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Measurement of the insensitive surface layer thickness of a PIN photodiode based on alpha-particle spectrometry

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ABSTRACT

In this work, the insensitive layer thickness of a PIN photodiode (SFH206K - Osram) has been measured by varying the incident angle of a collimated monoenergetic alpha particle beam. This technique is based on variations in the path lengths of alpha particles through the insensitive layer and the correspondent energy losses when they impinge on a diode surface at different angles. Therefore, the pulse heights of these alpha particles, closely related to the energies deposited in the active volume of the diode, also depend on their incident angle. So, the difference between the pulse height of alpha particles perpendicularly incident on the diode surface and at any incident angle enables the insensitive layer thickness to be assessed.

The result obtained (711 ± 23) nm, less than 1% of the intrinsic layer thickness, besides validating the employed method, demonstrates that the investigated diode is suitable for high resolution charged particle spectrometry.

Keywords: **alpha spectrometry, Si diode, PIN photodiode.**

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1. INTRODUCTION

PIN photodiodes have been extensively used to detect charged particles and photons, either for dosimetry or radiation spectrometry [1-5]. Both applications require the precise measurement of the deposited energy in the sensitive volume of the diode by the incoming radiation. Due to the special structure of a PIN photodiode, where an intrinsic silicon layer is sandwiched between thin p and n-type layers, the sensitive volume is determined by whether an external voltage is applied or not. When used as a dosimeter, the diode is usually unbiased; thus, its sensitive volume depends on the relationship between its thickness and the minority carrier diffusion length. In contrast, the diode is reversely biased and fully depleted as a spectrometer to achieve the best energy resolution. However, regardless of being externally biased, the charged particles or weakly penetrating photons might lose some energy in an insensitive or dead layer before reaching the sensitive volume of the diode. This dead layer, which in the PIN structure consists of the SiO_2 layer developed on the device surface and the signal electrode (p-layer) thickness, always depends on the applied voltage being minimum at the full depletion condition.

In this work, the insensitive layer thickness of a PIN photodiode (SFH206K - Osram) has been measured by varying the incident angle of a collimated monoenergetic alpha particle beam. This technique is based on variations in the path lengths of alpha particles through the insensitive layer and the correspondent energy losses when they impinge on a diode surface at different angles. Therefore, the pulse heights of these alpha particles, closely related to the energies deposited in the active volume of the diode, also depend on their incident angle. Consequently, variations in the energy loss due to variable angles of incidence potentially worsen the energy resolution, mainly in charged particle spectrometry. Thus, measuring the dead layer thickness is essential to evaluate the energy loss and its influence on the energy resolution of the incoming radiation in several silicon devices often used in dosimetry and spectrometry systems.

2. MATERIALS AND METHODS

A PIN photodiode SFH206K, supplied by Osram, with an active area of 7.35 mm^2, a capacitance of 72 pF (0 V), and dark currents smaller than 5 nA (0 V) is used in this work. To use this diode as a detector, the n^+ back pad was grounded while the reverse voltage was applied to the front pad (p^+). The signal from the detector was readout from the p^+ electrode through a DC-coupled field-effect transistor (FET) in the first stage of a tailor-made charge-sensitive pre-amplifier based on the hybrid circuit A 250 (Amptek). The pulses from the pre-amplifier were shaped and amplified by a linear amplifier (Ortec 572) with an adjustable shaping time constant and fed to a multichannel analyzer (Ortec Spectrum Ace).

The diode and the pre-amplifier were mounted on a copper plate perpendicularly fixed to the center of a mechanical rotation system. This assembly, set to the upper base of a stainless steel (AISI 304L) chamber, enabled the tilt of the front surface of the diode to the direction of incoming particles with an accuracy of 1°. A circular ^{241}Am source (5.3 kBq), directly coupled to a 1.6 mm thick teflon collimator with 0.5 mm in diameter, was set on the head of a linear motion micrometer feedthrough (Huntington L-2241-2) on a side flange of the chamber. Measurements were carried out under 133 µPa pressure and at an air conditioner controlled room temperature (22 ± 1) ºC.

The experimental parameters, such as source-diode distance (2 cm), reverse bias voltage (24 V), amplifier gain (10x), shaping time constant (2 µs), and ADC channels (2048), were optimized to achieve the best statistical counting and energy resolution. Under these conditions, the energy spectra of alpha particles hitting the diode at incident angles (θ) from 90° (normal incidence) down to 30° were performed. Data on each energy spectrum was fitted to assess the corresponding energy resolution and peak centroid to calculate the dead layer thickness of the diode, as schematically shown in Figure 1. The method was based on the energy loss of alpha particles traversing different path lengths within the dead layer before reaching the sensitive zone of the diode.

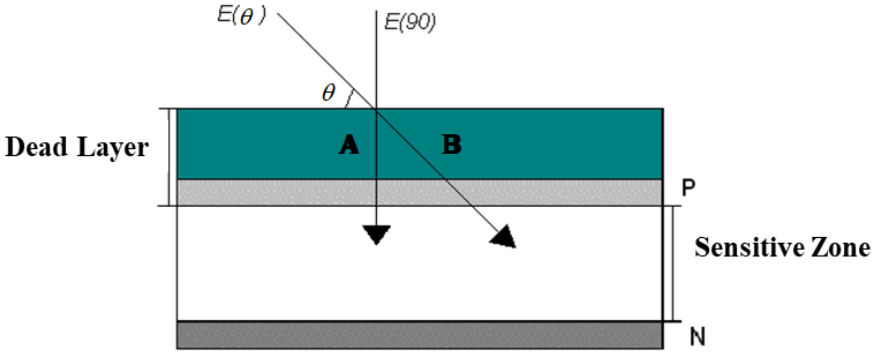

Figure1: *Energy loss in the dead layer of alpha particles hitting the surface of the diode at different angles.*

From Figure 1, the energy of alpha particles after their energy loss in the dead layer is given by Equation 1, for a normal incidence (90°), and Equation 2, for an incidence angle θ:

$$E(90) = E_0 - \frac{dE}{dx} \cdot A \tag{1}$$

$$E(\theta) = E_0 - \frac{dE}{dx} \cdot B \rightarrow E(\theta) = E_0 - \frac{dE}{dx} \cdot \frac{A}{\sin\theta} \tag{2}$$

Where E_0 is the initial energy of the incident alpha particle, dE/dx is the linear stopping in the silicon material, and A is the dead layer thickness. The difference between the energy (ΔE) deposited in the sensitive volume of the diode by alpha particles perpendicularly incident on its surface and at any angle (θ) is given by:

$$\Delta E = E(90) - E(\theta) = \frac{dE}{dx} \cdot A \cdot \left(\frac{1}{\sin\theta} - 1\right) = \frac{dE}{dx} \cdot A \cdot Z \tag{3}$$

The geometric factor Z (term inside the parentheses in Eq. 3) only depends on the incidence angle related to the surface of the diode. Then by Equation 3, the dead layer thickness can be assessed through the plot of (θ) as a function of Z, provided that the stopping power for alpha particles of a given energy is known and constant. Assuming that the energy loss takes place only in the insensitive layer of the photodiode, which holds for a very thin radioactive source and measurements performed at low pressure, the absorber medium might be considered uniformly composed of pure silicon (thin p-type contact) and silicon dioxide (electrode deposition).

The validity of equation 3 also depends on the dead layer thickness concerning the range of alpha particles, as follows. In the extreme case when the thickness is negligibly small, the energy loss is almost constant regardless of the incident angle so that no changes in the pulse heights are detectable. Conversely, for a very thick layer, the straggling and energy degradation of the alpha particles compromise the energy resolution, and the stopping power is no longer constant. Therefore, equation 3 only provides reliable data if the insensitive layer is thin enough to guarantee good energy resolution with detectable pulse heigh variations at different incident angles.

3. RESULTS AND DISCUSSION

Figure 2 shows the best, and the worst energy resolution (FWHM – Full Width at Half Maximum) spectra of ^{241}Am alpha particles that hit the front surface of the diode at incident angles of 90° and 30°, respectively. The energy spectra reassure the dependence of both the energy resolution and peak centroid position on the incident angle and, thus, on the path length of alpha particles through the dead layer. At normal incidence, where the distance traveled by the particle is as short as possible, the best energy resolution (16.2 keV) is achieved, enabling the fine structure lines (5.4856, 5.4416, and 5.3368 MeV) [6] of the ^{241}Am to be distinguished. However, for oblique incidence, the increase in the path length of the alpha particles enhances their energy loss and the straggling intensity. As both effects act together, the greater contribution of the lower energy alpha particles to the spectrum acquired at 30º shifts downward the channel position of the peak centroid. For the same reason, the peak profile is not symmetrical in the lower energy region worsening the corresponding energy resolution (73 keV). These statements hold for the energy resolution results achieved at different incident angles exhibited in Figure 3.

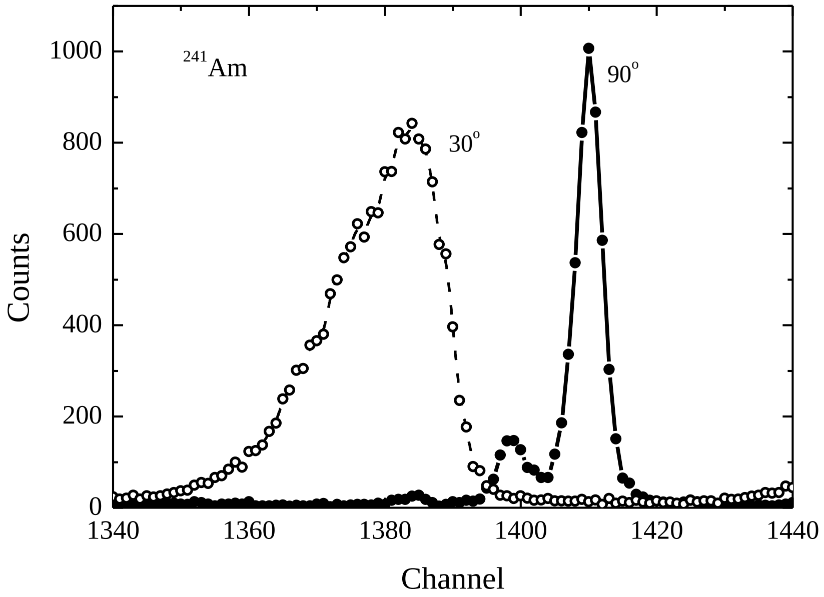

Figure 2: *Energy spectra of alpha particles with incident angles of 90° and 30° related to the surface of the diode. V= 24 V.*

Figure 4 shows the plot of the peak's centroids shift, converted in energy variation from a calibration curve previously established for the spectrometry system, as a function of the geometric parameter *Z*. It is important to note the increase in the data uncertainty attained at the more oblique incidence of the alpha particles. It is due to the energy resolution degradation (Figure 3) that compromises the data fitting and the corresponding centroid of the peaks.

Based on the linear coefficient of the plot (102 ± 3 keV), the alpha particle energy (5.486 MeV), and the linear stopping power in the silicon dioxide (143.6 keV/μm) [7], the dead layer thickness of the diode is found to be (711 ± 23) nm.

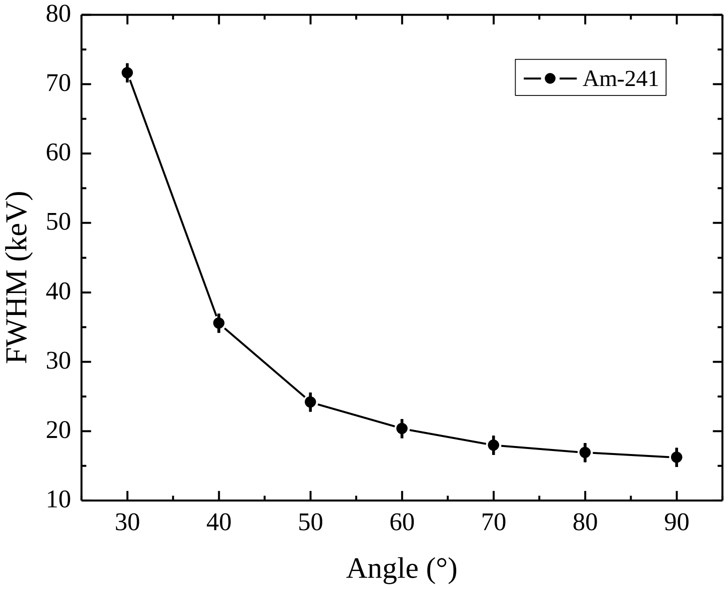

Figure 3: *Variation in energy resolution of alpha particles with an incident angle range of 30° - 90° related to the surface of the diode.*

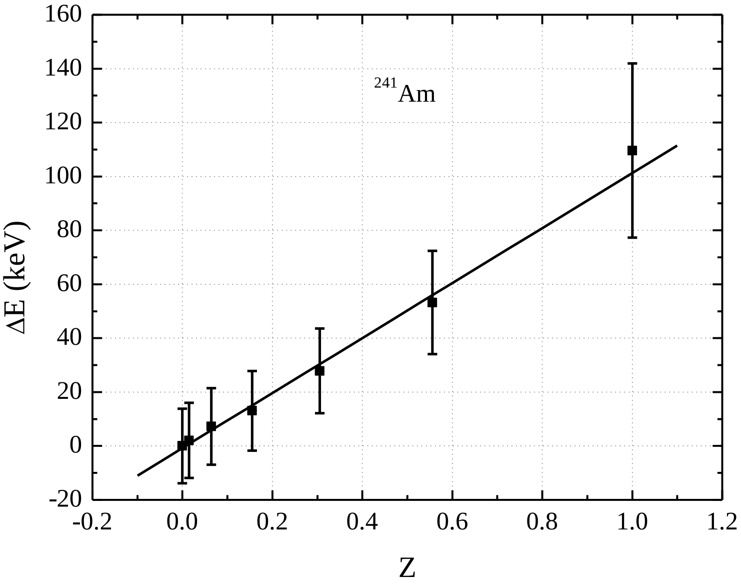

Figure 4: *Energy variation as a function of the geometric parameter Z.*

4. CONCLUSION

In this work, the dead layer thickness of a PIN photodiode (SFH206K - Osram) is proposed to be measured by varying the incident angle of a collimated monoenergetic alpha particle beam upon its surface. The result obtained (711 ± 23) nm, less than 1% of the intrinsic layer thickness, besides validating the employed method, demonstrates that the investigated diode is suitable for high resolution charged particle spectrometry.

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