electronic processor[10] having a good energy resolution and a high acquisition rate (100 ns shaping). Another telescope shown in Fig. 6 was constructed composed of 40 detectors 300 μm thick, 160 mm2 area, 150 μm distant from each other, used for photoproduction experiments and short lifetime measurements.[11]

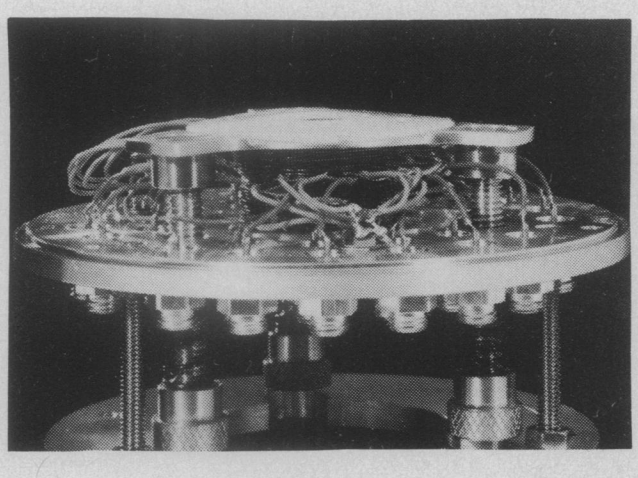

Fig. 6 : Telescope composed of 40 silicon detectors 160 mm2 area, 300 μm thick, 150 μm distant from each other.

The interest of such silicon detectors is the acquisition of early information on particle multiplicity and the knowledge of the interaction point. A combination of the thickness and the spacings of the silicon layers provides a direct measurement of the decay path of the particles produced, especially for very short-lived charmed particles.

Microstrip detectors

Heijne[9] et al. demonstrated the praticability of a silicon microstrip detector made by the surface barrier technique. Obviously, the passivated pn-junction technology is better adapted to such application :

- the devices, oxide passivated, are more reliable than surface barrier detectors ;
- the use of photographic masks enables more precise definition of the strips with much smaller pitches down to 20 μm.

At present planar versions of a 200 μm pitch (sensitive area 20 x 30 mm2, 300 μm thick) and a 50 μm pitch (10 x 25 mm2 area, 300 μm thick) have been realized.

The silicon detector is glued with an epoxy resin into a fiber glass printed circuit board which already contains the contacts in the form of gold plated copper strips. A photograph of the 200 μm pitch version is shown in Fig. 8. The front side of the strip detectors were contacted with an aluminium wire by ultrasonic bonding. The total current for 100 strips ranged from 130 nA to 380 nA at 150 V (2.000 ohm-cm material) in

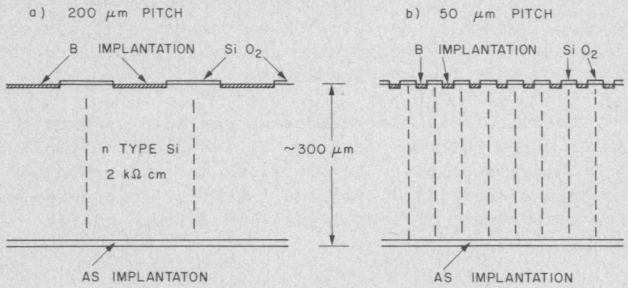

Fig. 7 : Structure of planar versions of a 200 um pitch and a 50 um pitch parallel microstrip detectors.

different samples. The capacitance of a strip including stray capacitance is about 4 pF.

The 200 μm pitch detector was tested at CERN in a beam of 10 GeV/c pions using the experimental set up and associated electronic equipment described by Heijne et al.[9] A fast current sensitive preamplifier designed by Jarron[9] and functionning with bipolar instead of field effect transistors was used. The electrical noise is relatively high (FWHM of 12-15 keV Si equivalent) but low enough compared to the main signal variation which originate from the fluctuations in deposited energy as given by the Landau distribution for minimum ionizing particles.

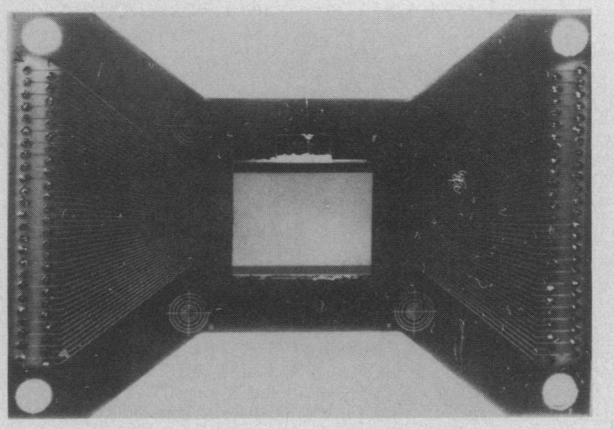

Fig. 8 : Silicon microstrip detector

A pulse height spectrum obtained in the beam of 10 GeV/c pions is shown in Fig. 9. The width of the pedestal noise distribution indicates a FWHM noise of 20 keV. The energy deposition spectrum, after pedestal correction, follows a Landau distribution.

In Fig. 10, the signal height for the pions is plotted as a function of the reverse bias. Complete charge collection is obtained above 120 V. The corresponding energy determined using a ^{57}Co source for calibration is about 80 keV for this 300 μm thick detector, in accordance with the most probable energy deposit value of about 27 keV per 100 μm for minimum ionizing particles.

In the way the microstrip detector was positionned between wire chambers with center of gravity read-out as sketched up in Fig. 11, beam tracks can be selected which pass through the detector and these should be recorded. From 10.000 tracks only

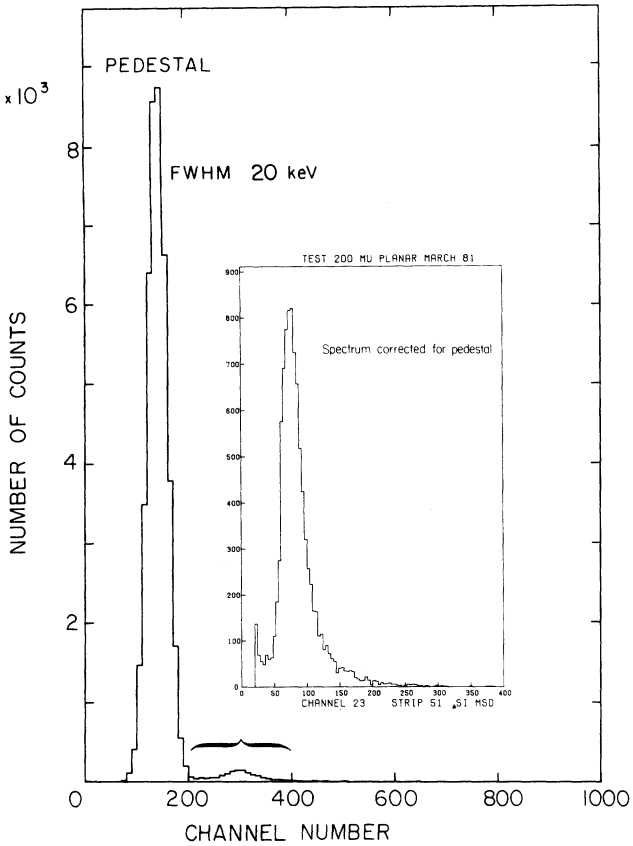

Fig. 9 : Pulse height spectrum of signals from a microstrip in the 10 GeV/c test beam. The width of the pedestal gives the noise. Enlargement of the Landau distribution, after pedestal correction is shown in the insert.

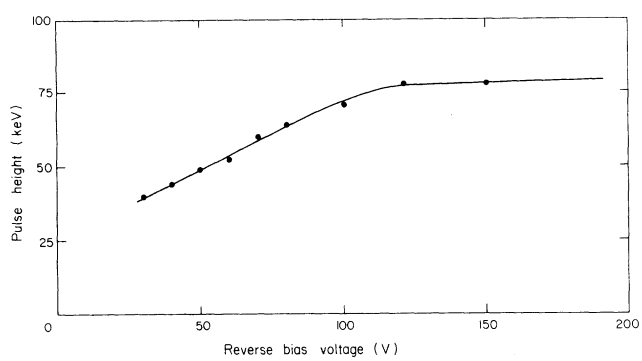

Fig. 10 : Most probable signal height (in keV) as a function of the reverse bias voltage. Complete charge collection is obtained above 120 V.

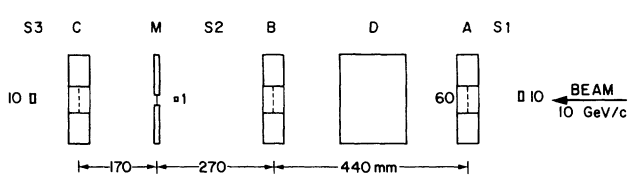

Fig. 11 : Situation of the microstrip detector (M) between wire chambers with centre of gravity read-out A, B and C. S1 and S2 are scintillators used for triggering.

6 were not found. The resulting efficiency is therefore 100 %, indicating that there are no dead zones between the strips.

Further high energy physics applications

Various applications can be expected :

- Beam profile monitor in a high intensity secondary beam.
- Fast beam hodoscope as described by Heijne and Jarron.[12]
- High precision vertex detectors, by combination of several slices.
- Vertex reconstruction detector, possibly for nuclear emulsion or mini bubble chambers.
- Specific trigger for high rate (10^8 events/s).
- Detector used inside the vacuum chambers of a storage ring.

Conclusion

Using the planar process it is possible to fabricate silicon detectors of extremely low reverse currents by the improvement of the charge carrier lifetimes and by the elimination of surface leakage currents. In addition to their obvious application for high performance charged particle spectroscopy, these detectors enable the spectroscopy of X-rays with energy resolutions of 1.5 keV at room temperature.

In high energy physics, applications are based mainly on two kinds of experimental arrangements : telescopes consisting of a stack of thin silicon slices, used as active targets and position sensitive microstrip detectors. Miniaturization of the associated electronics in under way in differents laboratories. The aim is to realize a detection system having better spatial and time resolution for multiple track events than multiwire proportional chambers and which can stand count rates in excess of 10^7 cm^{-2} s^{-1}.

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