Avalanche Diamond Detector

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Abstract

In this project, the possibilities of making an avalanche detector out of diamond were explored. Coplanar interdigitated electrodes of the same pattern but different electrode gap thickness of 10µm and 5µm were fabricated on a 4mm x 3mm, 700µm thick diamond and a 5mm x 5mm, 150µm thick diamond respectively. The charge collection efficiency (CCE), energy resolution and signal-to-noise ratio (SNR) of the detectors were then collected and benchmarked against a commercially available passivated implanted planar silicon (PIPS) detector. From the measurements, it was found that there was no avalanche effect in the 700µm thick diamond detector while some avalanche effect was observed for the 150µm thick diamond detector. However, there was also significant noise and poorer energy resolution observed in the 150µm detector. Thus, possible future experiments include the oxygen-termination of diamond surfaces and fabrication of etched subsurface interdigitated electrodes for both diamond samples to improve these parameters.
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Chapter One

Introduction

1.1 Diamond as a Detector Material

As compared to other semiconducting materials such as silicon, diamonds have numerous outstanding physical properties such as higher mechanical strength, thermal conductivities and electrical conductivities [1,2]. Particularly, its higher saturation carrier velocities and carrier mobilities at room temperature are extremely attractive features as generated charges can be collected in the order of nanoseconds, leading to higher responsivity of the detector. Also, due to diamond’s larger band gap of 5.6 eV, which is approximately five times higher than that of silicon, thermal excitations of electrons from the valence to the conduction band at room temperature are highly reduced. This in turn translates into lower noise generated during detection which is highly desirable for detectors. The 100-fold higher breakdown voltage of diamond as compared to silicon is also an extremely useful property for avalanche detectors since charge multiplication effects only occurs at high applied electric fields. Last but not least, diamond’s higher Wigner energy, which is the energy required to displace an atom from the lattice, makes it less susceptible to radiation damage during experiments. This is an extremely attractive feature for detectors when the detection of high energy radiation and operations under high radiation fluences are involved. Thus, as seen from the above-mentioned properties, it is evident that diamonds show huge potential in being a superior solid-state detector. Table 1.1 below summarises these main physical properties of diamond and presents a comparison with silicon.
<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band gap (eV)</td>
<td>5.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Energy to form e-h pair (eV)</td>
<td>13.2</td>
<td>3.6</td>
</tr>
<tr>
<td>Hole mobility at 300K (cm²V⁻¹s⁻¹)</td>
<td>1600</td>
<td>450</td>
</tr>
<tr>
<td>Electron mobility at 300K (cm²V⁻¹s⁻¹)</td>
<td>2200</td>
<td>1500</td>
</tr>
<tr>
<td>Saturation carrier velocity cm s⁻¹)</td>
<td>2.7 x 10⁷</td>
<td>10⁷</td>
</tr>
<tr>
<td>Breakdown voltage (V cm⁻¹)</td>
<td>10⁷</td>
<td>3 x 10⁵</td>
</tr>
<tr>
<td>Wigner Energy (eV)</td>
<td>43</td>
<td>15</td>
</tr>
<tr>
<td>Atom density (cm⁻³)</td>
<td>1.75 x 10²³</td>
<td>4.83 x 10²²</td>
</tr>
</tbody>
</table>

Table 1.1: A summary of the physical properties of diamond and silicon. The table is adapted from IIa Technologies Pte Ltd [1].

1.2 Reasons for the Relative Lack of Diamond Utilisation in Detectors

However, despite all these outstanding properties, diamond has not been extensively utilised in detectors. The utilisation of diamonds in applications is hampered by two main reasons, the first being the relatively high cost of diamond and the second being the technological difficulties in producing high quality, detector-grade diamonds.

Typically, detector-grade diamonds come from a class of diamonds known as Type II diamonds where the concentration of nitrogen contained is less than 5ppm. However, in general, it is already challenging to synthesis diamonds in the lab due to its rigid lattice structure and chemical inertness to reagents [2,3]. Since the 1950s, the main method of producing synthetic diamonds has been the high pressure and high temperature (HPHT) method which aims to mimic the natural growth conditions of diamonds. However, this method involves the use of a catalyst that results in the additional incorporation of nitrogen into the final diamond product [4]. It was only later in the 1980s when chemical vapour deposition (CVD) methods become industrialised such that high quality and low nitrogen concentration diamonds were increasingly produced. Even so, the growth rate of diamonds was still limited and few conditions produce polycrystalline CVD (pCVD) diamonds of high quality on all facets [5]. The successful production of single crystal CVD (scCVD) diamonds which are more desirable than pCVD diamonds was even lower. In general, the former is preferred due to the absence of grain boundaries which reduces the chances of charge
trapping and hence allows for higher electrical conductivities. It took over 40 years of research into improving the CVD process before Microwave Plasma CVD (MPCVD) technique became a commercially available diamond synthesis method in the 1990s. Thus, it was only until recently that the mass production of high quality, electronic-grade scCVD was possible, thereby pushing research involving electronic-grade diamonds.

1.3 Increased Incentives for Research into Diamond as Detectors
With these aforementioned improvements in CVD processes, the production of high-quality, electronic-grade scCVD diamonds of various thickness is now possible [3]. Consequently, the cost of production of diamonds have also been lowered, allowing for better accessibilities to utilising diamonds in research in general. Since then, there have been numerous research into the applications of diamond in various solid-state devices such as photodiodes for UV detection [3], radiation dosimeters to track radiation exposure [7], and subsequently in tracking layers of the Large Hadron Collider (LHC) used for high energy physics experiments conducted at CERN [8]. Thus, the application of diamonds has largely benefitted the experiments, and coupled with the increasing need for the development of more radiation hard materials for use in high energy experiments, there is an increasing incentive for researching into diamonds in various aspects.

1.4 Avalanche Effect in Diamond
One aspect that has been explored with diamonds is the possibility of making an avalanche detector. Avalanche detectors rely on the phenomenon of charge multiplication whereby the total number of collected charge carriers is higher than that generated by the incident radiation. This results in a higher signal-to-noise ratio (SNR) of signals generated and allows low energy radiation which would otherwise be hidden by noise to be detected. In-so-far, charge multiplication effects have been observed in both positively and negatively doped diamond structures [9,10], but it was only in a research conducted by Shukan et al. in 2016 that this effect was reproducibly observed in intrinsic scCVD thin diamond. In the research conducted by Shukan et al. (2016), charge multiplication effects were observed in a 3.2μm thick scCVD diamond upon incidence of 18MeV oxygen ions when high electric fields of more than 30V μm⁻¹ were applied to the sandwich electrodes [11].
1.5 Limitations to the Sandwich Electrode Structure and Possible Alternatives

In the research by Shukan et al. (2016), the sandwich electrode structure was used. As its name suggests, the configuration of such electrodes is such that two parallel electrodes are fabricated on the opposite ends of the diamond, thereby sandwiching the diamond in the middle. Even though charge multiplications have been successfully observed with the use of such electrodes, further improvements can be made. In the sandwich electrode structure, the oppositely biased electrodes are on both ends of the diamond such that charge carriers generated by incident radiation will have to transverse a larger distance to be collected. As a result of this larger distance, the chances of the charge carriers being trapped by possible defects also increase and this will lead to incomplete charge collection at the electrodes. This translates to a lower charge collection efficiency and can lead to inaccuracies in the determination of incident radiation energy. In addition, such electrodes might not be suited for use with thick diamonds due to the limitations in electronics that can generate extremely high voltages.

Thus, in this project, an alternative electrode structure known as the coplanar interdigitated electrodes is proposed. An advantage of this structure is that both oppositely biased electrodes are on the same side of the diamond and thus, the electrode separation can be smaller. In this way, charge carriers can travel a shorter distance to be collected, hence reducing the possibilities of charge trapping and allowing for a higher charge collection efficiency to be measured. In addition, this smaller separation also allows for a higher electric field to be achieved even with the application of a lower bias voltage. This subsequently eliminates the issues with generating high bias voltages for thicker diamonds when the sandwich electrode structure is used. Thus, another advantage of this structure is that it can be easily extended to diamonds of various thickness. Figure 1.1 illustrates the difference between these mentioned electrode structures.
1.6 Aims and Motivations of Project
Inspired by the project by Shukan et al. (2016), this project aims to obtain charge multiplication in type II, electronic-grade intrinsic scCVD thick diamonds with the use of the coplanar interdigitated electrode design. In this project, coplanar interdigitated electrodes with different electrode separations of 5μm and 10μm were fabricated on thick diamond samples of 150μm and 700μm respectively. Their charge collection efficiency (CCE), signal to noise ratio (SNR) and energy resolution were then measured.

1.7 Overview of Thesis
In the following Chapter, the necessary background theories for understanding this project will be elaborated on, and following in Chapter 3, the materials and methods involved in the fabrication and testing of a working diamond detector will described in detail. Chapter 4 will present the results and discussion for the conventional detector (4mm x 3mm, 700μm thick diamond sample) with no avalanche effects observed while Chapter 5 will be on that of the avalanche detector (5mm x 5mm, 150μm thick diamond sample) where charge multiplication effects are observed. Finally, the conclusion to this project and the possible future work in view of the results will be discussed in Chapter 6.
Chapter Two
Theory

2.1 Overview
This chapter presents some of the fundamental background knowledge required for a good understanding of the project. The general characteristics of the interactions of charged particles with matter as well as the general solid-state detector mechanism will first be introduced. After, the figure of merit used to determine if a detector is operating in the avalanche region, called the charge collection efficiency (CCE) will be introduced. Last but not least, some factors that can affect the CCE, such as the choice of electrode material and termination of the diamond surface, will also be discussed.

2.2 Interaction of Charged Particles with Matter
In this project, the radiation of interest are alpha particles. In matter, charged particles lose their energy mainly via coulomb scattering interactions with the detector’s atoms. At high energies of more than hundreds of keV, alpha particles have a higher probability of interacting with the electrons of the detector atoms and hence lose energy mainly via electronic stopping. At lower energies of below tens of keV, interaction with the nuclei of the detector atoms becomes prominent as well and towards the end, the charged particles lose the remaining of their energies via nuclear stopping. In general, most of the charged particle’s energy is lost at the end of their trajectories and the distance the particles can travel before fully losing their energies can be found from the Bragg peak. The trajectory of charged particles as they lose their energies is a straight-line path at higher energy during electronic stopping, followed by large, haphazard deflections from their straight-line paths. These deflections occur at lower energies as the particles undergo direct collisions with the nuclei of the detector atoms.
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Given that coulomb interactions are far range interactions and alpha particles have relatively huge masses, alpha particles only have a short range in matter and hence, can be fully stopped in thick solid-state detectors. From previous SRIM simulations and that from Pomorski et al. (2013), the mean range of the 5.486MeV alpha particles emitted from Am-241 is found to be around 10μm to 12μm in diamond [7]. Thus, alpha particles of energies ranging from 5.150MeV to 5.800MeV emitted from the mixed radioactive source used in this project will be fully stopped within the detectors, and most energy can be assumed to be deposited within the detectors.

2.3 Semiconductor Detector Mechanisms
Detection of radiation in semiconductors relies primarily on the generation of electron-hole pairs by the incident radiation. Upon impinging onto the detector, the incident radiation ionizes the atoms of the semiconductor material, generating free mobile charge carriers in the form of electron-hole pairs. These created electron-hole pairs are then drifted towards the electrodes according to the electric field, inducing a charge at both ends of the electrodes which is then registered as a signal by the front-end electronics. The total number of electron-hole pairs produced by the incident radiation is proportional to the energy of the incident radiation. Hence, the higher the energy of the incident radiation, the larger the induced charge and the larger the signal. It is good to note that while the generation of a signal in the front-end electronics is typically described as owing to the collection of charges at the electrodes, the actual situation is that the generation of signal is due to the rate of change of the instantaneous electric flux on the surface of the metal electrodes and not the physical collection of charges. The Shockley-Ramo theorem provides an elegant simplification of the heavily involved calculations of induced currents [12, 13], but for the purpose of this project, it is sufficient to understand that the phrase ‘collection of charges’ refers to the generation of a signal due to a change in electric flux on the surface of the electrodes.

2.3.1 Use of Intrinsic Diamonds in Detectors
Although there are significantly more extrinsic than intrinsic conventional semiconductors, the use of intrinsic diamonds as a detector material is common for the case of diamond detectors. This is a consequence of the limited number of suitable shallow dopants for creating extrinsic diamond. Shallow dopants are impurities that can improve charge carrier mobilities by introducing energy states near the valence or conduction bands of the intrinsic material. Since doping is essentially a
process whereby impurities are introduced to the lattice, it is important to ensure that dopants introduced improve charge mobilities instead of causing substantial charge-trapping. Thus, only shallow dopants should be used and not deep dopants. For diamonds, due to their rigid lattice structure and large band gap, only boron and phosphorous have been successfully used to create p-type and n-type diamonds respectively so far, but even so, the process has been extremely challenging [14]. Thus, the use of intrinsic diamonds as detector materials is also highly common. This is not too much of an issue however, as diamonds already have higher saturation carrier velocities and charge mobilities. Moreover, the large band gap of diamond also reduces the amount of charge carriers due to thermal excitations at room temperature, thereby reducing the amount of background noise in the detector. This then makes the use of pn-junctions unnecessary for diamond, and hence, intrinsic diamonds are also sufficient for the purpose of this project.

2.4 Figure of Merit: Charge Collection Efficiency (CCE)
In order to determine the region a detector is operating in, a crucial figure of merit known as charge collection efficiency (CCE) can be used. By definition, CCE is the ratio of the total number of charge carriers collected at the electrodes to the total number of charge carriers generated by the incident radiation. According to Hecht, the number of electrons arriving at the anode decreases exponentially with the distance of carrier generation from the anode. This average carrier drift length in the direction of the applied electric field, \( w_x(E) \) is the drift distance where the number of collected electrons has decreased to \( \frac{1}{e} \) of the number of electrons generated by the incident radiation, and is now known as the charge collection distance (CCD). Thus, the total number of collected charge is given by:

\[
Q_c = \int_0^x qN_x(E) \frac{dx}{D} = \frac{qN_G w_x(E)}{D} \left(1 - e^{-\frac{x}{w_x(E)}}\right)
\]  

(2.1)

Where \( Q_c \) is the total charge collected at the electrodes, \( N_x(E) \) is the total number of charge remaining after moving a distance \( x \) from the point of carrier generation to the electrodes under the electric field \( E \), \( D \) is the electrode separation, \( N_G \) is the total number of charge carriers generated at distance \( x \).
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Equation (2.1) can then be divided by the total charge generated by the incident radiation and rewritten as a function of CCE as follows:

\[
CCE(E) = \frac{Q_e}{Q_G} = \frac{w_x(E)}{D} \left(1 - e^{-\frac{x}{w_x(E)}}\right), \quad 0 \leq x \leq D
\]  

(2.2)

Mathematically, this parameter CCE can also be related to other various quantities such as the carrier mobilities and lifetimes as well as electric field in the detector. Assuming that the charge mobilities and lifetimes are constant, the electrode separation is much larger than the CCD, and that there are no distortions to the electric field in the detector, the CCE can be rewritten as follows for low electric fields:

\[
CCE(E) = \frac{Q}{Q_0} = \frac{CCD}{D} = \frac{(\mu_e \tau_e + \mu_h \tau_h)E}{D}
\]  

(2.3)

Where \( \mu_e \) and \( \mu_h \) are the mobilities of the electrons and holes respectively, and \( \tau_e \) and \( \tau_h \) are the lifetimes of the electrons and holes respectively. The derivation of equation (2.2) is given in the Appendix.

Qualitatively, how the CCE relates to the above quantities can be understood as follows. Firstly, CCD refers to the average drift length of the carriers, otherwise known as the distance that charge carriers can drift under an electric field before being trapped. Thus, the closer the value of CCD to the electrode separation D, the higher the chances of the charge carriers being able to drift to the electrodes to be registered as a signal. This then gives a higher CCE of the detector. Also, since CCD is basically a drift length, it can be rewritten as the product of the average velocities of the charge carriers and their mean lifetime, which is the average time that the charge carriers can exist in the detector before recombination. The average velocity of the charge carriers can be given by the product of the charge mobilities, which is defined as the average velocity of the charge carrier under the influence of an electric field. Therefore, the higher the charge carriers’ mobilities, lifetimes and the larger the electric field applied, the greater the CCD and hence CCE.
2.4.1 CCE for Conventional Detectors
For conventional detectors that do not display charge multiplication effects, CCE linearly increases with the applied electric field at low electric field before saturating at higher electric fields. Physically, this can be interpreted as the increase in the total number of charge carriers collected as the applied electric field becomes strong enough to separate the electrons and holes from each other to prevent recombination events. However, as electric fields continue to be increased, the rate of increase of charge carriers collected would fall as most electron-hole pairs generated by the incident radiation would have been collected, so the increase in CCE slows down at higher fields and begins to plateau. Figure 2.1 shows an illustration of typical CCE values for conventional detectors.

![Graph of CCE against applied bias voltage for typical semiconductors. Graph taken from Ref [15].](image)

However, in reality, the CCE will not reach unity due to the definite presence of defects in the lattice structure. Thus, some charge carriers will be trapped in the defects before reaching the electrodes and CCD will not be equal to electrode separation. Thus, CCE is at maximum asymptotic towards unity for any conventional detector operating in saturation region. This holds true even for extremely high-quality crystals such as the scCVD, detector-grade diamonds used in the project.
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2.4.2 CCE for Avalanche Detectors.

For avalanche detectors, charge multiplication effects would be present and hence, the CCE would be greater than 100%. This could be due to the electrons ejected by incident radiation being accelerated to sufficiently high kinetic energies such that they can produce secondary electron-hole pairs at high electric fields. According to McKay and Chynoweth [16,17], the number of additional electron-hole pairs that each primary electron can produce per μm is quantified by the charge multiplication factor, α. Using the Chynoweth equation for the sandwich electrode structure used by Shukan et al. (2016), this parameter is given by:

\[
\alpha = ae^{-b/E}
\]  

(2.3)

Where a and b are fitting parameters, and E is the applied electric field.

As such, the trend of the CCE in this region has been found to be exponential with the increase in applied electric field as seen in Figure 2.2. For the case of diamonds, even though the fitting parameters are not well established, the general exponential trend was still widely observed in the research by Shukan et al., (2016) for thin diamond detectors as well as in doped diamonds by Hiraiwa and Kawarada (2015). [18]. Thus, a general exponential trend might also be expected for the diamond detectors used in the project if they are operating in the avalanche regions as desired.
2.5 Optimisation of Detector Designs

While diamonds have extremely outstanding physical properties as mentioned in Section 1.1, what has been observed experimentally is highly different from these values. For example, even though diamonds have high theoretical breakdown voltages, experimental breakdown voltages measured in real diamond detectors can be as low as 1.7MVcm\(^{-1}\), which is one magnitude lower than theoretical [19]. Similarly, the CCE has also been found to saturate near as low as 60% for some diamonds [20]. Overall, this phenomenon can be attributed to imperfections in diamonds used as well as poor detector designs, of which the latter can be minimized through good experimental methodologies and optimising detector designs. In this section, some factors that can limit the CCE and detector performance is discussed.

2.5.1 Choice of Electrode Material

For detectors, the use of Ohmic contacts are desired so that charges can flow unimpeded from the detector material to the metal electrodes, thereby allowing fast and accurate registering of signals. In addition, ohmic contacts allow for the carrier concentrations in the detector to be maintained at equilibrium so that detector characteristics are not altered. However, in reality, there would always

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**Figure 2.2:** Graph of CCE against applied electric field. Graph taken from [11].

[Graph showing CCE against electric field]
be finite potential barriers for charge carriers at the interfaces, so typically metals with low Schottky barrier heights are chosen so that near Ohmic characteristics are obtained. The suitability of different metals for the diamond-metal surface contacts depend on the difference in work functions of surfaces. For hydrogen-terminated diamonds used in this project, some suitable materials found include Au and Pt [3, 21]. In practice, prior to deposition of the electrode material, a thin adhesion layer of typically Cr and Ti are also used to form stable carbides to the diamond and electrode material used. Thus, in order to improve the CCE obtained in the project, Cr and Au electrodes will be fabricated.

2.5.2 Termination of Diamond Surfaces
Other than affecting the work function, the kind of surface termination of diamond also affects its surface conductivity. As hydrogen-terminated diamond surfaces are found to have negative electron affinities, electrons that have been excited into the conduction band are able to escape into vacuum without facing much barrier. This thus allows for high surface conductivities of hydrogen-terminated diamond and also facilitates the collection of charges at the electrodes.
Chapter Three
Methodology

3.1 Overview
The fabrication of working diamond detector from a diamond sample first involves the fabrication of working electrodes on the diamond sample. Following, connections to front-end electronics have to be added to the diamond sample to make it a working detector before testing can be done. In this chapter, the details of electrode fabrication, detector assembly and testing will be elaborated.

3.2 Electrode Fabrication
Lithography is used throughout the course of the project to fabricate electrodes. Lithography refers to the process of transferring patterns onto a substrate, and in this experiment, two different lithography methods were used. The first method involves the use of a mask while the second employs direct laser writing. The latter method was used due to failed attempts with using the former method to fabricate working electrodes.

The general process of UV lithography is illustrated in Figure 3.1 below. This method of fabrication was done in the CIBA-ESP Lab clean room. The photoresist used in this experiment is a positive photoresist AZ1518 which has its polymer disintegrates when exposed to UV light.
3.2.1 Cleaning and drying of diamond sample:

Before electrodes can be fabricated, the diamond samples must be thoroughly cleaned as follows:

1. Place the diamond sample into a beaker and fill half the beaker with acetone. Place the beaker into a sonicator for 10mins.
2. Carefully empty the acetone into another beaker while ensuring that the diamond sample is still in the beaker. Rinse the beaker twice with isopropanol to remove the remaining acetone before filling half the beaker with isopropanol. Place the beaker into the sonicator for 10mins.
3. Repeat step 2 by using de-ionised water in place of isopropanol.
4. Using a Teflon tweezer, transfer the diamond sample into a clean, dried beaker. Once again, carefully hold the diamond sample up using the Teflon tweezer while drying the sample with small spurts of nitrogen gas. The diamond sample is dried when there are no more visible water molecules.
3.2.2 Spin-coating of Photoresist:
Before spin-coating the actual sample, care was taken to ensure that the interior of the spin-coater was thoroughly cleaned with acetone to prevent contamination of the sample. A test run at the desired parameters using only glass slides was also performed to ensure that the vacuum in the spin-coater was functioning well. After, the actual spin-coating was then performed as follows:

1. Firmly affix the diamond sample onto the centre of a clean glass slide by attaching sufficient carbon tape on both edges of the diamond sample. Care was taken to ensure that the diamond sample was firmly attached to the glass slide before spin-coating.
2. Load the glass slide into the spin-coater and using a plastic pipette, carefully transfer a drop of the AZ1518 photoresist onto the diamond sample while holding the pipette as upright as possible.
3. Close the spin-coater cover and programme the spin-coater as follows:
   
   Round 1: 800 rpm, 15s, 1000 rpm/s  
   Round 2: 5000 rpm, 45s, 1000 rpm/s  
   Round 3: 7000 rpm, 20s, 1000 rpm/s  
   Round 4: 0 rpm, 10s, 1000 rpm/s

4. Switch on the vacuum and enable the flow of nitrogen gas. Start the spin-coating.
5. When the spin-coating is done, transfer the glass slide onto a heater that has been pre-heated to 100°C to bake the photoresist for 90s.

3.2.3. UV-Exposure of Photoresist:
After baking for the coated photoresist to harden, UV-exposure is done using light of 365nm as follows:

1. Switch on the UV-exposure setup and wait for a few minutes until the power of the UV source has stabilised to 200W.
2. Clean the area of the desired pattern on quartz mask with acetone and affix the diamond sample to the mask using carbon tape. Care was taken to ensure that the side of the diamond with photoresist faces the mask.
3. With the mask facing the UV light source, place the mask and sample into the black box for irradiation for 90s.

3.2.4 Development of Photoresist:
After exposure, the photoresist must be developed. The developer used in this experiment is AZ400K mixed with de-ionised water in the ratio of 1:4 in volume. The procedures are as follows:

1. Clean a 10ml measuring cylinder with acetone, isopropanol and deionised water. Care was taken to ensure that no acetone or isopropanol remains in the measuring cylinder.
2. Using a pipette, transfer 2ml of AZ400K into the measuring cylinder and add 8ml of deionised water into the measuring cylinder.
3. Pour the resultant solution into a clean beaker and mix well.
4. Prepare another clean beaker containing sufficient deionised water to submerge the diamond sample.
5. Carefully remove the diamond sample from the mask with a Teflon tweezer and submerge the sample into the developer solution for 120s.
6. Submerge the sample into the beaker containing de-ionised water to wash off any remnants of the developer solution.
7. Drip-dry the sample and observe the sample under a microscope to ensure that the photoresist is properly developed and also that contaminants are absent. Care was taken to ensure that there were no breaks in the photoresist that could lead to short-circuiting of electrodes.

3.2.5. Magnetron Sputtering of Electrodes:
After getting properly developed photoresist, the diamond samples were placed into a magnetron sputtering machine to coat electrodes onto the sample. In this experiment, 20nm of chromium was first coated onto the sample to form contacts between the sample and electrode before 80nm of gold was coated as electrodes. The entire coated sample was then placed into a beaker filled with acetone and sonicated in brief periods until the pattern of the electrodes desired were obtained.
The details of operating the sputtering machine are available in operation manual in the CIBA-ESP lab and will not be included in this report.

### 3.2.6 Alternatives to the Lithography Process: Direct Laser Writing

During the fabrication process, it was observed that the electrodes obtained from the lithography method with the use of the Quartz mask in Section 3.2.3 were less than ideal and did not yield good electrodes. Relevant figures illustrating some of the defects in the electrodes fabricated from this method are shown in the Appendix.

In view of this, an alternative method employing direct UV laser writing was used instead. Experimentally, this method yielded a higher rate of working electrodes in this project and both electrodes of the detector were fabricated with this method. The rest of the procedures were the same as described above.

### 3.3 Assembly of Detector

After successful sputtering of electrodes, the diamond was mounted onto a Teflon holder attached to an SMA connector and wire bonding was done to connect the electrodes to copper contacts. Figure 3.2 shows a schematic of what the final detector should look like.

![Figure 3.2: Schematic of final detector assembled.](image-url)
3.4 Testing of Detector Performance

3.4.1 Experimental Setup

In order for incident radiation to be detected, the electron-hole pairs generated in the detectors by the radiation must be registered as a signal electronically. Typically, most detectors work under pulse-mode operation in which the cumulated induced charges in a fixed period are registered as a pulse in the electronics after reaching a certain threshold value. Experimentally, this is done by the following arrangement of the associated front-end electronics as shown in Figure 3.3.

![Figure 3.3: Schematic of experimental setup. The models of the electronics used for pulse processing are also listed.](image)

Firstly, the electron-hole pairs generated by the incident radiation in the detector are separated by the electric field and drifted towards their respective electrodes. This movement of charge carriers result in a transient current which can be integrated over time to give the total charge induced at the electrodes. This integration is done in the preamplifier, with the amplitude of the voltage produced proportional to the amount of charge induced and hence incidence radiation energy in a single detection event. However, as this voltage is normally too low to be registered in subsequent electronics, the preamplifier also steps up this voltage to operating range of the subsequent electronics, the amplifier.

In the amplifier, the output voltage from the preamplifier is then shaped into Gaussian form for example, to reflect the true voltage amplitude of the signal. The shaping function of the amplifier
AVALANCHE DIAMOND DETECTOR

is characterised by a parameter called the shaping time constant. In general, a longer shaping time constant prevents signal loss by allowing for more complete signal collection, but a shorter shaping time can prevent pile up of signals at high count rates of detection events. Also, since shaping time affects the contribution of noise in the electronics, it is crucial that this factor is optimized for optimal results. The signals are then amplified according to the gain selected to produce pulses in the range of 0V to 10V after passing through the amplifier. The amplitude can also be connected to readout electronics like oscilloscopes to check for the presence of signals as well as obtain information on the SNR.

Depending on their pulse height amplitudes, these output signals are then sorted into various channels which correspond to a range of voltages in the Multichannel Analyser (MCA). Thus, the output from the MCA is displayed on the computer as a pulse height spectrum which provides information on the number of pulses with a distribution of energies, allowing radiation spectrometry to be performed.

3.4.2 Characterisation of PIPS Detector

Since research into diamond is motivated by the need to find alternatives to conventional detector materials, the general performance of the diamond detectors must be compared to conventional detectors. In this project, the performance of the diamond detectors will be benchmarked against commercially available passivated implanted planar silicon (PIPS) detectors in terms of the CCE, SNR and energy resolution. In particular, the CCE of the diamond detectors, which is our main interest, will be obtained by assuming the CCE of the silicon detector operating at saturation regions to be 100%. All detector testing was done in the CIBA main lab and the alpha source used in this project was a triple source containing Pu-239, Am-241 and Cm-244. The experimental procedures used to characterize the detector are listed as follows.

1. Setup the experiment as illustrated in Figure 3.3 and wait for at least 3 minutes so that the vacuum chamber containing the detector can be fully vented.
2. Using the Amptek DPPMCA software, collect a pulse-height spectrum of 120s for the triple alpha source at a bias voltage of -50V at 20 gain, 50 gain and 100 gain while keeping the shaping time constant at 0.5μs.
3. Using OriginPro, a graphical analysis software, perform Gaussian curve fittings for the collected pulse height spectrum to obtain the 3 peak channel numbers for the respective energies.

4. Plot a graph of peak channel number against gain for all 3 peaks to obtain the respective peak channel numbers at a gain of 200 for the silicon detector.

5. Convert the 3 peak channel numbers obtained from Step 4. to the theoretical equivalent values of the peak channel numbers that would be obtained if diamond detectors were operating at saturation region. This value will be used as the reference peak channel for diamond detectors at 100% CCE.

\[ Ch_{Diamond} = \frac{3.6}{13.2} \times Ch_{Silicon} \]

Where \( Ch_{Diamond} \) is the peak channel number obtained with diamond detector operating in the saturation region and \( Ch_{Silicon} \) is the extrapolated peak channel number at a gain of 200 for the silicon detector.

The details of the conversion can be found in section C of the Appendix.

3.4.3 Characterisation of Diamond Detectors

After obtaining the theoretical peak channel number for diamond at 100% CCE, testing of the diamond detectors were done.

3.4.3.1 4x3mm, 700μm thick Diamond Detector

Throughout the course of detector testing, the parameters gain and shaping time were kept constant at 200 and 0.5μs respectively. These parameters were found to be the most optimal for the experiment, and hence they were used. The testing of the detector was carried out as follows:

1. Set up the experiment according to Figure 3.3 and wait for at least 3 minutes for the vacuum chamber to be sufficiently vented.
2. Using the Amptek DPPMCA software, collect the pulse height spectrum for the triple alpha source for a duration of 360s starting from a bias voltage of 1V.
3. Using the vertical scale control, adjust the scale for Volts/Div such that the amplitudes of the signal can be clearly shown on the oscilloscope. Note the amplitude down and repeat the same for noise. The signal-to-noise ratio (SNR) can then be calculated as follows:

\[ SNR = \left( \frac{A_{signal}}{A_{noise}} \right)^2 \]

Where \( A_{signal} \) and \( A_{noise} \) refers to the amplitude of the signal and noise respectively.

4. Repeat Steps 2 to 3 in increments of 1V until 10V, followed by increments of 5V from 10V to 50V and finally, 10V from 50V until signals can no longer be seen.

5. Repeat Steps 2 to 4 for the negative bias voltages.

6. Perform Gaussian fittings for all pulse height spectrum to obtain the all peak heights and calculate the CCE for diamond as follows:

\[ CCE = \frac{Ch_{Experimental}}{Ch_{Diamond}} \times 100\% \]

Where \( Ch_{Experimental} \) is the peak channel obtained experimentally at each bias voltage and \( Ch_{Diamond} \) is the theoretical peak channel of the diamond detector at 100% CCE.

7. The energy resolution was also calculated as follows:

\[ Energy \ Resolution = FWHM \times Energy \ Step \]

Where FWHM is the full width at half maximum of the peak pulse height in channel obtained from peak fittings, and energy step is the energy/channel in keV obtained from energy calibration of the pulse height spectrum.

3.4.3.2 5x5mm, 150μm Diamond Detector

The procedures for the testing of this detector is generally the same as that of the 4x3mm, 700μm thick diamond detector except for the different range of the bias voltages applied and the collection time of the pulse height spectrum. For this detector, the negative bias voltage applied ranged from -60V to -1900V and the positive bias voltage ranged from 60V to 1500V. All pulse height spectra were collected for a duration of 120s.
Chapter Four

Results and Discussion: Conventional Diamond Detector

4.1 Images of Assembled Detector

After electrode fabrication, the electrodes were viewed under a microscope to check for the presence of defects that would affect the operation of the detector. The diamond sample will only be assembled into a detector after ensuring that there are no breaks or connections between adjacent electrodes which will result in short circuiting. Figures 4.1 to 4.3 show the optical images of the detector obtained while Figure 4.4 shows the assembled detector used for testing. The dimensions of the diamond sample used are 4×3mm, 700μm.
Figure 4.1: Optical images of the electrode in the centre of the electrode structure under 5X magnification. The width of the electrodes used is 30µm and the electrode separation is 10µm.

Figure 4.2: Optical image of the electrodes towards the left side of the electrode structure under 5X magnification.
Figure 4.3: Optical image of the electrode towards the right side of the structure under 5X magnification. A portion of the aluminium wire can also be seen at the top right of the image.

Figure 4.4: Camera image of the final assembled detector. The dimensions of the diamond sample used are 4mm×3mm, 700μm.
4.2 Charge Collection Efficiency (CCE)

As mentioned in Section 3.4.3, the CCE of this detector was obtained at every applied bias voltage until the signal becomes indiscernible towards the higher voltages. For this detector, the applied bias voltage ranged from -240V to 190V. This translates to an applied electric field of $-24\,\text{V}\,\mu\text{m}^{-1}$ to $19\,\text{V}\,\mu\text{m}^{-1}$ for the 10μm electrode separation. The obtained results for CCE and their associated uncertainties are as shown in Figure 4.5.

![Figure 4.5: Graph of Gain against Electric Field applied (V μm$^{-1}$). The data points are represented by black dots while the uncertainties are represented by the red error bars.](image)
From calculations, charge multiplication effects were observed for applied electric fields of 0.8V/μm\(^{-1}\) and above for both positive and negative bias voltages. However, as seen from Figure 4.5, it is evident that the graph follows the trend of a conventional detector in the saturation region, suggesting that there was no onset of avalanche. Intuitively, the first attempted explanation was that perhaps the true experimental values of the CCE are within the percentage uncertainties of obtained values. However, as seen from Figure 4.6, this was not the case for the results obtained, so another explanation had to be given for this systematic upward shifting of the CCE values.

One possibility is that the PIPS detector used was degraded and not operating at 100% efficiency, thus giving lower than expected peak channel values that resulted in inaccuracies in subsequent calculations of CCE. Calculations of the PIPS detector’s energy resolution then indicated that this was the case as the obtained energy resolution of approximately \((67 \pm 2)\) keV is much higher than expected. The details of the calculation for the silicon detectors can be seen in the Appendix. In view of this, section 3.4.2 of the experiment was repeated using a new PIPS detector, and indeed
a much lower energy resolution of \((19.2 \pm 0.1)\) keV was obtained, indicating that the performance of the previous silicon detector was indeed degraded.

Thus, the theoretical values for peak channel numbers of diamond detectors operating at 100% efficiency should have been higher to give lower values of the CCE of diamond. This would then account for why the graph follows the trend of the CCE in the conventional region even if the CCE is over 100%. Thus, it can be concluded that there was no charge multiplication effect observed in the 4\,mm x 3\,mm, 700\,μm diamond detector, so the use of coplanar interdigitated electrodes of 10\,μm separation only produces a conventional diamond detector.

### 4.3 Energy Resolution

In addition to the CCE, the energy resolution of the detector was also calculated at every bias voltage applied. The energy resolution is characterized by a parameter called the full width at half maximum (FWHM) which can be obtained from Gaussian fittings of the peaks. In general, the larger the value of the FWHM, the more prominent the peak broadening and the lower the energy resolution of the detector. Thus, it is more desirable for radiation detectors to have lower FWHM values as it means that they can better resolve radiation with highly similar energies. The results obtained are as shown in Figure 4.7.
From Figure 4.7, it can be seen that the energy resolution of the detector generally improves with an increase in electric field. This is in line with theory as a stronger electric field allows for a more complete charge collection. Since the interaction of radiation with matter is stochastic, a higher number of collected charges would result in a narrower distribution of detected pulse energies and lead to a better reflection of the true energies of the incident radiation. This is illustrated in Figure 4.8 where the peaks of the triple alpha source become increasingly distinguishable with an increase in applied electric field. The evolution of the pulse height spectrum and energy resolution with increasing electric field can be seen in Section D.1 of the Appendix too.
Figure 4.8: Pulse Height Spectrum obtained at applied electric fields of 0.4V μm\(^{-1}\) (top), 0.8V μm\(^{-1}\) (middle) and 8.0V μm\(^{-1}\) (bottom) respectively.
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However, there will be a maximum energy resolution achievable as increasing the applied electric field after the detector has reached the saturation region will result in a larger increase in noise than in signals, so the energy resolution obtained deteriorates again. For this detector, this is especially evident in the negative electric field region after -16V μm⁻¹. The average energy resolution obtained after reaching saturation was obtained to be (77.7±0.7) keV for applied electric fields between 11V μm⁻¹ and 18V μm⁻¹, and (65.2 ± 0.4) keV for that between -9V μm⁻¹ and -15V μm⁻¹. In general, this is much poorer than the obtained (19.2 ± 0.1) keV of the new PIPS detector used. However, considering that silicon detectors have been developed and refined for years and that this is only a preliminary testing of the diamond detector, these values are still considerably good.

4.4 Signal-to-Noise Ratio (SNR)

Last but not least, the SNR of the diamond detector was also estimated. This was done by reading the oscilloscope values of the signal and noise during detector testing as mentioned in Section 3.4.3. Figure 4.9 shows the typical signal amplitude of approximately (6.0 ± 0.1)V when the diamond detector is operating in the saturation region while Figure 4.10 shows the typical noise amplitude which is estimated to be (30 ± 1)mV. This then gives an average SNR of (40 ± 2) × 10³ for the detector. Although this value is lower than that of typical PIPS detectors, this is still considerably good given that the signal is highly discernible from noise as seen from Figure 4.9.
Figure 4.9: Camera image of the oscilloscope display for the obtained signal at the saturation region. Each vertical division represents 1.0V.

Figure 4.10: Camera image of the oscilloscope display for noise in the saturation region. This region is the enlarged portion of noise in Figure 4.9. Each vertical division represents 10mV.
Chapter Five

Results and Discussion: Avalanche Diamond Detector

5.1. Images of Detector

As with the conventional detector, the fabricated electrodes were checked for defects under the microscope before assembly. Figures 5.1 to 5.4 show optical images of the electrodes under different magnifications while Figure 5.5 shows the final assembled detector used for testing. The dimensions of the diamond sample used are 5mm×5mm, 150μm.

Figure 5.1: Optical image of the electrodes towards the edges of electrode structure under 5X magnification. A portion of the aluminium wire used is also seen at the bottom right of the image.
Figure 5.2: Optical image of the electrodes in the centre region of the electrode structure under 5X magnification. The width of the electrodes is 30μm while the electrode separation is 5μm.

Figure 5.3: Optical image of the electrodes towards the side of the electrode structure under 20X magnification. The width of the electrodes is 30μm while the electrode separation is 5μm.
Figure 5.4: Optical image of the electrodes in the centre of the electrode structure under 20X magnification. The width of the electrodes is 30μm while the electrode separation is 5μm.

Figure 5.5: Camera image of the final assembled detector used for testing. The dimensions of the diamond sample used are 5mm×5mm, 150μm.
5.2 Charge Collection Efficiency (CCE)

Similarly, the CCE of the detector was calculated for every applied electric field until the signal was indiscernible. Figure 5.6 shows a graph of the CCE obtained with their associated uncertainties.

![Graph of Gain against Electric Field Applied. The data points are represented by black dots while the uncertainties are represented by the red error bars.](image)

From calculations, it was observed that the onset of avalanche occurred at applied electric fields of -112V μm⁻¹ for the negative biases and at 120V μm⁻¹ for the positive biases. The CCE values obtained are as high as nearly 300% for the negative bias voltages and 200% for the positive bias voltages. However, from Figure 5.6, it is evident that the CCE does not follow the predicted exponential trend which is expected of detectors displaying charge multiplication effects. In fact, the trend seems to be linear with the strong coefficient of determination values of approximately 0.9978 and 0.9965 for the negative and positive bias voltages respectively. Figures 5.7 and 5.8 show the graphs of the CCE against electric field with their best fit lines for the negative and positive biases.
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\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{gain_negative.png}
\caption{Graph of Gain against Electric Field (V $\mu$m$^{-1}$) for negative biases. The equation of the fitted linear curve is $y = (-8.69 \pm 0.06) \times 10^{-3} x + (0.018 \pm 0.004)$. The coefficient of determination is 0.9978.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{gain_positive.png}
\caption{Graph of Gain against Electric Field (V $\mu$m$^{-1}$) for positive biases. The equation of the fitted linear curve is $y = (8.40 \pm 0.09) \times 10^{-3} x + (0.024 \pm 0.004)$. The coefficient of determination is 0.9965.}
\end{figure}
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According to McKay and Chynoweth, charge multiplication in detectors is characterised by the exponential increase in CCE as the applied electric field increases. However, as seen from Figures 5.7 and 5.8, the linear trend obtained clearly deviates from the theoretical trend, and unlike the case of the conventional detector, this is unlikely to be a consequence of a systematic error. One possible reason is that the effective electric field strength in the detector was lower than expected due to polarization effects. At higher electric fields and prolonged experimental durations, polarization effects are more pronounced due to the larger amount of ionization events which may result in a larger space charge region. Consequently, this will reduce the effective electric field in the detector and lead to a smaller increase in CCE.

Another reason might be that the Mckay and Chynoweth equation is not applicable to the coplanar interdigitated electrode structure used in this project. This is due to the equation being derived from assumptions that the sandwich electrode structure was used. A closer look at the literature which reported the observation of this exponential trends also reinforces this possibility as the experiments employ the use of the sandwich electrode structure too. Thus, the differences in the electric field profiles between the sandwich electrode and coplanar interdigitated electrode structure might not have been properly accounted for, thereby leading to the observed deviation. In order to accurately estimate the trends of CCE against applied electric fields for the coplanar interdigitated electrode structure, computer simulations of the possible electric field profile have to be done. However, this is highly complicated and is out of scope of the project. Nevertheless, it is remarkable that such high avalanche effects are observed in diamond detectors, so indeed diamond is worthy of more research.
5.3 Energy Resolution

The energy resolution of the avalanche detector was also obtained, and Figure 5.9 shows the results.

![Graph of FWHM (keV) against Electric Field applied (V μm⁻¹).](image)

From the results, the energy resolution of the avalanche detector is not as good as that of the conventional detector. In fact, as seen from Figure 5.9, the general trend suggests that the higher the electric field, the higher the FWHM values and hence the poorer the energy resolution. This is possibly due to the inherent nature of charge multiplications which tend to result in a larger variation in the total number of electron-hole pairs collected. Thus, at higher electric fields where charge multiplication effects increase, the higher the amount of noise and hence the poorer the energy resolution. In addition, it was also observed that there was a significant amount of noise present in the detector during operation, and this is possibly due to the higher amount of surface leakage current. As a result, the detector has a poorer energy resolution, and this can also be seen
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from Figure 5.10 where there is only one peak instead of the three peaks expected of the triple alpha source.

Figure 5.10: Pulse Height Spectrum obtained at applied electric fields of -240V \( \mu \)m\(^{-1}\). This is also the typical pulse height spectrum obtained for the detector in general.
5.4 Signal-to-Noise Ratio (SNR)

Unlike the conventional detector, there was a relatively huge amount of noise in this detector during operation. Thus, the actual signal is indiscernible from noise from the oscilloscope as seen in Figure 5.11, so the SNR of this detector was not obtained.

![Figure 5.11: Camera image of oscilloscope display when the detector is operating in the avalanche region.](image)

Nevertheless, no other known literature has reported such a high value for gain as obtained in this project, so the results obtained in the project are still significant and diamond indeed has a good potential as an avalanche detector. Thus, more research should be conducted to optimize the detector geometry to improve the CCE, SNR and energy resolution, and realise diamond’s potential as an avalanche detector.
Chapter Six
Conclusion and Future Work

In conclusion, the aim of the project was achieved with the successful fabrication of an avalanche diamond detector using the coplanar interdigitated electrode structure. The onset of avalanche was observed in the 5x5mm, 150μm thick diamond detector at 120V μm⁻¹ and -112 V μm⁻¹ using coplanar interdigitated electrodes of 5μm gap separation. In view of the low signal-to-noise ratio and energy resolution obtained in the avalanche region, future works can include the fabrication of etched-subsurface coplanar electrodes aimed at reducing surface leakage currents, one of the main source noise. In addition, instead using hydrogen-terminated diamond which have been found to possess high surface conductivities [21], the diamond surface can be made oxygen-terminated to reduce the surface leakage currents. After oxygen termination, both coplanar interdigitated and etched-subsurface structures can then be fabricated again to study the effectiveness of such methods in improving the performance of diamond detectors.
Bibliography


Appendix

A. Derivation of Hecht’s Equation

In 1932, Karl Hecht studied the movement of charge carriers in the presence of trapping centres by looking at the movement of photoelectrons under the influence of electric fields in AgCl crystals. It was then found that the number of electrons arriving at the anode decreases exponentially with the distance of carrier generation from the anode. From Hecht’s observations, for a total charge $q_0$ generated by the incident radiation near the electrode, the remaining charge $q(x, t)$ after traversing a distance $x$ in time $t$ can be expressed as follows:

$$q(x, t) = q_0 e^{-\frac{t}{\tau}} \quad (A.1)$$

Where $\tau$ is the mean lifetime of the charge carrier before it gets recombined.

As for the charge induced in the electrodes $Q$ due to the charges moving along a distance $dx$, it can be given by:

$$Q = \int_0^{t_r} q(x, t) \frac{dx}{D} \quad (A.2)$$

Where $dx = v \, dt$, which is a product of the charge velocity and the time $dt$ passed, $D$ is the separation between the electrodes and $t_r = \frac{D}{v} = \frac{D^2}{\mu v}$ is the time required for the charge to travel between the electrodes, $\mu = \frac{v}{E}$ is the charge mobility in the electric field $E$ and $V$ is the bias voltage applied.

Substituting (A.1) into (A.2),

$$Q = \int_0^{t_r} \frac{q_0 v}{D} e^{-\frac{t}{\tau}} dt = \frac{v t_r}{D} q_0 (1 - e^{-\frac{t_r}{\tau}}) \quad (A.3)$$
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Equation (A.3) can then be divided by \( q_0 \) and rewritten as CCE:

\[
CCE = \frac{Q}{q_0} = \frac{\nu \tau}{D} \left( 1 - e^{-\frac{\nu \tau}{\tau}} \right) \tag{A.4}
\]

Equation (A.4) can then be expressed as other quantities such as charge mobilities, bias voltage applied and mean carrier drift as follows:

\[
CCE = \frac{\lambda}{D} \left( 1 - e^{-\frac{D^2}{\mu \tau \nu}} \right) = \frac{\mu \tau \nu}{D^2} \left( 1 - e^{-\frac{D^2}{\mu \tau \nu}} \right) \tag{A.5}
\]

Where \( \lambda \) is the mean carrier drift distance.

Thus, at small \( V \), the exponential term becomes negligible and CCE is a linear function of \( V \) or electric field applied. Equation (A.5) can then be simplified form as follows:

\[
CCE = \frac{CCD}{D} = \frac{(\mu_{\text{h}} \tau_{\text{h}} + \mu_{\text{e}} \tau_{\text{e}})E}{D} \tag{A.6}
\]
B. Lithography: Challenges Encountered

As mentioned in Section 3.2.6, the fabrication of electrodes with the use of the Quartz glass mask during lithography was largely unsuccessful. Some issues encountered during this process include obtaining photoresists that were not completely developed despite attempts to optimize UV exposure and photoresist development timings. Figure B.1 below shows an example of underdeveloped AZ1518 photoresist on the diamond sample after development with the AZ400K developer.

![Figure B.1: Optical image of underdeveloped AZ1518 photoresist on the 150μm diamond sample under 5X magnification.. The width of the electrodes used is 40μm with 10μm gap between them.](image)

It was then suspected that the developer solution used was contaminated as other students using similar developer faced similar issues. A fresh developer solution was then used and indeed, the photoresist could be properly developed even with the same UV exposure time and development time. However, there were still significant areas with defects for the electrodes obtained after sputtering and the detectors did not work during testing. Figure B.2 shows an example of the defects.
In view of the limited time, an alternative method of lithography which employs direct UV laser writing was used. The electrodes obtained from this method of fabrication were much better in quality and allowed the detector to work. Figures B.3 to B.5 show the obtained electrodes.

Figure B.2: Optical image of fabricated electrodes under 5X magnification. The dark areas towards the left are areas where the sputtered metals did not properly adhere to the sample.

Figure B.3: Optical image of the electrodes in the centre region of the structure under 5X magnification. The width of the electrodes is 30μm and the separation between the gap is 10μm.
Figure B.4: Optical image of the electrodes in the centre region of the structure under 20X magnification. The width of the electrodes is 30μm and the separation between the gap is 10μm.

Figure B.5: Optical image of the electrode towards the side of the structure under 5X magnification. The aluminium wire bonding is also seen at the right of the image.
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C. Results for Silicon

As mentioned in Chapter 3, a commercial PIPS detector was used as a benchmark of comparison for the diamond detectors in this project. The pulse height spectrum obtained and the subsequent conversions of the obtained peak channel numbers to the corresponding peak channel numbers for diamond detectors operating at a CCE of 100% are as follows.

C.1 Identification of Peak Channels

C.1.1 Pulse Height Spectrum and Peak Fitting

The pulse height spectrum for the PIPS detector is first obtained and the peaks are Gaussian-fitted using a data analysis and graphing software OriginPro. Figure C.1 shows the pulse height spectrum obtained for 60s at an applied bias voltage of -50V. The gain used was 100gain while the pulse shaping time used was 0.5μs.

![Pulse Height Spectrum of PIPS detector used as benchmark for the conventional detector. The collection duration was 60s with a bias voltage of -50V. The gain used was 100 with a shaping time of 0.5μs.](image)

Figure C.1: Pulse Height Spectrum of PIPS detector used as benchmark for the conventional detector. The collection duration was 60s with a bias voltage of -50V. The gain used was 100 with a shaping time of 0.5μs.
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This process of acquiring pulse height spectrum and peak fitting was then repeated for a gain of 20 and 50 while the other parameters remained constant. Table C.1 summarises the peak channel values obtained for each spectrum.

<table>
<thead>
<tr>
<th>Gain</th>
<th>Peak 1</th>
<th>Peak 2</th>
<th>Peak 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>474.74047 ± 0.01288</td>
<td>505.93708 ± 0.01109</td>
<td>535.45975 ± 0.01111</td>
</tr>
<tr>
<td>50</td>
<td>1189.93774 ± 0.0319</td>
<td>1267.41409 ± 0.03045</td>
<td>1340.86817 ± 0.03014</td>
</tr>
<tr>
<td>100</td>
<td>2371.60443 ± 0.0662</td>
<td>2525.69603 ± 0.0546</td>
<td>2671.91818 ± 0.06045</td>
</tr>
</tbody>
</table>

Table C.1: Peak channel numbers and their uncertainties obtained from OriginPro.

C.1.2 Extrapolation and Conversion of Peak Channels

In order to obtain the corresponding peak values at a gain of 200, the peaks were plotted against gain. Figure C.2 shows the graph obtained.

![Graph of Channel Number against Gain](image)

*Figure C.2: Graph of Peak channel number against Gain.*
AVALANCHE DIAMOND DETECTOR

Each corresponding peak at a gain of 200 was then obtained according to the equation of the best fit line. Since the energy required to produce an electron-hole pair in diamond is different from that of silicon, the peak channels obtained have to be corrected as follows:

\[ Ch_{Diamond} = \frac{3.6}{13.2} Ch_{Silicon} \]

Where \( Ch_{Diamond} \) refers to the peak channel of the diamond detectors operating at 100% CCE, \( Ch_{Silicon} \) refers to the peak channel obtained for silicon at 200 gain, and the factor of \( \frac{3.6}{13.2} \) is the ratio of the energies required to create an electron-hole pair in silicon to diamond.

The final obtained values are as shown in Table C.2.

<table>
<thead>
<tr>
<th>Peaks</th>
<th>Peak Channel</th>
<th>After Extrapolation</th>
<th>After Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak 1</td>
<td>4742.84212 ± 14.54358</td>
<td>1293.502 ± 3.966</td>
<td></td>
</tr>
<tr>
<td>Peak 2</td>
<td>5050.56073 ± 15.27313</td>
<td>1377.426 ± 4.165</td>
<td></td>
</tr>
<tr>
<td>Peak 3</td>
<td>5342.66414 ± 15.90812</td>
<td>1457.090 ± 4.339</td>
<td></td>
</tr>
</tbody>
</table>

Table C.2: Peak Channel numbers and their uncertainties after extrapolation and conversion to corresponding diamond peak channels.

C.1.3 Energy Resolution

The energy resolution of the PIPS detector is also obtained by the calculation of the FWHM of the peaks using the parameter, \( w \) from Gaussian peak fitting. Typically, Gaussian functions are given by:

\[ f(x) = ae^{-\frac{(x-b)^2}{2c^2}} \]  \hspace{1cm} (C.1)
AVALANCHE DIAMOND DETECTOR

Where a, b and c are constants. a gives the peak height of the function, b the position of the peak ad c the standard deviation.

The FWHM is then given by:

\[ FWHM = 2\sqrt{2\ln(2)}c \tag{C.2} \]

However, in OriginPro, the Gaussian fitting function is given by:

\[ y = y_0 + \frac{A}{w\sqrt{\pi}} e^{-\frac{2}{w^2}(x-x_c)^2} \tag{C.3} \]

Where \( y_0, A, w, \) and \( x_c \) are fitting parameters.

Thus, some conversions have to done to express the FWHM in terms of the parameter \( w \) obtained in OiginPro. By a comparison of equations (C.1) and (C.3), the \( c \) is related to \( w \) as:

\[ \frac{2}{w^2} = \frac{1}{2c^2} \]

\[ c = \frac{1}{2}w \tag{C.4} \]

This then gives us the final form of the FWHM that can be used for direct calculations using \( w \):

\[ FWHM = \sqrt{2\ln(2)}w \tag{C.5} \]

The FWHM in terms of energy can then be obtained by multiplying (C.5) with the energy step of the spectrum, which is basically the energy per MCA channel. The energy step can be obtained by plotting a graph of peak energies against the peak channels and the value of the gradient will be the energy step. Table C.3 shows the corresponding peak channels to the energies of the alpha particles from the triple alpha source while Figure 34 shows the plotted graph of energy calibration.
AVALANCHE DIAMOND DETECTOR

<table>
<thead>
<tr>
<th>Source</th>
<th>Peak Energies (keV)</th>
<th>Peak Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu-239</td>
<td>5150</td>
<td>2371.60443 ± 0.06620</td>
</tr>
<tr>
<td>Am-241</td>
<td>5486</td>
<td>2525.69603 ± 0.0546</td>
</tr>
<tr>
<td>Cm-244</td>
<td>5800</td>
<td>2671.91818 ± 0.06045</td>
</tr>
</tbody>
</table>

Table C.3: Energies of the triple alpha sources and their corresponding peak channels obtained using the PIPS detector at 50V and 100 gain.

From calculations, the energy resolution of the PIPS detector is obtained to be an average of (67 ± 2) keV. The energy resolution of the new PIPS detector is also calculated in the same way and obtained to be (19.2 ± 0.1) keV.
D. Peak Fittings of Pulse Height Spectrum

D.1 Conventional Detector

Selected pulse height spectrum at various electric fields are shown in Figures D.1.1 to D.1.1.3. These figures show the evolution of the spectrum with increasing electric fields until saturation.

*Figure D.1.1: Gaussian Fitted Pulse Height Spectrum at 0.4V μm⁻¹ (top) and 0.8V μm⁻¹ (bottom).*
Figure D.1.2: Gaussian Fitted Pulse Height Spectrum at 1.2V μm⁻¹ (top) and 2.5V μm⁻¹ (bottom).
Figure D.1.3: Gaussian Fitted Pulse Height Spectrum at 5.0V μm⁻¹ (top) and 8.0V μm⁻¹ (bottom).
D.2 Avalanche Detector

Figures D.2.1 to D.2.4 show the evolution of the pulse height spectrum at various electric fields.

*Figure D.2.1: Gaussian Fitted Pulse Height Spectrum at -16V μm⁻¹ (top) and -20V μm⁻¹ (bottom).*
Figure D.2.2: Gaussian Fitted Pulse Height Spectrum at -48V μm$^{-1}$ (top) and -80V μm$^{-1}$ (bottom).
Figure D.2.3: Gaussian Fitted Pulse Height Spectrum at -120V μm⁻¹ (top) and -180V μm⁻¹ (bottom).
Figure D.2.4: Gaussian Fitted Pulse Height Spectrum at -240V μm⁻¹ (top) and -320V μm⁻¹ (bottom).