TECHNICAL PAPER

Experimental study of gamma radiation induced degradation of a piezoresistive pressure sensor

Vinod Belwanshi[1,2] · Sebin Philip[1] · Anita Topkar[1,2]

Abstract

This paper reports the experimental investigation of gamma radiation induced degradation of a piezoresistive pressure sensor with total dose exposure up to ∼ 40 Mrad. The output response of a piezoresistive pressure sensor and the magnitude of piezoresistors constituting the Wheatstone bridge were measured at various total doses after exposure to gamma radiation using a Cobalt-60 source. The bridge piezoresistor magnitudes did not show any change after irradiation up to a total dose of 40 Mrad. However, the pressure sensor exhibited a significant degradation in the performance in terms of reduced sensitivity and linearity after the exposure to 10 Mrad. The pressure sensor demonstrated a decrease of response by about 75% beyond the gamma dose of 30 Mrad. Additionally, a small increase in the offset voltage and increased hysteresis in the pressure response were also observed.

1 Introduction

Microelectromechanical systems (MEMS) have a wide range of applications in several fields of science and engineering such as automotive, process control industry, space, medical, biomedical, consumer electronics, RF communications, optical displays, etc. MEMS technology allows close integration of sensors/actuators along with the signal processing electronics on the same chip, particularly for silicon based technologies, for the realization of system on chip (SOC), or system in the package (SIP). Compact, low power, high performance sensing or actuating system could be built using such SOC or SIP approach. Reliability of MEMS is an important crieteria for the deployment of MEMS based systems in various applications as mentioned above. As MEMS incorporate mechanically moving parts, specific reliability tests are required for evaluating the mechanical reliability in addition to standard electrical reliability tests which are employed for integrated circuits (Sundaram et al. 2011).

Standard methods for the evaluation of reliability of MEMS involve accelerated testing, temperature cycling, shock and vibrations, burn in, etc. Due to advancement in MEMS technology, microsystems are being increasingly used in harsh or inaccessible environments involving high temperature, high pressure, (bio)-chemical, mechanical disturbances such as shock and vibrations, electromagnetic noise, radiation, or high vacuum (French et al. 2016). Such environments are encountered in the industries such as oil/process, chemical, automotive, space, aircraft, medical implants, etc. (French et al. 2016). Since most of the industrial or consumer applications of MEMS does not involve operation in harsh environments, standard relia-bility test methods used for commercially available MEMS do not include testing of MEMS reliability or failure in such environments. For applications such as space and near nuclear reactors, the radiation hardness of MEMS is of prime concern. Radiations are classified as (1) charged particle radiations such as electrons, protons and other charged particles and (2) uncharged radiations such as neutrons, X-rays, gamma rays. These radiations loss energy in the matter through ionizing energy loss or non ionizing energy loss. Heavy particles such as protons, neutrons and other charged particles are known to create displacement damage in silicon (Srour et al. 2003). Charged particles, X-rays and gamma rays cause ionization of the materials which lead to trapping of charge carriers in electrically active defects.

✉ Anita Topkar
anita@barc.gov.in

[1] Electronics Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India

[2] Homi Bhabha National Institute, Anushaktinagar, Mumbai 400094, India

A lot of research has been carried out to understand radiation induced degradation of silicon based devices and integrated circuits using ionizing radiations such as gamma radiation (Ma and Dressendorfer 1989; Faccio and Cervelli 2005). However, radiation induced degradation of MEMS is still not well understood because of higher complexity in terms of materials, packages, types of input–output parameters and sensing or actuating mechanisms. Reviews of radiation effect on silicon based MEMS and emerging MEMS and NEMS based on a variety of materials have been presented by Shea (2009) and Arutt et al. (2017) respectively. A few studies have been reported on experimental investigation of radiation effects on MEMS technology based sensors (Knudson et al. 1996; Lee et al. 1996; Edmonds et al. 1998; McClure et al. 2002; Holbert et al. 2003; Miyahira et al. 2003; Marinaro et al. 2008; Shea 2009; Wang et al. 2011; Arutt et al. 2017; Pitt et al. 2017). The effect of ionizing radiations such as gamma, protons and non ionizing radiations such as neutrons on different types of MEMS has been presented in these reports. It has been observed that ionizing radiation causes significant degradation in the performance of accelerometers (Knudson et al. 1996; Lee et al. 1996; Edmonds et al. 1998; Pitt et al. 2017), optical mirrors (Miyahira et al. 2003), RF relay switches (McClure et al. 2002) and resonators (Wang et al. 2011). The operation of these devices is based on the electrostatic or piezoelectric actuation of the mechanical elements. The degradation in the performance of these devices has been attributed to the accumulation of radiation induced trapped charges in the dielectric/silicon dioxide layer under the mechanical element of the MEMS devices due to the radiation environment. Also, the failure mode was observed to be strongly dependent on the device architecture and technology used for the fabrication.

The published literature on the study of radiation effect in piezoresistive MEMS devices is very limited. A study of radiation effect due to proton fluence of the order of $10^{16}/cm^2$ on MEMS silicon strain gauges has shown that the radiation observed damage is because of the displacement damage in silicon which resulted in the change of effective gauge factor (Marinaro et al. 2008). Considering the expected total particle fluence of $10^{11}/cm^2$ which would be accumulated in a device over a 30 years lifetime, from this study, it was concluded that the silicon strain gauges are relatively robust to radiation damage for the operation at high altitudes. Holbert et al. have demonstrated the degradation in the output response of a bulk micromachined piezoresistive accelerometer and a silicon on insulator (SOI) pressure sensor under high gamma dose (Holbert et al. 2003). Both sensor types were found to experience similar performance degradation with a drift in offset voltage and a slight increase in sensitivity. The drift in offset voltage for all sensors was attributed to the change

in resistance of the silicon piezoresistors due to the decrease of the volume for current flow. The ionizing radiation induced generation of oxide and interface trapped hole charges was considered to create a depletion region surrounding the periphery of the gage resistors causing reduction of volume for current flow (Holbert et al. 2003).

Silicon is prominently used in piezoresistive MEMS as an electrical element as well as a mechanical structural element. Even at the high end of typical doses of Mrad for space applications, the amount of damage to silicon as a mechanical element is considered rather small with no remarkable change in Young's modulus (Shea 2009). Radiation based performance degradation of MEMS is strongly dependent upon the sensing/actuation mechanism, device design and various material used for the fabrication. Hence the radiation induced degradation of capacitive MEMS such as accelerometers, gyros, etc., has been observed to be different than that for MEMS based on piezoresistive sensing mechanism. MEMS technology based piezoresistive pressure sensor is being the most widely used MEMS sensor for process control instrumentation in near nuclear reactor applications. Hence radiation induced degradation and failure mechanism of the pressure sensors need to be understood for improving the radiation hardness of such sensors. Therefore, we have examined the performance degradation of a MEMS technology based piezoresistive pressure sensor under high gamma radiation environment. The results of this experimental study are presented in this paper.
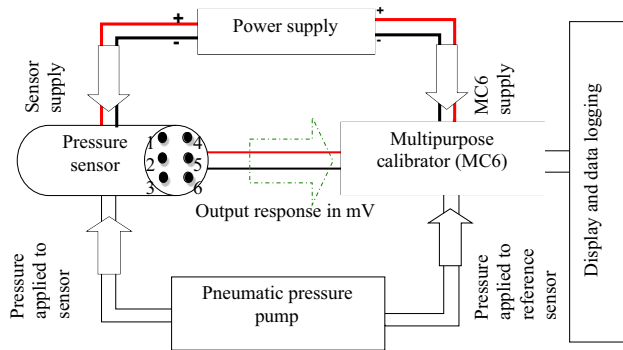
2 Experimental

The gamma radiation induced degradation of the piezoresistive pressure sensor was investigated by exposing the sensor to gamma radiation in a Cobalt-60 chamber. The schematic diagrams of the pressure sensor chip and the packaged sensors used for this study are given in Fig. 1a–c. The sensor comprised of a stainless steel (SS) oil filled housing with the silicon chip isolated by a thin SS diaphragm from the sensing medium. The silicon pressure sensor chip incorporated p-type piezoresistors on a n-type diaphragm. The chip was bonded to a glass substrate and was mounted on a substrate header with pins provided for electrical connections. Prior to gamma exposure, the pressure response of the sensor was measured using a pressure calibrator. The schematic diagram of the experimental setup used for the measurement of pressure response is presented in Fig. 2.

A multipurpose calibrator (MC-6, Beamex) was used as a data logger and calibrator. The input pressure to the pressure sensor under test was applied by a pneumatic pressure pump, (PGPH, Beamex). The piezoresistive
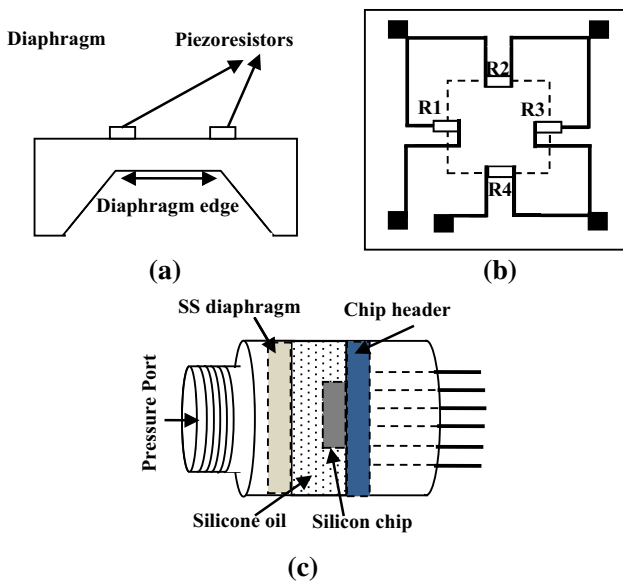
Fig. 1 Schematic diagram of the pressure sensor **a** cross section of the sensor chip, **b** top view showing piezoresistors over the diaphragm, **c** packaged sensor

Fig. 2 Schematic diagram of the experimental setup used for the measurement of pressure response after exposure to gamma radiation

pressure sensor was powered with a 5 V external power supply. The four bridge resistances of the pressure sensor were measured using a high resolution digital multimeter. The measurements were carried out up to a maximum pressure of 50 bar. For studying the gamma radiation effect, the pressure sensor was kept in a Cobalt-60 chamber for specific durations at a dose rate of 1.05 krad/min. Since, in situ characterization was not feasible, the sensor was irradiated for a particular dose and was subsequently taken out from the irradiation chamber for the characterization of pressure response in between the irradiations. The measurements with gamma radiation exposure were carried out up to the total dose of 40 Mrad at which the permanent failure of the pressure sensor was observed. The results of various measurements performed are presented in the next section.

3 Results and discussion

The pressure sensor response was evaluated in terms of sensitivity, offset voltages and hysteresis for various total doses of gamma radiation. Also, the bridge resistances were measured for various total dose exposures in order to verify if there is any change in the resistor values. The results are presented and discussed below.

3.1 Response for increasing pressure (forward sweep) and for decreasing pressure (backward sweep)

The pressure sensor response in terms of output voltage for various input pressures was measured using pressure sweep measurements. The pressure was increased from zero to 50 bar (forward sweep) and then decreased from 50 bar to zero again (backward sweep). The data recorded for forward sweep is plotted in Fig. 3.

The plots obtained at various total dose exposures show that there is a significant decrease in output response (voltage) with accumulated dose of gamma radiation. In a similar manner, the output voltage data is plotted for the backward sweep (Fig. 4). From Figs. 3 and 4, it can be seen that the degradation of pressure sensor response is significant after total dose exposure of 10 Mrad. Moreover, a small increase in the offset voltage with the increase of accumulated gamma dose is also observed for the forward and backward sweeps.

The comparison of the data presented in Figs. 3 and 4 indicate that after gamma radiation exposure, the response of pressure sensor for increasing pressures and for decreasing pressures is not identical. The deviation of response from the pre-rad value for doses of 20 Mrad or
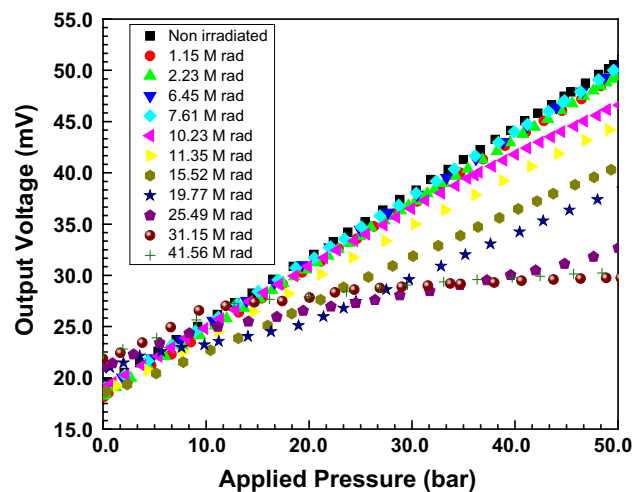

Fig. 3 Forward sweep measurements showing the pressure sensor performance with total gamma dose
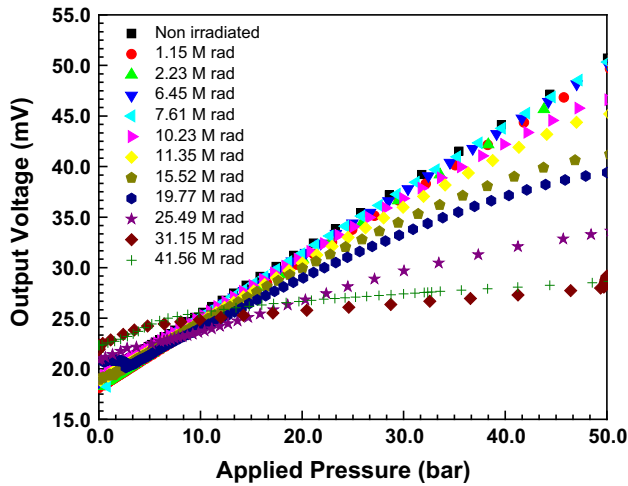
Fig. 4 Backward sweep measurements showing the pressure sensor performance with total gamma dose

higher is more for the forward sweep as well as backward sweep compared to that observed at lower doses. Using the data plotted in Figs. 3 and 4, the pressure sensor response for various total doses of the gamma radiation was examined at a 50 bar applied pressure (Fig. 5). It is observed that there is no significant decrease of the output voltage up to a total dose of 10 Mrad and subsequently the pressure sensor demonstrate a rapid degradation. Beyond total dose exposure of 30 Mrad, the percentage decrease in the pressure sensor output voltage is about 75%. The sensitivity of the pressure sensor was calculated by fitting a straight line to the output voltage vs pressure plot at different gamma doses. The sensitivities obtained at various total doses are plotted in Fig. 6 for forward pressure scans.

The pressure sensor sensitivity decreased from about 0.125 mV/V/bar for the non irradiated sensor to about 0.05 mV/V/bar for the 25 Mrad irradiated sensor. For total
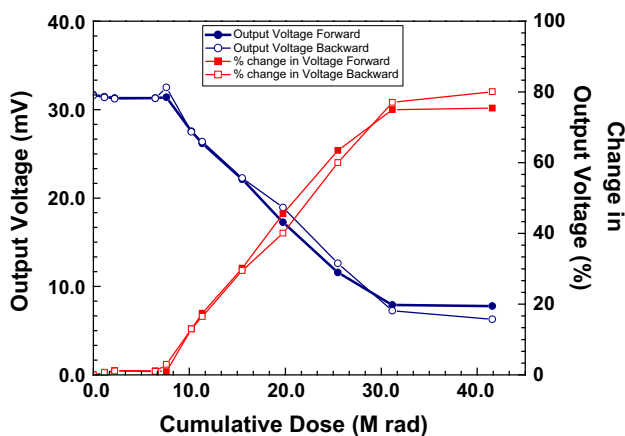
Fig. 5 The output voltage response at 50 bar and percentage change in the output voltage of the piezoresistive pressure sensor due to total gamma dose
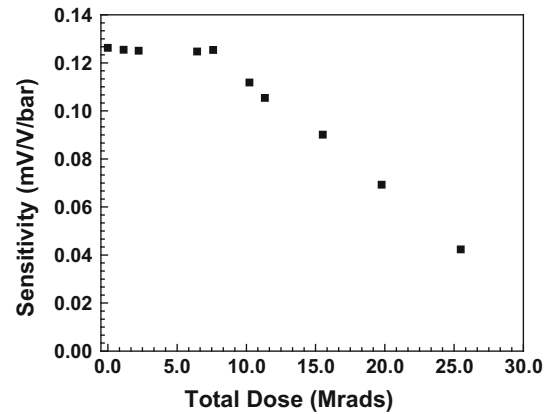
Fig. 6 Changes in the sensitivity of the piezoresistive pressure sensor (in mV/V/bar) with total gamma dose

doses higher than 25 Mrad, the output voltage vs pressure plot was highly nonlinear. Hence the sensitivity could not be extracted using straight line fitting for higher total doses exceeding 25 Mrad.

3.2 Linearity of response

As the response of pressure sensor is theoretically expected to be linear with the input pressure, the data plotted in Fig. 2 was fitted using a linear fitting. The obtained R^2 values (measure of linearity) were in the range of 0.98–1.0 for total doses up to 25 Mrad.

However, for total doses exceeding this dose, the pressure sensor response could not be fitted to a straight line. For lower gamma doses up to 30 Mrad, the pressure sensor shows nonlinear behavior in terms of reduced output voltage for higher input pressures exceeding about 40 bar and for lower input pressures, the response was linear. However, for total doses exceeding 30 Mrad, the pressure sensor shows drastic reduction in output voltage with a highly non linear response.

3.3 Offset voltage

The offset is referred as the output response at the zero input condition. The offset voltages obtained from the data presented in Figs. 3 and 4 at different gamma doses are plotted in Fig. 7. The plot shows a trend of increasing offset voltage after exposure to a total dose of 15 Mrad.

3.4 Hysteresis loop

To verify if the pressure sensor exhibits hysteresis in the response, the response of the piezoresistive pressure sensor was recorded under constant increasing and decreasing applied pressure. Due to gamma radiation exposure, the pressure sensor shows hysteresis of pressure response i.e.
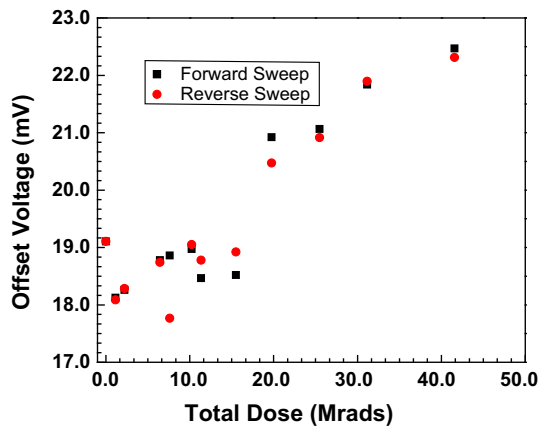
Fig. 7 Offset voltage variation as a function of total gamma radiation dose

Fig. 9 The variation of Wheatstone bridge resistances with total gamma dose

the output at a specific applied pressure is not identical for increasing and decreasing applied pressures. The maximum deviation of the response between increasing and decreasing applied pressure cycles is known as hysteresis. It was observed that prior to irradiation the pressure sensor did not exhibit any hysteresis. However, as shown in Fig. 8, the hysteresis increases with total dose exposure.

3.5 Wheatstone bridge resistance measurement

In order to study if there is any variation of the magnitude of bridge piezoresistors, the piezoresistors were measured using a digital multimeter. The measured values of piezoresistors for various total dose exposures are presented in Fig. 9. The average magnitudes and standard deviation of four piezoresistors from the data plotted in Fig. 9 were calculated. The piezoresistors do not show any significant change due to the gamma exposure and the standard deviations are within 1%.
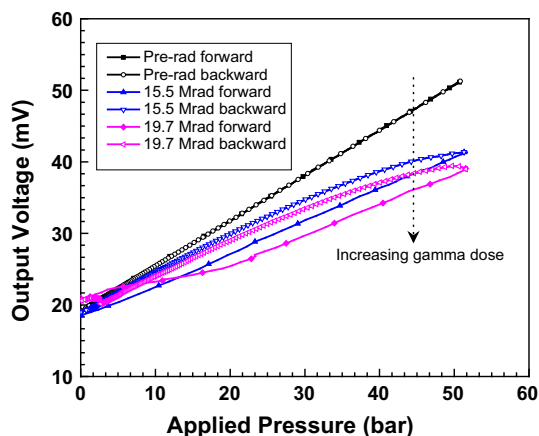

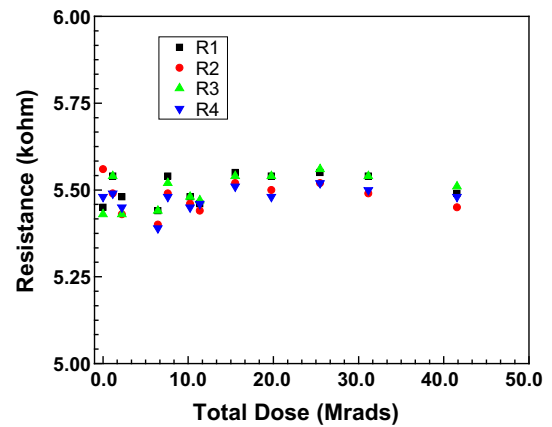Fig. 8 The hysteresis observed in the pressure sensor response due to total gamma dose

4 Conclusions

The effect of gamma radiation on a piezoresistive pressure sensor was experimentally investigated. It was observed that the pressure sensor showed insignificant change in the performance up to total gamma doses of 10 Mrad. However, beyond this dose, the sensor exhibited degradation of various parameters such as decrease of sensitivity, increased hysteresis, increased non linearity of response and marginal increase of offset voltage. The sensor showed significant decrease of sensitivity after 10 Mrad exposure and beyond 30 Mrad, the sensitivity decrease was about 75%.

The sensor used in the present study was packaged with silicone oil and a thin SS diaphragm as isolation media. The operation of such sensor is very complex as it is a system involving mechanical, microelectronics and fluidic parts (Chuan and Chen 2011). The pressure is applied on the SS diaphragm and is transmitted to the silicon membrane through the silicone oil. Hence the changes in the sensor performance in terms of sensitivity, offset voltage and hysteresis observed could be attributed to a combined effect of the degradation of (1) mechanical properties of the silicon diaphragm, (2) electronic properties of piezoresistors, (3) compressibility of the silicone oil medium and (4) mechanical properties of SS isolation diaphragm.

The gamma radiation induced degradation of the properties of individual elements and their combined effect would govern the total degradation of the pressure sensor. There are very limited reports of experimental studies of gamma radiation induced degradation of piezoresistive pressure sensors (McCready et al. 2002; Holbert et al. 2003). The radiation induced degradation of the pressure sensor was observed to be sample dependent. McCready et al. reported that commercially available piezoresistive pressure transducers (Kulite Semiconductor XTE-190-25A

and XCE-062-25A) failed after radiation exposure to 10–100 krad (McCready et al. 2002). Their subsequent experiment with pressure transducers (Kulite Semiconductor XTE-190-25A) in a pulsed neutron and gamma radiation demonstrated that the pressure transducers withstood total neutron fluence of 8.7×10^{15} n/cm^2 and total gamma dose of 4.4 Mrad (Si). Holbert et al. examined the response of Kulite SOI piezoresistive pressure transducers subjected to a high gamma dose using a Co-60 source (Holbert et al. 2003). The transducers incorporated temperature compensation circuit. They reported a catastrophic failure of a pair of biased Kulite XTE-190-25A pressure transducers at doses of 7.3 and 24.3 Mrad. A pair of transducers irradiated in unbiased mode survived 11 Mrad of gamma dose. From various experiments it was concluded that unbiased versus biased sensor operation does not have a dramatic effect on the catastrophic failure dose. An output voltage drift with no input pressure i.e. offset voltage of 1–3% was observed for the total dose of about 20 Mrad (Holbert et al. 2003). The changes in piezoresistor magnitude were thought to be the cause of this drift. In the present work, the sensor studied was with only the piezoresistors in a Wheatstone bridge configuration without any additional circuit for temperature compensation.

In the present work we do not observe an abrupt failure of the pressure sensor. There is a gradual degradation with total gamma dose and there is no significant change of the piezoresistor magnitude. It has been reported that the radiation induced displacement damage due to protons can produce a change in resistance of the individual piezoresistor elements of silicon strain gauges (Marinaro et al. 2008). This was primarily ascribed to the effect of charge carrier removal due to charge carrier trapping at induced defects. However, Co-60 gamma radiation with energy of about 1 MeV is not expected to cause displacement damage. It has been proposed that gamma radiation causes trapped oxide charges and interface states generation in the silicon dioxide region surrounding the piezoresistors (Holbert et al. 2003). This results in the formation of a depletion edge around the piezoresistors causing effective area for the current flow to reduce and hence increase of piezoresistor values. The increase of piezoresistor magnitude depends on the doping type and concentration, and on the piezoresistor dimensions. The increase is expected to be lower for larger piezoresistors, higher doping concentration and for n type doping. Since the piezoresistor doping in the present case was p type, larger piezoresistor dimensions and higher doping concentration could be the possible reasons for no change in the piezoresistor magnitudes with gamma radiation.

The offset voltage of the sensors exhibited a trend of increasing offset with total dose. The offset voltage of the pressure sensor is caused mainly because of mismatch of piezoresistors due to geometric deviation from the nominal value and stresses generated in the chip during fabrication or packaging (Bao 2005). As the piezoresistors do not show measurable changes due to gamma radiation, the increase of offset voltage at high gamma doses could be attributed to changes in the stresses present in the chip or degradation of mechanical properties of the materials constituting the sensor. Since, no degradation of the piezoresistors was observed, degradation in the mechanical properties of the silicon membranes and other parts, compressibility of filling oil could be the possible cause of performance degradation. A very few studies have examined the effect of radiation on mechanical properties of materials incorporated in MEMS. A significant decrease of modulus of elasticity of a 2 μm thick silicon nitride membrane has been reported with exposure to X-rays (Wells et al. 1995). The changes in Young's modulus of silicon due to non ionizing energy loss (NIEL) has been reported for high proton fluences of the order of 10^{16}/cm^2 (Marinaro et al. 2008). For doses of the order of Mrad, the amount of damage to silicon is considered small resulting in insignificant change in the mechanical properties of silicon (Shea 2009).

From the experiments conducted, it is could be concluded that the observed degradation of pressure sensor response was primarily because of the isolation medium i.e. oil and SS diaphragm. Further experiments would pin point the mechanisms of the degradation of the pressure response. Many applications demand pressure sensors with media isolation using silicone oil and SS diaphragm. Hence for the development of radiation-hard pressure sensors, it would be essential to minimize the radiation induced degradation of the properties of all materials which constitute the pressure sensor.

References

Arutt CN, Alles ML, Liao W et al (2017) The study of radiation effects in emerging micro and nano electro mechanical systems (M and NEMs). Semicond Sci Technol 32:0130051–14

Bao M (2005) Analysis and design principles of MEMS devices. Elsevier

Chuan Y, Chen L (2011) The compensation for hysteresis of silicon piezoresistive pressure sensor. IEEE Sens J 11:2016–2021. https://doi.org/10.1109/JSEN.2011.2105474

Edmonds LD, Swift GM, Lee CI (1998) Radiation response of a MEMS accelerometer: an electrostatic force. IEEE Trans Nucl Sci 45:2779–2788. https://doi.org/10.1109/23.736528

Faccio F, Cervelli G (2005) Radiation-induced edge effects in deep submicron CMOS transistors. IEEE Trans Nucl Sci 52:2413–2420. https://doi.org/10.1109/TNS.2005.860698

French P, Krijnen G, Roozeboom F (2016) Precision in harsh environments. Microsyst Nanoeng 2:16048. https://doi.org/10.1038/micronano.2016.48

Holbert KE, Nessel JA, McCready SS et al (2003) Response of piezoresistive MEMS accelerometers and pressure transducers to high gamma dose. IEEE Trans Nucl Sci 50:1852–1859. https://doi.org/10.1109/TNS.2003.821373

Knudson AR, Buchner S, McDonald P et al (1996) The effects of radiation on MEMS accelerometers. IEEE Trans Nucl Sci 43:3122–3126. https://doi.org/10.1109/23.556914

Lee CI, Johnston AH, Tang WC et al (1996) Total dose effects on microelectromechanical systems (MEMS): accelerometers. IEEE Trans Nucl Sci 43:3127–3132. https://doi.org/10.1109/23.556915

Ma TP, Dressendorfer PV (1989) Ionizing radiation effects in MOS devices and circuits. Wiley, New York, pp 218–220

Marinaro DG, McMahon P, Wilson A (2008) Proton radiation effects on MEMS silicon strain gauges. IEEE Trans Nucl Sci 55:1714–1718

McClure SS, Edmonds LD, Mihailovich R et al (2002) Radiation effects in micro-electromechanical systems (MEMS): RF relays. IEEE Trans Nucl Sci 49 I:3197–3202. https://doi.org/10.1109/tns.2002.805406

McCready SS, Harlow TH, Heger AS, Holbert KE (2002) Piezoresistive micromechanical transducer operation in a pulsed neutron and gamma ray environment. In: IEEE radiation effects data workshop, pp 181–186. https://doi.org/10.1109/redw.2002.1045551

Miyahira TF, Becker HN, McClure SS et al (2003) Total dose degradation of MEMS optical mirrors. IEEE Trans Nucl Sci 50:1860–1866. https://doi.org/10.1109/TNS.2003.820764

Pitt EB, Barth EJ, Diggins ZJ et al (2017) Radiation response and adaptive control-based degradation mitigation of MEMS accelerometers in ionizing dose environments. IEEE Sens J 17:1132–1143. https://doi.org/10.1109/JSEN.2016.2640199

Shea HR (2009) Radiation sensitivity of microelectromechanical system devices. J Micro/Nanolithogr MEMS MOEMS 8:31303–31311. https://doi.org/10.1117/1.3152362

Srour JR, Marshall CJ, Marshall PW (2003) Review of displacement damage effects in silicon devices. IEEE Trans Nucl Sci 50:653–670. https://doi.org/10.1109/TNS.2003.813197

Sundaram S, Tormen M, Timotijevic B et al (2011) Vibration and shock reliability of MEMS: modeling and experimental validation. J Micromech Microeng. https://doi.org/10.1088/0960-1317/21/4/045022

Wang L, Tang J, Huang QA (2011) Gamma irradiation effects on surface-micromachined polysilicon resonators. J Microelectromech Syst 20:1071–1073. https://doi.org/10.1109/JMEMS.2011.2162495

Wells GM, Chen HTH, Wallace JP et al (1995) Radiation damage-induced changes in silicon nitride membrane mechanical properties. J Vac Sci Technol B Microelectron Nanom Struct Process Meas Phenom 13:3075–3077