SILICON DRIFT DETECTORS - A NEW TECHNOLOGY FOR A COMPACT TRACKING SYSTEM

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We will describe our experience in constructing a large area Silicon Vertex Detector for the STAR experiment at the Relativistic Heavy Ion Collider (RHIC). Based on the successful completion of this device we propose to consider Silicon Drift Detectors as a viable option for a Silicon based tracking system in a linear collider experiment. The advantages of this technology compared to other semi-conductor devices as well as gas detector based tracking options will be described. We will also discuss the details of a proposed design for a compact tracker within the framework of the 'small (S)' option of the American Linear Collider studies.

1 Introduction

In the last decade Silicon Drift Detectors have matured into a potential alternative to Silicon Strip, Silicon Pixel, CCD based and even gas based detectors for vertexing and tracking applications in High Energy Physics. The STAR experiment at the Relativistic Heavy Ion Collider (RHIC) decided in the early 90's to use Silicon drift detectors (SDD) for its Silicon Vertex Tracker (SVT). Presently, the detector is in its final phase towards a successful completion by mid 2000. In collaboration with Brookhaven National Laboratory, UT Austin, Ohio State University, Lawrence Berkeley Laboratory and a group of French and Polish collaborators, we designed and constructed this three barrel device, consisting of 216 Silicon wafers (6.3 by 6.3 cm) which corresponds to a total of 103,680 channels and about 0.7 m^2 of Silicon [1]. In addition during the summer of 98, a prototype consisting of 15 SVT wafers was successfully used as a tracking device in a BNL Heavy Ion fixed target experiment, E896. This array was the first Silicon drift detector based tracking device ever constructed [2,3]. Other heavy ion experiments have used single drift wafer as charge or hit counters [?,5], but with the advent of the SVT we have demonstrated that drift detectors can be successfully mass produced and applied to large detector systems. Their properties in terms of resolution and efficiency are comparable to Silicon pixel or CCD based detectors, but their intrinsic feature of obtaining three-dimensional position information with a one dimensional, large pitch readout from a single detector layer makes them superior in performance and in cost compared to any other semi-conductor technology. The low channel count is ideal for a large area tracking device. In the following chapters we will briefly describe the principles of a Silicon Drift Detector in comparison to other more common detector technologies, show the performance of the present SDD design, propose a layout for a compact tracking device and show some performance simulations. Finally we will address future R+D issues and draw some conclusions.

2 Principles of a Silicon Drift Detector and a comparison to other technologies

Silicon Drift Detectors are novel position sensing silicon detectors which operate in a manner analogous to gas drift detectors [6,7]. A charged particle traversing the Silicon wafer will generate an electron cloud. Most particles are minimum ionizing and will deposit around 24,000 electrons in a wafer of 300 μm thickness. For the SVT high resistivity (around 3 KΩ/cm) neutron transmutation doped (NTD) n-type Silicon wafers were used as a substrate. The original 4 inch diameter material allows the production of a 6.3 cm by 6.3 cm wafer. The detectors are divided into two distinct drift areas of 3 cm drift length each. Equal bias to both sides generates bi-directional drift towards the top and bottom of the detector. After several iterations during the R+D phase of the SVT, we were able to minimize the inactive guard area around the detector to 3 mm. Field shaping electrodes of p-type material are implanted symmetrically on both surfaces in a regular strip pattern. The pitch between cathodes in the STAR SDD is 135 μm. A high voltage gradient (up to 600 V/cm) is applied to these shaping electrodes and fully depletes the Silicon thus creating a deep potential well that attracts free electrons produced by the passage of charged particles through the detector. The surface electrodes are symmetrically connected to a voltage divider network that produces an independent electrostatic field parallel to the surface of the wafer. The field transports the electrons towards the edge of the detector where signals are read out on a segmented anode (pitch = 250 μm). Under suitable conditions, the electron drift velocity is constant, so that a measure of the drift time is equivalent to a measurement of the position in the drift direction. During drift the initial cloud of electrons expands two-dimensionally due to diffusion and Coulomb repulsion. Upon arrival at the readout anodes the charge is thus generally shared among a few anodes and a few drift time samples. Charge sharing techniques can be used to determine the original position of the cloud to an accuracy of less than 20 μm in drift and anode direction [1,?].. Besides the excellent position resolution the detector also provides very reliable energy loss information, which can be used for particle identification. In comparison to other vertexing and tracking technologies a Silicon drift detector has certain advantages and disadvantages:

Silicon Drift Detectors are commonly operated at room temperature, but the position resolution depends very little on the ambient temperature level. SVT wafers have been tested from 15^{o}C to 40^{o}C. In STAR we will operate the detector at a controlled 75^{o}F and at 50% humidity. The detector performance is very susceptible to the stability of the ambient temperature, though,‘. A 1^{o}C change leads to a 1% in drift velocity), so the temperature needs to be controlled to an accuracy of 0.2^{o}C. To further monitor and correct for drift velocity variations the SVT detectors are equipped with charge injection lines at fixed drift distances which can be pulsed with a calibrated input charge during detector operation.

Silicon Drift Detectors require a drift time of about 5 μs. Due to the small event rate at any Linear Collider, readout rate should not be an issue, though. The SDD drift is still about a factor 10-20 faster than any large area Time Projection

Chamber (TPC) drift, and the detectors have sufficient resolution to distinguish tracks from different bunches in a bunch train should any kind of event pile-up occur.

Silicon Drift Detectors are the only semi-conductor technology that yield unambiguous three dimensional information with a large pitch one dimensional readout. Silicon Strip detectors need more than one layer to achieve the same information content, and are therefore susceptible to stereo angle ambiguities. In CCD and Silicon pixel devices, the resolution is directly related to the pixel size due to the lack of charge sharing. Good resolution therefore requires small pixels and thus a large channel count. In contrast a SDD is comparable to a TPC but it yields about a factor 30 better single track and double track resolution. Silicon Drift Detectors generate a very low capacitance output which requires the preamplification to be very close to the anodes. This leads to a sizable radiation length contribution. In the present SVT design the radiation length has been optimized to 1.5% per layer including the electronics and the cooling system. We will discuss various options for minimizing the radiation length in the final chapter. Optimized Silicon Drift Detectors should have a radiation length comparable to Silicon Pixel Detectors. Both technologies might not be able to compete with CCD applications in this regard, though.

3 Features of the present SDD design

Recently the latest SVT-SDD design has been commercially fabricated in collaboration with SINTEF in Norway. As of June 99 around 300 wafers were produced and tested under stringent quality control specifications [2]. The resulting yield is close to 70%.

Besides a SVT system test and single wafer tests performed in the laboratory, fifteen wafers were used to build a tracking device for a fixed target heavy-ion experiment (E896) at the AGS accelerator in BNL. [2]. The following performance characteristics were obtained under both conditions.

Electronics characteristics: The SVT group has designed a Multi-Chip Module (MCM) that hosts a bipolar Preamplifier/Shaper (PASA) and a CMOS Switched Capacitor Array (SCA). The overall system noise was measured to be around 530 rms electrons compared to a 24,000 electron signal strength. Thus the signal to noise ratio is about 40:1 for minimum ionizing clusters. The power consumption of about 13 mW/channel requires water cooling for the electronics to keep the temperature gradient on the detector itself to below 0.3^0C. The clock frequency of the SCA defines the segmentation of the drift time (e.g. 25 MHz = 40 ns time pixel = 250 μm drift pixel for a drift velocity of 6 μm/ns (HV_{max}=1500 V)). The symmetry between the anode pitch and the time pixel size (both 250 μm) leads to a symmetric position resolution in both directions if no non-linearity effects are induced by detector bulk properties.

position and two-track resolution: Silicon Drift Detectors are dynamic detectors with slightly varying position resolution as a function of drift time. These changes can be due to material induced drift non-linearities (Silicon bulk defects) or simple changes in the signal to noise ratio based on increasing diffusion [2]. Fig.1a shows the integrated charge as a function of drift distance. Fig.1b shows the typical cluster amplitude for the same clusters. Although the amplitude is steadily decreasing with increasing drift distance, the integrated charge stays constant, indicating that there is no evidence for charge loss in the detector. The effects of non-linearities on the position accuracy can be seen in Fig.2. On average the measured position resolution is between 10 and 20 μm for the present batch of STAR Silicon Drift Detectors. The two-track resolution for the longest drift time is about 500 μm, but a more detailed offline waveform analysis can reduce this value to about 300 μm.

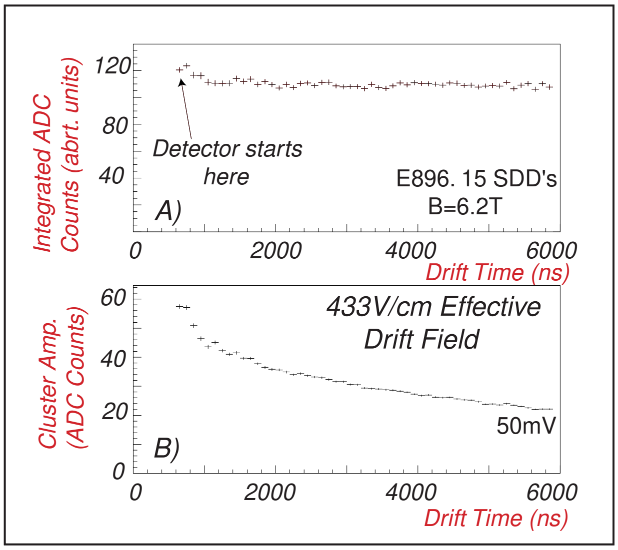

Figure 1: Integrated charge and amplitude for reconstructed hit clusters as a function of drift distance measured during a heavy-ion beam time in BNL-AGS experiment E896

dynamic range and energy loss: Although less relevant for High Energy Physics applications it is interesting to point out that the SVT detectors allow the measurement of the energy loss of particles from minimum ionizing levels up to about thirty times minimum ionizing. The detector itself can measure even higher charges. At this level the range is electronics limited. This large dynamic range is mostly relevant for the detection of very low momentum protons and pions. Instant Coulomb repulsion on the drift detectors distributes even the largest cluster at the smallest drift distance over several readout pixels. The electronics is designed with a large voltage swing to avoid saturation. The de/dx resolution of a six layer drift detector is about 8%, which is comparable to the resolution that can be accomplished in a large volume TPC. Any gas detector has additional separation strength in the relativistic rise region though.

radiation damage studies: The detectors were tested under controlled neutron and γ-ray radiation. Details of the test results can be found elsewhere [9,10].

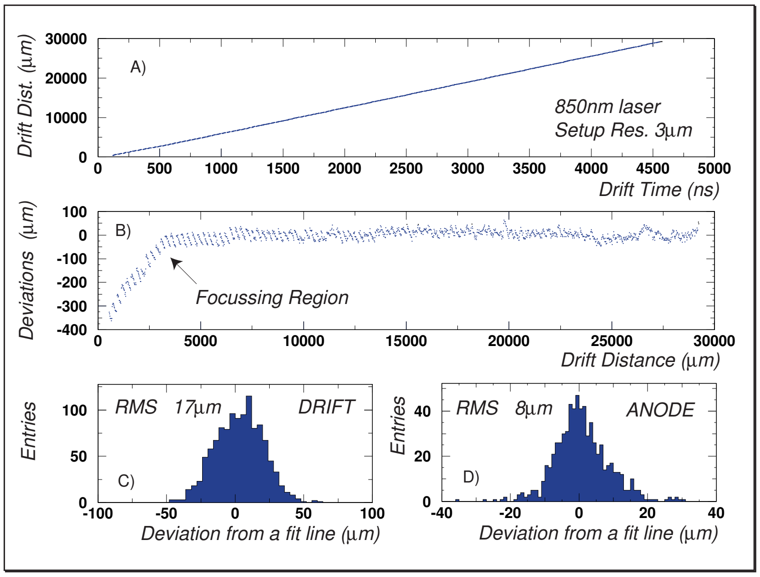

Figure 2: Drift linearity and its deviations as a function of drift distance plus the resulting position accuracy for a typical Silicon Drift Detector.

Neutron radiation causes mostly displacement damage in the bulk, whereas the γ radiation affects the surface properties. The intrinsic inversion point (n-type to p-type) for the 3 kΩcm starting material is at $2{\times}10^{13}$ n/cm^2. We have performed γ-radiation tests at levels between 10^{10} and 10^{12} γ/cm^2. Neutron radiation tests were limited to dosages of 10^{12} n/cm^2. In the case of large γ radiation the surface leakage current increases which leads at the maximum dosage level to a signal to noise reduction by about 15%. Still, the effect on detector resolution is negligible. In the case of neutron radiation at the maximum level, the position resolution starts to degrade based on non-linearities which are due to displacement damage. The wafers anneal at room temperature within a few months. In summary, the present batch of detectors shows only negligible effects up to a radiation level of about 10^{11} n/cm^2. This level can be improved by an order of magnitude or more by reducing the resistance of the implanted resistors. These implants are most susceptible to displacement damage. The frontend electronics did not show any degradation at the 10^{12} n/cm^2 level.

magnetic field effects: Assuming that a possible layout for a Linear Collider Detector might require the operation of a vertexing or tracking detector in a strong magnetic field, the results from the E896 experiment might be of specific importance. Here the drift detectors were operated in a 6T dipole field. The drift direction was aligned with respect to the field, but off-axis components were measured to be as large as 0.1T. Due to magneto-resistance the increased B field slows the drift velocity. The effect can be easily calibrated though. The conclusion is that the detectors perform very well up to the maximum field. Details of the effects of magnetic fields on drift detectors can be found in [11].

4 A Design for a compact Linear Collider Experiment

A design has been worked out on the basis of the 'small' detector option which was originally proposed during the Snowmass meeting [12]. This option is based on a compact tracking volume inside a strong, superconducting magnet. Neither a TPC nor a Drift Chamber might lead to sufficient resolution in such a small volume. It was therefore suggested to consider a Silicon based large tracking detector in connection with a CCD or Silicon Pixel based vertex detector.

Based on performance and feasibility simulations we propose a six layer Silicon Drift Tracker (SDT) with a max. cos $\Theta = 0.91$. To improve the momentum resolution we propose to arrange the six layers in three doublets at radii of 15 cm, 43 cm, and 72 cm, respectively. The maximum radius was chosen based on the anticipated gap size of a superconducting magnet, the required momentum resolution, and the maximum layer length that can be supported by a reasonably sized support structure strongback. The layer lengths are 100 cm, 180 cm, and 300 cm, respectively. The full device corresponds to 37 m^2 of Silicon and will consist of 3754 wafers (10 cm by 10 cm active area cut from 6 inch wafer). Assuming a 200 μm pitch the channel count is around 3.75 Million channels.

Strongbacks to support detector ladders of lengths larger than 100 cm will require a specific shape and material. We suggest triangular Carbon Fiber structures to give stiffness to the structure and minimize radiation length. Cooling can be accomplished by simple air cooling assuming that the frontend power dissipation on the detector can be held below 10 mW/channel. The necessity of frontend electronics integration in the active area of the detector can be solved in a variety of ways. We presently investigate to either integrate the amplification stage into the wafer itself (see next chapter) or to bond the frontend to the wafer via TAB (tape automated bonding) rather than conventional wire bonds. One advantage of the TAB will be the option to mount the electronics right above the wafer itself, which will lead to a configuration comparable to a bump bonded pixel detector.

5 Performance Simulations

All our simulations are based on the performance presently achievable with the existing STAR detectors. We assumed position resolution of 10 μm and 20 μm in anode and drift direction, respectively, and a radiation length of 1% per layer. Under these assumptions a momentum resolution of about 8×10^{-2} for 1 GeV/c particles can be achieved. The resolution is almost constant up to 100 GeV/c.

We assume that future R+D will be able to reduce the radiation length to about 0.3% per layer, which improves the momentum resolution at 1 GeV/c to about 1×10^{-3}, which is close to the nominal resolution for a large volume TPC, see Fig.3.

Several groups in the American LC study group have performed specific simulations with the small detector configuration as described in this paper. We encourage the reader to review the contributions by Homer Neal (chargino and slepton

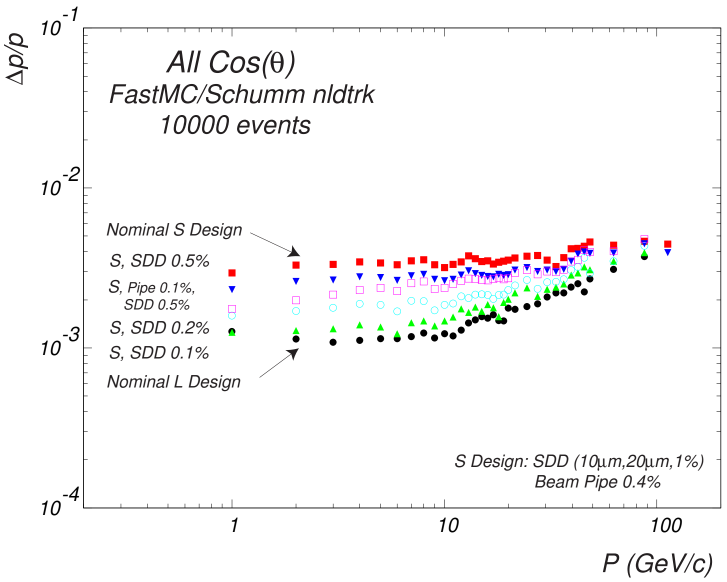

Figure 3: Momentum Resolution as a function of Tracking Detector Layout.

searches), David Wagner (Z mass reconstruction), David Gerdes (top mass reconstruction), and Mike Ronan (W mass reconstruction) to this conference.

6 Future R+D Issues

Future R+D for any high energy physics application of Silicon Drift Detectors will include:

Radiation length reduction can be accomplished by implanting the amplification stage of the readout electronics. First attempts towards a monolithic Silicon Drift Detector have been made [8]. The challenge will be to keep the production yield high for detectors with electronics implants. Another option will be to thin the detectors to less than 300 μm, probably as low as 150 μm. The challenge is again to keep the production yield high, in particular for large area (6 inch) wafers.

Radiation hardness can be improved by decreasing the resistivity in the Neutron Transmutation Doped (NTD) n-type material. Presently the bare wafers have a resistivity of about 3 KΩcm. Values down to 1 KΩcm can be tolerated and will lead to an increase in the inversion dosage by about an order of magnitude. Also a reduction in the resistance of the implanted resistor will make those parts less susceptible to displacement damage from neutron radiation. In the electronics chain one could produce the SCA in a radiation hard CMOS process rather than the standard process. The bipolar PASA is intrinsically radiation hard.

Increased position resolution and two-track resolution can be accomplished by optimizing the spacing of the anodes as well as the number of time-samples. Presently the anode pitch is chosen to match the occupancy requirements in a heavy-ion environment. A smaller pitch at higher drift velocity could lead to resolution improvements. Laser injection tests have shown that the intrinsic limit of the SDD position resolution is below 5 μm. A higher drift velocity will require a higher maximum voltage (up to 3 kV might be tolerable) on the wafer plus a larger number of time samples. Switched Capacitor Arrays of up to 512 time samples (compared to the presently used 128 samples) have been designed and successfully manufactured. To support the higher maximum voltage on the detector any external or internal resistor chain will have to be stiffened by decreasing the resistor values. Also, a reduction in the electronics noise based on moderate design changes in the preamlifier layout will improve the position resolution and will lead to a more constant resolution over the full drift length.

7 Conclusions

Silicon Drift Detector technology seems to be perfectly suited for the high resolution requirements in applications for high energy collider experiments. The linear SDD developed for STAR features a one-dimensional readout which yields excellent three dimensional position resolution. Based on the resulting cost effective, large area coverage capabilities Silicon drift detectors can be considered a competitive alternative to gaseous tracking detectors like TPC's or drift chambers, in particular because they fit into a small detector environment which can be realized by utilizing superconducting magnets that generate high magnetic fields in a small sized volume. The vertexing capabilities of a Silicon detector, which are most relevant for heavy quark tagging, are superior to any size gas detector design.

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