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Optimising sensor geometry of a photodiode based detector for the direct detection of strontium 90 in groundwater.

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Abstract. Strontium-90, as one of the primary beta emitting radionuclides produced during nuclear fission, strontium-90 contaminates groundwater at nuclear decommissioning sites after leaks and spills. Its presence in the groundwater presents a long-term site risk, and its activity must be routinely monitored. Existing techniques see groundwater samples collected from deep underground boreholes and sent to remote labs for analysis [1]. These procedures are expensive, time consuming and produce chemical waste, whereby eliminating the need for sample collection and treatment, the net lifetime monitoring costs of strontium 90 can be reduced [2]. In this paper authors present an optimisation of a beta detector, based on submersible photodetector, which can be used in real-time, in-situ beta detection. In order to directly detect and characterise strontium 90 in groundwater, it is essential to maximise the number of beta particles incident on the photodiode surface and ensure that they are fully absorbed within the sensitive region of the detector. This work has developed a Geant4 software framework for investigating the energy deposition by beta particles on photodiode detectors. A series of simulations have been performed to investigate radiation absorption in silicon, cadmium telluride and gallium arsenide detectors. Variations in sensitive area and detector thickness were modeled to determine their suitability for strontium-90 detection in groundwater. The optimal detector geometry of gallium arsenide photodiodes was further investigated. The simulation results and analysis suggest that the optimal detector will feature a large surface area, at least 1 cm2, and an intrinsic layer approximately 400 m thick.

1. Introduction

Leaks of waste at nuclear decommissioning sites have resulted in the contamination of the groundwater table as radionuclides enter the environment. Strontium 90, the principle beta emitting radionuclide found at decommissioning sites, has a half-life of 28.8 years and decays at 0.546 MeV. s daughter, Yttrium 90, decays at 2.278 MeV with a significantly shorter half-life of 64 hours [1]. Nuclear sites must plan the routine monitoring of ^{90}Sr for decades and current techniques are time consuming, produce secondary waste and are expensive. Currently groundwater samples are taken from underground boreholes and analysis is performed in off-site laboratories. Samples are radiochemically treated, and activity is measured by liquid scintillation, Cherenkov or proportional gas counting methods [2]. By detecting radiation directly and in situ, the need for sample collection can be eliminated which may reduce the worker dose and lifetime monitoring costs [3]. This paper proposes the optimal physical characteristics for a photodiode detector for in situ ^{90}Sr measurement in groundwater.

Photodiodes have been used to detect ionising radiation. Photodiodes are semiconductor materials produce a current pulse in response to ionising radiation when operating under a reverse bias voltage. Incident radiation separates electron-hole pairs within the intrinsic region, producing a current pulse in proportion to the energy deposited by the incident particle. Photodiodes are comprised of multiple layers, as positively, p, and negatively, n, doped layers are brought together, charge separates and an intrinsic, i, layer is created. The intrinsic layer is the sensitive region and responsible for charge generation as ionising radiation is absorbed within the detector. The intrinsic layer can be formed by placing a layer of undoped semiconductor between p and n regions, forming a p-i-n junction, or the deposition of metal contacts onto the semiconductor material, forming an ohmic or Schottky diode.

Many different semiconductor materials can be used to fabricated photodiodes. Each material has unique properties and therefore the most appropriate one for each application must be considered. Silicon is the most widely available and used semiconductor. Its low atomic number, 14, and narrow bandgap, 1.17 eV, mean that silicon detectors are often cooled to minimise thermal noise [4]. GaAs has a higher atomic number, 32, and a bandgap of 1.42 eV which makes it viable at room temperature [5]. In recent years, GaAs photodiodes have been developed as gamma and X-ray detectors[6, 7, 8, 9, 10]. CdTe has an even higher atomic number, 50, than GaAs, and an even wider bandgap, 1.5 eV. CdTe may be a more effective absorber of ionising radiation with low nosie operation at room temperature [11, 12, 13].

2. Monte Carlo Simulations

This research consists of Monte Carlo simulations aimed at finding the most effective semiconductor material for absorbing beta radiation released during ^{90}Sr decay. The goal is to develop a novel detector which is deployed into contaminated groundwater directly. The ratio between the number of particles which deposit energy in the detector and the number of particles emitted should be amplified through detector design. In this case the detector must be capable of fully absorbing the beta particles released during ^{90}Sr decay, up to 0.546 MeV, and ^{90}Y decay, up to 2.278 MeV. If the detector is too thin it will fail to register a significant portion of the particles incident on its surface and will be inefficient at determining the activity of the source of radiation. Simulations are carried out with Geant4, a Monte Carlo simulation code written in C++.

How effectively detectors will absorbed radiation will be determined in part by their thickness. Detectors of varying thickness were modelled with 100 mm^2 surface areas. A beam of 1×10^7 0.546 MeV electrons was fired into the centre of the detector and the energy deposition of each particle was recorded. Silicon detectors fully absorbed fewer particles than GaAs and CdTe when the material was thinner, due to its lower atomic number and only began to absorb particles at a thickness above 200 μm. The GaAs detector absorbed fewer particles than CdTe until the thickness reached 300 μm. As the detectors became thicker the increase in particles absorbed in GaAs and CdTe detectors plateaued while Si detectors began to absorb more and more radiation. This is a consequence of differing levels of electron backscattering in each material. As backscattering is less prevalent in Si, it is able to completely absorb a greater proportional of particles when the thickness is sufficient.

A more realistic groundwater borehole scenario was modelled to consider the real world application of such a detector. This was achieved by modelling a 5 cm diameter and 2.5 cm deep cylinder of groundwater, and its contamintion with 10 $\times 10^7$ isotropic decaying ^{90}Sr ions and ignored the resulting ^{90}Y . The surface area of the detectors was increased from 1 mm^2 to 100 mm^2 while the thickness was held constant at 400 μm . Figure 2 displays the results. Only 162 hits were recorded in a detector with a 1 mm^2 surface area, and the maximum energy

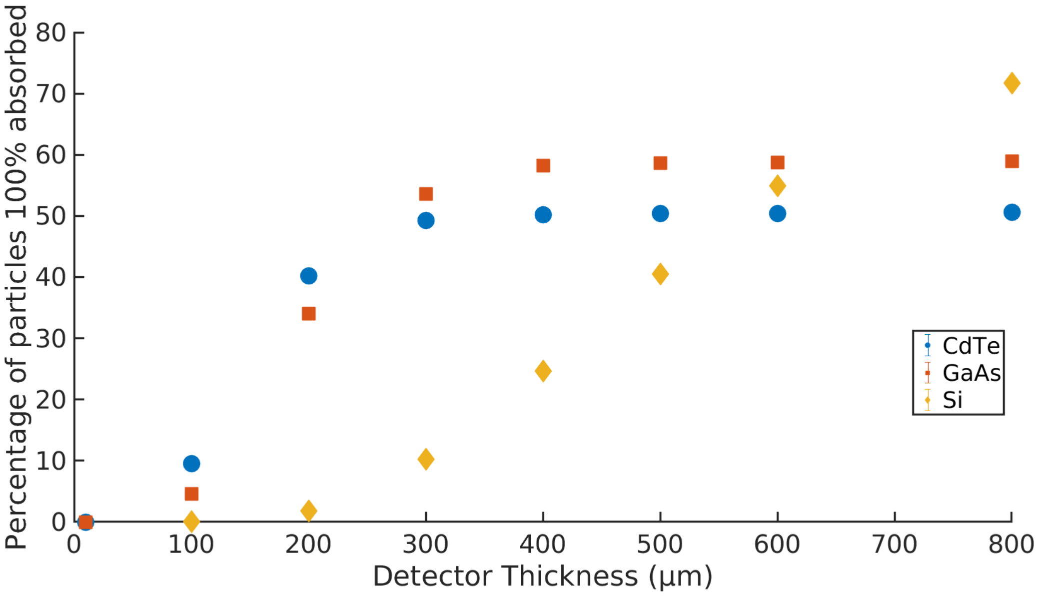

Figure 1. A comparison of 0.546 MeV beta particle absorption in GaAs (squares), CdTe (circles), and Si (diamonds) detectors of varying thickness. Errors are plotted, but not visible due to marker size.

deposited in the detector with at least 5 counts was 0.103 MeV. As the surface area increased to 100 mm^2 detector counted a total of 13015 particles. As the radiation is emitted from random positions and in random directions, most of the particles will never reach the detector or are attenuated before they reach the sensor.

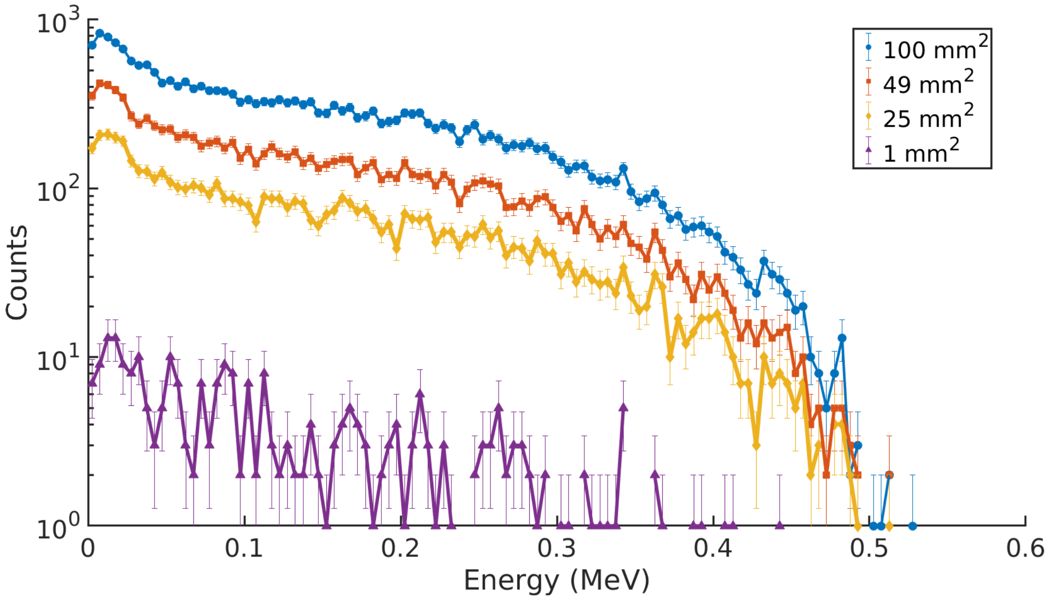

Figure 2. ^{90}Sr spectra observed in 400 μm thick GaAs detectors with increasing surface surface areas.

3. Conclusion

A detector for the direct detection of ^{90}Sr in groundwater must maximise the number of particles incident on and fully absorbed within the detector. This paper has developed a Geant4 simulation code for examining the thickness, surface area and materials which can maximise the absorption of ^{90}Sr and ^{90}Y decay in a photodiode detector. The complete absorption of 0.546 MeV beta particles plateaus for CdTe for approximately 300 μm thick devices with 50.6 % of particles completely absorbed. GaAs completely absorbs a maximum of 58.9 % particles after 400 μm of material. GaAs performs better as an absorber for particles as the effect of backscattering is reduced compared to CdTe. However, CdTe detected more particles at higher energies, 2.28 MeV, where a minimum of 400 μm thick devices was required with 1 mm thick devices offering the greatest absorption. A wide area diode is required to sufficiently capture the fully range of radiation released from ^{90}Sr decay in groundwater. Simulations which modelled a groundwater borehole scenario determined that a 100 mm^2 surface area detector had the greatest detection efficiency. The spectra from 10^8 decaying ^{90}Sr ions, and the resulting ^{90}Y daughters, in 1 mm thick and 100 mm^2 CdTe and GaAs detectors were compared. Each material offered the similar detection efficiency, but the shape of the spectra collected varied slightly. While CdTe offered marginally better absorption in the energy range from 1.725 - 2.3 MeV, the backscattering which resulted upon contact with lower energy particles produced a larger peak at low energies compared to that observed in the GaAs detector.

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References

[1] Chiste V 2005 Table de Radionucleides http://www.lnhb.fr/nuclides/Sr-90_tables.pdf
[2] Vajda N and Kim C K 2010 *Applied Radiation and Isotopes* **68** 2306–2326 ISSN 0969-8043
[3] Turkington G, Gamage K A A and Graham J 2018 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **911** 55–65 ISSN 0168-9002
[4] Knoll G F 2000 *Radiation Detection and Measurement* 3rd ed (New York: Wiley) ISBN 978-0-471-07338-3
[5] Bertuccio G 2005 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **546** 232–241 ISSN 0168-9002
[6] Šagátová A, Zaťko B, Nečas V, Dubecký F, Ly Anh T, Sedlačková K, Boháček P and Zápražný Z 2018 *Applied Surface Science* **461** 3–9 ISSN 0169-4332
[7] Chernykh S V, Chernykh A V, Didenko S I, Baryshnikov F M, Burtebayev N, Britvich G I, Chubenko A P, Guly V G, Glybin Y N, Zholdybayev T K, Burtebayeva J T and Nassurlla M 2017 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **845** 52–55 ISSN 0168-9002
[8] Lioliou G, Whitaker M D C and Barnett A M 2017 *Journal of Applied Physics* **122** 244506 ISSN 0021-8979
[9] Erd C, Owens A, Brammertz G, Bavdaz M, Peacock A, Lämsä V, Nenonen S, Andersson H and Haack N 2002 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **487** 78–89 ISSN 0168-9002
[10] Wu X, Peltola T, Arsenovich T, Gädda A, Härkönen J, Junkes A, Karadzhinova A, Kostamo P, Lipsanen H, Luukka P, Mattila M, Nenonen S, Riekkinen T, Tuominen E and Winkler A 2015 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **796** 51–55 ISSN 0168-9002
[11] Shin S H, Niizawa G T, Pasko J G, Bostrup G L, Ryan F J, Khoshnevisan M, Westmark C I and Fuller C 1985 *IEEE Transactions on Nuclear Science* **32** 487–491 ISSN 0018-9499
[12] Sun G C, Samic H, Bourgoin J C, Chambellan D, Gal O and Pillot P 2004 *IEEE Transactions on Nuclear Science* **51** 2400–2404 ISSN 0018-9499
[13] Becker J, Tate M W, Shanks K S, Philipp H T, Weiss J T, Purohit P, Chamberlain D, Ruff J P C and Gruner S M 2016 *Journal of Instrumentation* **11** P12013–P12013 ISSN 1748-0221