Sensing Capabilities of Piezoelectric Wafer Active Sensors in Extreme Nuclear Environment

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ABSTRACT

There is considerable demand for structural health monitoring (SHM) at locations where there are substantial radiation fields such as nuclear reactor components, dry cask storage canister, irradiated fuel assemblies, etc. Piezoelectric wafer active sensors (PWAS) have been emerged as one of the major SHM sensing technologies. In order to use PWAS to perform SHM in nuclear environment, radiation influence on sensor and sensing capability needs to be investigated to assure the reliability of the PWAS based method. Radiation may cause degradation or even complete failure of sensors. Gamma radiation is one of the major radiation sources near the nuclear source. Therefore, experimental investigation was completed on the gamma radiation endurence of piezoelectric sensors. The irradiation test was done in a Co-60 Gamma Irradiator. Lead Zirconate Titanate (PZT) and Gallium Orthophosphate (GaPO4) PWAS were exposed under gamma radiation at 100 Gy/hr rate for 20 hours. Electro-mechanical (E/M) admittance signatures and electrical capacitance were measured to evaluate the PWAS performance before and after every 4 hours exposure to gamma radiation. PWAS were kept at room temperature for 6 days after each 4 hours radiation exposure to investigate the effect of time on PWAS by gamma radiation. It was found that, PZT-PWAS show variation in resonance frequency for both in plane and thickness mode E/M admittance. Where, the changes in resonance amplitudes are larger for PZT-PWAS. GaPO4-PWAS E/M impedance/admittance spectra don’t show any reasonable change after gamma irradiation. A degradation behavior of electrical properties in the PZT-PWAS was observed. Capacitance value of PZT-PWAS decreases from 3.2 nF to 3.07 nF after exposing to gamma radiation for 20 hours at 100 Gy/hour. This degradation behavior of electrical properties may be explained by the pinning of domain walls by some radiation induced effect. GaPO4-PWAS doesn’t show reasonable degradation in electrical properties. GaPO4 has good radiation endurance, although amplitude sensitivity is relatively low.

Keywords: Structural health monitoring (SHM), resonance/anti-resonance frequency, capacitance, gamma radiation, PZT, GaPO4, PWAS.

1. INTRODUCTION

There is considerable demand for nuclear SHM at locations where there are substantial radiation fields. For example, one of the major parts of a nuclear power plant is the removal and disposal of spent fuel rod assemblies. In past, reactors were built to store spent fuel rod in a storage pond ranging from three to five years. The period of storage is determined either by the need for the fuel to lose more of its radioactivity or the availability of a permanent disposal site. From there fuel assemblies could be sent to long term disposal or reprocessed. However since 1977, due to federal policies relating to reprocessing of irradiated fuel and disposal irradiated fuel permanently, on-site irradiated fuel storage facilities have been built for storing these irradiated fuel assemblies to prevent the forced shutdown of these plants due to the overflowed of storage pools [1]. Dry cask storage canister system (DCSS) is such storage canister, which is used to maintain in a temporary storage area at the reactor site for some predetermined period. Casks come in different sizes. They are tall enough to hold spent fuel, which can be 14 feet long, and they can weigh up to 150 tons. As of December 2014, just over 2,000 casks have been loaded and are safely storing nearly 84,000 spent fuel assemblies [2]. The radioactivity from the canister is about 10 rems per hour and outside of the shielding is 25 mile rem per year. In August 26, 2014 NRC approves 60 years short term on site storage and 100 years long term storage of spent fuel on site [1][2]. However, steel canisters may start failing within 30 years due to stress crack, corrosion due to favorable moderate temperature and irradiation instability etc. It is important to inspect where, a canisters are cracking or how deep is the
existing cracks. Existing crack through the canister wall may release radiation to the surrounding environment. Regular inspection and tests on cask components is essential for providing safe storage after years. Therefore, it is important to build a SHM method for dry cask storage canister for long time evaluation and damage assessment. The permanently installed sensors can provide state of the structures at any time over the entire service life, which is advantageous over traditional ultrasonic nondestructive evaluation (NDE) techniques. DCSS is a critical safety facility in a nuclear power plant and it needs of monitoring over prolonged service periods. One of the major goals is to improving DCSS reliability, sustaining the safety, and extending the life. Therefore, it is important to develop proper SHM technologies that can better diagnose their state of structural health.

When sensing element works in the subject DCSS environment, radiation may cause degradation or even complete failure of the sensors. Gamma radiation is considered as one of the major radiation sources near the DCSS. Therefore, experimental investigation is being conducted on the gamma irradiation endurance of piezoelectric sensors. In this research, both Lead Zirconate Titanate (PZT) and Gallium Orthophosphate (GaPO4) types PWAS were investigated. PWAS were exposed to gamma irradiation at 100 Gy/hr for every 4 hours for 5 times (Cumulative dose: 2000 Gy). Radiation dose is well above the radiation dose near the DCSS as reported by U.S. NRC [1]. Electro-mechanical (E/M) impedance/admittance signature was evaluated before and after the exposure. For PZT-PWAS, variation in resonance frequency was observed, whereas larger variation was found in resonance amplitude. For GaPO4, E/M admittance spectra show only small change after gamma irradiation. A degradation behavior of electrical properties in the PZT-PWAS was observed after gamma radiation. GaPO4-PWAS doesn’t show reasonable degradation in electrical properties. Therefore, GaPO4-PWAS has good radiation endurance than PZT-PWAS.

2. STATE OF THE ART

Piezoelectric wafer active sensors (PWAS) have emerged as one of the major SHM technologies; the same sensor installation can be used with a variety of damage detection methods: propagating ultrasonic guided waves, standing waves (E/M impedance) and phased arrays. [3][4]. PWAS transducers are very small, lightweight and inexpensive transducers. PWAS transducers can be bonded on a host structure or between layers of a structure easily. PWAS transducers require low power that makes it feasible for onsite inspection in SHM and NDE applications. PWAS transducers are made of piezoelectric material with electrodes on both sides. To use PWAS transducer as an SHM transducer, electrodes must be connected to the piezoelectric material and the piezoelectric materials must be polarized. Out-of-plane electric field is applied in order to polarize the PWAS transducer in the same direction. Piezoelectric materials convert mechanical energy into electrical energy or vice versa. The traditional PWAS transducers use piezoelectric material Lead Zirconate Titanate (PZT). PWAS transducer material has been attracted by researchers due to its enhanced sensing, actuation or both capabilities. PZT with large coupling coefficient, high permittivity and quick time to respond make it to be an excellent candidate as piezoelectric transducer in SHM and NDE applications [5]. Property enhancement was made at the expense of temperature, electric field, and stress stability. Property enhancement is achieved by chemical composition to allow domain wall motion to extrinsically contribute to the piezoelectric effect. This compound class shows much better piezo-electrical and piezo-mechanical efficiency than naturally occurring piezoelectric materials [6]. Commercially available APC 850 PWAS transducer was used in this research [7]. The wafers disk is 7 mm in diameter and 0.2 mm in thickness. The wafer has a PZT thin film with silver (Ag) electrode on both sides. The Curie point of APC 850 PWAS transducer is 350°C [7]. GaPO4 material is quartz type (α-quartz) belongs to the class of compounds M-X-O4. GaPO4 Single crystal GaPO4 as piezoelectric materials has been investigated by many researchers [8][9]. GaPO4 possess a low piezoelectric constant and low dielectric constant compared to PZT. But compared with quartz crystal it possesses nearly all the advantages of quartz with higher electromechanical coupling and has thermally stable physical properties up to 950°C. Furthermore it displays no pyroelectric effect. This article also presents the potential impact on EMIS signature and material properties of GaPO4 as a piezoelectric material after exposure to elevated temperature. Commercially available high quality GaPO4-PWAS (PIEZOCRYST GMBH) [10] was used in this research. The wafers were x-cut GaPO4 single crystal disks of 7 mm diameter and 0.2 mm thickness. The wafer had a GaPO4 single crystal thin film with electrode on both sides.

In physics, radiation is the emission or transmission of energy in the form of waves or particles through space or through a material medium. There are two types of radiation: ionizing (more than 10 eV) and non-ionizing. A common source of ionizing radiation is radioactive materials that emit α, β, or γ radiation. Gamma radiation consist gamma ray (γ), which is extremely high-frequency electromagnetic radiation and therefore consists of high-energy photons [11]. Gamma
radiation is the main source of radiation near DCSS. The measurement unit for gamma radiation dose is the Gray, equal to 1 Joule of absorbed energy per kg of material. The damage caused by gamma rays to PWAS sensors is dependent on the total accumulated dose. The major mechanisms for piezo material performance degradation via gamma ray interaction are: The primary degradation mechanism is depoling, accumulated exposure to ionizing radiation can cause internal defect and radiation-induced charges can be trapped near the electrodes. Such concentration of charge could potentially affect polarizability [12]-[16]. A comprehensive literature study was already conducted by Sinclair et al in a review paper [16]. In this paper, effects of gamma radiation on piezoelectric properties for several candidate materials were presented. Reliable operation was found of PZT after doses of 1.5 MGy. Ionization damage threshold is 400 MGy of gamma, but only if temperature and neutron fluence are kept low. Signal amplitude decrease of 13% after dose of 22.7 MGy in a customized transducer assembly; drop is believed to be due to a change in piezoelectric efficiency. Tittmann et al. [17] reported Radiation tolerance of piezoelectric bulk single-crystal aluminum nitride. Theoretical study of ferroelectric properties degradation in perovskite ferroelectrics and anti-ferroelectrics under neutron irradiation was conducted by Kulikov et al. [18]. Radiation, temperature and vacuum effects on piezoelectric wafer active sensors were studied by Giurgiutiu et al. [19]. The change in resonance and anti-resonance frequencies and amplitudes were obtained experimentally in that paper.

3. EXPERIMENTS

Experimental set up for E/M impedance/admittance measurement is shown in Figure 1. E/M impedance/admittance and electrical capacitance of were measured before and after exposure to radiation. Commercialized HP 4194A impedance analyzer was used. For PZT, the E/M impedance/admittance were collected from 250 kHz to 350 kHz with a step size of 50 Hz during in plane mode and 10 MHz to 13 MHz with a step size of 1 kHz during thickness mode measurement. For GaPO$_4$, the E/M impedance/admittance were collected from 270 kHz to 300 kHz with a step size of 1 Hz during in plane mode and 8 MHz to 11 MHz with a step size of 1 kHz during thickness mode measurement. The real part of the admittance is used for E/M impedance/admittance method as it has been reported to be less sensitive [20].

![Figure 1 Experimental setup for E/M impedance/admittance measurement.](image)

Gamma radiation is the major sources of nuclear radiation adjacent to DCSS. In order to determine the stability of PWAS under gamma radiation, the following (Figure 2) experimental procedure was followed. For experiment study, radiation dose was set to 100 Gy/hr for 20 hours (Cumulative dose: 2 kGy). PWAS were kept at room temperature for 6 days after each 4 hours radiation exposure to investigate the effect of time on PWAS after exposure. A set of six nominally identical free PWAS (PZT and GaPO$_4$) were tested (Figure 3 (a)). The irradiation test was done in a Co-60 Gamma Irradiator (by JL Shepherd and Associate) as shown in Figure 3 (b).
4. RESULTS AND DISCUSSION

The major mechanisms for piezo material performance degradation via gamma ray interaction are considered as follows:

1. The primary degradation mechanism is depinning of domain
2. Accumulated exposure to ionizing radiation can cause internal defect
3. Radiation-induced charges can be trapped near the electrodes. Such concentration of charge could potentially affect polarizability

Due to this degradation, variation in impedance/admittance signature can be observed. Note that in addition to gamma radiation, temperature due to operational condition may have effect on the impedance/admittance.
4.1 Effect of resonance frequency and amplitude on PWAS

Figure 4 and Figure 5 show the resonance frequency and amplitude in both in plane mode and thickness mode after and before radiation exposure. The error bar is obtained from statistical analysis of 6 PWAS. The resonance frequency increases with increasing radiation dose in both in plane and thickness mode. E/M admittance spectra depend on PWAS transducer material properties such as stiffness coefficient, piezoelectric constant, dielectric constant, density and different losses in PWAS transducer material. Any kind of change in PWAS transducer material state can be noticed as shifts in resonance frequency. The spectral peaks observed in the real part of the E/M admittance spectrum follows the resonance. Resonance amplitude is decreased with increasing radiation dose. Slight variation is observed in resonance frequency and amplitude when data were taken after 7 days from radiation exposure. That means time has only a slight effect on PZT after radiation. It should be noted that the standard deviation or error is higher in amplitude values. Therefore, the use of an SHM method based on tracking the peak amplitude would not recommended.

![Figure 4 PZT-PWAS in plane (a) resonance frequency (b) resonance amplitude](image)

![Figure 5 PZT-PWAS thickness mode (a) resonance frequency (b) resonance amplitude](image)
Figure 6 and Figure 7 show the resonance frequency and amplitude of GaPO$_4$-PWAS for both in plane mode and thickness mode. Only a slight variation is found in resonance frequency. The changes in resonance amplitudes are larger. For practical use in harsh radiation environments, piezoelectric GaPO$_4$-PWAS is shown to be an excellent candidate.

![Figure 6 GaPO$_4$-PWAS in plane](a) resonance frequency (b) resonance amplitude

![Figure 7 GaPO$_4$-PWAS thickness mode](a) resonance frequency (b) resonance amplitude

### 4.2 Effect of capacitance on PWAS

Figure 8 shows the effect of gamma radiation on capacitance of (PZT-PWAS and GaPO$_4$-PWAS). A degradation behavior of capacitance value in the PZT-PWAS was observed. Capacitance value of PZT-PWAS decreases from 3.2 nF to 3.07 nF after exposing to gamma radiation for 20 hours at 100Gy/hour. GaPO$_4$-PWAS doesn’t show reasonable degradation behavior in electrical properties.
The PZT material used in PWAS transducer is a ferroelectric material and, for most ferroelectric materials the existence of domain structure or domain wall make a significant influence on the material properties. In PZT solid solution system the material properties may be changed due to change in the domain wall motion. The material properties of PWAS transducer depend on both intrinsic and extrinsic properties. The material properties from a single domain are denoted as the intrinsic properties of the material, while the contributions from extrinsic parts of the material mainly from domain wall motion. It is expected that both intrinsic and extrinsic contributions are influenced by domain wall motion. So the dielectric properties depend on both extrinsic and intrinsic contribution of PZT material. There are several polarization mechanisms contributing to the dielectric response [17]: (i) electric polarization: the relative displacement of the negatively charged electron shell with respect to the positively charged core; (ii) ionic polarization: as observed in ionic crystals and describes the displacement of the positive and negative sublattices under an applied electric field; (iii) orientation polarization: the alignment of permanent dipoles via rotational movement; (iv) space charge polarization: polarization due to spatial inhomogeneities of charge carrier densities; (v) domain wall motion: movement of high energy domain wall due to reorientation of dipole. Domain wall motion plays a decisive role in ferroelectric materials and contributes significantly to the overall dielectric response. The change in electrical capacitance may arise from the pinning of domain walls, this process restricts domain to reorient in favorable direction due to irradiation which is the primary degradation mechanism. Due to depinning overall piezoelectric effect may change and can cause change in electrical properties.

5. CONCLUSIONS

A compensation technique can be proposed base on the fact that, the changes in resonance frequencies have a linear relationship with radiation dose. This relation could provide radiation compensation in nuclear environment and could be useful for proper damage detection. A details experiment was conducted to evaluate PWAS after gamma radiation. Changes in resonance frequency and amplitude in the sensors were evaluated. It was found that, for PZT-PWAS, slight variation in resonance frequency for both in plane and thickness mode was observed. Where, the changes in resonance amplitudes are larger. For GaPO4, E/M impedance/admittance spectra don’t show any reasonable change after gamma irradiation. This research could provide a number of future benefits: (a) radiation compensation for proper damage detection (b) developing proper damage detection method in SHM applications for nuclear environment (c) a proper SHM technique in nuclear environment with limited number of transducers (d) developing a method for transducer characterization to separate defective transducers for impedance and admittance based SHM technique.
ACKNOWLEDGMENT

The authors would like to acknowledge the help from The School of Medicine, USC for irradiation facility. The authors are grateful for the financial support from US Department of Energy (DOE), Office of Nuclear Energy, under grant numbers DE-NE 0000726 and DE-NE 0008400.

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