Development of a low-cost monitor for radon detection in air

Soraia Elísio\textsuperscript{1,2} and Luis Peralta\textsuperscript{1,2}

\textsuperscript{1} Faculdade de Ciências da Universidade de Lisboa
\textsuperscript{2} Laboratório de Instrumentação e Física Experimental de Partículas

Abstract: An active device for radon detection in the air was developed. The monitor operates in pulse counting mode for real-time continuum measurements. The presented prototype has a relatively simple design made of low-price and easy to acquire components which made it possible to develop an inexpensive device. The device uses as sensor the SLCD-61N5 Si-PIN planar photodiode, which has an area of 9.67x9.67 mm\textsuperscript{2}, sensitive to alpha particles. An Arduino Uno microcontroller was used as data acquisition system. Signals were observed when placing an $^{241}$Am source near the sensor. The sensor's sensitivity is bias dependent, but the device can operate even at modest voltage. As a result of a one-month test in a rich radon atmosphere, a positive high correlation was obtained between our prototype and a Geiger-Müller detector.

1. Introduction

Exposure to ionizing radiation from natural sources is continuous and inevitable for all living organisms. According to UNSCEAR, radon once accumulated in houses present the main contribution to exposure from natural sources and consequently a risk factor for health. However, the main concern is due to the inhalation and deposition of the solid radon progeny in the respiratory tract. Since alpha particles interact strongly with matter, they deposit all their energy in a very small volume of bronchial tissue. The cumulative dose of alpha radiation to cells can lead to the development of lung cancer.

There are many different instruments and techniques available for radon detection and quantification in air. The methodology essentially involves the interaction of either charged particles or gamma-rays with the sensor material. The most common means for the measurement of radon is through the detection of alpha emission from the decay of $^{222}$Rn (5.49 MeV), $^{218}$Po (6.00 MeV) and $^{214}$Po (7.69 MeV). Among the wide range of available devices, the passive detectors have been used in large-scale radon surveys, mainly the CR-39 detectors, due to their simplicity, lightweight and low price. However, active detectors working with electrostatic attraction of the charged radon progeny have been developed by many authors for radon measurements [1-5].

In this paper, we present an active detector for radon in air using a low-cost silicon PIN photodiode (cost of the order of ten euro) as main sensor. Besides that, we also use a flexible Arduino Uno microcontroller as the data acquisition system. The device operation is based on the counting of alpha particles interactions with the photodiode sensitive volume, mainly due to the decay of $^{218}$Po and $^{214}$Po, without discrimination in energy. This work presents the results of experiments carried out in laboratory environment with radon and its progeny exhaled from rocks. Measurements were performed simultaneously with a Geiger-Müller detector for comparison purposes. Our main aim was to develop radon detection device that can be used by university students in field trips or academic work.
2. Prototype development

The developed radon monitor is divided into three main parts: the sensitive sensor and amplification chain, the signal formatting chain, and the data acquisition system. Figure 1 shows a block diagram of the system design.

![Block diagram of the detection system.](image)

The first part consists of a low-cost Silonex SLCD-61N5 silicon PIN photodiode as the sensor sensitive to alpha particles and the signal amplification chain. The active area of the photodiode is $9.67 \times 9.67 \text{ mm}^2$. Both, the window thickness and depletion layer thickness are not provided by the manufacture. The total sensor's thickness is 0.4 mm. To achieve an efficient collection of radon solid progeny unattached or attached to aerosol a reverse voltage is applied to the photodiode. Thus, the anode of the sensor is negatively biased with respect to the ground. When a charged particle hits the sensor, a small current is produced with intensity proportional to the deposited energy. The generated current is converted to voltage signal using a charge-sensitive preamplifier. For alpha particles with 7.69 MeV from $^{214}\text{Po}$ decay an output signal of the order of magnitude of a few mV is expected at the pre-amplifier output. The amplification of the signal to the volt range is made by a two-stage amplifier.

The second block has the task to format the signal before feeding it to the acquisition system. The analogue signals are converted into logic pulses by a discriminator that produces logic pulses, with fixed amplitude, when the signal at the amplifier output is above a threshold. The threshold was experimentally adjusted considering the amplitude of small signal pulses relative to noise. A timer working in inverse monostable configuration is used to set a constant width for the pulses fed to the Arduino.

The device third part consists of the data acquisition system where an Arduino UNO microcontroller is used. The microcontroller scores and stores the number of counts in a defined time interval. The scoring of the asynchronous hits is made via an interrupt to the microcontroller. The number of hits in a given time lapse is written into a file in the computer along with the timestamp.

A picture of the first assembled radon monitor prototype is depicted in figure 2. An aluminium box fabricated by HAMMOND, with $22.2 \times 14.5 \times 5.5 \text{ cm}^3$ is used to contain the full setup. Holes were drilled on the box side to allow the gas to enter by diffusion. The box interior was painted matt black. A labyrinth formed by two black slices were placed in the middle of the box preventing exterior light from reaching the sensor.
To test the system for alpha particles detection an $^{241}$Am alpha source was used. This source emits alpha-particles with energy of 5.48 MeV smaller the 6.00 and 7.69 MeV alpha-particles emitted by the $^{218}$Po and $^{214}$Po radon progeny. The detection of $^{241}$Am alpha-particles will be useful to set the low threshold for alpha-particle detection and noise rejection.

Figure 3a shows a typical amplifier output signal in absence of incident charged particles, while figure 3b shows a typical signal when a $^{241}$Am source is placed on the top of the sensor. Pulses with amplitude in the range 0.40 V to 1.8 V were observed. The trigger threshold was thus set below 0.40 V. The timer pulse width is set to 150 $\mu$s (figure 3c), enough not to be missed by the Arduino.
3. Radon tests

3.1 Sensor bias dependence

To test the system for radon detection under laboratory conditions uranium oxide rich rocks were used as radon source. The rocks were placed in a container and the gas diffuses through a hose into the test chamber (an acrylic box) where the radon monitor prototype and a Geiger-Müller detector are placed. Temperature and pressure were monitored using a BME280 sensor [6] connected to an Arduino.

Past works [2,5] point out a count rate dependence on sensor bias of radon detectors base Si-PIN photodiodes. To check for this dependence the test box was filled with radon for a few days and then counting tests were carried out at different sensor bias. The SLCD-61N5 photodiode has a reverse breakdown voltage of -20 V and the tests were made at three voltage values: -9 V, -15 V and -20 V.

Figure 4 presents the measurement results of the prototype device for different values of the applied bias to the photodiode. Each experimental point corresponds to the counts acquired in a ten-minute interval. The results are compared with the measurements of a GM-10 Geiger-Müller detector placed inside the test box.

From the data it can be seen that the detection response depends on the applied bias to the sensor, increasing the sensitivity of the detector with the increase of the reverse voltage. When -9 V is applied a ratio between prototype counts and GM counts of about 0.2 is obtained. For -20 V bias the same ratio is improved to about 0.5. This effect is due to the increase of the electrostatic attraction of the radon progeny to the sensor's anode. The voltage dependence presents a challenge in the device calibration, but the increased sensitivity makes the use of higher reverse voltage attractive.

![Figure 4. Data collection for the radon prototype and GM control. The prototype sensor is biased at three different bias voltages. Each data point corresponds to 10-minute acquisition.](image-url)
3.2 Long term acquisition

A one-month term acquisition was performed with the prototype inside the test box filled with radon. Figure 5 presents the counts in 10-minute intervals for both the radon monitor prototype and the Geiger-Müller detector. The sensor bias voltage was set to -18 V during this acquisition, slightly lower than the previously tested higher value. This value can be obtained from 2 standard 9 V batteries, enabling an easy stand-alone operation of the device. As it can be seen from figure 5 the number of counts given by the prototype follows a similar pattern to that of the Geiger-Müller detector over the measurement period. However, the Geiger-Müller detector presents a higher average number of counts. This is a consequence of this device detecting all kind of charged particles and gamma radiation from radon and background, in contrast with the monitor prototype that only detects alpha particles from the radon gas.

The cut on both plots at the 10th day was due to a power failure in the laboratory. Since radon gets into the test box by diffusion this power failure did not affect the radon concentration. On the graph regular counting oscillation are observed. These oscillations are related to the day/night temperature variations seen in figure 6.

Prototype and Geiger counts were added up for one hour counting and the result presented in the scatter plot of figure 8. A Pearson correlation test was then applied to 931 points and a Pearson-R value equal to 0.977 obtained. This R value corresponds to a p<0.001 indicating a high positive correlation between the data of our detector and those of the GM-10 counter.

![Figure 5. One-month data collection for the radon monitor prototype and GM control. The prototype sensor is biased with -18 V. Each data point corresponds to 10 minute acquisition.](image)

![Figure 6. Temperature and barometric pressure measured with a BME280 sensor connected to an Arduino UNO microcontroller.](image)
To roughly assess the radon concentration inside the test box, a 3 X 3 inch$^2$ NaI(Tl) detector was placed in contact with one side of the box. The increase in the count rate of the 609 keV gamma-peak from the $^{214}$Bi decay relative to background was used to estimate the concentration inside the box. In order to obtain the detection efficiency a Monte Carlo simulation using the Penelope program [7-9] was carried out. The obtained radon concentration values inside the test box were in the 10 to 100 kBq/m$^3$ range for prototype counts in the range of 100 to 1000 counts per hour. This gives roughly a sensitivity of 0.01 counts/(Bq/m$^3$) per hour. To get an uncertainty of 10% for a concentration of 300 Bq/m$^3$ (the limit value recommended by the 2013/59/Euratom Council Directive [10]) a minimum collection time of 33.3 hours will thus be needed.

![Graph](image.png)

Figure 7. GM counts vs Prototype counts (blue points). A clear linear correlation between both counts is observed. The fitted straight line is presented in red.

4. Conclusion

The SLCD-61N5 is a low-cost planar photodiode with active area of 9.67 x 9.67 mm$^2$ sensitive to alpha particles. The sensor was connected to an electronic chain consisting of a preamplifier, amplifier, discriminator, timer and an Arduino UNO microcontroller connected to a personal computer so that information of the number of counts could be extracted and analyzed.

Operability was established under laboratory conditions using both an $^{241}$Am source and radon gas exhaled by rocks containing uranium ore. For radon gas the detection sensitivity increases with reverse bias voltage. Bearing in mind a battery-operated device a -18 V was chosen as the photodiode's reverse bias. A one-month data collection in a rich-radon atmosphere was then obtained. The correlation between the prototype monitor counts and the counts obtained with a Geiger-Müller detector, used for control, is very good.

The device sensitivity has been estimated to be 0.01 counts/(Bq/m$^3$) per hour. For radon concentration in the hundreds of Bq/m$^3$ range, measured values with uncertainty in the 10% range can be obtained within a few days.

The developed prototype has value as didactic device, since it is an open system and can be easily used by students to learn about radon detection.
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