Silicon Drift Detectors, present and future prospects

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Abstract

Silicon drift detectors provide unambiguous two dimensional position information for charged particle detection with a single detector layer. A large area silicon drift detector was developed for the inner tracking detector of the STAR experiment at RHIC. In this paper, we discuss the lessons learned and the future prospects of this technology.

1 Silicon Drift Detector developed for STAR

Silicon drift detectors (SDD's) are charged particle detection devices capable of providing two dimensional position information with a single detector layer. The operating principle is based on creating a drift channel inside a depleted silicon wafer, thus working like a solid-state drift chamber. By measuring the drift time together with the distribution of signals along the readout anodes, position information is obtained in both dimensions [1].

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A large area (6.3 $cm \times$ 6.3 cm) SDD was developed for the inner tracking detector (SVT) of the STAR experiment [2] at the RHIC collider. The SDD's were produced using 4-inch diameter, 280 μm thick, neutron transmutation doped N-type silicon wafers with an approximate resistivity of 3 $K\Omega cm$. Each detector is divided in two symmetrical halves in which the electrons drift in opposite directions toward the detector edge where 240 anodes on each side collect the ionized charge. Special effort was spent in maximizing the active area of this detector to optimize tracking efficiency while maintaining low radiation length. The main contribution of non-active area of the SDD is the HV guard area that in the final design was reduced to 6 % of the total detector area. Further details of the detector geometry can be found in references [3,4]. Extensive characterization measurements performed using laser induced charge injection show excellent drift linearity with position resolution better than 20 μm in the drift direction and 10 μm in the transverse (anode) direction. The low input capacitance of the readout anodes (below 1 pF) results in low electric noise, measured to be better than $530e^-$ in the STAR/SDD. Finally, studies with neutron and gamma irradiation in the range of 10 to 100 times more than the radiation levels expected at RHIC show good detector performance after irradiation. Some degradation of the anode leakage current and voltage linearity was observed, though not enough to impare the operation of the detector through 10 years of RHIC operations [5,6].

A total of 350 SDD were produced for STAR. Each detector was tested in a passive probe station measuring voltage linearity and anode leakage currents. These measurements served as selection criteria to obtain 250 accepted wafers, corresponding to a 70% production yield. The complete SVT assembly requires 216 detector wafers.

Previously, 15 STAR SDD were utilized in a heavy ion, fixed target experiment (E896) at the Alternating Gradient Synchrotron Accelerator at Brookhaven National Laboratory [7]. The detectors were assembled as a charged particle tracking device placed inside a 6.2 Tesla magnetic field very near the interaction target. Results from data analysis show excellent detector performance and in particular, good energy resolution that allows dE/dx particle identification and high track reconstruction efficiency (above 95 %).

Recently, 7 STAR SDD and the corresponding front-end electronics [8] were assembled on a SVT ladder configuration, and mounted inside the interaction volume of the STAR experiment. Readout electronics, data acquisition and slow controls system have also been installed to operate the detector ladder. Results from cosmic ray tests show successful integration of all systems and hits measured in the SVT detector ladder have been connected to tracks measured with the outer tracking detector of STAR, the Time Projection Chamber (TPC). The complete SVT is scheduled to be installed by the end of the year 2000.

2 Design considerations for future applications

Here we consider two types of possible applications for the SDD and discuss design considerations based on our experience and progress with the development of the STAR/SDD. Detector design optimizations vary with the application intended.

2.1 Charged particle tracking detectors

For charged particle tracking applications, one can aim for a full semiconductor based tracking device that could replace the gas drift detectors like the TPC's. In this case, it is desirable to cover as large an area as possible while maintaining good position resolution, low radiation length and radiation hardness. In addition, due to the considerable amount of single wafers required, it is necessary to consider design optimizations for production yields.

Figure 1 summarizes the area coverage of vertex and tracking detectors according to the main technologies developed in the last two decades. SDD have comparable area coverage to active pixel detectors and CCD based detectors. However, SDD's have the advantage that the number of readout channels is an order of magnitude smaller, as demonstrated in figure 2.

To increase the total detector area (using 6-inch wafers), perhaps there are two main issue to consider. The first issue is the increase of the maximum drift distance. To maintain the present position resolution (20 μm), higher drift velocities and thus higher electric fields would be required. Voltage breakdown limits and leakage current generation has to be considered in the guard area design while trying to maintain it at minimal for tracking efficiency. Another issue to consider in the case of larger detectors is the processing uniformity. In the STAR/SDD detector, contamination during the oxidation step of the processing generated localized defects that resulted in high leakage current sections of the detector thus affecting the production yield.

A large fraction of the radiation length of the overall detector system is due to the necessity of placing the front-end electronics near the anodes, thus inside the interaction volume. One of the solutions proposed is the use of implanted amplification stages on the same wafer. This has already been tried with active pixel detectors, where production yield seems to be the main concern [9].

Finally, the continuing use of silicon detectors in high energy and heavy ion physics experiments requires that these devices can sustain high levels of radiation generated in higher luminosity accelerator facilities. One possibility for improving the radiation hardness is to reduce the resistivity of the bulk mate-

Fig. 1. Development of area coverage of main vertex tracking detector technologies: Microstrip, CCD, Active Pixel and Silicon Drift detectors over the last few decades. Information extracted from [10]

Fig. 2. Development of number of channel of main vertex tracking detector technologies over the last few decades.

rial which will increase the inversion dosage. Another solution proposed is the use of oxygen doped materials. Presently we have utilized $3K\Omega$cm Neutron Transmutation Doped n-type material. New radiation hard SDD will have to be coupled to radiation hard electronics. Development of radiation hard CMOS technology is well underway.

2.2 Small compact tracking systems and single detector for X-ray and imaging detectors

SDD technology can also be applied for small compact tracking devices (such as the one utilized in experiment E896) with high granularity and position resolution so that it can be used in very high occupancy environments such as in the proximity of interactions in high energy and relativistic heavy ion experiments or for space applications. For X-ray and imaging applications, one would also like to improve the position resolution, but mainly reduce noise levels for good energy resolution.

The finest granularity (smaller pixels) achievable with the SDD's is limited by the decrease of the signal to noise ratio due to the fact that the electron cloud is shared over many readout pixels (both in the drift direction and in the anode direction).

In the anode direction, with the STAR/SDD, the readout pitch size is 250 μm, and the charge is normally shared over 3 to 5 anodes. A Gaussian fit to the distribution yields a position resolution on the order of 10 μm. By increasing the drift speed, it is possible to reduce the charge spread, thus improving the signal to noise ratio and allowing finer readout pixel granularity. Another advantage of reducing the readout anode size is the reduction of the input capacitance which contributes to reduce the total noise level.

In the drift direction, the position resolution is mainly determined by the drift linearity which is defined by the uniformity of the electric field inside the detector bulk. The cathode potential linearity can be improved by reducing the implanted resistor value, thus reducing the effects of surface leakage currents. However, a lower limit to the resistor value is defined by the power dissipation due to the fact that implanted resistors are an undesirable source of thermal gradients. Reducing the cathode pitch can also improve the position resolution by reducing drift non-linearities caused by the charges trapped in the oxide interface between cathodes. The STAR/SDD were fabricated using 500 $k\Omega$ implanted resistor values and a cathode pitch of 135 μm.

Finally, since the electron mobility in the silicon bulk is temperature dependent, it is useful to have a calibration mechanism to monitor the drift velocity. To maintain a minimum impact on the voltage linearity of the drift region, it is desirable to keep these injection structures as small as possible. However this can stand as a challenge to achieve good charge injection efficiency. Different configurations were experimented [11] and the best performance was achieved with an MOS type injector line (10 μm wide) placed between cathodes at several drift distances. Further studies are still underway with hybrid type of injection structure where a layer of n+ implant underneath an MOS injector line is expected to improve the number of induced charges.

With higher drift speed and finer cathode pitch we expect to be able to achieve position resolutions as low as 5 μm. With the reduction of the implanted resistor values and the drift velocity monitoring with charge injection it is possible to obtain a very robust and stable detector. In this type of applications, it might also be practical to reduce the temperature, which contributes to increase the drift velocity and further reduce the electronic noise.

3 Summary and Conclusions

The remarkable position resolution and high granularity achievable with silicon drift detectors make these devices an excellent choice for high energy and high multiplicity tracking environments. Furthermore, the low input capacitance of the readout anodes (below 1 pF) provides a good signal to noise ratio not only for position measurements but also for ionization measurements.

A large area silicon drift detector based tracking and vertexing device is in its final assembly stage and will soon be installed in the interaction volume of the STAR experiment at RHIC.

The success of the production and performance of the STAR/SDD indicates that it is possible to further develop this technology to broaden its applicability, such as in self standing three dimensional tracking detectors and small compact imaging devices.

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