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Development of radiation-resistant neutron sensor using a diamond detector

Fields of mixed radiation (neutrons, γ-rays, etc.) exist in various environments around nuclear power plants and particle accelerators. The neutron and γ-ray components of these fields should be monitored separately to characterize the radiological environment. Conventional radiation monitors comprising a ^{3}He proportional counter and ionization chamber are used to prevent workers from being exposed to excessive doses of low levels of radiation around their sites. However, in harsh environments, such as that surrounding the Fukushima Daiichi Nuclear Power Plant (NPP) after the accident in 2011, and in state-of-the-art high-intensity accelerators, such as SuperKEKB and J-PARC, the real-time monitoring of neutrons and γ-rays in their caves, which provides diagnostic information about the systems, can be challenging because of the extremely high levels of radiation.

We collaborated with Japanese experts from the Applied Research Laboratory and Institute of Particle and Nuclear Studies in KEK, the National Institute for Materials Science (NIMS), and the National Maritime Research Institute (NMRI) and developed a prototype of a submerged remotely operated vehicle (ROV) equipped with certain sensors. We targeted the localization and characterization of the fuel debris in the flooded primary containment vessel (PCV) on-site at the Fukushima Daiichi NPP. Figure 1 depicts a conceptual image of the ROV system [1].

To detect spontaneous fission neutrons emitted from submerged fuel debris with a neutron flux in the range of $10^2 \sim 10^6$ cm^{-2}s^{-1}, a compact neutron sensor was developed by combining a diamond detector and a radiation-resistant integrated read-out circuit. We designed this circuit such that it could be incorporated into the ROV to measure the rare signals of neutrons associated with the debris, apart from large amounts of γ-rays with a dose rate of up to 100 Gy/h emitted by the ^{137}Cs, which was widely dispersed in the PCV.

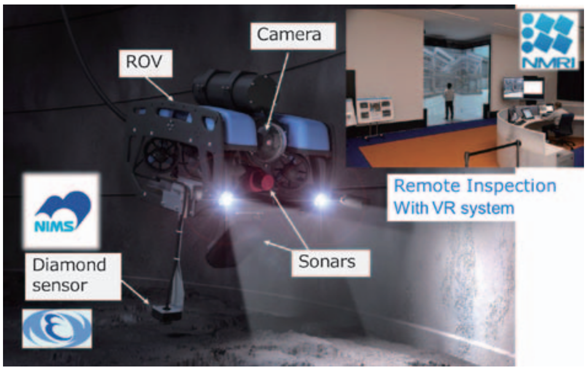

Fig. 1. Conceptional image of the ROV system.

Diamond possesses intrinsic properties, such as a large band gap (5.5 eV), high electron-hole mobility, and low atomic number. Therefore, diamond detectors fabricated using chemical vapor deposition (CVD), combined with a thin layer of ^{6}LiF thermal neutron converters (1.9 μm thick), were selected as promising candidates for neutron sensors owing to their excellent radiation durability, high count rate capabilities (>1 MHz), low electronic noise, and ability to operate at high temperatures. To evaluate the performance, two CVD diamond detectors with different thicknesses (25 and 140 μm) were characterized using a B6-C compact thermal neutron diamond detector manufactured by CIVIDEC Instrumentation GmbH [2]. Experimental measurements were conducted with a mixed α-source composed of ^{148}Gd (3.183 MeV), ^{241}Am (5.486 MeV), and ^{244}Cm (5.805 MeV), as well as γ sources (^{60}Co and ^{137}Cs) and thermalized neutrons from a ^{241}Am–Be neu-

Fig. 2. KEK graphite pile with a SOKENDAI student conducting the experiments.

tron source in a 2.5 m × 1.9 m × 1.9 m graphite pile at KEK, as shown in Fig. 2. The detectors exhibited high charge collection efficiencies (CCEs) exceeding 90%, low leakage currents (below 20 pA at room temperature), and energy resolutions of approximately 1% for the 5.486 MeV α-particles. The results of the comparative study on the neutron and γ-ray responses of the detectors demonstrated that the sensitivity to the γ-rays was significantly reduced by decreasing the thickness of the detector. The 25 μm thick diamond could discriminate between neutrons and γ-rays even at an air-absorbed γ-ray dose rate of 107 Gy/h. Owing to the low γ-sensitivity of the CVD diamond detector, a suitable threshold could be set for neutron events against γ-rays in environments with a high γ dose rate. This demonstrated that the CVD diamond detector detected debris in approximately 1 s with a statistical error of 10% at S/N = 10 in the PCV environment for a neutron flux and γ dose rate of 10^6 cm^{-2}s^{-1} and 100 Gy/h, respectively. Moreover, simulation using the PHITS code [3] predicted that when the detector layout on the converter layer was improved, debris could be detected in 14 min even for a low neutron flux of 10^2 cm^{-2}s^{-1}.

We fabricated several transistors with normal and radiation-resistant structures using a 65 nm CMOS semiconductor process. The γ-ray irradiation test was conducted at the Takasaki Advanced Radiation

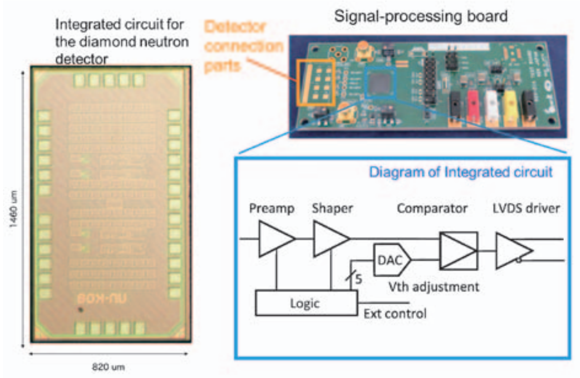

Fig. 3. Integrated read-out circuit of the diamond sensor.

Research Institute in the National Institutes for Quantum and Radiological Science and Technology (QST) to investigate the total ionizing dose effect of γ-rays. Figure 3 shows the integrated read-out circuit manufactured using transistors that can operate over 1 MGy. Further experiments are planned to characterize the signal-processing integrated circuit, combined with the ROV system, using a full-scale mockup test facility in Naraha. This radiation-resistant signal processing integrated circuit technology is foreseen to be useful for beam loss monitoring and remote control systems in high-energy accelerator facilities.

References

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