Evaluation of silicon tuning-fork resonators under space-relevant radiation conditions

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ABSTRACT

This work reports on irradiations made on silicon bulk-acoustic wave resonators. The resonators were based on a tuning fork geometry and actuated by a piezoelectric aluminum nitride layer. They had a resonance frequency of 150 kHz and a quality factor of about 20000 under vacuum. The susceptibility of the devices to radiation induced degradation was investigated using ⁶⁰Co γ -rays and 50 MeV protons with space-relevant doses of up to 170 krad. The performance of the devices after irradiation indicated a high tolerance to both ionizing damage and displacement damage effects. The results support the efforts towards design and fabrication of highly reliable MEMS devices for space applications.

Keywords: Tuning fork resonator, Oscillator, Proton irradiation, Gamma-ray irradiation, Radiation test, Space application, Micro-electromechanical systems, Reliability.

1. INTRODUCTION

Micro-electromechanical systems (MEMS) resonators are attractive potential candidates for sensing applications, frequency referencing and signal filtering. As a possible substitute for quartz crystal oscillators they promise low power consumption, low fabrication tolerances and ease of integration with IC electronics. The applicability of such resonators in space depends on their ability to operate reliably under the demanding environmental conditions imposed by the spacecraft's trajectory. Radiation induced degradation can cause severe impairment of the device performance. The tolerance of MEMS to radiation depends on the operation principle, the design and the material selection. In consequence of the multisided MEMS typology a wide range of radiation effects and tolerances has been reported and design rules for enhanced radiation tolerance have been proposed [1]. The majority of degradation effects are caused by ionizing damage, especially charge trapping in dielectrics, and structural defects induced by non-ionizing energy losses (NIEL).

First, relevant radiation conditions for space applications are summarized and the choice of the radiation sources is discussed. Then the fabrication of the MEMS devices and the experimental setup for the dynamical characterization of the resonators are described. The following section contains the specifications of the radiation tests, before the results are presented and discussed.

2. CHOICE OF SOURCES FOR RADIATION HARDNESS ASSESSMENT

The composition, flux density and energy of the radiation are subject to considerable variations over time and orbit, and radiation hardness assessment tests can only approximate the conditions in operation [2],[3]. The main contributions to radiation damage are made by electrons, protons and electron-induced Bremsstrahlung. Due to the complexity and variability of conditions encountered during space missions the effect of radiation is commonly simulated by a limited

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Figure 1: Electronic stopping power of protons, electrons and secondary electrons created by γ -rays and 10keV x-rays. The figure is adopted from [9], [10] and is containing data from [10](*), [11](*), and SRIM-2008 calculations.

number of radiation sources and energies, reproducing the total doses absorbed over the device lifetime (e.g. conditions specified in [4]). The total ionizing damage dose (TID) absorbed by a space system shielded by 4 mm of aluminum is on the order of 1 krad/year in low earth orbits and 10 krad/year in geostationary orbits [5]. The total dose level usually requested in the qualification testing of generic EEE parts is 100 krad [4]. For comparison, the expected ionizing dose of a tracking detector in the Large-Hadron-Collider (LHC) at CERN is 1 Mrad, obtained after 1.5 years of operation, which is much higher than most space doses [6].

Figure 1 shows the linear energy transfer (LET) of different radiation types versus the particle energy. The LET denotes the ionizing energy deposited per unit length in the track of an impinging particle and is normalized by the material density. The energy range of the proton and electron sources correspond to the energies observed in space [2].

A commonly used source of ionizing damage is γ -rays produced by the radioactive decay of ^{60}Co . The decay to ^{60}Ni occurs under the emission of photons with energies of 1.17MeV and 1.33MeV. Gamma-radiation induced damage is mainly caused by the Compton Effect leading to direct ionization and energy deposition by the secondary electrons. The secondary electron energy is in the range of 0.1-1MeV [7][8]. In devices where the radiation induced damage is correlated with ionization effects, the ^{60}Co γ -rays are expected to produce similar effects as electron irradiation because the spectrum of γ -ray induced secondary electrons closely resembles space-relevant electron spectra [10]. In analogy to this, 10 keV x-rays are expected to reproduce ionization-mediated degradations caused by ~ 10 MeV protons [12]. This hypothesis has been studied in detail in metal-on-silicon (MOS) devices, which are mainly affected by charge trapping in thin oxide layers. In [13] and [14] the threshold voltage shift of MOS transistors has been evaluated under irradiation with protons, electrons and ^{60}Co γ -rays and doses of up to 500 krad(SiO_2). While the radiation-induced change of the threshold differed significantly between 41.4MeV protons and γ -rays a strong correlation between 10keV x-rays and protons was found. These observations have been attributed to variances in the charge yield and in the electron-hole pair distributions [13]. The fraction of electron-hole pairs that escape this initial recombination in the first fractions of a second depends on the electric field in the material and the distribution of electron-hole pairs. Impinging particles with high stopping powers create a dense population of ionization events, whereas for lower stopping powers the mean distance between electron-hole pairs is larger. Therefore the charge yield is larger for radiation with lower stopping power than for radiation with higher stopping power and radiations creating similar distributions of ionization events affect irradiated specimen in a similar way. These experiments indicated that degradation effects due to ionization can be regarded as equivalent between ^{60}Co γ -rays and electrons with space-relevant energies because the two radiation sources have similar LET.

Non-ionizing energy losses cause the displacement of atoms and the creation of vacancies and interstitials. These structural defects may be electrically active, influencing the carrier mobility and minority carrier lifetime. Displacement damage is predominantly caused by heavy ions and protons. The secondary electrons generated by ^{60}Co γ -rays usually carry enough energy to displace atoms from their lattice position and create recoils. The displacement damage induced by ^{60}Co radiation has been investigated theoretically on the basis of the energy distribution of secondary electrons created by Compton scattering of γ -rays [7][8]. However, the obtained NIEL differed significantly between the two

Figure 2: NIEL for electron, proton and ^{60}Co -radiation versus the particle energy. For ^{60}Co the energy of the secondary electrons is shown for the two references [7](‡) and [8](†).

studies. The displacement damage factor ratio K_e/K_γ between 1MeV protons and ^{60}Co radiation was found to be 2.4 in reference [7] and 302 in reference [8], but the reason for this discrepancy was unclear to the authors of the latter paper. However, the total displacement damage induced by electrons and γ -rays is orders of magnitude lower than proton-induced damages (Figure 2).

Heavy ions are less abundant but are important sources of single-event effects due to their large stopping power [3]. However, the feature sizes of the MEMS tuning fork resonators investigated here are on the micron-scale and the operation does not rely on thin depletion regions or p-n junctions. Therefore single-event effects are not expected to affect the devices.

Based on these considerations, the ^{60}Co gamma- and proton-radiation were selected for the radiation hardness assessment tests on the silicon tuning fork resonators.

3. RESONATOR DESIGN, FABRICATION AND CHARACTERIZATION

The tuning fork resonators were fabricated on silicon-on-insulator (SOI) wafers. Their mode of operation and functional layout were based on resonators presented by CSEM previously [15][16][17]. The fork tines were patterned into the device layer by deep reactive ion etching (DRIE). They had a length of 900 μm , a thickness (in the plane of oscillation) of 100 μm and a width of 22 μm . A one micron thick layer of piezoelectric aluminium nitride (AlN), with metallic top and bottom electrodes was used to drive the resonators. The devices were wafer-level packaged by eutectic bonding using a glass cap wafer with through-glass-vias, and the dies were then separated by diamond blade dicing. In the electrically active mode the tines oscillated in the plane of the wafer.

The electrical characterization of the devices was made under controlled conditions using a measurement test setup as shown in Figure 3. The impedance of the resonators was measured by sweeping the excitation frequency across the resonance and recording the impedance's absolute value and phase by a HP4192A impedance analyzer. A LabViewTM program on a personal computer was used to control the impedance analyzer.

The response of the piezoelectric resonators to the driving (AC) voltage was modeled by the Butterworth-van-Dyke (BvD) equivalent circuit [16][18]. Such a circuit is characterized by four parameters which account for the mass, the elasticity and the damping of the mechanical resonator and for the electrical capacitance between the electrodes used for the actuation of the piezoelectric layer. From the impedance curves the four BvD parameters were extracted by non-linear fitting and were then used to calculate the resonance frequency and quality factor of the resonators.

The electromechanical properties of the resonators were evaluated under vacuum ($p < 5 \times 10^{-3}$ mbar) where the resonance was not affected by air damping. Throughout the measurements the temperature and pressure of the chamber were monitored. The temperature dependency of the resonance frequency was $-3.5(\pm 0.5)$ Hz/K (23ppm/K) while no

Figure 3: Schematic view of the measurement test setup.

temperature dependent variation of the quality factor was observed. A correction was applied to the resonance frequencies normalizing to a reference temperature of 25°C. Neither the resonance frequency nor the quality factor were affected by a DC bias ($0 \pm 5V$). For the purpose of evaluating the repeatability of the experiments the impedance characteristics of 34 devices was recorded three times with one week time between the measurements. The standard deviation of the resonance frequency was 1.2 Hz, corresponding to 11 ppm for the relative resonance frequency variation. The standard deviation of the quality factor was 450.

During the proton irradiation tests another impedance analyzer was used (Agilent 4292A). The reproducibility of this setup was inferior to the other setup due to a lower frequency resolution (2.5Hz instead of 0.2Hz). The reproducibility of the resonance frequency and the Q-factor were estimated to be 75ppm and 2500, respectively.

Figure 4 shows a measurement of the phase and magnitude of the impedance of a tuning fork resonator near the operation frequency. The fitted curve of the BvD equivalent circuit is shown in the same graph. Good fits were obtained near the anti-resonance where the amplitude of the Impedance had a minimum. At the resonance where the two tines moved in phase and the electrical impedance was at a maximum the fitted line deviated from the experiment. This was related to parasitic elements in the circuit and the fact that the impedance was close to the specified limit of the impedance analyzer. However, the tuning fork resonators are commonly operated in the anti-resonance mode where a good agreement between the fit and the measurements was obtained. In the following this will be referred to simply as the resonance frequency.

4. ENVIRONMENTAL TEST CONDITIONS

The materials in the device which are supposed to be most susceptible to radiation damage are the silicon-dioxide and the piezoelectric AlN. Charge accumulation in these layers could lead to biasing of the piezoelectric material. This would reduce the driving force of the actuator and thus higher driving voltages would be required to drive the resonator. Trapped charges in the piezoelectric layer could affect the resistance and capacitance of the AlN. With regards to the silicon which makes up for the bulk of the tuning fork tines and dominates their mechanical properties, a displacement-damage induced change in Young's modulus may be possible. However, experimental evidence suggests that single-crystal silicon is highly resistant to such an effect [19][20].

4.1 ^{60}Co Total Ionizing Dose test

The irradiation of the resonators with γ -rays from a ^{60}Co -source was carried out to study the susceptibility of the devices to ionization damage and charge trapping in one of the functional layers. The radiation campaign was conducted following a radiation test plan based on the ESCC radiation test procedure [4]. A total number of 28 devices were irradiated and 3 devices were used as a non-irradiated control group. The total ionizing doses to which the devices were exposed ranged from 3 krad(Si) to 170 krad(Si). Four samples were irradiated at each irradiation level. Two devices in each group were floating (non-defined potential) and two were biased at 50mV (defined potential), which corresponds to the AC voltage applied during operation. The devices were electrically characterized directly after the irradiation. The

Figure 4: Impedance absolute value (above) and phase (below) of the resonator near the operation resonance frequency. The black circles are the measurement points and the blue line is a fit of the Butterworth-van-Dyke equivalent circuit.

electrical characterization was subsequently repeated after one week and after 4 weeks. The devices were annealed at room temperature between the measurements.

4.2 Proton irradiation

Proton irradiation simultaneously inflicts ionizing and non-ionizing damage. For radiation tests with protons it is essential to ensure that the protons fully penetrate the device package and reach the radiation-sensitive parts. The penetration depth increases with the ion energy. On the other hand, the stopping power, which (along with the flux) determines the duration of the irradiation, is inversely related to the ion energy. Therefore, a compromise needs to be found with regards to the penetration depth, the relevant energy range and the stopping power.

Using SRIM-2008 [21] the proton irradiation of the packaged devices was simulated. In these simulations the sample structure consisted of a simplified material stack of 0.5 mm Pyrex, 20 μm air and 0.48 mm Silicon. The resonators were located at the surface of the silicon layer, right below the air gap. A proton energy of 50 MeV resulted in full penetration of the protons into the device and over 99.9 percent of ions fully crossed the simulated layers. In the simulations 10^6 ion impact events were calculated. The effect of the cap was to reduce the energy of the protons on their trajectory towards the silicon microresonator due to the energy losses in the Pyrex. As the stopping power increases with decreasing ion energy, the energy loss in the silicon was slightly higher in the shielded devices than it would be in directly irradiated silicon (Figure 5). However, the difference of only 2% lied within the uncertainty of the beam flux and energy, therefore the effect of shielding by the cap was negligible.

In total, 19 resonator devices were used for the irradiation campaign. They were repartitioned into 6 sample groups which were irradiated at different doses (Table 1). One sample group was used as an un-irradiated reference. The MEMS components were floating during the irradiation and the post-irradiation annealing. In each sample group (except group 2) one device was biased at 200 mV during the irradiation.

The proton irradiations were carried out at the Proton Irradiation Facility (PIF) of the Paul-Scherrer Institute (Villigen, CH). The proton flux was approximately $1 \times 10^8 \text{ p cm}^{-2} \text{ s}^{-1}$ and the proton energy was 50 MeV. At these conditions the stopping power (i.e. the energy deposited per unit path length) was 0.23 eV/ $\text{\AA}$ near the irradiated surface (Figure 5). The corresponding dose rate of 16 rad/s resulted in an irradiation time of 62 s for 1 krad.

The electrical characterization of the devices was made directly after the irradiation and repeated 3 days and 2.5 weeks thereafter. Between the measurements the devices were annealed at $20 \pm 3 \text{ }^\circ\text{C}$.

Figure 5: Comparison of the stopping power [eV/A] of directly irradiated silicon (dotted line) in comparison with the silicon microresonator under the Pyrex cap (dashed line).

Table 1: Sampling of piezoelectric resonators in the proton irradiation

	Proton energy (MeV)	Flux (cm ⁻² s ⁻¹)	Fluence (cm ⁻²)	TID (krad)	# resonators tested	Comment
Group 1	50	1x10 ⁸	6.3x10 ¹⁰	10	4	1 biased (200mV)
Group 2	50	1x10 ⁸	1.3x10 ¹¹	20	2	
Group 3	50	1x10 ⁸	2.5x10 ¹¹	40	3	1 biased (200mV)
Group 4	50	1x10 ⁸	5.0x10 ¹¹	80	4	1 biased (200mV)
Group 5	50	1x10 ⁸	9.5x10 ¹¹	150	3	1 biased (200mV)
Group 6	-	-	-	-	3	Control

5. RESULTS

No change of the optical appearance was observed after the irradiation tests. The resonance characteristics of the devices after ⁶⁰Co irradiation and after proton irradiation are shown in Figure 6 and Figure 7, respectively. In both figures the left graph displays the relative change of the resonance frequency while the right graph shows the absolute change of the Quality factor, relative to the state before irradiation. Each data point in the graphs corresponds to one resonator measured at one time after the irradiation. The areas shaded in gray limit the values of $\Delta f_{res}/f$ and ΔQ which lie within one standard deviation of the repeatability of the measurement.

The irradiation did not induce a significant change in any of the measured parameters neither for the proton irradiation nor for the γ -rays. No difference was found between the floating and the biased devices. Moreover also after one week and after four weeks no deviations in the resonances were found.

Although the resonance frequencies and quality factors measured after irradiation were mostly within one standard deviation of the experimental repeatability, the irradiated devices showed a higher scattering of the measurement points than the control specimen, especially in the proton irradiation tests (Figure 7). Further experiments, preferably at higher doses, would be required to assess the repeatability of this observation and clarify the fundamental processes by which radiation damage is induced and accumulated in the system. Nevertheless, these results indicate that the tuning fork resonators are highly resistant to ionizing damage and may perform well under radiation conditions relevant for space applications.

Figure 6: Resonance characteristics of the tuning fork resonators after irradiation with ^{60}Co γ -rays. The x-axis denotes the absorbed dose. (Left) Relative change in the serial resonance frequency (Right) Absolute change of the quality factor. ($\diamond$ Directly after the irradiation, Δ 7 days after the irradiation, and $\square$ 4 weeks after the irradiation).

Figure 7: Relative change of the anti-resonance frequency (left) and Quality factor (right) during the irradiation campaign ($\diamond$ Directly after the irradiation, Δ 3 days after the irradiation, and $\square$ 17 days after the irradiation).

6. DISCUSSION

The piezoelectrically activated tuning fork resonators present a very good immunity to irradiation both for ionizing radiation and displacement damage effects. This is explained by the fact that the MEMS device is not dependent on electrostatic actuation, where charge trapping by dielectrics can induce serious degradation of the device performance [1]. In the tuning fork devices tested here a charge trapping could lead to screening of the actuation voltage. However, only small energies are required to actuate the tuning fork in its resonance, and the doses tested did not induce measureable deteriorations of the actuation mechanism. The results also confirmed that the ionizing damage and displacement damage have only little effect on the Young's modulus of the materials, most notably on the silicon which accounts for the bulk of the tuning fork tines and dominates the mechanical properties of the resonators.

7. CONCLUSIONS

In this contribution the effect of space-relevant radiation on silicon tuning fork resonators driven by piezoelectric AlN has been investigated. It was shown that the devices were highly resistant to radiation induced degradations of doses of

up to 170 krad(Si). This work supports the efforts taken towards design and fabrication of highly reliable MEMS devices and demonstrates that silicon tuning fork resonators may be well suited for space applications.

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