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J. L. Jones
B. W. Blackburn
F. H. Ruddy
J. G. Seidel
R. W. Flammang

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Novel Silicon Carbide Detector for Active Inspections*

J. L. Jones, B.W. Blackburn, F.H. Ruddy[a], J.G. Seidel[a], and R.W. Flammang[a]
Idaho National Laboratory
Idaho Falls, Idaho, USA, 83415-2802
a-Westinghouse Electric, Pittsburgh, Pennsylvania

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Abstract: *The need to address increasingly challenging inspection requirements (such as large volume objects, very fast inspection throughputs, potentially significant shielding, etc.) for such items as nuclear materials and explosives will require the use of active interrogation technologies. While these active technologies can successfully address these challenges by inducing unique, temporal signatures, the inspection environment will also induce overall "background signals" that can be orders of magnitude larger than the induced signatures. Detectors that can successfully operate in these types of customized, inspection environments (pulsed and continuous) and successfully extract induced signature data are clearly needed and will effectively define the limitations of any active inspection system. A novel silicon carbide detector is now being investigated to successfully address both neutron- and photon/bremsstrahlung-type inspection applications. While this paper describes this detector and highlights efforts related to neutron inspection, it will focus on its neutron and gamma-ray/photon detection performance in neutron- and bremssstrahlung-type inspection applications.*

Keywords: active interrogation; neutron detection; gamma-ray detection, prompt radiation emissions, fast timing.

Introduction

Since September 11, 2001, active inspection technology investment has significantly increased, especially for national security applications[1]. Active inspection technologies include both photon and neutron methodologies[1-4]. Many, if not all, of these technologies rely on proven detection systems that were originally designed for passive applications. Unfortunately, successful deployment of these detector systems in actively-induced environments requires excessive shielding and operations typically far outside their nominal operational expectations.

The Idaho National Laboratory (INL) has been developing active interrogation techniques for decades to detect shielded threats[1-2]. One such system is the Pulsed Photonuclear Assessment (PPA) technique[2] in which induced-photonuclear interactions within nuclear elements, such as ^{235}U, result in delayed neutron and gamma-ray emissions. These emissions are collected by an array of detectors and then utilized to determine the presence of nuclear materials. Delayed radiation, however, constitutes only a very small fraction of the emissions produced during photonuclear reactions. The magnitude of prompt emissions produced during the interrogating pulse of photons, or shortly thereafter, can be orders of magnitude greater than the delayed emissions. There is strong evidence that these actively-produced prompt radiations can have distinguishable characteristics to facilitate nuclear material detection and identification. This approach offers the potential to dramatically reduce interrogation times, increase inspection throughputs, and limit the inspection dose to the cargo. This paper highlights the joint research being conducted by the INL and Westinghouse personnel utilizing silicon carbide (SiC) detectors in support of the INL active inspection effort.

Silicon carbide detectors are a relatively new class of radiation detectors. Developed by Westinghouse[5-7] for in-core radiation measurements, these detectors are a composite of doped layers of SiC sandwiched between two metal contacts as shown in Figure 1. Depending on the applied voltage, depletion regions of 10-100 µm can be induced in the detectors with band gaps on the order of 3.25 eV. Ionizing radiation generates electron-hole pairs that are pulled apart under an applied electrical field, creating a current that is then amplified and recorded. Some of the advantages of SiC detectors are that they are ultra-fast (i.e., risetimes of <1 to a few ns), capable of processing high count rates, able to operate during and within nanoseconds of the end of an intense neutron/photon pulse, and are relatively photon insensitive.

This paper will show SiC's ability to differentiate neutrons from photons and highlight some performance data related to potential inspection applications.

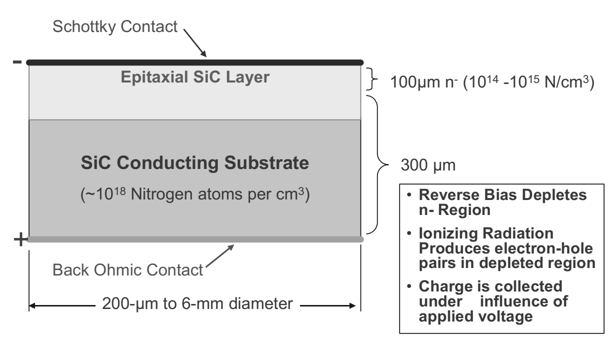

Figure 1. Schematic representation of a SiC Shottky diode.

Neutron and Photon Detection Responses

Experiments to measure detector efficiency utilizing state-of-the-art digitization and data acquisitions were conducted at the Idaho National Laboratory's Health Physics Instrumentation Laboratory (HPIL). HPIL is a National Institute of Standards and Technology (NIST) traceable facility that enables detector performance assessments using extremely well characterized and calibrated neutron and gamma-ray fields. During the course of the experiments, the detector was exposed to gamma and neutron fields in a controlled quantitative spatial environment. At each location computer-controlled, calibration equipment reported the dose rate (R/hr) at that location. Flux-to-dose conversions were then utilized to calculate the incident flux of radiation which was compared to the measured count rates. Count rates were acquired through direct digitization of the signal from a single 28.3-mm^2 SiC (with a 100 µm polyethylene neutron conversion layer) and a maximum depletion bias voltage of -900V, followed by post-irradiation processing to identify pulses based on requisite pulse height and width.

Initial evaluations were conducted with ^{137}Cs and ^{60}Co sources which were counted separately at predetermined distances in a pure gamma irradiation cell. Neutron measurements were conducted using a 3-mg ^{252}Cf source in the Neutron Low Scatter Facility at HPIL. The detector signal output was digitized using an Acqiris DC282, four channel, 10-bit digitizer operating at a sampling rate of 8 GS/s. The DC282 was controlled by a personal computer operating a custom-designed National Instruments© LabView application. Table 1 shows the SiC detection efficiency results for the HPIL testing and highlights the detector's preferential neutron sensitivity.

Table 1. Experimental parameters for the gamma and neutron efficiency calculations at HPIL

Source	Dose (R/hr)	Flux (γ or n/cm2-s)	CPS	INTRINSIC EFFICIENCY	Error
Cs137	30	1.999E+07	90.2	1.59E-05	33.71%
Cs137	300	1.999E+08	821.6	1.45E-05	12.12%
Cs137	828	5.516E+08	2765.5	1.77E-05	7.83%
Co60	18	7.545E+06	253.8	1.19E-04	21.44%
Co60	195	8.174E+07	2615.2	1.13E-04	8.45%
Co60	510	2.138E+08	7064.1	1.17E-04	6.50%
Cf252	5.843	4.640E+04	260.0	1.98E-02	16.10%
Cf252	551.64	4.381E+06	2940.0	2.37E-03	8.15%

When a SiC diode is exposed to ionizing radiation, the shape and timing of the signal produced is dependent largely on the type of radiation causing the interaction. Gamma radiation will interact primarily through Compton scattering with atomic electrons of the silicon, carbon, or nitrogen dopants in the materials. Neutrons, on the other hand, interact either through proton recoils generated in the polyethylene conversion layer placed on the upper edge of the diode or through (n,n'), (n,α) or (n,p) reactions directly in the silicon or carbon, if the neutron energy is sufficient. These heavy charged particles deposit their energy within a few tens of microns of the originating location. This results in a faster charge collection time when compared with gamma events. By exploiting differences in the rise-time of the signal, gamma-ray signals may be discriminated from neutron events. Experiments geared toward the exploitation of these differences were conducted by INL and Westinghouse personnel at the Idaho Accelerator Center and then at the Pittsburgh facility in joint experiments. The initial experiments utilized 100 µCi sources of ^{60}Co and ^{137}Cs and a 1E4 n/s ^{252}Cf source. While these sources gave generally good results, which are illustrated in Figure 2, a stronger AmBe source available at the Westinghouse facility yielded much clearer data as seen in Figure 3. Generally, most of the high-amplitude neutron-induced pulses have rise times less than 2 nanoseconds; the pulses width rise times greater than 2 nanoseconds are due to gamma-rays from the Cf252 source and can be easily discriminated against the slower neutron induced pulses on the basis of both amplitude and rise time.

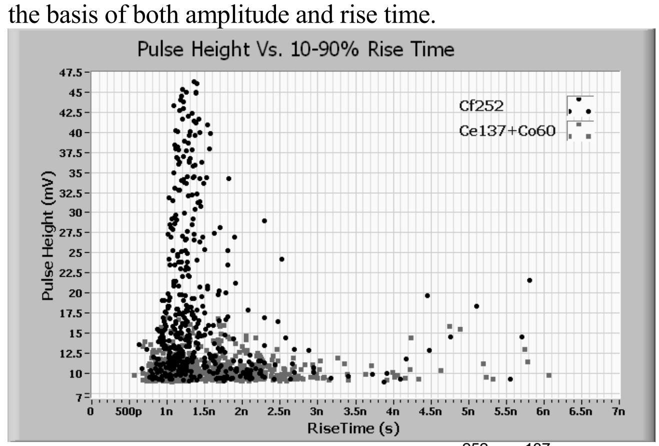

Figure 2. Pulse height vs. rise time for the ^{252}Cf, ^{137}Cs, and the ^{60}Co sources. (All saturated and noise signals were removed before processing.)

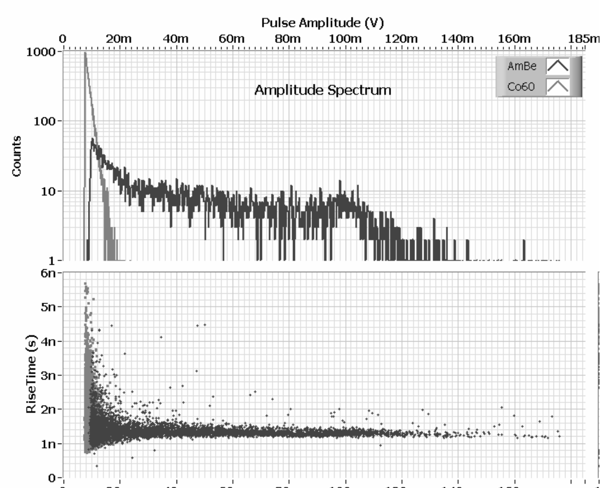

Figure 3. Pulse height vs. rise time for the AmBe and ^{60}Co sources.

Application Performance

To assess application performance, the SiC detector has initially been assessed with both neutron and bremsstahlung interrogation sources. It is fully expected that improvements in detection performance will continue to occur with increased operational experience and enhanced detection efficiency methods.

DT-neutron tests were conducted at the Westinghouse facility with the SiC detector at about 5 cm from the neutron source. The SiC detection performance is shown in Figure 4. Note the obvious neutron rise time band is centered at about 1.3 ns and is clearly separated from the other related emissions.

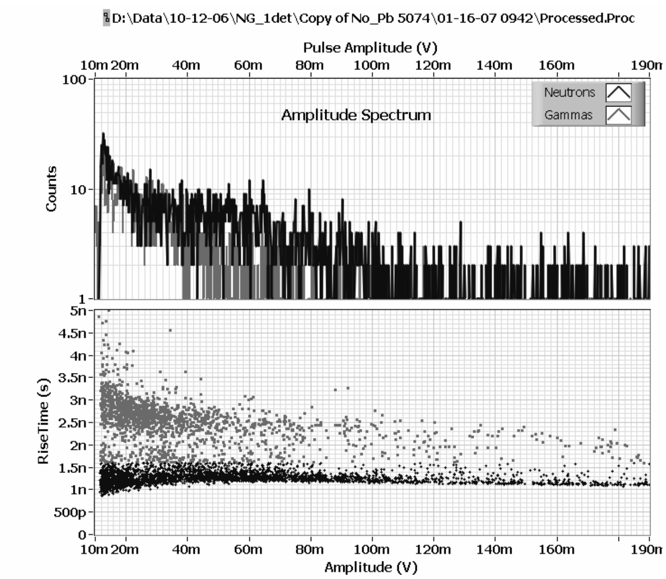

Figure 4. Pulse height and rise times for a DT generator.

Initial bremsstrahlung assessments utilized a nominal 14-MeV electron accelerator (i.e., Linac). The photon source was well shielded with source collimation to assure only forward-directed, energetic photon production. To minimize and better understand the SiC detector response within a higher energy, accelerator photon environment, an off-axis detector position was selected (i.e., ~2.5 m downstream of the photon source and positioned about 1.2 m below the beam axis). Figure 5 presents the detector response for an unshielded detector. Note the increased photon contribution (i.e., rise times greater than 2 ns). Figure 6 shows a similar response with the detector shielded from the Linac with 10 cm of lead. The corresponding photon reduction is readily observed while retaining some of the important neutron signal.

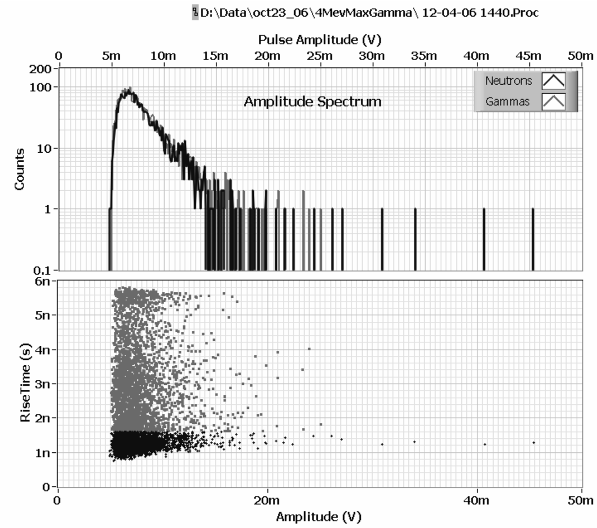

Figure 5. Pulse height and rise times for a nominal 14-MeV Linac

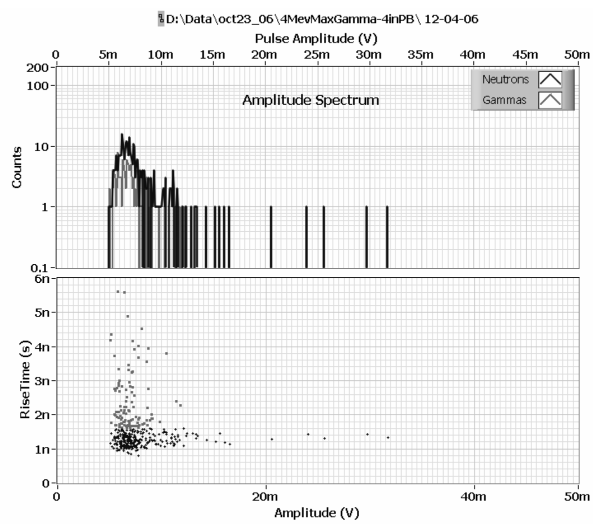

Figure 6. Pulse height and rise times for a nominal 14-MeV Linac (Detector shielded from Linac source by 10 cm of lead.)

Conclusions

SiC detectors had originally been developed to operate at elevated temperatures and in harsh radiation fields to support commercial nuclear reactor power monitoring applications. This harsh radiation field applicability makes these detectors ideally suited for a critical role in active inspection applications, especially those involving nuclear material detection. Excellent neutron/gamma pulse discrimination has been shown using a combination of pulse rise time and pulse amplitude. Overall results showed better than 1000-to-1 neutron-to-gamma discrimination. In addition, these ultra fast-responding detectors can provide unique signature timing information. The successful performance of this detector-type to date within intense photon and neutron fields clearly invites continued application research coupled with active inspection technology development.

References

1. Jones, J. L., “Active, Non-Intrusive Inspection Technologies for Homeland Defense,” *Sixth International Meeting on Nuclear Applications of Accelerator Technology (ACCAP’03)*, Conference Proceedings, San Diego, CA, pp. 33-41, June 2003.

2. Jones, J. L., et al., “Detection of Shielded Nuclear Material in a Cargo Container,” *Nuclear Instruments and Methods in Physics Research A*, **562**, (2006) 1085-1088.

3. D. Slaughter, et al., “Preliminary results utilizing highe-energy fission product gamma-rays to detect fissionable material in cargo,” *Nuclear Instruments and Methods in Physics Research B*, **241** (2005) 777-781.

4. W. Berrtozzi, “A Comprehensive Technology to Address the Cargo Container Security Threat,” 2005 *IEEE Nuclear Science Symposium Conference*, Record N1-4, Puerto Rico, November 2005.

5. A. R. Dulloo, F. H. Ruddy, J. G. Seidel, T. Flinchbaugh, C. Davison, and T. Daubenspeck, “Neutron and Gamma Ray Dosimetry in Spent-Fuel Radiation Environments Using Silicon Carbide Semiconductor Radiation Detectors”, in *Reactor Dosimetry: Radiation Metrology and Assessment, ASTM STP 1398,* John G. Williams, David W. Vehar, Frank H. Ruddy, and David M. Gilliam, Eds., American Society for Testing and Materials, West Conshohoken, PA, 2001, pp 683-690.

6. F. H. Ruddy, A. R. Dulloo, B. Petrović, and J. G. Seidel, “Fast Neutron Spectrometry Using Silicon Carbide Detectors”, in *Reactor Dosimetry in the 21st Century*, J. Wagemans, H. A. Abderrahim, P. D’hondt, and C. De Raedt (Eds.), World Scientific, London (2003) pp 347-355.

7. F. H. Ruddy, A. R. Dulloo, J. G. Seidel, M. K. Das, S.-H. Ryu, and A. K. Agarwal, “The Fast Neutron Response of 4H Silicon Carbide Radiation Detectors”, *IEEE Transactions on Nuclear Science* **53**, 1666 (206).