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A model for stripping of α-particle spectrum interaction effects in CVD diamond detectors

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ABSTRACT

A simple model is put forward to express the experimental behaviour of alpha-particle interaction effects in CVD diamond detectors. The model depends on the stripping methodology adopted, which makes it suitable to routinely analyzed alpha-particle spectra. The spectra, each with different width/peak broad due to the presences of defect/impurity were stripped off using MATLAB. The performance observed for the detectors illustrates two possibilities: a response around the mean spectrum height (good resolution) and a response with inferior performance (poor resolution). This showed improved information of the actual interaction effects of the different diamond grades when used for alpha sensing applications (detectors).

Keywords: CVD- diamond, alpha-particles, Specific ionization, Stripped spectra, Defects/impurities

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INTRODUCTION

For alpha-particles to traverse any material there must be an interaction, which will affect its detection in two ways: first, the energy spectrum is distorted because of the energy loss associated with the interactions in any mass interposed between source and detector. Secondly, a particle entering the active detector volume will interact, at least once with the detecting medium and hence be detected [15].

Energy loss outside the detector is undesirable; the task of an experimenter is to design a spectrometer with zero mass between the source and the detector. Such an ideal system cannot be built, and the only practical alternative is a spectrometer that results in such a small energy loss outside the detector, which allowed reliable corrections to be applied to the measured spectrum [15].

In certain measurements, the particles do not stop but they go through it and emerge with only a fraction of their energy deposited in the detector. Then a correction to the spectrum of the existing particles will have to be applied because of energy straggling; a term used to describe the statistical fluctuations of energy loss [15].

The detector performance and stability are determined by structural imperfections and impurities in the material, which influence the induced current signal. In polycrystalline diamond detectors, it was known that grain boundaries act as charge trapping centers, severely limiting the spectroscopic performance [7]. Diamond slabs grown by Chemical Vapour Deposition (CVD) comprised of many diamond crystallites of different orientations and separated by grain boundaries. These may affect the electrical properties of the material by acting as traps and/or recombination centres, thus degrading the charge collection efficiency [1].

Devices based on single-crystal high-pressure, high-temperature diamond (HPHT) were found to be limited by the small area of the available substrates. Moreover, homoepitaxial growth does not rule out completely the presence of defects as in natural diamond or in other single crystal materials. The study of defects with many different solid state and nuclear techniques has given a deeper insight on the physics of the transport in CVD diamond [8], yet a thorough picture of defects and their influence on carrier lifetime in CVD diamond was lacking [9].

Severe detrimental effects of defect levels may occur in diamond. These effects can significantly alter the detection properties of devices. In fact, it was clear that the response of devices was reduced through defects and impurities [2]. If the device state is to be optimized either due to ionization mechanism (trapping), or a significant rise in temperature (trap release), the internal electric field as well as the carrier lifetime of the device can be modified thereby influencing the detector response to give a better result for the problem [8].

With the progress in the technology of personal computers, PC-based software packages started to play a key-role in the control, acquisition and validation of the data in any nuclear experiment. Because of the range of applications of alpha-particle spectrometry, analysis software packages were among the most used software in any nuclear laboratory. They were being used in such important applications as environmental studies, low level monitoring, radioactive waste analysis and safeguards [3].

Alpha-particle spectra were usually very complex to analyze. Only a few radionuclides emit monoenergetic alpha particles and very often two or more lines from the same radionuclide overlap. Most alpha emissions have energies between 4 and 6MeV, and with the energy resolution achievable in realistic conditions, a typical alpha-particle spectrum contains one or several groups of overlapping lines. The difficulty of the analysis depends on the amount of information that one tries to obtain from the spectrum and reaches its maximum when a full analysis was performed to obtain the energies and intensities of all spectral components [3].

An unavoidable fact in diamonds is the presence of defects, including CVD wafers. These affect the response of diamonds to radiation in various ways. In this work pile-up, background noise or fluctuations, ionization and excitation energy losses effects were stripped off using a high performance language Matrix Laboratory (MATLAB) to model a simple stripping procedure considering the measures of likelihood formulated analytically as the CVD diamond detectors interact with α-particle radiation. The CVD diamond detectors were characterized [8] and information about their levels of impurities and the material quality were established. To correct for these losses, (the collisional and radiation losses, background noise and/or fluctuations) a method must be sort for, to unfold the information in the measured spectrum to yield the true spectrum. Modeling of spectra such as that of alpha-particles requires a thorough understanding of it interaction with matter.

MATERIALS AND METHODS

To realized the needed stripping model, as alpha particles interacted with diamonds observed from the experimental spectrum. The combining measures of likelihood (probabilities) of an incident particle in a given energy interval producing an electron-ion-pair and the likelihood of the scattered (interaction losses) and pile-up fraction also deposited in the diamond wafers was considered as:

- The likelihood of an incident alpha-particle interacting and get deposited within the detector volume was measured;
- The likelihood of an ion-pair was produced (by ionization) due to energetic electrons (secondary electrons) and result to subsequent release of bremsstrahlung (Compton Scattering) to deposit Compton recoil energy was formulated; and
- The likelihood of the excited ions (pile-up and fluctuations) detected by the detector was computed.

These three measures of likelihood above made it possible to calculate the fractional error. To do this, the observed electron-ion pair produced was stripped off in order to eliminate pile-up and the electronic noise (statistical) from the background. Interactions of charged particle with a detector can be defined by measure of likelihood [12] but a more useful definition used was in terms of the stopping power or number of ion pairs formed per unit distance (specific ionization). The analytical functions proposed here to describe the model consist of the following:

- The number of ion-pair formed per cm of travel (specific ionization) in the diamond was calculated as:

$$I(E_i) = \frac{E_i(KeV)}{W \times R_{di}} \ (ionpairscm^{-1}) \quad (1)$$

where
E_i = incident energies of the alpha-particle,

W = average energy expended to create an ion or electron-hole pair in diamond (for diamond the value of 12.8eV/ion-pair was reported [10],
R_{di} = range of alpha particle in the detecting medium (Eq. 2 & 3),
i= 1, 2, 3, ------, n integers referring to each spectrum energy.

This equation was used to calculate the specific ionization for each 12.8eV energy (E_i) interacting with the diamond detector.

- The range or energy loss characteristics was estimated to assume that the specific ionization or stopping power per atom of CVD diamond is additive. This assumption is known as the Bragg - Kleeman rule [5].

$$\frac{R_d}{R_a} = \frac{\rho_a \sqrt{A_d}}{\rho_d \sqrt{A_a}} \tag{2}$$

where R_d and R_a are the ranges in the detecting medium and air, ρ_a and ρ_d are densities of air and the detector material and A_a and A_d are the atomic weights of air and the detector material.

- The range of alpha particles in diamond was computed using a simpler equation for range (cm) of alpha in air in the energy range $4 < E < 8MeV$ [13].

$$R_a = 0.325 E_i^{\frac{3}{2}} \quad ; R_a \text{ in cm} \tag{3}$$

- The fractional energy input of the alpha particles lost as radiation to create the electron-ion pairs produced that interact with bremsstrahlung was expressed as:

$$E_{min} = E_i \Big/ \left(1 + \frac{2E_i}{1022}\right) \tag{4}$$

where
E_{min} is the minimum amount energy of the outgoing photon which escapes the detector or lost as radiation.

- The energy that may have contributed to the ion produced charges was expressed as:

$$E_{max} = \frac{2E_i^2}{1022 + 2E_i} \ (keV) \tag{5}$$

where the factor 1022KeV of the scattering equation is the energy of two electron rest mass $2m_e c^2 = 2 \times 511keV$ [6].

- The spectrum correction factor of the detector was formulated as:

$$f_{pi} = \frac{I(E_i) - I_{(E_{max}-E_i)i}}{I(E_i)} \tag{6}$$

where $I_{(E_{max}-E_i)i}$ = the number ion-pairs associated with radiation and collisional losses [4].

- Corrections due to electronics and statistical noise were estimated assuming a Poisson distribution so that the fluctuations (excitations) and pile up are characterized by a standard deviation in the number of charge carriers [14].

- The corrected number of ion-pairs or stripped (ions) counts expression that takes into account all the ion-pairs produced either by collisional, radiation losses and excitations that have to be stripped off the spectrum was expressed as:

$$I_{pi} = \left[I_0(E_i) - \left(I_0(E_i) \cdot f_{Ei} + 2\sqrt{I_0(E_i).f_{Ei}} \right) \right] \tag{7}$$

where
$I_0(E_i)$ = the experimental counts (ions) at energy E_i,

f_{Ei} = the fractional error causing the background effects (collisional and radiation losses), pile up effect and fluctuations (excitations) observed in the spectrum and it is defined based on the spectrum correction factor as $f_{Ei} = 1 - f_{pi}$,

$I_0(E_i).f_{Ei}$ = the mean or average number of ion-pairs,

$2\sqrt{I_0(E_i).f_{Ei}}$ = the standard deviation of the ion-pairs due to collisional loss that causes the pile up effects and fluctuations (excitations), the factor 2 is introduced to account for each ion-pairs created.

RESULTS

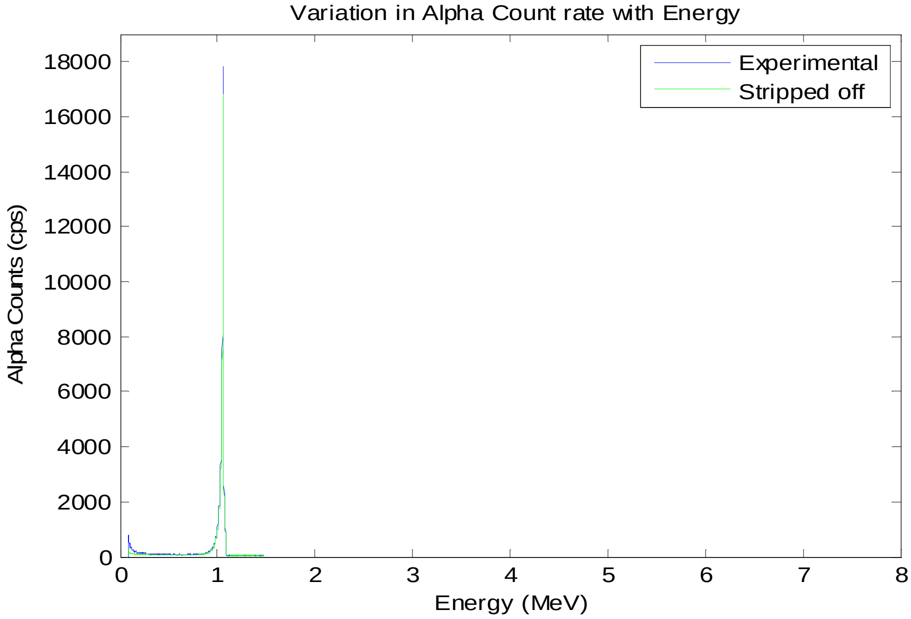

Figure 1: Variation of alpha count rate with energy for a Detector Grade CVD diamond (DG)

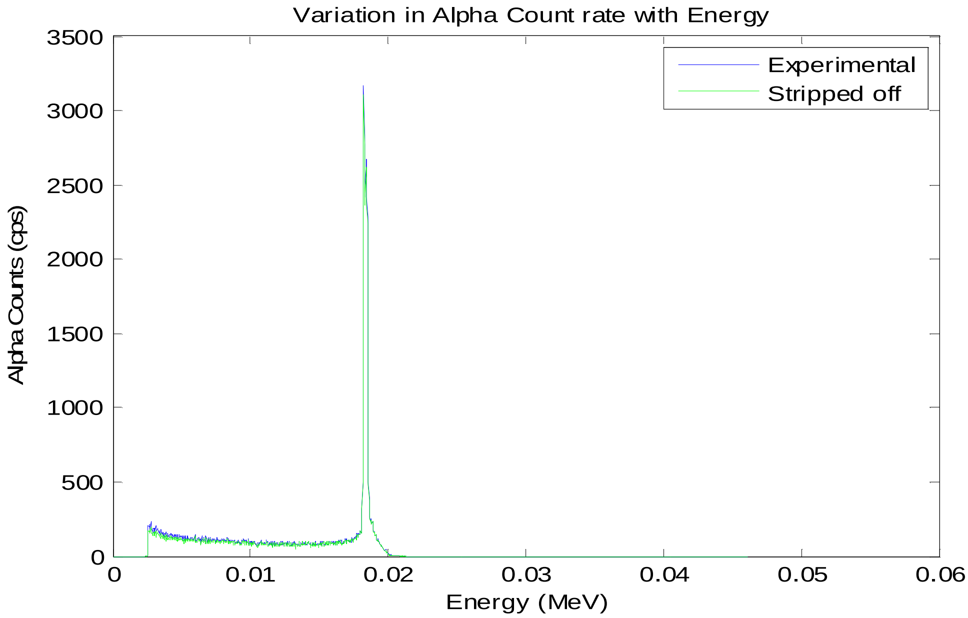

Figure 2: Variation of alpha counts rate with energy for a Single Crystal CVD diamond (SC)

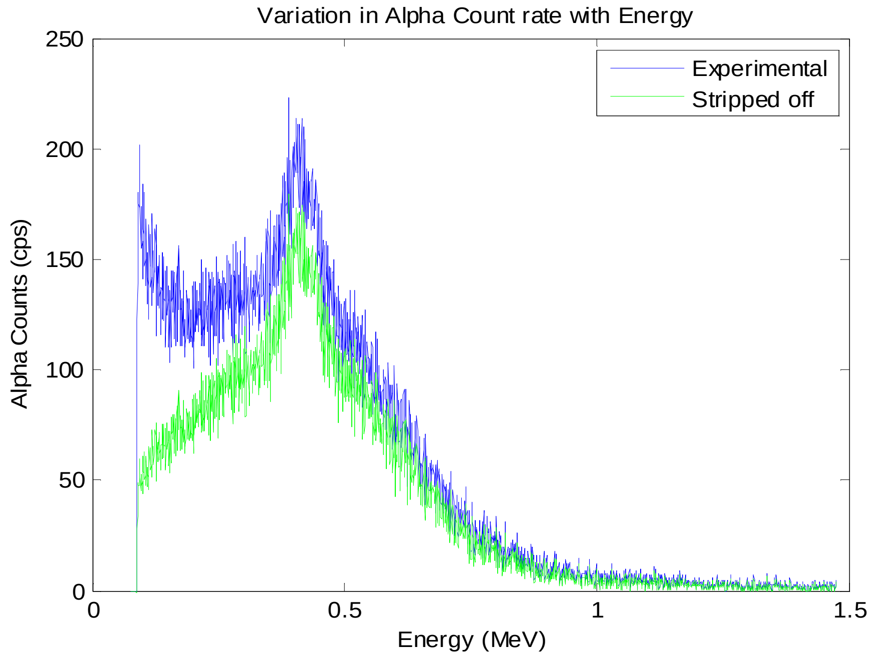

Figure 3: Variation of alpha count rate with energy for an Optical Grade CVD diamond (OG)

DISCUSSION

Each of the figures consists of two plots, the experimental plot and the stripped plot after correction. The Detector Grade and Single Crystal CVD diamonds (Fig. 1 & 2) spectra are observed to have an improved and more defined peak value, while the Optical Grade CVD diamond (Fig. 3) spectrum is observed to be wide; without a well defined peak value.

The stripping methodology put forth made it possible to resolve fine details in the incident energies of the alpha-particle radiation and that has obviously improved the width of the spectra. The performance observed for the detectors illustrates two possibilities: a response around the mean spectrum height (good resolution) and a response with inferior performance (poor resolution. The influence of the pair produced counts that causes asymmetry in the spectra (OG in particular) could be related to the defects levels of the diamond wafer.

To illustrate a typical application of this model, the spectrum for the variation of alpha count rate with energy of a Detector Grade CVD diamond is presented in Fig. 1. The spectrum closely follows the experimental data and the stripped spectrum shows no evidence of systematic differences. The reduced number of peak parameters makes the fit easier and more stable than using complex models. On the other hand, the statistical description of the peak resolutions of the spectra is out of the scope of this model and can only be obtained with more refined descriptions which require intensive calculations.

Software that can code all the probable interactions of alpha particle with CVD diamond grades shall go a long way in bringing out completely the true and exact information needed for better spectrometric performance of diamond detectors (Fig. 3).

CONCLUSION

The spectrum stripping model was observed to have influenced the broadness of the CVD detectors and better resolved the spectra. It has provided improved information of the actual performance characteristics of the different diamond grades when used for alpha sensing applications.

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