New materials are being developed as replacements or upgrades to silicon detectors for use in extreme radiation environments. Diamond and silicon carbide are two candidate materials. Devices have been manufactured and tested in both materials. In this paper we discuss the present status and recent progress achieved.

1. Introduction

Detectors and radiation monitors of future experiments will be situated in radiation environments several orders of magnitude harsher than those of any current detector. In this environment, the components, both sensor material and electronics, will need to be exceedingly radiation hard in order to provide the high precision information required for physics analyses. At present detectors for radiation monitoring and tracking close to the interaction region are based on the mature silicon technology which functions very well in relatively low radiation environments (e.g. the LEP experiments, CLEO, etc.). Silicon is, by its nature, not radiation hard and great efforts are being made at “engineering in” the necessary hardness. Much progress in this area has been achieved, especially with oxygenated silicon. However, the practical limits on the radiation hardness of silicon still falls short of what is required for many future experiments.

Diamond and silicon carbide have properties which indicate they may be more radiation hard than silicon. These materials are compared with silicon in Table 1. Chemical vapor deposition (CVD) diamond is being investigated by the CERN RD42 group; silicon carbide is being investigated by the CERN RD50 group.

Although diamond and silicon carbide appear ideal in many respects they do have one major limitation: the large band gaps which produce
Table 1. Comparison of diamond, silicon carbide and silicon properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>4H-SiC</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band Gap [eV]</td>
<td>5.5</td>
<td>3.3</td>
<td>1.12</td>
</tr>
<tr>
<td>Breakdown field [V/cm]</td>
<td>$10^{11}$</td>
<td>$4 \times 10^6$</td>
<td>$3 \times 10^5$</td>
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<tr>
<td>Resistivity [\Omega \cdot cm]</td>
<td>$&gt;10^{11}$</td>
<td>$10^{11}$</td>
<td>$2.3 \times 10^5$</td>
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<tr>
<td>Intrinsic Carrier Density [cm$^{-3}$]</td>
<td>$&lt;10^3$</td>
<td>$1.5 \times 10^{10}$</td>
<td></td>
</tr>
<tr>
<td>Electron Mobility [cm$^2$V$^{-1}$s$^{-1}$]</td>
<td>1800</td>
<td>800</td>
<td>1350</td>
</tr>
<tr>
<td>Hole Mobility  [cm$^2$V$^{-1}$s$^{-1}$]</td>
<td>1200</td>
<td>115</td>
<td>480</td>
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<tr>
<td>Saturation Velocity [km/s]</td>
<td>220</td>
<td>200</td>
<td>82</td>
</tr>
<tr>
<td>Mass Density [g cm$^{-3}$]</td>
<td>3.52</td>
<td>3.21</td>
<td>2.33</td>
</tr>
<tr>
<td>Atomic Charge</td>
<td>6</td>
<td>14/6</td>
<td>14</td>
</tr>
<tr>
<td>Dielectric Constant [eV/atom]</td>
<td>5.7</td>
<td>9.7</td>
<td>11.9</td>
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<tr>
<td>Displacement Energy [eV/atom]</td>
<td>43</td>
<td>25</td>
<td>13-20</td>
</tr>
<tr>
<td>Energy to create e-h pair [eV]</td>
<td>13</td>
<td>8.4</td>
<td>3.6</td>
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<tr>
<td>Radiation Length [cm]</td>
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<td>8.7</td>
<td>9.4</td>
</tr>
<tr>
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<td>4.28</td>
<td>3.21</td>
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<td>Ave. Signal Created/100 \mu m [e]</td>
<td>3600</td>
<td>5100</td>
<td>8900</td>
</tr>
<tr>
<td>Ave. Signal Created/0.1% X$_0$ [e]</td>
<td>4400</td>
<td>4400</td>
<td>8400</td>
</tr>
</tbody>
</table>

Table 1. Comparison of diamond, silicon carbide and silicon properties.

2. CVD Diamond Detectors

2.1. Principles of Diamond Detectors

In Fig. 1, we show the basic principle of using diamond as a particle detector. A voltage is applied across a layer of diamond a few hundred microns thick. When a charged particle traverses the diamond, atoms in the crystal lattice sites are ionized, promoting electrons into the conduction band and leaving holes in the valence band. On average, 3,600 electron-hole pairs are created per 100 \mu m of diamond traversed by a minimum ionizing particle. These charges drift across the diamond in response to the applied electric field producing a signal that can be measured.

A feature of polycrystalline CVD (pCVD) diamond sensors is that their quality improves with exposure to radiation for exposures up to about 1 kRad. This “pump-up” effect is due to an increase of carrier lifetime caused by passivation of deep traps. Because diamond has such a large band gap there may exist traps more than 1 eV from the valence or conduction bands.
Exposure to radiation fills these traps with electrons (holes) produced by the radiation. If the traps are far enough from the conduction (valence) bands, the rate of thermal ionization of these traps will be low and they will remain passivated for long times. Polycrystalline CVD diamonds kept in the dark have been observed to remain pumped for months. Exposure to room light ionizes the traps and depumps the diamond.

In Fig. 2, we show the collected charge as a function of electric field, using a $^{90}$Sr source after “pumping”. To obtain this distribution the diamond is metallized with solid electrodes on each side, an external voltage is applied across the diamond and the collected charge is measured. Polycrystalline CVD diamonds all have the characteristic that the collected charge reaches a plateau at an electric field of approximately $1\text{V/µm}$. 

![Diagram of a diamond detector](image)

Figure 1. A schematic view of a diamond detector.

![Graph of collected charge vs. electric field](image)

Figure 2. The collected charge signal versus electric field from a polycrystalline diamond sample measured using a $^{90}$Sr source. The saturation of the collected charge occurs at an electric field of $\sim 1\text{V/µm}$. 
The measured pulse height distribution, using a $^{90}\text{Sr}$ source, of an as-received sample from the manufacturer is shown in Fig. 3. Operating at an electric field of 1 V/$\mu$m the charge distribution has the shape of a Landau separated from zero. The charge collection is symmetric with applied voltage. The most probable charge is $\approx 5500$ e and 99% of the distribution is above 2250 e.

Figure 3. Charge signal from a production reactor diamond sample measured using a $^{90}\text{Sr}$ source. The two curves (Side A/Side B) are the results for positive and negative applied voltages respectively. No cuts to the data have been applied.

From the mean value, $\langle Q \rangle$, of the signal spectrum one derives the charge collection distance, the average distance the electrons and holes move apart in the diamond:

$$d = \frac{\langle Q \rangle}{36 \text{ e}/\mu\text{m}} \quad (1)$$

where 36 e/$\mu$m is the average number of electron-hole pairs generated by a minimum ionizing particle along 1 $\mu$m in diamond. Since the collection distance is usually smaller than the thickness of the pCVD material, the collection distance serves as a useful tool to compare diamonds. A charge collection distance of 205 $\mu$m corresponds to a mean charge of 7400 e.

2.2. Progress on the Improvement of CVD Diamond

Over the last few years, the RD42 Collaboration has worked closely with Element Six Ltd. to achieve improvements in the charge collection distance and uniformity of pCVD diamond. This work has now resulted in large scale
wafers of high quality diamond. In Fig. 4 we show a recent polycrystalline CVD wafer ready for test with contacts placed at one centimeter intervals.

![As grown pCVD wafer ready for test with contacts at one centimeter intervals.](image)

In Fig. 5, we show the collected charge of a recent diamond which resulted from the research program. The gain of the system used to characterize this diamond was $124 \, \text{e}/\text{mV}$. We observe a most probable (MP) charge ($61.7 \, \text{mV}$) of 7650 $\text{e}$ and an average charge ($78.85 \, \text{mV}$) of 9750 $\text{e}$. For this diamond 99% of the charge distribution is above 3000 $\text{e}$ indicating a clear separation of the charge signal from the pedestal. The mean charge corresponds to a collection distance of 270 $\mu\text{m}$.

This currently available diamond material is of sufficiently high quality that the RD42 collaboration has undertaken studies of its performance as a particle detector. The results of beam tests at CERN for these devices yielded position resolution slightly better than that expected for the pitch divided by $\sqrt{2}$, the digital resolution. In the best devices, the measured signal-to-noise was 60:1 with 2 $\mu\text{s}$ shaping time electronics and 8:1 with 25 $\mu\text{s}$ peaking time electronics.

2.3. Radiation Hardness Studies of CVD Diamond Trackers

In Fig. 6, we show the collected charge of a pCVD diamond strip detector after irradiation with a fluence of 24 GeV protons of $1 \times 10^{15} \, \text{p}/\text{cm}^2$.
Figure 5. Charge signal from a recent diamond sample measured using a $^{90}$Sr source in the laboratory. The histogram is taken for each scintillator trigger (upper trace). An individual single diamond pulse is shown in the second trace and the average of all pulses is shown in the third trace.

and after $2.2 \times 10^{15}$ p/cm$^2$. While the strip contacts before and after irradiation with fluences of $1 \times 10^{15}$ p/cm$^2$ were unchanged the contacts were replaced after a fluence of $2.2 \times 10^{15}$ p/cm$^2$ and then characterized in the test beam. At $1 \times 10^{15}$ p/cm$^2$ we observe that the shape of the signal-to-noise distribution is narrower than before irradiation and entries in the tail of the distribution appear closer to the most probable signal. At $2.2 \times 10^{15}$ p/cm$^2$ and after re-metallization we observe essentially the same signal-to-noise distribution as at $1 \times 10^{15}$ p/cm$^2$ indicating that very little further damage occurred to the diamond bulk. The most probable signal-to-noise was 41 before irradiation and 35 at $1 \times 10^{15}$ p/cm$^2$ and also at $2.2 \times 10^{15}$ p/cm$^2$. We find a reduction of maximum 15% in the most probable signal-to-noise after irradiation with $2.2 \times 10^{15}$ p/cm$^2$. The noise was measured to remain constant at each beam test. Since the beam test with the detector irradiated with a fluence of $2.2 \times 10^{15}$ p/cm$^2$ used new contacts the observed decrease of 15% is attributed to damage in the diamond bulk. This work has spurred research in the development of radiation hard diamond contacts.

Fig. 7 shows residual distributions before and after irradiation at $1 \times 10^{15}$ p/cm$^2$ and $2.2 \times 10^{15}$ p/cm$^2$. We observe that the spatial resolution improves from $(11.5 \pm 0.3)$ $\mu$m before irradiation to $(9.1 \pm 0.3)$ $\mu$m at $1 \times 10^{15}$ p/cm$^2$ and to $(7.4 \pm 0.2)$ $\mu$m at $2.2 \times 10^{15}$ p/cm$^2$. At present the explanation for this effect is that the irradiated material is more uniform in
the sense that the landau distribution is narrower. The spatial resolution of nearly 7 μm with a detector of 50 μm strip pitch is comparable to results
obtained with silicon detectors.

In Fig. 8 and Fig. 9 we show the corresponding plots for a pCVD diamond strip detector after irradiation with 300 MeV pions. The results of this irradiation are generally similar to the proton irradiation with a 50\% loss of signal-to-noise and a 25\% improvement in resolution at a fluence of $2.9 \times 10^{15} \, \pi / \text{cm}^2$.

A summary of the present status of polycrystalline CVD diamond is listed below:

- Polycrystalline CVD diamond from production reactors now ‘regularly’ exceeds 200 \, \mu m charge collection distance.
- Polycrystalline CVD detectors require externally applied electric fields of $\sim 1 \, \text{V/\mu m}$ for operation.
- Research pursued by RD42 in conjunction with Element Six yielded pCVD diamonds with 270 \, \mu m collection distance. This appears to be close to the limit of the pCVD process.
- The typical position resolution with a polycrystalline CVD detector is slightly better than the pitch divided by $\sqrt{12}$.
- After irradiation of $\approx 10^{15}$ the most probable charge decreases slightly while the position resolution improves.
3. Single Crystal CVD Diamond-The New Development

In late 2002 Element Six announced that it had successfully produced a single crystal diamond by the CVD process. The samples they produced were synthesized with a microwave plasma-assisted CVD reactor using a specially prepared (100) oriented single crystal synthetic diamond substrate. This material, single crystal CVD (scCVD) removes many if not all of the issues of pCVD material. In particular there should be no grain boundaries and therefore none of the defects and traps associated with grain boundaries. The RD42 group was asked to investigate these new diamonds.

In Fig. 10 we show the pulse height spectrum observed from a 440 µm thick scCVD diamond. We observe a most probable charge of 14,000e, a FWHM of 4000e and a 10,000e separation between the pedestal and the beginning of the charge distribution. The FWHM/MP for this single crystal CVD diamond is approximately 0.3, about one third that of polycrystalline CVD diamond and about two thirds that of silicon.

In Fig. 11 we show the high voltage characteristics of this material. The scCVD diamond collects all the charge at an electric field well below 1 V/µm. Based on these first test results, this new material seems extraordinary and may resolve many if not all of the issues associated with polycrystalline material.
Figure 10. The pulse height distribution of a scCVD diamond operating at 500V. The two curves are for positive and negative voltage applied.

Figure 11. The collection distance versus electric field of a scCVD diamond.

4. Silicon Carbide

The properties of silicon carbide are in some sense the geometric mean between silicon and diamond. As a result one hopes to take advantage of the strengths of both. The CERN RD50 group has taken the lead in this development testing both semi-insulating silicon carbide with ohmic contacts and epitaxial silicon carbide with schottky contacts. In semi-insulating material the charge collection depends on native defects; epitaxial material has low native defects but presently can only be made in thin layers. At present, a signal-to-noise of 7:1 was attained with a 40 μm thick epitaxial silicon carbide detector. All of the charge was collected for electric fields
above 1.5 V/µm. For a full discussion the reader is referred to the paper in these proceedings by G. Casse.

5. Conclusion

The development of CVD diamond and silicon carbide is progressing rapidly. These materials have already shown that they have the radiation resistance to be used above hadron fluences of \(1 \times 10^{15}/\text{cm}^2\). At present, diamond development is more mature than silicon carbide. Polycrystalline CVD diamond trackers have achieved a signal-to-noise of 60:1 with 2µs shaping time and signal-to-noise of 8:1 with 25 ns peaking time. Silicon carbide trackers are presently being fabricated. Tests with 40µm thick epitaxial silicon carbide material show a signal-to-noise of 7:1 with 2 µs shaping time. In the next few years we should see the development of larger single crystal CVD diamond and thicker epitaxial silicon carbide.

Acknowledgments

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References

2. The RD42 website is http://rd42.web.cern.ch/RD42.
6. The RD50 website is http://rd50.web.cern.ch/RD50; see also the paper by G. Casse in these proceedings.
7. Element Six Ltd., King's Ride Park, Ascot, Berkshire SL5 9BP UK.