A 55 cm^2 Cylindrical Silicon Drift Detector

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Abstract

AZTEC, a large area cylindrical silicon drift detector was designed, produced and tested. AZTEC will be the building block of the NA45 and WA98 micro vertex detectors at CERN. Several AZTEC detectors are placed down stream from the target to measure trajectories of charged particles produced in the extreme forward direction.

The active area of AZTEC is practically the full usable surface of a 100 mm diameter wafer. The electrons drift radially from the center towards the outside. The sensing anodes are located at a radius of 42 mm. The center of the wafer is cut out and forms a passage for the non interacting beam. With a minimal radius for this hole the active region of the drift detector starts at an inner radius of 3.1 mm. Any larger radius can be selected if necessary. With this geometry and a typical operating voltage the maximum drift time is less than 4 μs.

Due to constrains in the mask layout the readout region and field electrodes are designed along the 360 sides of a symmetric polygon. All structures on one surface of the wafer are rotated by 0.5° with respect to the other surface. In the middle plane of the detector, where the electrons are mostly transported, the effective geometry is close to a smoothed polygon with 720 sides, cancelling practically all effects of the non-perfect cylindrical symmetry.

The radial position of fast charged particles is measured by the electron drift time within the detector. The drift velocity can be monitored by 48 injection points at three different radii.

The azimuthal angle is measured by the 360 read out anodes. Each anode is subdivided into five segments, which are interlaced with the neighboring anodes. By this methode the azimuthal resolution is improved and corresponds to a 720 channel read out.

Introduction

AZTEC is a second generation cylindrical silicon drift detector to be used for a very forward tracking in the heavy ion experiments NA45 and WA98 at CERN SPS. The design of the detector was carried out as an improvement on a 3" diameter detector, which performance was also reported during this Symposium [1]. There are the following differences between the two designs: 1) Increase of the active area from 32 cm^2 to 55 cm^2. 2) Improved approximation of ideal circles with polygons of 360 instead of 120 sides. 3) Increase of the designed drift field, which will allow an increase of the drift velocity of electrons from 6.5 to 10 μm/s. 4) Introduction of injection pads at three different radii to measure the drift velocity of electrons with a simple voltage pulse. 5) Development of interlaced anodes to improve the azimuthal resolution of the detector.

The first point reflects the progress in the technology of the silicon detector production. The 4" high resistivity wafers are now common and large detectors can be fabricated free of fatal defects.

The second point took advantage of the progress in the mask design software. 3° used to be the minimal angle allowed at the time the 3" cylindrical detector was designed. The 3° rule lead to a polygonal structure with 120 fold symmetry. The drift of electrons within this structure resulted in a deterioration of the ϕ resolution with the old design. The new design uses 360 fold symmetrical patterns on both sides of the detector. Moreover, the pattern on one side of the detector is rotated by 0.5° with respect to the other side. Signal electrons are transported in the middle of the wafer, where the field is smoothed to almost ideal cylindrical geometry.

The increase of the drift velocity within the detector is desirable for the implementation of the multiplicity trigger from the detector. The multiplicity trigger can be formed only after the signal charges from the whole detector have arrived to the anodes. The improvement of the multiplicity trigger is mainly due to a smaller diffusion in the longitudinal and the transverse directions. The charge sharing among neighboring anodes and subsequent waveform samples is reduced leading to a simple implementation of the trigger.

Most of this paper is dedicated to the design of the interlaced anode readout. The following part will describe the reasons for the interlacing and the determination of the optimal anode splitting. Then we will describe the design of the true anode geometry, which leads to the desirable collection properties by following drifting electrons in the anode region in a full three dimensional simulation. We will present test results of the charge sharing on the interlaced anode structure. We will describe the way how to carry the surface leakage current generated on the Si-SiO_2 interface towards the sink anode passing the readout anodes. The injection system for the detector calibration will be shortly described.

Interlaced Anode Readout

In the detector the signal electrons are drifting radially towards an outside ring of anodes. During the drift the size of the electron cloud increases mainly due to diffusion. The increase is more rapid in the transverse, that is $\phi \times r$ direction, where the diffusion is combined with a spreading effect of the radial geometry. In [2] the problem was studied and it was shown that the size measured by r.m.s. in the ϕ direction equals

$$\sigma^2 = 2Dt(1 + vt/r_0)$$

where D is the diffusion constant, t the drift time, v the drift velocity and r_0 the initial position of the cloud. We have assumed that the cloud was point like for $t = 0$. The transverse size of the electron cloud arriving on the anode ring is almost a linear function of the drift time. σ varies by a factor of 4 within the area required by the experiment.

Let us study the criteria to determine the transverse size of the anodes. We can think of the anodes with their following readout channels as sampling points along a ring. The $\phi \times r_{anode}$ coordinate replaces time in the sampling theorem. If we take $r_0 = 15$ mm, $v = 1$ cm/μs and $r_{anode} = 42$ mm the r.m.s. of an electron cloud arriving onto the anode ring is 230 μm. The gaussian shape of the signal along the anode ring can be Fourier transformed giving again a gaussian function with r.m.s. in linear frequency $\sigma_{lin} = 1/2\pi\sigma$. Taking a linear frequency, where the value of the gaussian decreases to 1/10 of its maximal value as the maximum frequency of interest, we obtain the sampling distance $a = 1.46\sigma$ or 336 μm in the considered case. An implementation of more anodes would correspond to an oversampling and would not improve the performance of the detector for signal electrons arriving from radii less than 15 mm. The calculated anode spacing would require about 780 anodes around the perimeter of the detector.

Such a small anode spacing would lead to an excessive charge sharing among the anodes for electrons arriving from small radii. As mentioned above the sharing would complicate the realization of a multiplicity trigger and a large number of channels would make the system more difficult to handle.

Let us keep the number of anodes at 360, that is one anode per degree of perimeter. The excessive charge sharing for the signal electrons arriving from longer distances is now much less of a problem. However, we do not have enough charge sharing for those signals produced by particles crossing the detector close to the anodes. Some amount of charge sharing is desirable to measure the $r \times \phi$ coordinate by weighting charges collected by neighboring anodes. When the size of the electron cloud is much smaller than the anode spacing we have a strange situation. If the electrons arrive close to the boundary between two anodes, the position is measured very precisely (within view μm). However, if all charges arrive within one anode no weighting is possible and the resolution of the detector is defined only by the anode spacing.

The picture of linear frequencies and the sampling theorem used for the determination of the minimal anode spacing can be recalled again. Electrons produced close to the anodes arrive to the anode ring with only little spread due to the diffusion and contain linear frequencies above the Nyquist frequency. Here we are undersampling the signal. The usual way to avoid undersampling, which is also used when reading the drift time information, is the insertion of a low-pass filter to eliminate all frequencies above the Nyquist frequency in the signal before sampling. In our case we should try to spread out the arriving charges in transverse direction.

Interlacing the anodes is a practical way to achieve the same effect. Each anode, instead of being one contiguous collecting electrode, is divided into five parts as it can be seen on Fig. 1. A large central part (366 μm wide) is bonded to the preamplifier and is connected to the leftmost and to the rightmost parts of the 1° segment. Two narrow, 61 μm wide parts situated within the segment are connected to the neighboring anodes. The narrow part on the left hand side is connected to an amplifier located left and the narrow part on the other side is connected to an amplifier on the right side. All interlaced anode configurations are identical, hence the preamplifier of the central anode is also connected to the corresponding narrow parts from its two neighboring anodes.

With the shown interlaced anode structure, signals with a small transverse spread are more likely to be sensed by two readout channels, than it would be the case with a contiguous anode structure. Fig. 2a shows the error for the signal due to a particle crossing the detector at a radius of 12 mm. The series of curves corresponds to different widths of the individual anode parts. The width of the anode connected to the neighboring amplifier is written next to the curve. The central part of the anode was held at a constant width of 366 μm. We can see that for the central curve, the charge sharing is perfect. Fig. 2b shows the error for a signal arriving from a radius of 30 mm. The maximum error for the central curve is still less than 5 μm. Fig. 2c shows the error for signals arriving from a radius of 37 mm, that is the drift path is only 5 mm. Here the error for the central curve is about 50 μm.

The measured positions in Fig. 2 were derived by simply calculating the center of gravity of the charges collected on the anodes. It is possible to use a better algorithm for the calculation of the positions. The systematic errors of a more sophisticated analysis are smaller than the errors shown on Fig. 2.

Signal Electron Bifurcation

During their drift toward the anodes, electrons bifurcate somewhere within the silicon and decide into which part of which anode to arrive. Fig. 3 shows these three dimensional trajectories of electrons drifting toward the anodes with the bifurcation points well visible.

The geometry of the interlaced anodes must be such that the distances between the projection of the bifurcation points onto the anode ring have the requested values. A full three dimensional simulation of the electric field [3] in the anode region was used for the interlaced anode design. Fig. 4. summarizes the main points of the design. Trajectories of individual electrons were simulated for electrons drifting from a long distance at different values of the coordinate along the anode ring, called x-coordinate. The x-coordinate of the landing point of the electrons at the anode surface is plotted. The distances on the x-axis of the plot between the point of discontinuity are the values requested for the design. Let us point out that the width of the anode parts on the silicon surface is not equal to their calculated dimensions.

Experimental Test of the Interlaced Anodes

Fig. 5 is a microphotograph showing three interlaced anodes of a detector produced at [4]. There is a large notch in the central part of each anode. The notch was introduced to decrease the sensitivity of the position of the bifurcation points on the bias of the electrode in the anode region. The bias is different for different doping densities of the silicon bulk material. The present design is optimized for a wide range of doping densities of the silicon.

There are 20 windows in the aluminum of the first ring in front of one of the anodes on Fig. 5. The missing aluminum in the windows allows the light from a glass fiber, driven by a laser to penetrate into the silicon. The precision of the light position is defined by these windows. The light intensity is adjusted to produce the same number of electron-hole pairs as a minimum ionizing particle.

Results of a test are shown on Fig. 6. The upper part shows the fraction of the charge collected by three neighboring preamplifiers for light incident into 20 windows in aluminum in front of one anode. The sharp transitions are due to the negligible diffusion of the electrons during their short drift time. The location of these transitions are at the designed positions. The bottom part shows the charge sharing for a drift distance of 7 mm, that is, the light was injected at a radius of 35 mm. There are no windows in the aluminum of the ring and the azimuthal positions of the injection points are slightly shifted. However, the plot shows that there is an important charge sharing between two neighboring preamplifiers for most of the injection points.

Treatment of the Surface Current and Drift Velocity Monitoring

It is a typical property of carefully processed silicon detectors that more leakage current is produced at the Si-SiO_2 interface than in the bulk of the detector. AZTEC was designed to collect the surface leakage current in a sink (guard) anode rather than in the readout anodes of the detector. To accomplish this task, electrons generated at the interface are retained close to the surface while transported towards the sink anode. The attractive force of positive charges in the oxide and at the interface keeps the electrons close to the surface. The details of the design were already studied for the 3" predecessor version [2]. However, in the anode region a new complication arises for the AZTEC detector. In the old design a simple interruption in the ring of discrete anodes could be implemented to let the surface current pass to the sink anode. For AZTEC, due to the interlacing and the way how parts of the anodes are interconnected, no interruption of the anode structure in the azimuthal direction is possible.

The transfer of the surface electrons around the anodes is done on special aluminum traces implemented at every fifth anode of the array. One anode with this connection is visible on Fig. 5 and is shown in more detail on Fig. 7. The aluminum line, which carries the surface electrons is indicated with an arrow. It has n^+ contacts to the silicon on both ends. Electrons enter the line at the contact in the region between the first ring (with openings into the aluminum) and are reinjected into the region on the sink anode at the bottom contact. The electric field in the region of injection is such that the injected charge of electrons does not interferes with the connection between the two parts of the anode, which surrounds the injection point.

The monitoring of the drift velocity in the AZTEC detector is done by injecting charges from small area n^+ contacts into the detector. They are located between the p^+ rings of the detector structure. Fig. 8 shows one out of 16 injection contacts placed on one ring. The bonding pad to supply the injection pulse is also visible. There are 3 injection rings on the anode surface of the detector.

Conclusions

A large area cylindrical silicon drift detector was designed, produced and tested. It has 360 interlaced anodes providing the azimuthal resolution equivalent of 720 simple anodes. First experimental results have verified that the design yields the calculated optimal charge splitting. The amount of leakage current is reduced by collecting surface generated electrons in a sink anode. The drift velocity is monitored by measuring the drift time of electrons injected into the detector under control of an external voltage pulser at 48 injection points at three different radii.

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Figures

Fig. 1 Principles of interlaced anodes. One anode covers 1°. A large central part of the signal anode is bonded to the preamplifier and is connected to the leftmost and to the rightmost anode parts. The two most narrow parts shown are connected to the neighboring anodes amplifiers. The preamplifier of the central anode is also connected to the corresponding narrow parts from its two neighboring anodes.

Fig. 2. Systematic error in the studied interlaced anode system. Fig. 2a, 2b, 2c are for particles crossing the detector at radii of 12 mm, 30 mm and 37 mm respectively. The zero position is the anode center and the curves end at the boundary between two anodes. At both extremes the systematic error is zero due to the symmetry of the geometry. Each curve corresponds to a different width of the narrow region (connected to the other amplifier), once the dimension of the largest region was selected. The width corresponding to the central curve was chosen for the design.

Fig. 3. Trajectories of electrons in a three dimensional simulation close to the anode ring. Electrons are drifting in the middle plane of the detector before arriving to the anode region. Bifurcation points inside the silicon volume are visible. The distance between the bifurcation points is generally different from the width of the anode parts on the silicon surface.

Fig. 4. x-coordinate of the arrival of an electron at the interlaced anode as a function of its coordinate within the regular part of the electric field in silicon. Discontinuities in the curve correspond to the positions of bifurcation. the positions of these discontinuities along the x-coordinate of the plot must correspond to the design values. Regions of anodes unreachable to signal electrons can be seen.

Fig. 5. Microphotograph of a part of the drift detectors anode region. Electrons drift from the top to the bottom of the picture, where the interlaced anodes are located. One river for transporting surface leakage current runs from the top to the anode region. A special feature on every fifth anode transports this current to the sink anode. Windows in the aluminum rings facilitate the detector testing with a laser light.

Fig. 6. Experimental results of a laser test. Fraction of charge collected on three adjacent preamplifiers, when light was injected in front of one anode covering 1° of azimuthal angle. Triangles, circles and squares indicate charge collected by central, left and right amplifiers respectively. The upper picture corresponds to the injection through the windows in aluminum right in front of the anode. The bottom picture corresponds to a drift of 7 mm.

Fig. 7. Details of an anode with a special aluminum connection (indicated by an arrow) to carry the surface current. The surface current is taken from an n^+ contact to the silicon at the top of the line in the drift region of the detector. It is reinjected into the bulk of the detector at the bottom of the picture in the region of the sink anode.

Fig. 8. Details of the injection structure of the detector. The bonding pad is located on the top of the p^+ ring electrically insulated by 0.11 μm of SiO_2. The aluminum of a narrow ring between two p^+ rings is connected through this bonding pad to a pulser. At the right hand side of the narrow ring an n^+ injection point is visible. The distance between two p^+ rings is 140 μm.