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Diamond Detectors for Future Particle Physics Experiments†

W. Dulinski[a], K.K. Gan[b], S. Han[c], J. Hassard[d], A. Howard[d], H. Kagan[b], S. Kanda[e], D. Kania[f], R. Kass[b], S.K. Kim[g], R. Malchow[b], E. Nygard[h], L.S. Pan[c], S. Roe[i], J. Straver[i], S. Schnetzer[j], R. Stone[j], Y. Sugimoto[k], R. Tesarek[j], W. Trischuk[i], G.B. Thomson[j], R. Turchetta[a], R. Wagner[c], P. Weilhammer[i], C. White[b], S. Zhao[b]

[a] *LEPSI, CRN Strasbourg 67037, France*
[b] *Department of Physics, The Ohio State University, Columbus, OH 43210, USA*
[c] *Research Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[d] *Blackett Laboratory, Imperial College, London, SW7 2BZ, UK*
[e] *Department of Physics, University of Hawaii, Honolulu, HI 96822, USA*
[f] *Laser Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*
[g] *Department of Physics, Seoul National University, Seoul, Korea 151-742*
[h] *University of Oslo, 0316 Oslo 3, Norway*
[i] *CERN,CH-1211 Geneva, Switzerland*
[j] *Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08854, USA*
[k] *KEK, Tsukuba-shi, Ibaraki-ken, Japan 305*

Abstract

Diamond has recently been shown to be a viable material for detectors in experiments at the next generation of particle accelerators. This contribution surveys the properties of diamond which give it advantages, the results achieved to date, the remaining unresolved issues, and the possible applications for diamond detectors in the future.

1. Introduction

The inherent properties of diamond make it an ideal material for close-in tracking detectors especially in the high rate, high radiation environments of future colliders such as the LHC. We have constructed and tested micro-strip detectors using high quality Chemical Vapour Deposited (CVD) diamond. While this is an important first step a number of issues remain: establishing the radiation hardness of the material to be sufficient to survive in regions of high energy physics detectors where silicon cannot, and maximisation of the charge observed when a minimum

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Property	D	Si	Ga As
Band Gap [eV]	5.5	1.12	1.43
Breakdown field [V/cm]	10^7	3×10^5	4×10^5
Resistivity [Ω-cm]	$> 10^{11}$	2.3×10^5	10^8
Intrinsic Carrier Density [cm^{-3}]	$< 10^3$	1.5×10^{10}	$\sim 10^8$
Electron Mobility [$cm^2V^{-1}s^{-1}$]	1800	1350	8500
Hole Mobility [$cm^2V^{-1}s^{-1}$]	1200	480	400
Saturation Velocity [km/s]	220	82	80
Mass Density [gm cm^{-3}]	3.5	2.33	5.32
Atomic Charge	6	14	31, 33
Dielectric Constant	5.7	11.9	13.1
Thermal Exp. Coef. [10^{-6}/K]	0.8	2.6	6.9
Thermal Cond. [W cm^{-1} K^{-1}]	10-20	1.5	0.45
Cohesive Energy [eV/atom]	7.37	4.63	
Energy to create e-h pair [eV]	13	3.6	4.2
Radiation Length [cm]	12.0	9.4	2.3
Sp. Ionisation Loss [MeV/cm]	4.69	3.21	5.6
Ave e-h pairs/100 μm [e]	3600	8900	13000
Ave e-h pairs/0.1% X_0 [e]	4500	8400	3000

Table 1. The physical properties of diamond, silicon and gallium arsenide at 293K.

ionising particle traverses the material. Work on the radiation hardness of the material is underway with a number of irradiations complete and others in the planning stages. Two ways of increasing the detected charged particle signal are investigated by increasing the intrinsic charge collection distance of the material and by optimising the contacts on the surface of the detector.

Diamond offers unique possibilities for particle detector applications [1],[2]. This is primarily due to its very tightly bound lattice which results in extraordinary electrical, mechanical and thermal properties. Its atomic structure results in very few free charge carriers and hence very low leakage currents in the presence of an external electric field. Its high carrier mobility also suggests that as a simple ionisation detector intrinsic diamond may be one of the best choices. In Table 1 we list some of the physical parameters of diamond along with silicon and gallium arsenide for comparison.

One of the few drawbacks seen from Table 1 is that the number of electron-hole pairs created by a minimum ionising particle in diamond is smaller than either in silicon or gallium arsenide. This stems mainly from the larger band gap in diamond and hence the larger energy necessary to create a pair. However in the limit that the signal collection distance, the average distance an electron and hole separate under the influence of an applied electric field [3], can be made comparable to the thickness of the material the signal in diamond can be made half as big as that in silicon and then many of the other advantages of diamond may become real assets. As a result of R&D work undertaken for detectors being designed for the SSC and LHC the charge collection distance in CVD diamond has increased from a fraction of a micron five years ago, to almost 75 microns today. This represents charge collection distances that are almost 3 times larger than those found in natural single-crystal diamonds. One of the main reasons for such large advances has been in learning to grow CVD diamond with low defect densities and large crystallites.

In developing a detector with this material the surface preparation is also an issue. Good ohmic contact between the surface electrodes and the diamond is necessary to remove charge as it is created by the traversal of charged particles. Otherwise this charge builds up at the surface and results in a polarisation field which offsets the applied bias. The studies we are undertaking aim to optimise this aspect of detector fabrication as well.

To make a viable high energy physics detector one way to accomodate a low signal is to lower the noise in the readout electronics. Several of the physical properties of diamond are assets here as well. The very low leakage currents which result from the material's high resistivity imply reduced shot noise. The dielectric constant of diamond is half that of silicon thus all load capacities in a comparably laid-out diamond detector will be half those found in a silicon detector. We aim to develop detectors which have signal to noise ratios of at least 15:1 to allow pattern recognition with a diamond based tracker as well as to facilitate the association of hits in a diamond detector to tracks reconstructed elsewhere. In order to reach this goal it will be necessary to increase the diamond signal by about a factor of four over that available today and also to reduce the noise in LHC type amplifiers by a factor of two or more.

It is possible to study, in many ways, the material produced when CVD diamond is grown. Some of these can be related to the charge collection distance in the material. Cathodoluminescence, photoluminescence and absorption spectroscopy can reveal impurities and defects in the material. Graphitisation can be studied with Raman spectroscopy and SEM/TEM techniques. A survey of these methods can be found in [4].

2. Results in Particle Testbeams

Early on in the SSC research programme it was decided to demonstrate diamond's potential in a simple calorimeter [5]. The calorimeter was designed to allow a direct comparison with silicon active layers. The success of this detector gave us confidence to move on to the application of diamond in a tracking detector.

It is a measure of diamond's versatility that some of the diamond material used in the calorimeter was recycled into the detector material for the first

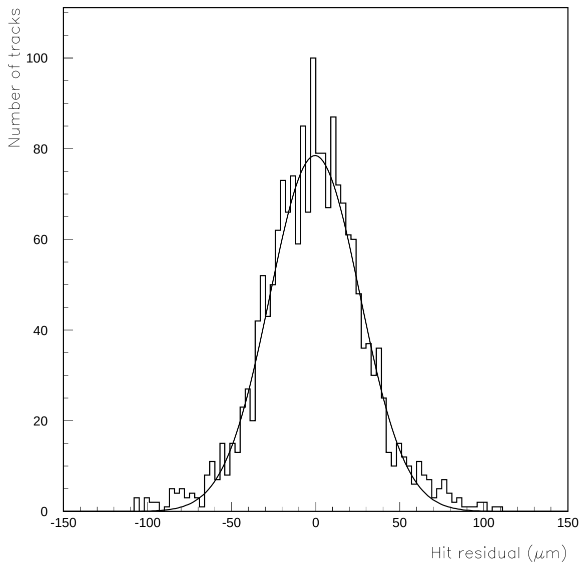

Figure 1. The experimental position resolution of the diamond detector, compared to the predicted charged particle impact point based on the silicon telescope information. The fit of a single Gaussian gives a sigma of 26 μm.

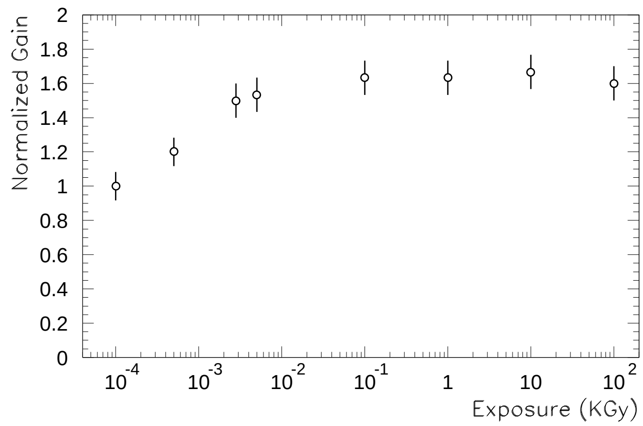

Figure 2. Exposure of CVD diamonds to ^{90}Sr and ^{60}Co photons. The first four points were Sr irradiations while the others were done with Co. The gain plotted is the charge collection distance observed after a given dose relative to the unirradiated collection distance.

tracker [6]. In this work a silicon telescope [7] consisting of 4 reference point measurements in the x and y projections allowed us to pinpoint the position of 50 GeV pions with 3 μm precision on the surface of the diamond detector.

The diamond detectors used in this work were planar $8\times 8\times 0.3\,\mathrm{mm}^3$ with 50 μm wide strips on 100 μm centres. A bias voltage was placed across the smallest dimension of the detector to push holes towards the readout strips which were arrayed on the surface. The detector strips were DC coupled to individual Viking [8] channels. Data were taken with normally incident particles, at a variety of bias voltages and with a 2 μs shaping time. Our analysis showed that at a bias voltage of 195V we obtained a S/N of 6.2 ± 0.2 and a position resolution of 25 ± 1 μm. The efficiency of the detector was greater than 86 %; no correction for dead channels was made.

From these data we infer an average signal size of 1400 ± 180 electrons consistent with the charged particle signal expected from tests of the diamond's collection distance measured before construction of the tracker. While this signal size is not adequate for an LHC detector, where the shaping times will have to be about 50 times smaller and hence the noise can be expected to be at least 7 times larger, it does provide first evidence that CVD diamond can be used as a charged particle tracker.

3. Radiation damage in Diamond Detectors

There are two primary manifestations of radiation damage in solid state detectors. One is an increase in leakage current and the other is a decrease is signal pulse height. The tightly bound lattice structure of diamond suggests that it will be insensitive to large doses of radiation. Previous studies (neutrons [9],[10] and 1.5 MeV electrons [11]) have shown that natural diamond is very resistant to both types of damage.

During the last few years we have undertaken several studies of radiation damage to CVD diamond detectors. In each study the collection distance was measured before and after the irradiation. In the first study we used photons (1.2 and 1.3 MeV) from a ^{60}Co source. As can be seen from Figure 2 up to doses of 10 MRad there is no evidence of degradation of the electronic properties in CVD diamond. As can also be seen from this figure, at low doses the collection distance improves with accumulated dose. This curious effect is generally believed to be due to a passivation of charged traps.

In addition to the photon irradiation described above we have recently completed irradiations with 5 MeV alpha particles (no change in the gain up to 10^{13} alpha's/cm^2), 300 MeV pions (under analysis), and 500 MeV protons (under analysis). Preliminary results seem to confirm the radiation hardness expected. In the near future we will complete our irradiation program with studies of neutrons and electrons.

4. Future Directions for Diamond Detectors in Particle Physics

In the coming year it should be possible, by actively working with manufacturers, to obtain high quality CVD diamonds with collection distances of 200 μm. At this level, diamond-based detectors would work at the LHC and at HERA-B. Other detector configurations (*e.g.* pixels) could also be considered.

We note in closing that the use of diamond is not restricted to particle detection. Diamond is already used extensively in thermal management and it may also play a role in mechanical support.

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