Neutron Detection Performance of Silicon Carbide and Diamond Detectors with Incomplete Charge Collection Properties[☆].

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Abstract

The benefits of neutron detection and spectroscopy with carbon based, wide band gap, semiconductor detectors has previously been discussed within literature. However, at the time of writing there are still limitations with these detectors related to availability, cost, size and perceived quality. This study demonstrates that lower quality materials - indicated by lower charge collection efficiency (CCE), poor resolution and polarisation effect - available at wafer scale and lower cost, can fulfil requirements for fast neutron detection and spectroscopy for fluxes over several orders of magnitude, where only coarse energy discrimination is required.

In this study, a single crystal diamond detector (D-SC, with 100% CCE), a polycrystalline diamond (D-PC, with $\approx 4\%$ CCE) and semi-insulating silicon carbide (SiC-SI, with $\approx 35\%$ CCE) have been compared for alpha and fast neutron performance.

All detectors demonstrated alpha induced polarisation effects in the form of a change of both energy peak position and count rate with irradiation time. Despite these operational issues the ability to detect fast neutrons and distinguish neutron energies was observed.

This performance was demonstrated over a wide dynamic range (500 - 40,000 neutrons/s), with neutron induced polarisation being demonstrated in D-PC and SiC-SI at high fluxes.

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1. Introduction

Carbon based semiconductor detectors such as silicon carbide (SiC) and diamond (D) offer a number of advantages for fast neutron detection purposes. The low atomic number (Z) of carbon means that the maximum amount of energy transferable through elastic scattering with incident neutrons is 28% [1] allowing for direct fast neutron detection within these materials, removing manufacturing and efficiency issues associated with conversion layers [2].

Furthermore the low Z number ensures that SiC and D are less sensitive to photon radiation relative to other semiconductor detectors. The result would be a reduced neutron-gamma cross-sensitivity in mixed radiation fields, which is a particularly important feature in most neutron environments.

However, although the use of SiC and D semiconductors for radiological detection applications was demonstrated as far back as the 1950's [3][4], they are still considered a relatively immature detector technology. In fact, it wasn't until a resurgence in the 1990's, driven by the need for electronics which could withstand high temperatures and radiation doses, that high quality, low defect material started to become available. As such there are only a handful of commercial suppliers in the world that grow SiC and D for detection applications. This, combined with the complexity of fabricating these materials, means that the cost remains relatively high, with good quality epitaxial silicon carbide (SiC-EP) and electronic grade single crystal diamond (D-SC) being in the order of 175 times and 5000 times more expensive than silicon PIN detectors per mm^2 (2014 wafer costs).

Cheaper, lower grade material is available in the form of semi-insulating silicon carbide (SiC-SI) and polycrystalline diamond (D-PC), 30 times and 170 times more expensive than silicon PIN per mm^2 respectively, but these detectors generally demonstrate incomplete charge collection characteristics and relatively poor resolution.

With the exception of SiC-EP, all these detectors have also demonstrated some form of the so-called *polarisation effect* during irradiation, that being a change in the acquired spectrum and / or count rate with time [5][6][7]. This

particular effect is prevalent in low doped, wide band gap semiconductors and is a result of charge carriers being trapped for long periods of time, leading to a change in the space charge distribution.

Despite these issues, the ability to directly detect neutrons has previously been demonstrated in SiC-SI [8], D-SC [9] and D-PC [10], among others. Work has now been conducted to quantify and compare the effect of incomplete charge collection, poor energy resolution and polarisation effects on the neutron detection capabilities for each of these detectors. This demonstrates that suitable neutron detection performance and stability is possible with all the detectors tested, increasing the options available for practical applications where large areas/volumes are needed.

2. Theory

Semiconductor Detectors

In practical semiconductor detectors, defects and impurities may be introduced during growth, fabrication and operation. These factors may introduce *traps* within the band gap region of a semiconductor's electronic structure which act to capture the created charge carriers (electrons or holes) and immobilise them for a period of time or even neutralise them completely.

These traps exist at specific energy levels (E_t) within the band gap region, which the trapped charge carriers must subsequently overcome in order to once again freely move through the material. The trap energy level (E_t) for specific carrier traps is referred to relative to the band energy, so either the conduction energy band ($-E_c$) for electron trapping or the valance band ($+E_v$) for hole trapping.

As given by Lutz [11], the average emission time of a trapped charged carrier, or the *detrapping time*, (t_t) is dependent upon both the temperature (T) and the energetic location of the trap within a specific material. Therefore shallow traps are quite close to the allowed energy bands and charge carriers tend to migrate between the energy levels quickly. However, deep traps tend to exist near the mid-point of the forbidden region and as such the amount of energy required for the trapped carriers to migrate back to the allowed energy band may be large [1][12]. This therefore may result in quite long periods of immobilisation, especially within wide band gap semiconductors where the mid-point energy may be larger than even the band gap of standard semiconductors like silicon, as illustrated in Table 1.

E_t (eV)	σ (cm ²)	t_t (at 300K)	Reference
0.31	3×10^{-16}	0.5 ms	[13]
0.38	3×10^{-16}	-	[14]
0.39	3.2×10^{-19}	13 ms	[15]
1.14	9.5×10^{-14}	≈ 13 hrs	[15]
1.23	4×10^{-13}	≈ 76 days	[15]
1.86	-	$\approx \times 10^9$ yr	[16]

Table 1: Properties of traps in CVD diamond. σ is the capture cross-section for charge carriers.

Within CVD diamond, the main source of defect is thought to arise from nitrogen interstitials from the atmosphere [13][16][17]. Traps also exist due to the grain boundaries of the lattice crystals formed during the growth process [17] and are particularly important when considering polycrystalline diamond, where multiple grain boundaries exist [13].

However, there seems to be some variation among the literature, which may be down to the variation of techniques used to identify the traps (TSC¹, PICTS², alpha particle response measurements, etc [15]) or due to the continual development in the quality of diamond growth (i.e. samples vary) [13], but there is a general consensus of shallow traps around 0.3-0.4 eV and deep traps around 1.1-1.3 eV.

Lebedev [12] discusses the main trap energy levels for SiC in great detail, with common impurities and defects being at much shallower levels than for D (relative to the Conduction and Valence band, the trap energy levels are in the region of -0.97eV and +0.63eV respectively). Consequently the charge carrier detrapping time would be expected to be less in SiC than that observed in D. Once again there is variation in the literature as to the origin or type of traps, but a significant volume of work discusses the so-called Z1 defect from 0.63 to 0.68 eV which seems to be common across all variations of SiC.

¹Thermally stimulated current technique

²Photo-induced current transient spectroscopy

The concentration of traps and the length of time carriers are trapped in them is an important factor in the quality of a detector. If any of the charge carriers are lost or delayed, so that they do not fully induce their charge during the integration time of the system, then the induced charge on the electrodes will be incomplete and the resultant signal pulse reduced. Furthermore, the emissions of detrapped electrons and holes outside of the integration time of their associated event, may also add to the noise of the system [11].

The ability of a detector to fully complete the collection of created charge is a measurable quantity simply given by its charge collection efficiency (*CCE*),

$$CCE = \frac{Q_c}{Q_0} \quad (1)$$

where Q_c and Q_0 are the amount of charge collected and created respectively.

As the velocity of the charge carrier is proportional to the applied electric field ($\vec{E}$) and the charge carrier drift mobility (μ) [1], the *CCE* is dependent upon not only the material, but also the applied electric field strength, as small fields lead to a slow movement of charge carriers and therefore increased probability of trapping or recombination, where as larger fields reduce the probability. As such it is more convenient to consider the mobility lifetime product of electrons ($\mu_e\tau_e$) and holes ($\mu_h\tau_h$) as a characteristic property of that material.

The mobility lifetime product for each respective charge carrier is a combination of the μ within the material and the mean carrier lifetime (τ), that being the average period of time the created carriers exist free and hence can travel before they are trapped. It is therefore possible to define the movement of the charge carriers in terms of the mean drift length (λ),

$$\lambda_e = \mu_e\tau_e E \quad (2)$$

$$\lambda_h = \mu_h\tau_h E \quad (3)$$

as essentially $v = \lambda/\tau$, if it is assumed that v is constant throughout the material. This quantity, which is strongly dependent upon $\mu\tau$, is extremely important in determining the quality of a material as λ needs to be equal to or greater than the sensitive region of the detector in order to approach 100% *CCE*, i.e. the charge carriers must be able to travel the distance between electrodes in order to be fully collected by them.

119 As proposed by Hecht [18], for the simple case of charge carriers passing
 120 through a parallel electrode geometry, λ can be determined via Equation 4 [1],

$$CCE = \frac{\lambda_e}{x} \left[1 - \exp\left(\frac{x_i - x}{\lambda_e}\right) \right] + \frac{\lambda_h}{x} \left[1 - \exp\left(-\frac{x_i}{\lambda_h}\right) \right] \quad (4)$$

121 where x is the detector thickness and x_i is the radiation interaction location
 122 measure from the cathode. In Equation 4 it is assumed that the electric field
 123 is constant throughout the detector, which is a reasonable assumption for
 124 this simplified geometry.

125 In situations where the interaction depth of the radiation incident upon
 126 the anode is small compared to the thickness of the detector ($x_i \ll x$), this
 127 expression can be simplified to,

$$CCE = \frac{\lambda}{x} \left[1 - \exp\left(\frac{x}{\lambda}\right) \right] \quad (5)$$

128 and as such the mobility lifetime product of the electrons ($\mu_e \tau_e$) and holes
 129 ($\mu_h \tau_h$) can be independently determined by irradiating the anode or cathode
 130 respectively.

131 *Neutron Interactions*

132 As can be seen from Figures 1a and 1b the most common fast neutron
 133 reaction in Si and C is elastic recoil scattering where the incident neutron (n)
 134 transfers a portion of its kinetic energy to the absorbing material through
 135 direct collisions.

136 Elastic interactions result in a change of direction and energy for the
 137 incident neutron, making it a scattered neutron (n'), as well as a gain of
 138 energy and momentum for the nucleus which recoils. If the energy transferred
 139 to this nucleus is such that its velocity is greater than that of its orbital
 140 electrons, it will lose those electrons and move through the medium as a heavy
 141 charged particle. The Q value (the amount of energy required or released
 142 for the reaction) for this interaction is 0 (neglecting the binding energy of
 143 the nucleus in the lattice, which is a few tens of eV) as conservation laws
 144 dictate that the energy of the reaction products (recoil nucleus and scattered
 145 neutron) must be the same as the incident particle.

146 From [1], when a neutron with nonrelativistic energy ($E_n \ll 939\text{MeV}$) is
 147 incident upon a target nucleus, conservation of momentum and energy, the
 148 recoil angle (θ) of the nucleus with mass number A is given by,

(a) Carbon-12

(b) Silicon-28

Figure 1: Elastic, absorption and total neutron cross sections (σ) against neutron energy (E_n), taken from NIST neutron scattering lengths and cross sections database [19], KAERI ENDF Cross section data [20] and BNL National Nuclear Data Center [21].

$$\cos\theta = \sqrt{\frac{1 - \cos\Theta}{2}} \quad (6)$$

149 where Θ is the scattering angle of the incident neutron and it is assumed
 150 that the target nuclei are at rest. Therefore the recoil energy (E_r) is given
 151 by Equation 7 [1],

$$E_r = \frac{4A}{(1+A)^2}(\cos^2\theta)E_n \quad (7)$$

152 From Equation 7 it is clear that the maximum transfer of energy occurs
 153 when the scattering angle of the incident neutron is 180° or the recoil angle
 154 of the nucleus is 0° (i.e. a head on collision). The neutron interactions will
 155 occur at various incident angles thus producing recoil products over a range
 156 of angles, resulting in a lower *average* energy transfer, as demonstrated in
 Figure 2.

Figure 2: Energy transfer ratio (E_r/E_n) against angle of recoil nucleus.

157 The transfer of energy is further maximised when the mass of the absorber
 158 nuclei is small. For example the maximum conversion ratio (E_r/E_n) for
 159 hydrogen is 1.0, where as for carbon and silicon it is 0.28 and 0.13 respectively.

160 For this reason, low Z materials are often used as fast neutron absorbers,
 161 of which hydrogen, often in the form of water (H_2O) or plastic ($-CH_2-$), is by
 162 far the most popular. These low Z materials can be used for direct detection
 163

164 (such as proton recoil detectors) or for conversion detection (hydrogenous
165 convertor layer producing detectable recoil protons), although conversion
166 based detectors can suffer from low intrinsic efficiencies limited by a com-
167 bination of successive interaction probabilities and self-attenuation [2].

168 At higher neutron energies ($>1\text{MeV}$) specific nuclear absorption reactions
169 may begin to contribute more to the overall neutron interaction method, as
170 demonstrated in Table 2.

171 For mono-energetic neutron sources the emission energy is very well de-
172 fined, with some facilities capable of energies determined to be within $\pm 1.5\%$.
173 For radionuclide sources however, there is a very wide range of neutron en-
174 ergies emitted due to the complex nature of the interactions occurring. With
175 Cf-252 and AmBe radioisotope neutron sources, for example, despite having
176 an average energy of 2.1MeV and 4.1MeV , neutrons can be emitted with en-
177 ergies ranging from, in principle, thermal energies ($<0.025\text{eV}$) up to 15MeV
178 and 11MeV respectively [23].

179 Furthermore, gamma and X-ray emissions are present due to interactions
180 within the radionuclide, surrounding material or due to the radioactive decay
181 itself, as demonstrated in Figure 3. However, these plots do not take into
182 consideration scattering or interactions from the test environment, which
183 would likely change the neutron spectral distribution and add to the non-
184 neutron radiation environment present (e.g. ionising photons).

185 *Gamma Interactions*

186 For the predominant processes by which X-ray and gamma-ray ionising
187 photons interact with matter (Photoelectric Absorption, Compton Scatter-
188 ing and Pair Production), the probability of each process is proportional to
189 both the energy of the incident photons (E_γ) and the atomic number (Z) of
190 the material through which they are travelling. Consequently, low Z mate-
191 rial aids fast neutron interactions while also minimises gamma interactions,
192 aiding discrimination between the two radiation types.

193 At higher energies, usually in the order of $>2\text{ MeV}$, direct nuclear re-
194 actions also start to become significant, leading to the emission of highly
195 ionising, heavy charged particles or neutrons, [25][26]. However, the ionising
196 photon energies used within this investigation fall under these limits and as
197 such these reactions will not be discussed.

Reaction	14MeV Neutron Cross-section (b)	Reaction Energy Threshold (MeV)	Q-value (MeV)	Branching (MeV)
$^{12}\text{C}(\text{n},\text{n}')^{12}\text{C}$	0.2106	-	0	-
$^{12}\text{C}(\text{n},\text{n}')^{12}\text{C}^{+2}$	0.2106	4.8088	-4.4389	-
$^{12}\text{C}(\text{n},\alpha)^9\text{Be}$	0.0623	6.4196	-5.7012	$\alpha_0 = 8.298$ $\alpha_1 = 6.614$ $\alpha_2 = 5.869$
$^{12}\text{C}(\text{n},\text{n}')3\alpha$	0.2000	8.4286	-7.3666	-
$^{12}\text{C}(\text{n},\text{p})^{12}\text{B}$	0.0002	13.7401	-12.5865	$\alpha_0 = 1.413$ $\alpha_1 = 0.460$
$^{28}\text{Si}(\text{n},\text{n}')^{28}\text{Si}$	0.1244	-	0	-
$^{28}\text{Si}(\text{n},\text{n}')^{28}\text{Si}^{+2}$	0.1244	1.8425	-1.7790	-
$^{28}\text{Si}(\text{n},\alpha)^{25}\text{Mg}$	0.1780	2.7653	-2.6537	$\alpha_0 = 11.34$ $\alpha_1 = 10.76$ $\alpha_2 = 10.37$ $\alpha_3 = 9.734$ $\alpha_4 = 9.381$ $\alpha_5 = 8.544$ $\alpha_6 = 7.941$ $\alpha_7 = 7.932$ $\alpha_8 = 7.438$ $\alpha_9 = 7.375$ $\alpha_{10} = 7.286$ $\alpha_{11} = 7.069$ $\alpha_{12} = 6.986$
$^{28}\text{Si}(\text{n},\text{p})^{28}\text{Al}$	0.2794	4.0042	-3.8599	$\alpha_0 = 10.14$ $\alpha_1 = 10.11$ $\alpha_2 = 9.167$ $\alpha_3 = 9.126$ $\alpha_4 = 8.767$

Table 2: Fast neutron nuclear reactions within Si and C, taken from [20][21][22]. Values $\alpha_0, \alpha_1 \dots \alpha_n$ represent the ground to excited states of emission.

Figure 3: Theoretical AmBe neutron energy spectrum lethargy distribution ($B_E \cdot E$) [23] with Am-241 X-ray and gamma emission intensities (I_g) [24] against energy (E).

3. Experimental Methods

The single crystal diamond detector (D-SC) was fabricated from high purity, electronic grade, single crystal diamond grown by Element Six Ltd[©] using the chemical vapour deposition (CVD) technique [27]. 4mm×4mm platinum contacts were sputter deposited onto the 5×5mm by 500μm thick sample at the University of Surrey, following a thorough cleaning process of boiling sulphuric acid and potassium nitrate, then de-ionised water, acetone and isopropanol respectively. The detector was mounted on a ceramic board and bonded with 24μm gold wire. During testing, unless otherwise stated, this detector was operated at -200V bias.

The polycrystalline diamond detector (D-PC) was fabricated from 20×20mm by 300μm thick polycrystalline CVD diamond from Diamond Detectors Limited[©] [28]. This material was thoroughly cleaned prior to contact fabrication using aqua regia, acetone and isopropanol respectively. ø6.5mm gold metal contacts were sputtered deposited at the University of Surrey and the completed detector mounted on a bespoke, low impedance (50Ω) printed circuit board and bonded with 24μm gold wire. The detector was operated at -400V bias during the investigation.

The semi-insulating SiC detector (SiC-SI) was fabricated from Cree[©] 4H-

217 SiC material [8]. The SiC-SI was $7\times 7\text{mm}$ by $360\mu\text{m}$ thick and had a net
218 doping of less than 10^5cm^{-3} . The $5\times 5\text{mm}$ contacts consisted of Ti/Pt/Au
219 Schottky contacts and Ni/Au ohmic contacts, applied via a combination of
220 photo-lithography and vacuum-deposition. The detector was mounted upon
221 a printed circuit board at the University of Surrey and operated at -400V .

222 For all the testing conducted the detectors were mounted within either a
223 light sealed diecast metal test box or vacuum cryostat connected to ORTEC
224 142A charge sensitive preamplifiers; ORTEC 570 or 572 shaping amplifiers;
225 an ORTEC 710 quad-bias supply; and ORTEC Easy-MCA with associated
226 Maestro software.

227 All alpha spectra tests were conducted with a 3.7kBq Am-241 source
228 inside a vacuum chamber at a pressure of $8\times 10^{-2}\text{mbar}$. Alpha polarisation
229 testing was conducted in air with a 60kBq Am-241 source.

230 Neutron testing was conducted in air, at AWE and Thermo Fisher Scientific[©]
231 (Beenham) for radionuclide sources, as well as the National Physical Labo-
232 ratory (NPL[©]) for radionuclide and mono-energetic neutron sources. Where
233 possible, these tests were conducted in fields greater than 4mSv/h and ir-
234 radiated for times exceeding 2 hours in order to obtain reasonable counting
235 statistics in all channels.

236 Between each radiation exposure the detectors were exposed to at least
237 15 minutes of room ambient light while at 0V bias in order to de-polarise the
238 detector.

239 Energy calibration of the detectors was conducted using pulser-capacitor
240 calibrations as described by Siegbahn [29].

241 4. Results

242 All of the detectors under test showed distinguishable alpha spectra as
243 demonstrated in Figure 4, with the energy resolution above background noise
244 improving as the bias increases. The SiC-SI and D-SC detectors were also
245 able to demonstrate suitable resolution in order to distinguish the trailing
246 edge of the alpha source used, an artefact from the source not being ex-
247 ternally plated with Am-241 material and resulting in a portion of lower
248 energy alpha particles emissions due to the subsequent interactions with the
249 emission window.

250 The effect of applied bias on the charge collection efficiency (CCE) and
251 intrinsic efficiency (count rate/incident radiation flux) has been depicted in
252 Figure 5. The D-SC shows the best alpha spectroscopy performance with

Figure 4: Count rate, normalised to incident flux, against energy. All detectors were tested at 8×10^{-2} mbar with a 3kBq Am-241 alpha source. The different peak positions are a direct result of the *CCE* of the detector.

100% *CCE* and intrinsic counting efficiency from around -200V. This detector also shows 100% *CCE* above +200V, but the intrinsic efficiency is limited to 60-70% due to a slightly higher noise threshold level during the positive bias testing because of poor electrical continuity.

Using the simplified version of the Hecht equation (Equation 5) the mobility lifetime products of the electrons ($\mu_e \tau_e$) and holes ($\mu_h \tau_h$) in D-SC were determined to be $(5.6 \pm 0.1) \times 10^{-5} \text{cm}^2 \text{V}^{-1}$ and $(6.1 \pm 0.3) \times 10^{-5} \text{cm}^2 \text{V}^{-1}$ respectively. This is in good agreement with the results presented by Abdel-Rahman [30], with deviations related to the peak position selection and polarisation effects, which make the analysis sensitive to the source activity and measurement duration.

The SiC-SI detector shows an increase in intrinsic efficiency with negative bias up to a maximum of 100%, despite a maximum *CCE* of 35% over the same range. The minimum depletion width suggested by capacitance measurements ($94 \mu\text{m}$) is more than sufficient relative to the alpha penetration depth ($18 \mu\text{m}$ from SRIM [31]) and does not vary significantly with bias. Therefore the low *CCE* and high intrinsic efficiency (ϵ_i) is likely a result of the incomplete charge collection due to defect or impurity traps within the material.

272 In contrast to these results, the work conducted by Ruddy *et al.* on
 273 similar detector material [8] showed a *CCE* of 27% at a maximum bias -
 274 400V. It was proposed in that work that the maximum bias was a limit of
 275 the package the detector was mounted in. It should however be noted that
 276 during this investigation the SiC-SI detector achieved $\approx 60\%$ *CCE* at -900V
 277 during characterisation.

278 The calculated mobility lifetime products were determined to be $(3.77 \pm$
 279 $0.01) \times 10^{-6} \text{cm}^2 \text{V}^{-1}$ and $(0.34 \pm 0.01) \times 10^{-6} \text{cm}^2 \text{V}^{-1}$ for the electrons and
 280 holes respectively. The ratio of the mobility lifetime products ($\mu_e \tau_e / \mu_h \tau_h =$
 281 11) is in good agreement with the expected SiC electron-hole mobility ratio
 282 (reported μ_e / μ_h range from 9 to 16 [32]).

283 Finally the D-PC detector demonstrated a very small charge collection
 284 efficiency of approximately 4% and only 30-35% intrinsic efficiency for both
 285 positive and negative bias, corresponding to mobility lifetime products of
 286 $(8.0 \pm 0.9) \times 10^{-8} \text{cm}^2 \text{V}^{-1}$ and $(6.7 \pm 0.7) \times 10^{-8} \text{cm}^2 \text{V}^{-1}$ for electrons and
 287 holes respectively.

288 Figure 6a shows the effect on the D-SC AmBe neutron spectrum as the
 289 amount of lead ($Z = 82$) between the source and detector increases. Fig-
 290 ure 6b also shows the experimentally determined attenuation (i.e. observed
 291 reduction in intrinsic count rate) of the AmBe neutrons as a function of
 292 lead thickness. This has been plotted against the theoretical attenuation of
 293 Co-60 gammas [33] (important for fission created gammas) and Am-241 gam-
 294 mas [33] (one of the main gamma emitters from the AmBe) to demonstrate
 295 that even a few mm of lead will fully attenuate the main gamma emissions
 296 from the AmBe source without seriously affecting the neutron spectra ($< 1\%$
 297 attenuation) recorded by the detectors. In fact, the rate of attenuation is
 298 still greater for Co-60 than it is for AmBe neutrons, with 11mm of lead
 299 attenuating the AmBe signal by $\approx 28\%$ and the Co-60 by $\approx 51\%$.

300 It is worth noting that the data in Figures 6a and 6b is important when
 301 considering how to optimise these detectors for practical applications as it es-
 302 sentially shows that by reducing the X-ray or gamma ray influence with high
 303 Z filtration, any cross-sensitivity threshold can be reduced, thus increasing
 304 the neutron/gamma count rate ratio. Although some neutron attenuation
 305 will occur as a result of the filtration, it will not be to the same extent
 306 as the X-rays or gammas, subsequently leading to a better neutron-gamma
 307 cross-sensitivity ratio (more neutrons per gamma).

308 From this work it is with a high level of confidence that the data pre-
 309 sented in Figure 7 demonstrates that the detectors are directly detecting fast

Figure 5: Charge collection efficiency (CCE) and intrinsic efficiency against bias for D-SC, D-PC and SiC-SI. For detectors with suitable geometry and electric field profile assumptions, a simplified Hecht fit has been plotted.

Figure 6: The effect of lead on the gamma and neutron detection performance of D-SC detector at -400V.

neutrons despite low charge collection efficiency and / or polarisation issues. The Cf-252 and mono-energetic neutron data in particular emphasises this as the gamma emissions from these sources are both low intensity and low energy. Furthermore, by comparing the end point energies of each spectrum it is clear that a simple energy threshold level could be used to discriminate neutron energies.

The results presented in Figure 7 have been normalised to the incident flux of the neutron radiation. For the mono-energetic sources, the incident flux primarily consists of the main neutron energy and therefore the position on the y-axis in the graphs presented is a good representation of the sensitivity of the detectors to that radiation type. For radionuclide sources however, this method of normalisation is less accurate as there is a wide spectrum of incident neutron energies, each of which have different interaction probabilities. It does however give a reasonable indication of the relative sensitivity over the entire energy range.

Data points with the suffix *LG* represent data taken with a lower gain calibration setting. This was required for radiation sources where the maximum energy was larger than the calibrated energy range of the detectors. Aside from allowing the higher energy spectra to be acquired, it also changed the energy binning leading to a perceived increase in sensitivity over some regions, particularly those with high counting statistics (i.e. lower energy channels).

331 For D-SC this led to a change in the energy bin width to 9.5keV/channel
 332 from 18.8keV/channel; 4.7keV/channel from 10.9keV/channel for D-PC; and
 333 2.6keV/channel from 6.1keV/channel for SiC-SI. As such, both the *standard*
 334 and *LG* data have been shown in the graphs in order to give a better indi-
 335 cation over the entire neutron spectra energy range.

336 Analysis of Figure 7 shows that the D-SC detector provides the best over-
 337 all neutron performance, with the observed end point energies corresponding
 338 to the expected maximum energies for all the neutron sources tested and
 339 the count rate per incident neutron is higher relative to the other detectors
 340 under test. This seems reasonable when considering the high neutron energy
 341 transfer ratio (Figure 2), larger thickness and the *CCE* of the detector. The
 342 D-SC performance is also in excellent agreement with the work of Pillon *et*
 343 *al.* [9] with clear nuclear reaction and recoil features.

344 The D-PC demonstrates reasonable neutron detection characteristics de-
 345 spite the very low *CCE*, highlighting the benefit of carbon based detectors.
 346 In fact the end point energies for this detector seem to exceed expectations,
 347 as they are significantly higher than would be expected for a detector at
 348 around 3-4% *CCE* which is likely a result of both the high energy transfer
 349 ratio (E_r/E_n) of carbon and the neutron interactions being more uniform
 350 across the detector relative to alpha particles (i.e. no localised trapping).
 351 However, there are no clear nuclear reactions or recoil features within the
 352 spectra, which will be a direct result of the low peak resolution in the detec-
 353 tor.

354 The SiC-SI spectrum presented for AmBe is similar to that presented by
 355 Bryant [34] and the features correspond to the simulated response in the same
 356 paper. The endpoint energies are also comparable to the expected maximum
 357 energies for all the neutron sources tested when taking into account the *CCE*
 358 of the material ($\approx 32\%$) although the overall sensitivity is not as high as the
 359 diamond detectors, likely related to the lower energy conversion efficiency of
 360 the Si atoms within the detector.

361 As can be seen in Figure 8 the performance of these detectors is main-
 362 tained over a fairly wide dynamic range of neutron fluxes. This shows that
 363 the observations are indicative of direct neutron detection as the count rate
 364 increases linearly with the radiation dose received, demonstrating that the
 365 chosen low energy threshold is effectively discriminating electronic noise and
 366 that the counts observed are all due to real events.

367 All the detectors demonstrated some issues with stability during irradiation,
 368 namely changes to the acquired spectrum and / or count rate with time.

Figure 7: Count rate, normalised to incident flux (I/ϕ), against energy (E). All exposures were conducted at NPL[®]. *LG* represents a lower gain calibration setting used during test so that the high energy points were visible in the spectrum.

Figure 8: Total count rate above a given threshold against incident radiation flux for Cf-252 neutron radiation. Linear fit displayed with log-log gradients of 1.004, 1.000, 0.955 for D-SC, D-PC and SiC-SI respectively.

369 This so-called *polarisation effect* is dependent upon the concentration of ion-
370 isation within the detectors, with highly ionising particles (such as alphas)
371 producing very quick polarisation effects, as demonstrated in Figure 9. This
372 is because these particles tend to create a large amount of charge carriers at
373 shallow depths within the detector ($\approx 17\mu\text{m}$ for diamond and $\approx 18\mu\text{m}$ for
374 SiC [31]) resulting in a high trapping rate over a small region[5][6][7]. This
375 leads to the creation of a localised space charge barrier close to the electrode,
376 through which further electrons and holes must pass to be fully collected.

377 For SiC-SI and D-PC, over the time frame tested, this leads to a po-
378 tentially paralyzable effect within the detector as the spectrum moves into
379 the noise region and no further pulses can be registered. This effect high-
380 lights the difference between the mobility lifetime products of the detectors,
381 with D-PC having the lowest $\mu\tau$ product and the highest polarisation rate
382 as charge trapping is very likely.

383 D-SC on the other hand had a relatively good $\mu\tau$ product, resulting in
384 a low polarisation rate and even recovery of the count rate over longer time
385 periods. This count rate recovery is a direct observation of *priming* whereby
386 the traps within the material are steadily filled with the created charge carri-

ers until they reach saturation point, after which a stable field, and therefore spectrum, is maintained [6]. The relatively good mobility lifetime product of this material ensures that the subsequently created electrons and holes are capable of traversing the detector even with an altered space charge region. Therefore, as the charge carrier creation rate is maintained for a constant irradiation field, the count rate steadily returns to the original value as less charge carriers are trapped and lost from the counting system.

For neutrons the charge carriers are created, on average, more uniformly throughout the entire detector thickness, therefore the subsequent trapping would be distributed more evenly, diluting the overall space charge build-up and reducing the polarisation effect [35]. As such, it is expected that the polarisation rate for neutrons would be less than alphas, as observed in Figure 9.

In fact, for all the detectors under irradiation from 6mSv/h Cf-252 neutrons, there was little or no polarisation observed (<5% variation over 80,000s) as the rate of de-trapping is greater than or equal to the rate of trapping (or charge carrier generation). However, as the dose rate increases the rate of polarisation increases for the low *CCE* material (<50%) as would be expected for increased charge carrier creation, but rarely discussed in the literature for neutrons.

Despite the onset of polarisation effects as the neutron dose rate is increased, operation is still possible, further demonstrated in Figure 8. For the D-PC detector in particular, the count rate stabilises during neutron induced polarisation, despite alpha induced polarisation leading to paralyzable affects. This demonstrates the point at which trapping and de-trapping is in equilibrium across the whole volume of the detector, where as the alpha data demonstrates the equilibrium at a shallow irradiation depth. As the neutron equilibrium is dependent upon the number of charge traps within the detector, potentially this uniform neutron polarisation effect could also be used in the future to characterise charge trap concentrations within detectors.

5. Conclusion

Work has been conducted to demonstrate that carbon based, wide band gap, semiconductor detectors with lower charge collection efficiency (*CCE*), poor resolution and polarisation effect can fulfil requirements for fast neutron detection and spectroscopy over a fairly wide dynamic range. This demonstrates that suitable neutron detection performance and stability is possible

Figure 9: Count rate variation (I/I_0) against time as a function of radiation type. Alpha source was a 60kBq Am-241 at 8×10^2 mbar. Cf-252 data were taken at approximately 6mSv/h and 180mSv/h.

with lower quality polycrystalline diamond (D-PC) and semi-insulating silicon carbide (SiC-SI) detectors, increasing the potential options available for practical neutron applications where large areas/volumes are needed.

Single crystal diamond (D-SC) was shown to have 100% *CCE*, however, under the influence of alpha radiation it demonstrated the polarisation effect, by which the energy peak and count rate varied with irradiation time.

Paralyzable alpha induced polarisation effects were also observed in the D-PC and SiC-SI detectors, as well as low *CCE* (<5% and <50% respectively).

Despite incomplete charge collection efficiency, poor energy resolution or polarisation issues, all these detectors did perform as fast neutron detectors over a fairly wide range of neutron fluxes, with less than 20% variation in the neutron count rate over the time tested.

Polarisation as a result of neutron irradiation was investigated within these detectors for neutron dose rates of 6mSv/h and 180mSv/h, which, in the case of polycrystalline diamond and semi-insulating silicon carbide, is the first time it has been demonstrated. Overall it was shown that the polarisation rate for neutrons was less than alphas and could result in a stable detector, subject to the incident flux. This directly demonstrated that uniform charge carrier creation reduced the polarisation effect relative to the high-concentration charge carrier creation from shallow penetrating alpha particles.

Subsequently it can be concluded that despite, what is generally considered, unfavourable detection characteristics these detectors can be effective direct fast neutron detectors.

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