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Effects of gamma radiation on suspended silicon nanogauges bridge used for MEMS transduction

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Abstract

This paper proposes a study on the resilience to radiation of MEMS sensors based on piezoresistive transduction by means of suspended silicon nanogauges. It is particularly interesting for applications in severe environment like in space or in nuclear plant. This work shows that the resistivity of a single nanogauge exhibits a sensitivity of 16.5 ppm/kGy whereas the silicon nanogauges bridge used for MEMS transduction is immune to radiation with a variation of – 4 ppm/h, like in normal operation. It is the consequence of the differential measurement at the terminals of the two nanogauges that enables to cancel radiation effects.

1. Introduction

Top-down integration of P-doped suspended silicon nanogauges has allowed the compact integration of state-of-the-art Inertial Measurement Unit (IMU) [1]. Therefore, piezoresistive nanowires (0.25×0.25×5 μm^3) can efficiently be used for motion read-out of high performance static or resonant MEMS sensors. This transduction mechanism has already been successfully implemented in various MEMS sensors such as, for example, accelerometers, gyroscopes and pressure sensors [2,3,4,5]. Initially developed for consumer applications (smartphone, video game …), the M&NEMS platform from CEA-Leti offers high performance that could be used for high-end applications (automobile, space, robotics …). Nonetheless, it leads to the emergence of new problematics such as the sensitivity to radiation [6]. This is common to several new technologies used for MEMS and NEMS sensors as 2D materials, piezoelectric sensors, opto-mechanical systems, etc. For example, space exploration and the use of robots for nuclear decommissioning require sensors to be resilient to high radiation dose in order to maintain the robot in operation during the mission [7,8]. Thus, it is fundamental to confirm the capability of MEMS and NEMS sensors to address these applications.

The radiation dose is measured in gray (Gy). This unit corresponds to the absorption of one joule of radiation energy per kilogram of matter. Table 1 gathers typical thresholds of radiation effects on human.

Table 1
Typical thresholds according to absorbed radiation dose (source: Wikipedia)

Dose	Effect
1 mGy	Average annual dose of gamma radiation in France
10 mGy	Abdomen medical scan
1.2 Gy	Average dose absorbed by Hiroshima survivor within a 10 km radius
> 5 Gy	Lethal dose for human
15 kGy	Specifications for space applications (ESCC)

The radiation effects on accelerometers and pressure sensors based on piezoresistive detection have already been studied in 2003 at Arizona State University [9]. A good resilience to gamma radiation up to tens of kGy has been demonstrated allowing these sensors to work efficiently in severe environments. The small remaining sensitivity to gamma radiation is dependent on the section of the piezoresistor and on the dopants' type and

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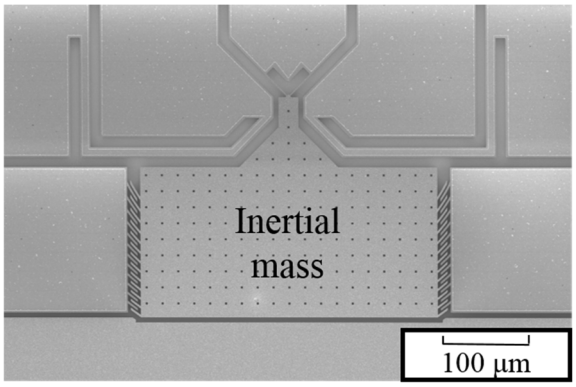
concentration [9]. In P-doped piezoresistor, it can be explained by the generated trapped positive charges in the surrounding oxide layer [8]. It induces an electric field across the piezoresitive structure. To remain continuous at the boundary Si-SiO_2, positive charges from doping in silicon migrate towards the center of the piezoresistor. A depletion region that changes electrical conduction properties is generated [9]. The smaller the section, the larger the effect on the resistivity. Nonethelesss, the larger the dopants concentration, the smaller the depletion region. Indeed, charges recombination will be localized in a small area. For M&NEMS nanogauges, the small size of the piezoresitor is counterbalanced by the high dopants concentration ($5x10^{19}$ at.cm^{-3}).

The objective of this study is to evaluate the behavior of suspended piezoresistive nanogauges based MEMS sensors under gamma radiation (γ) with a dose rate of 600 Gy/h during one week in order to reach a total dose of 100 kGy. It covers the needs for space applications as mentioned in the ESSC (European Space Components Coordination) specification that requires a resilience to radiation up to a total dose of 15 kGy with a "typical" dose rate between 3.6 Gy/h and 1 800 Gy/h.

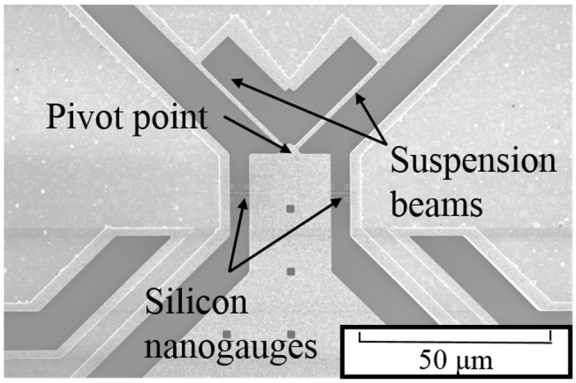
2. Device and experimental setup description

The device used in this study is a static accelerometer with piezoresistive transduction by means of two suspended silicon nanogauges. The inertial mass (Fig. 1.(a)) is attached to the substrate by two suspension beams that create a pivot point at their intersection (Fig. 1.(b)). When an acceleration is applied to the sensor, the mass is free to move around the pivot point putting alternatively the two nanogauges, mounted in a half Wheatstone bridge, into compression and tension respectively (Fig 1.(c)). The interest of using a half Wheatstone bridge is to cancel the effects that are common to the two nanogauges and to measure only the resistance variation resulting from the displacement of the mass thanks to a differential measurement at their terminals. It has already been demonstrated that this method allows to cancel temperature effects [1].

One can assume that the two nanogauges statistically absorb the same dose of gamma radiation when exposed to a given gamma radiation source. As a result, the radiation effects are similar for the two nanogauges. Their resistances R_1 and R_2 present a relative variation that can be expressed according to the temperature variation dT, the radiation dose $d\gamma$ and the deformation of the nanogauges $d\epsilon$ by:



(a)



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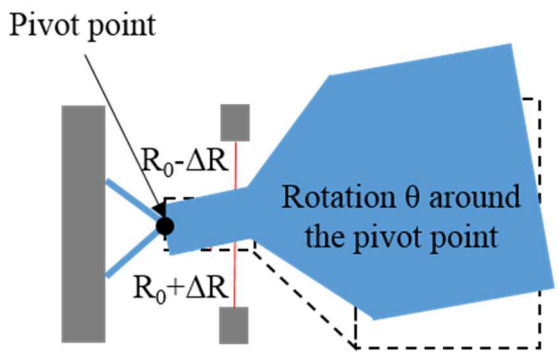


(c)

Fig. 1. SEM image (a) of the x-axis accelerometer before packaging and (b) Zoom on pivot area; (c) Principle scheme showing the displacement of the inertial mass around the pivot point during operation.

$$dR_1/R_0 = \alpha_{TCR}dT + \alpha_\gamma d\gamma - \Pi_l d\epsilon \quad (1)$$
$$dR_2/R_0 = \alpha_{TCR}dT + \alpha_\gamma d\gamma + \Pi_l d\epsilon \quad (2)$$

with R_0 the value of the resistance at rest, α_{TCR} the temperature coefficient of resistance, α_γ the radiation dose dependant coefficient of resistance

and Π_l the piezoresistive gauge factor. For $\Pi_l = 45$, typical value for M&NEMS nanogauges, and for a stress of 200 MPa, allowing to remain in the linear regime, the maximum resistance variation due to the displacement of the mass is estimated at around $5x10^4$ ppm or 100 Ω.

In order to study radiation effects on the piezoresistive transduction, the common mode cm and the differential mode dm can be defined:

$$cm = (\ln(R_1) + \ln(R_2))/2 \quad (3)$$
$$dm = (\ln(R_1) - \ln(R_2))/2 \quad (4)$$

The differential of these two modes gives:

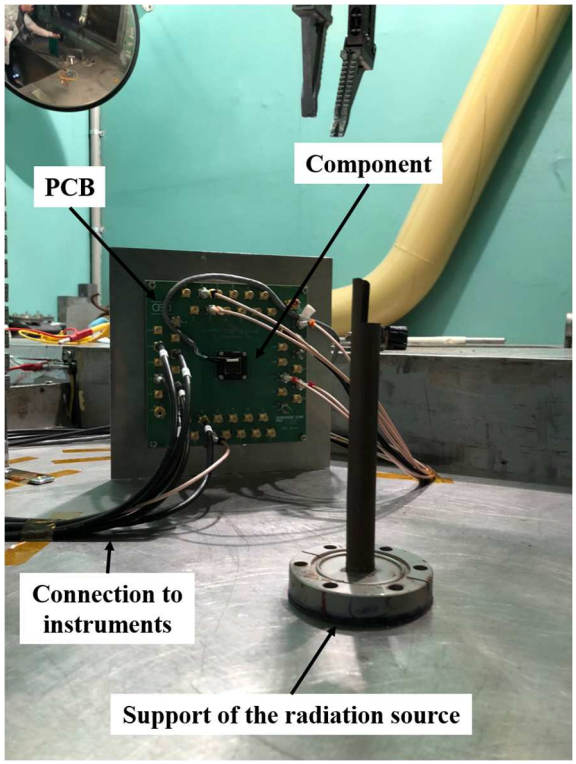
$$d(cm) = \alpha_{TCR} dT + \alpha_\gamma d\gamma \quad (5)$$
$$d(dm) = \Pi_l d\epsilon \quad (6)$$

These two modes allow to decouple the common contributions of the two nanogauges (temperature and radiation) and the mechanical contribution. As a result, dm will be used for the useful signal of the sensor. The results presented in this paper are obviously transposable to other types of components that integrate half Wheatstone bridge or full Wheatstone bridge in the same configuration.

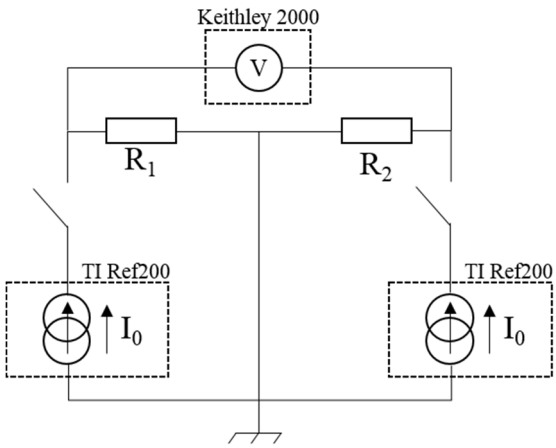
The accelerometer is mounted in a ceramic package to report connection on a printed circuit board (PCB) (Fig. 2.(a)). The two nanogauges are biased by a current I_0 of 100 µA (TI Ref200) and the voltage at their terminals is measured every 5 minutes with a precision voltmeter (Keithley 2000) and a switching matrix (Fig. 2.(b)). Coaxial cables of 12 m length are connected to the PCB on the one hand, inside the radiation cell, and to instruments on the other hand, outside the radiation cell. A Platinum temperature sensor (Pt100), resilient to radiation, is used to record the temperature during the test. The PCB is positioned into the radiation cell at a specific distance (around 50 cm) of the support of the radiation source (Fig. 2.(a)). Before the experiment, this distance has been determined theoretically in order to obtain the expected dose rate on the component (600 Gy/h). Then, it has been verified experimentally by using a Geiger counter.

In order to evaluate the radiation effects on the suspended silicon nanogauges bridge, the experiment is done in two steps for three bridges:

- Before irradiation: Nanogauges resistance is measured during 48 hours with the same instruments and in the same conditions
- During irradiation: Nanogauges resistance is measured during 160 hours (nearly one week) in the radiation cell in the presence of the gamma radiation source (Cobalt 60) with a constant dose rate.



(a)



(b)

Fig. 2. (a) Installation in the radiation cell showing the distance between the radiation source and the PCB as well as the cables used for connection with instruments outside the cell; (b) Experimental setup used to measure nanogauges resistance (switching matrix is represented by two switches).

The study has been performed simultaneously on three components and the results obtained for the three bridges are similar. For the sake of clarity, the

results presented in the next sections are based on a single bridge.

3. Characterization of a suspended silicon nanogauges bridge before irradiation

The results of the first step of the study are presented in this section. They allow to extract the resistance temperature coefficient of the nanogauges and to evaluate the variation of the sensor signal without inertial forces and radiation. The resistance evolution with time of the two nanogauges is represented in Fig. 3.

We can observe resistance fluctuations that can be related to the temperature variation during the two-day test. In the section 2, the nanogauges resistance models indicate their dependence on the displacement of the inertial mass, on the temperature and on the radiation dose (Eq. 1 & 2). In this section, the device under test (DUT) is tested at rest ($d\epsilon = 0$) and it is not submitted to radiation ($d\gamma = 0$). As a result, the resistance is only temperature-dependent. In order to evaluate this contribution, we plot cm (Eq. 3) as a function of temperature (Fig. 4.(a)). A linear curve fitting of experimental points allows to extract α_{TCR} = 1 402 ppm/K. This is in good agreement with the theoretical value expected for P-doped silicon at 5x10^{19} at.cm^{-3} [10]. cm that initially fluctuates by 3 000 ppm is reduced to 200 – 300 ppm after temperature correction illustrated by the deviation of experimental points from the linear curve fitting. The remaining fluctuation can be the consequence of non-optimized experimental conditions. Indeed, the temperature sensor is not inside the ceramic packaging that could induce a small error between measured and effective temperature of sensor environment. It represents a rejection of temperature effects of one order of magnitude that is fully acceptable for silicon nanogauges bridge integrated in M&NEMS sensors.

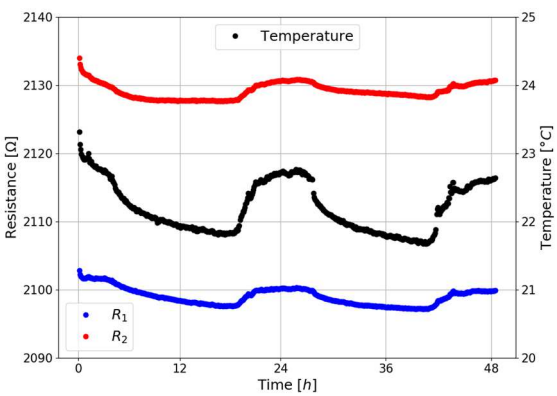
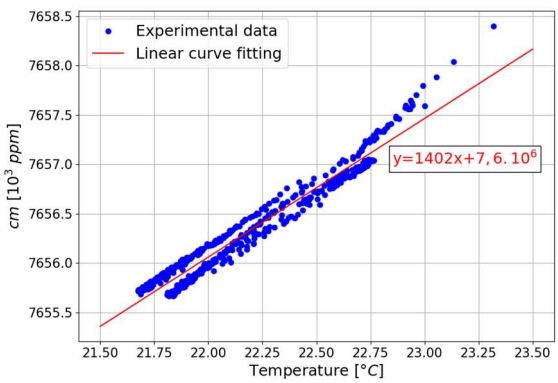


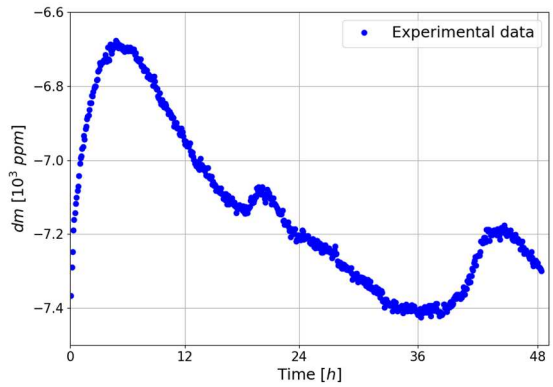
Fig. 3. Evolution of the two nanogauges resistance of the bridge during 48 h before irradiation (raw data). The temperature is also given as a function of time.

The rejection of temperature effects can also be illustrated by Fig. 4.(b) that represents dm (Eq. 4) as a function of time. In the previous section, we have shown that dm, used as useful signal for the sensor, only depends on the displacement of the inertial mass. The nanogauges bridge is characterized with the DUT at rest and Fig. 4.(b) validates the good rejection of temperature effects. Nonetheless, stress relaxation in the substrate could generate stress in nanogauges and thus variation of dm. As a result, a relatively low but non-zero variation of the useful sensor signal is obtained at – 6 ppm/h.

These results are fundamental for the study of radiation effects on nanogauges because the presence of the radioactive source in the vicinity of the DUT will considerably increase the ambient temperature. The nanogauges resistance can be corrected, using α_{TCR}, to eliminate the temperature effects. The



(a)



(b)

Fig. 4. Characterization of the suspended silicon nanogauges bridge before irradiation: (a) cm as a function of the temperature (TCR determination); (b) dm as a function of time (sensor useful signal).

resistance at 25°C is given by:

$$R_0 = \frac{R_{1,2}}{1+\alpha_{TCR}(T-25)} \quad (7)$$

with $R_{1,2}$ the resistance of the nanogauge 1 or 2.

4. Radiation immunity of a suspended silicon nanogauges bridge

For the second step of the study, during irradiation at 600 Gy/h, we can also study the evolution of R_1 and R_2 with time (Fig. 5). A variation lower than 0.5 % is observed during the test in the radiation cell. It is the consequence of the increasing Total Integrated Dose of radiation and temperature modification. It is in accordance with the small effect of gamma radiation on the Wheatstone bridge signal discussed by Belwanshi *et al.* in a recent paper. Indeed, they do not observe significant changes of the piezoresistors value up to 400 kGy with a dose rate of around 600Gy/h (standard deviation within 1 %) [11]. Nonetheless, they have observed changes of piezoresistive pressure sensor performances under radiation in terms of linearity, sensitivity and offset voltage. It has been attributed to mechanical modification of the sensor structure. It brings a new perspective for future works with mechanical characterization of M&NEMS accelerometers under radiation that could provide additional interesting results.

After temperature correction (Eq. 7), cm, illustrated by Fig. 6.(a), is only radiation dependent (Eq. 5). A linear curve fitting allows to extract a radiation dose dependent coefficient of resistance, α_γ, equal to 16.5 ppm/kGy. We can observe several singularities between experimental points and linear curve fitting (Fig. 6.(a)):

- Up to 3 kGy, the divergence remains unexplained. It could be the consequence of a double radiation dose dependent coefficient of resistance. A first one when the nanogauges are not irradiated yet and a second one, lower, after a period of irradiation synonym of a saturation regime.
- Between 15 kGy and 18 kGy, the temperature follows the same trend. It could be the consequence of a non-optimal temperature measurement and correction.
- At 55 kGy and 95 kGy, the radiation source is isolated in order to allow human intervention in the cell. It could be the consequence of manipulation of cables used between the PCB and the instruments.

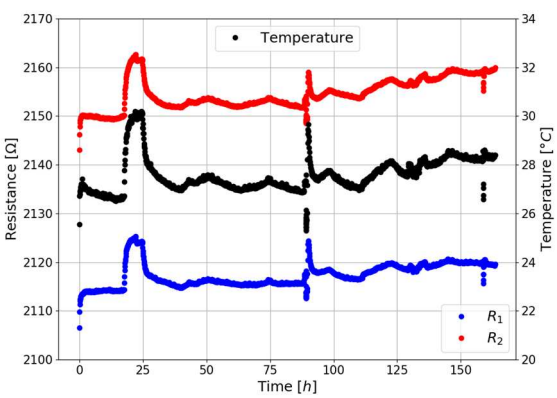
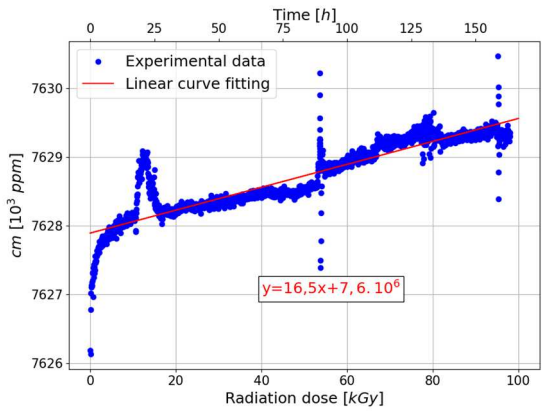
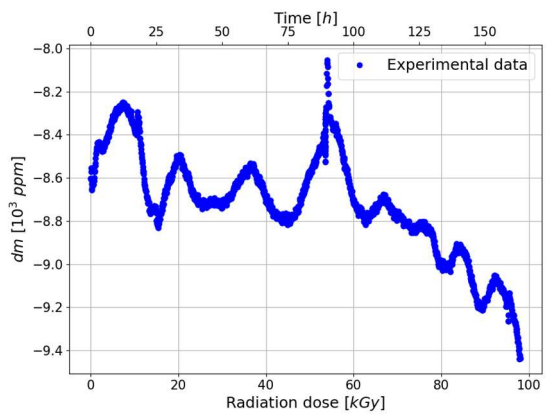


Fig. 5. Evolution of the two nanogauges resistance of the bridge during irradiation at 600 Gy/h (raw data). The temperature is also given as a function of time.



(a)



(b)

Fig. 6. Characterization of the suspended silicon nanogauges bridge during irradiation at 600 Gy/h: (a) cm as a function of the radiation dose (determination of the radiation dose dependent coefficient of resistance); (b) dm as a function of the radiation dose (sensor useful signal). Exposure time is given on top axis.

As for temperature effects, most of variation due to radiation are rejected by studying dm (Eq. 3), represented as a function of the radiation dose in Fig. 6.(b). A variation of only – 4 ppm/h is measured during one week. This variation is of the same order of magnitude than without radiation. As a result, the useful sensor signal is immune to radiation up to a total dose of 100 kGy with a dose rate of 600 Gy/h. Radiation leads to electrical changes in semiconductors but also mechanical changes due to the interaction with high energy photons and bombarded energetic particles [12]. It can generate stress modification in silicon layer and thus explain the fluctuation of dm observed in Fig. 6.(a). Indeed, the stress in the silicon layer is transmitted to the nanogauges through their anchors resulting in resistance modification by piezoresistive effect.

5. Conclusion

Suspended silicon nanogauges bridge based MEMS seems to be a good candidate for applications that require a high resilience to gamma radiation. This brings new opportunities for M&NEMS technology to reach a new market with higher requirements. As exposed in the introduction, space applications and robotics' applications in severe environment could enter in the scope of this technology. Indeed, the ^{60}Co γ radiation effects on the resistivity are relatively low with a radiation dose dependent coefficient of resistance of 16.5 ppm/kGy, reduced by the use of a half Wheatstone bridge and the differential mode. The latter allows a good rejection of temperature and radiation effects.

Future works include the improvement of the assembly in the ceramic package (MEMS sensor and temperature sensor). Characterization of mechanical resonance during irradiation could also be an interesting experiment to evaluate their effects on mechanical properties. Finally, we have developed test structures with silicon nanogauges bridge connected to the substrate by flexible anchors. It will be interesting to study the radiation response of this type of structure that decouples radiation effects and the consequence of substrate stress relaxation on nanogauges resistance.

Acknowledgements

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