Recent Results with CVD Diamond Trackers

The RD42 Collaboration

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We present recent results on the use of Chemical Vapor Deposition (CVD) diamond microstrip detectors for charged particle tracking. A series of detectors was fabricated using 1×1 cm^2 diamonds. Good signal-to-noise ratios were observed using both slow and fast readout electronics. For slow readout electronics, 2 μs shaping time, the most probable signal-to-noise ratio was 50 to 1. For fast readout electronics, 25 ns peaking time, the most probable signal-to-noise ratio was 7 to 1. Using the first 2×4 cm^2 diamond from a production CVD reactor with slow readout electronics, the most probable signal-to-noise ratio was 23 to 1. The spatial resolution achieved for the detectors was consistent with the digital resolution expected from the detector pitch.

1. INTRODUCTION

High luminosity hadron colliders such as the LHC at CERN pose an immense challenge to par-

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ticle detection technology. At the design luminosity of 10^{34} cm^{-2}s^{-1}, with two 7 TeV proton beams colliding every 25 ns, there are $\sim 3 \times 10^{13}$ neutrons and $\sim 2 \times 10^{14}$ pions per square cm per year traversing a detector at a distance of 6 cm from the interaction region. Any silicon strip detector located less than 25 cm from the interaction region or any silicon pixel detector located less than 10 cm from the interaction region might need to be replaced annually. Diamond detectors offer a possible solution for this high rate and high radiation environment, providing high precision tracking to tag b, t, and Higgs particles etc.

Diamond can operate in this hostile environment due to its strong bonding between atoms. The large band gap allows the application of a large electric field across the diamond and no p-n junction is necessary to operate the device. The large electric field sweeps the charge to the collection surface at high speed. For a detector with a thickness of ~ 400 μm, the charge collection time is ~ 2 ns.

The practical use of diamond as a particle detector is made possible by the development of the chemical vapor deposition (CVD) process. This process allows diamond to be produced economically over a large area with high purity. The RD42 collaboration [1] was established at CERN in 1994 to investigate and improve the properties of CVD diamonds, to develop radiation-hard diamond detectors, and to develop low-noise front-end electronics for the high luminosity experiments at the LHC.

2. Test Setup

Diamonds fabricated by the manufacturers [2] are characterized using the setup shown in Fig. 1. A diamond is metalized with Cr/Au electrodes on both sides and placed in front of a collimated ^{90}Sr source which delivers electrons up to a maximum energy of 2.28 MeV. Electrons traversing the diamond strike a scintillator to provide a trigger for the readout electronics. The signal is amplified using a charge integrator circuit and can be viewed on a digital scope or recorded on a computer for further analysis. From the measured charge Q, one can estimate the charge collection distance d_c, the average distance that electrons and holes drift apart in an electric filed (we typically operate at ~ 1 V/μm) before being trapped:

$$d_c = \frac{100\ \mu\mathrm{m}}{3600\ e} \times Q[e]\ ,$$

where 3600 electron-hole pairs are created by a minimum ionizing particle traversing 100 μm of diamond. The setup provides a fast characterization and sorting of the quality of the diamond before we fabricate the microstrip detectors.

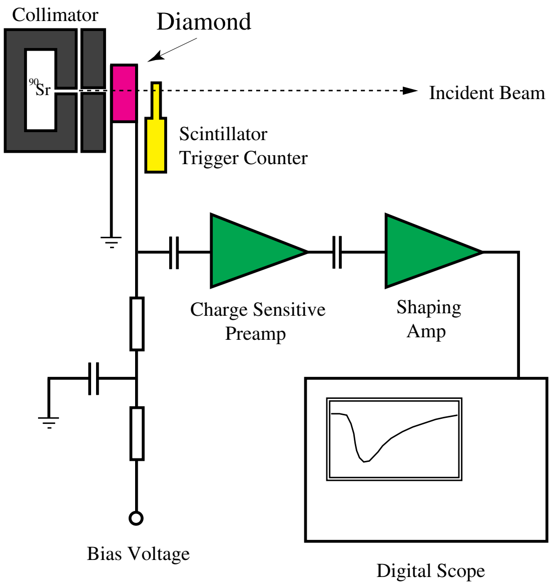

Figure 1. Source test setup.

The schematic of a microstrip detector is shown in Fig. 2. The strip pitch is 50 μm and strip width is 25 μm. The physical size of the device is 10×10 mm^2 with strip lengths of 8 mm. The thickness of the diamond is typically 300 to 600 μm.

The trackers are tested in a 100-GeV pion beam at CERN. The test utilizes a telescope consisting of eight planes of silicon microstrip detectors [3] as shown in Fig. 3. These provides two x measurements and two y measurements upstream

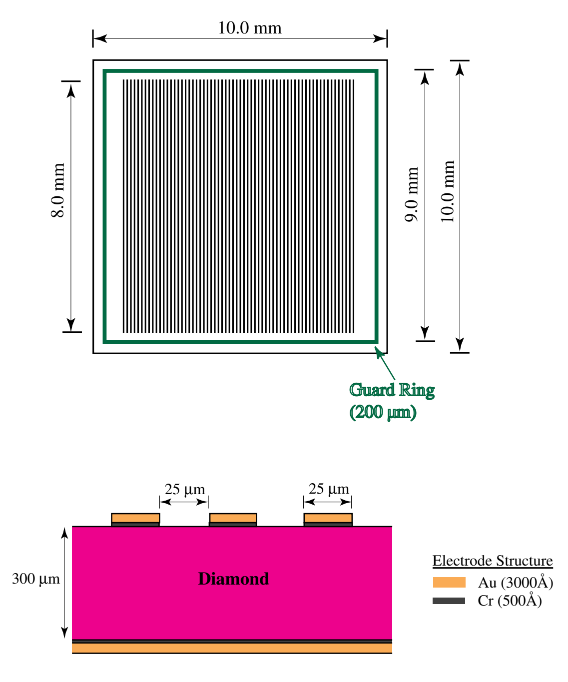

Figure 2. Schematic view of a diamond microstrip detector.

and downstream of a tracker under study. The position resolution of tracks projected onto the tracker under test was better than 2 μm.

Two different types of front-end readout chips have been used. Both chips have 128 channels. The VA2 chip [4] has a shaping time of $\sim$ 2 μs. The equivalent noise charge (ENC) is 80 e + 14 e/pF. The SCT128HC chip [5] has a 25 ns peaking time with analogue delay buffer pipeline for 40 MHz readout frequency. The chip is optimized for the high capacitive load of silicon microstrip detectors and thus is not ideal for the low capacitance of the diamond detectors. SCT128HC was produced using the radiation-hard DMILL [6] process and has an ENC of 650 e + 70 e/pF

3. Result with Slow Electronics

The pulse height spectra for a 432 μm thick diamond as measured in a 100-GeV pion test beam is shown in Fig. 4. Two techniques were used to measure the spectra: cluster and transparent analyses. In the former, the pulse height is a sum of the signal from adjacent strips above five times the single-channel noise. In the latter, the pulse height is a sum of the signal from the strip predicted by the silicon telescope plus one adjacent strip on each side. Both spectra are similar and well separated from zero.

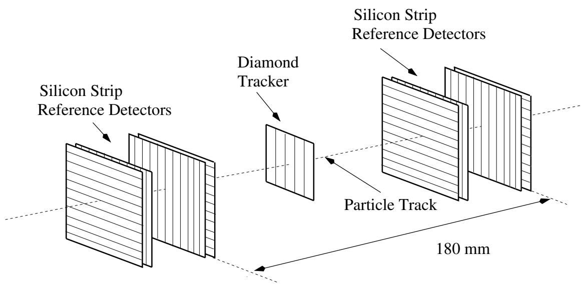

Figure 3. Silicon telescope for test beam measurements.

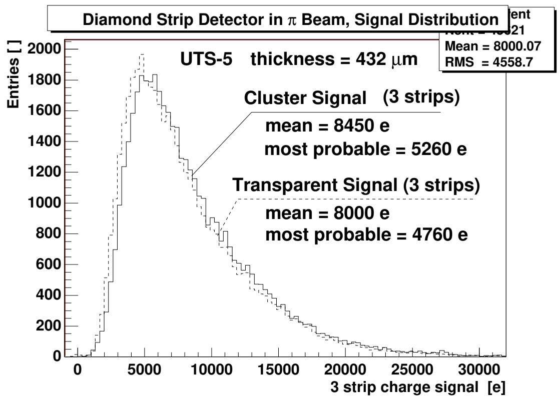

Figure 4. Pulse height distribution of a 432 μm thick detector with VA2 electronics.

The most probable signal to single-channel noise ratio is 50 to 1. The most probable signal observed is $\sim$ 5000 e. The spatial resolution was measured using the residual distribution of the measured minus extrapolated hit position where the measured hit position is determined using a two-strip center-of-gravity method. This method is known to have short comings and non-linear eta algorithm should give better resolutions. The residual resolution (Fig. 5) has a standard deviation of 12.4 μm, which is slightly better than the digital resolution expected from the 50 μm strip pitch.

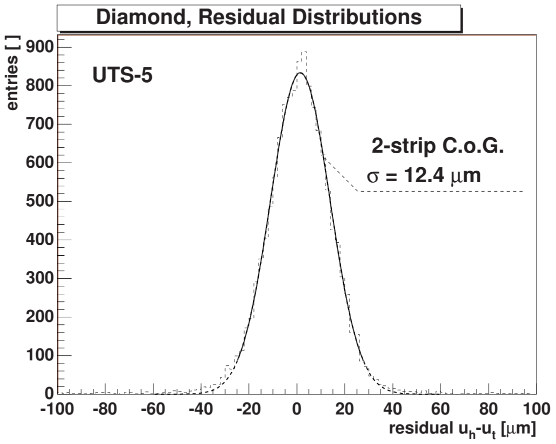

Figure 5. Residual distribution of a 432 μm thick detector with VA2 electronics measured using a two-strip center-of-gravity method. The curve shows a fit using a Gaussian function.

The spatial resolution can be improved by analyzing the pulse height distribution across the detector. Our study reveals that under the strip, the pulse height is constant with little charge sharing. However, the charge sharing is linear between strips. This information can be used to optimize the strip width of microstrip detectors.

4. Uniformity

The uniformity of the polycrystalline diamond is of particular interest since it may limit the spatial resolution achievable through charge sharing. With current statistics, the uniformity can be probed at the 100×100 μm^2 level. Figure 6 shows the average signal size (gray scale coded) of a 3×2 mm^2 region in 100×100 μm^2 bins. On average, there are 40 tracks per bin. A quantitative measure of uniformity is given by the ratio of the standard deviation of the average pulse height per bin to the average pulse height. The ratio for the diamond is $\sim$ 34%. This should be compared with $\sim$ 8% we observe from silicon measured with the same technique. To better quantify the uniformity of diamond requires finer bins and more data. This study is in progress.

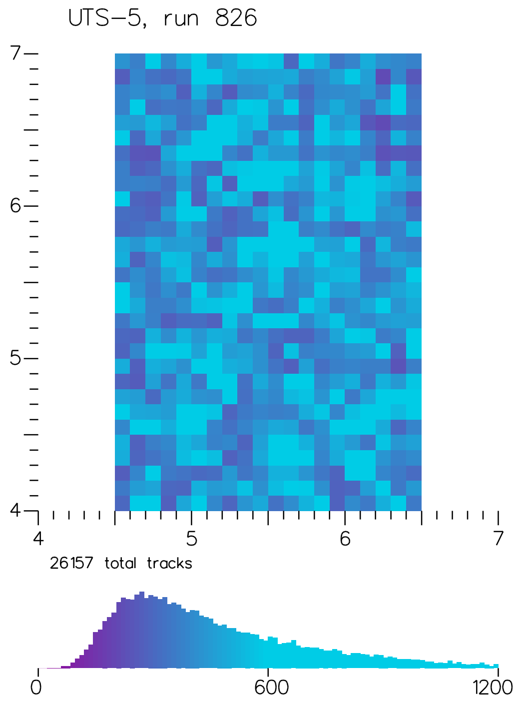

Figure 6. Mean collected signal charge vs. track hit position in 100×100 μm^2 bins.

5. Result with Fast Electronics

Slow electronics is useful for the initial study of diamond microstrip trackers while fast SCT electronics is more relevant for the LHC application.

The pulse height spectra for the same 432 μm thick microstrip detector described above but readout with SCT128HC electronics are shown in Fig. 7. We observe a most probable signal to noise ratio of 7 to 1 from the transparent three-strip analysis. The cluster analysis with seed signal to noise cut of 5 to 1 shows the effect of the cut. The spatial resolution achieved using a three-strip center-of-gravity method is $\sim$ 16.5 μm as shown in Fig. 8.

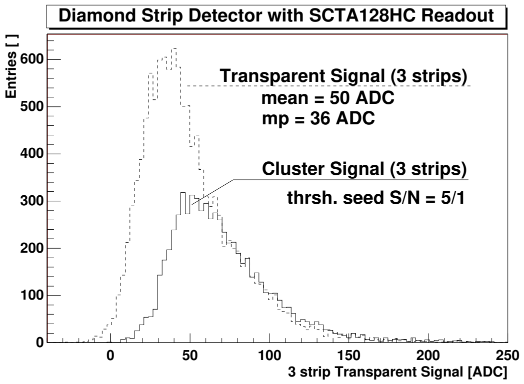

Figure 7. Pulse height distribution of a 432 μm thick detector with SCT128HC electronics.

6. Result with Large Area Diamond

Diamond trackers used in a practical applications are expected to be significantly larger than the 1 $\times$ 1 cm^2 trackers described so far. A microstrip detector has therefore been fabricated from a diamond of more appropriate size, 2 $\times$ 4 cm^2. This tracker was one of five fabricated from the first wafer from a production reactor. The most probable signal measured from a transparent analysis was $\sim$ 3500 e, corresponding to a signal to noise ratio of 23 to 1. The spatial resolution achieved was $\sim$ 14 μm, using a three-strip center-of-gravity method. The quality of the large area diamond from the production reactor is slightly lower than the quality of the 1 $\times$ 1 cm^2 pieces we have tested from the research reactor. The process should be fully transferred in the near future.

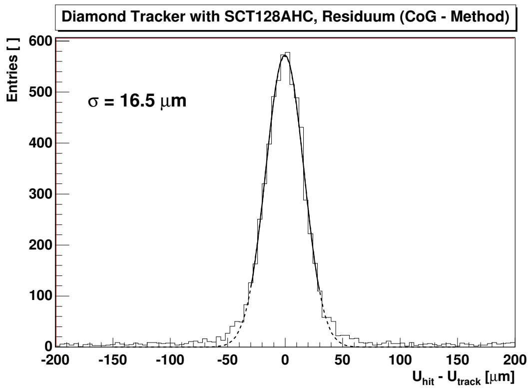

Figure 8. Spatial resolution of a 432 μm thick detector with SCT128HC electronics measured using a three-strip center-of-gravity method. The curve shows a fit using a Gaussian function.

7. Conclusion

Tremendous progress has been made in the last few years in demonstrating the feasibility of using diamond as a particle detector. The most probable signal observed was $\sim$ 5000 e with slow electronics (2μs), corresponding to a signal to noise of 50 to 1. The signal to noise ratio achieved with the same diamond using fast electronics (25 ns) was 7 to 1. For a 2 $\times$ 4 cm^2 diamond with slow electronics, the ratio obtained was 23 to 1. The spatial resolution achieved with all the trackers is $\sim$ 15 μm, comparable with the digital resolution. In the near future, the goal is to achieve a most probable signal of $\sim$ 7500 e. In addition, diamond trackers will be tested using the recently fabricated fast electronics designed to take advantage of the low capacitance of diamond. The strip width will be varied and the position algorithm refined to further improve the spatial resolution. The uniformity of diamond will be studied with smaller binning and higher statistics. The results of these tests should yield a diamond tracker well suited for LHC applications.

Acknowledgments

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