

IONIZING SPACE RADIATION EFFECTS ON SURFACE ACOUSTIC WAVE RESONATORS

W.J. Stapor, J.H. Hines,¹ and D.H. Wilson²
 Naval Research Laboratory
 Washington, D.C. 20375-5000

ABSTRACT

We have investigated ionizing radiation total dose effects on SAW resonators. Sensitivity to radiation is substrate material dependent, with pure substrates showing less radiation degradation in performance. An unexpected reduction in sensitivity was found for devices coated with a 400 Å layer of SiO_x.

INTRODUCTION

Surface acoustic wave (SAW) devices are currently used in many signal processing and communications systems. The fundamental SAW device shown in Figure 1 consists of two sets of interdigital planar metal electrodes deposited on

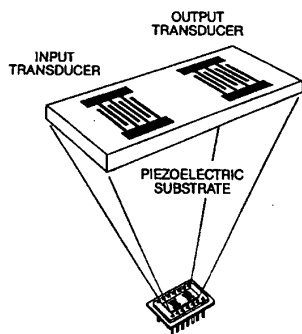


Figure 1. Schematic of a surface acoustic wave (SAW) device.

a polished piezoelectric substrate material such as quartz or lithium niobate. A SAW device converts the input

electromagnetic signal into a surface acoustic wave and back to an electromagnetic signal on the output. Because of their inherent ruggedness, reliability, compact size, and performance capabilities, SAW devices are naturally suited to space systems applications. However, when considering their use in space, it is often necessary to know the effects of ionizing radiation on these devices. Our work evaluates the operation of several types of SAW resonators not previously investigated, and determines the parameter shifts that occur when these devices are exposed to a variety of space-like radiations including ⁶⁰Co gamma, high energy electron, and proton.

Surprisingly, not much has been published on space radiation effects in SAW devices. Previous experimental work on various lithium niobate and quartz SAW delay lines [1,2,3] concentrated primarily on nuclear environments, i.e. permanent displacement effects from neutron irradiation ($E > 10$ keV) and ⁶⁰Co gamma rays, and transient radiation from high intensity flash x-rays. Their results indicated little change in the performance characteristics being measured due to the radiation, transient and total dose. Consequently, their conclusions suggested that all SAW devices were basically "hard" to ionizing radiations or that all SAW devices are not severely affected by radiation induced parameter shifts. This may be the case for such broad passband devices as delay lines, however, the generalized conclusion may be misleading when characterizing radiation effects in other SAW devices such as resonators and filters with narrow passband frequency response. Our work concentrates on the space environments and on SAW resonators not previously investigated.

EXPERIMENT

In order to observe device performance variations induced by radiation exposure, it was first necessary to select an appropriate test structure for use in this experiment. As mentioned above broadband SAW filters did not show significant performance variations, and thus are unsatisfactory as a vehicle for investigating SAW radiation sensitivity. What was needed was a considerably more sensitive type of SAW device which would be suitable as a test structure. As shown in Figure 2, the two port, single pole SAW resonator chosen for this investigation consists of input and output monolithic aluminum interdigital

¹ Currently at Sawtek, Inc., Orlando, FL 32860-9501, and the Electrical Engineering Dept., Univ. of Central Florida, Orlando, FL 32816.

² Currently at Digit Head, Inc., Washington, DC 20037, and Sachs Freeman Associates, Landover, MD 20785

SAW RESONATOR FILTER

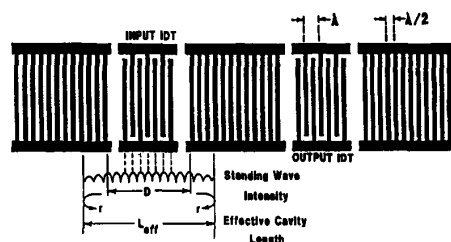


Figure 2. Schematic of two port, single pole SAW resonator showing arrangement of interdigital transducers (IDTs).

transducers (IDTs), along with three sets of aluminum reflective strips. This structure, when properly dimensioned, creates a resonant cavity in which a standing wave develops when an RF input is applied to the input transducer. This resonant behavior causes the single pole resonator to have a narrow bandwidth (21 kHz) and a relatively high Q (10,000) for the devices tested. These characteristics, combined with the rapid but unambiguous change in the phase across the passband make the single pole SAW resonator among the most sensitive of SAW devices, and hence an ideal test structure.

Two available types of single pole 199 MHz SAW resonators were irradiated to determine space radiation performance, some fabricated on air-swept 40° Y-rotated quartz substrate, and some fabricated on non-swept quartz. In addition, some of the resonators on non-swept quartz were coated with a $400 \text{ \AA}$ RF sputtered layer of SiO_x . All three device types were identical except for their substrates and SiO_x surface coating. (The surface coating is approximately SiO_2 . The exact stoichiometry was not checked, so, the coating is referred to as SiO_x .) The non-swept quartz used for these devices is a commercial electronic grade quartz which may contain a substantial number of impurities in the form of interstitial atoms or impurity atoms replacing Si or O atoms at lattice sites. Air-swept quartz has a lower concentration of impurities due to the sweeping process. Basically, this process consists of melting a small zone of the grown crystal boule, and slowly moving this molten zone down the boule. The impurities have a higher solubility in the molten SiO_2 than in the crystal form, and will preferentially remain in the melt and be "swept" to one end of the boule. The quartz which recrystallizes behind the molten zone is thus of a higher purity. This sweeping process may be done many times in order to increase the purity of the resultant crystal. The available 199 MHz SAW resonator targets allowed a direct comparison of

results on swept and non-swept substrates without complications introduced by variations in operating frequencies and design geometries.

The irradiations and parameter measurements on several devices were performed at three facilities, the NRL ^{60}Co pool for the ^{60}Co gammas, the NRL Linac for the 40 MeV electrons, and the UC Davis Cyclotron for the 60 MeV protons. Before and after each irradiation increment, ten performance characteristics were measured for the devices under test as well as a set of control devices withheld from the radiation. The measured parameters were;

- 1) the frequency at which a predetermined insertion phase occurs, $F(\phi = 165^\circ)$, in MHz,
- 2) the minimum insertion loss, $IL(\min)$, in dB,
- 3) the frequency at which minimum insertion loss occurs, $F(IL_{\min})$, in MHz,
- 4) the phase corresponding to the frequency of minimum insertion loss, $\phi(IL_{\min})$, in degrees,
- 5) the center frequency (measured at the -3 dB point relative to the minimum insertion loss, $F(BW_3)$, in MHz,
- 6) the 3 dB bandwidth, BW_3 , in MHz,
- 7) the device Q ,
- 8) the maximum group delay over the passband, $GD_{\max}$, in μsec ,
- 9) the frequency at which the maximum group delay occurs, $F(GD_{\max})$, in MHz,
- 10) and the phase corresponding to the frequency of maximum group delay, $\phi(GD_{\max})$, in degrees.

The control devices served to verify that no drift occurred on the sensitive measuring equipment and that the observed changes in the devices under test were actually due to the radiation. Resolution for the frequency measurements was typically 1.25 ppm. There were approximately 4 control devices and 4 target devices at each level of radiation. Only total dose effects were examined due to the scope of the experiment. No attempt was made to examine transient behavior or annealing.

RESULTS

The key results are shown in Figures 3, 4, and 5. These figures show the total average frequency shift, ΔF_{avg} ,

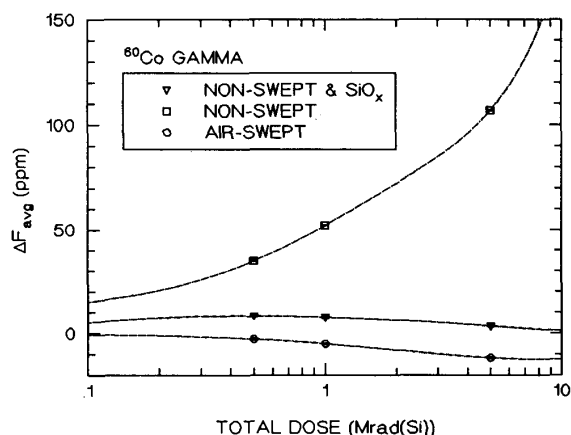


Figure 3. Average frequency shift versus total dose from ^{60}Co gamma radiation.

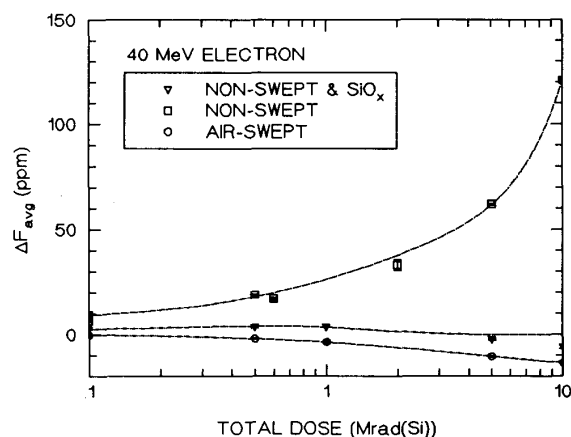


Figure 4. Average frequency shift versus total dose from 40 MeV electron radiation.

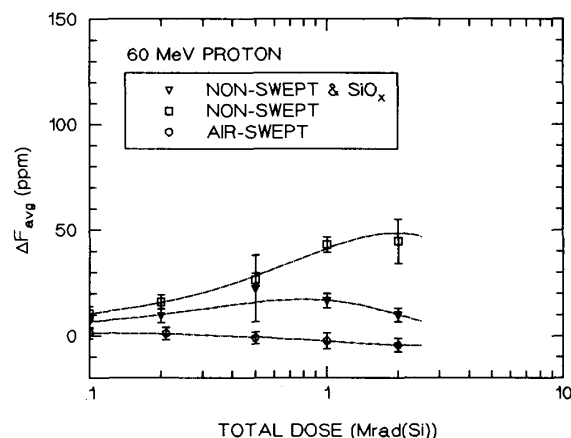


Figure 5. Average frequency shift versus total dose from 60 MeV proton radiation.

in parts per million as a function of total dose accumulation for ^{60}Co gamma, 40 MeV electron, and 60 MeV proton radiations. The total dose axis is a log scale starting with 100 Krad(Si). There was no significant shift of any parameter before the 100 Krad(Si) level. The average frequency shift is taken here as the total average shift from each of the above mentioned frequency specifications including $F(\text{IL}_{\min})$, $F(\text{BW}_3)$, $F(\text{GD}_{\max})$, and $F(\phi=165^\circ)$. Each of these parameters shifted approximately the same direction and amount with respect to their initial values. Data are plotted in Figures 3, 4, and 5 with uncertainties (which were small, typically less than a few percent) along with dashed curves which are best fits from a reasonable and practical parameterization described later.

In each case, the swept quartz substrate devices showed negative frequency shifts relative to the control devices over the total dose ranges. The change was no more than -20 ppm up to 10 Mrad(Si) total dose for each of the radiations. The other performance parameters for the swept quartz devices showed only small changes and probably would not have any significant effects on most systems applications.

The non-swept devices showed positive frequency shifts relative to the control devices for each radiation. These changes were much larger than the changes in the swept devices. The largest shift was approximately +120 ppm for the 40 MeV electron data at 10 Mrad(Si). Such a large shift could be detrimental to the operation of a long lived space based system. The other parameters also shifted measurably when compared to control devices, but not substantially with respect to the nominal device parameters as a function of total dose.

Two practical parameterizations have been found to characterize the frequency shifts as a function of total dose. One parameterization gives the frequency shift as a linear function of the square root of the total dose for both the uncoated air-swept and non-swept devices as in the following

$$\Delta F_{\text{avg}} = C_1 \cdot \sqrt{\Phi} + C_0 \quad (1)$$

Table 1. Fitted parameters, C_1 and C_0 , for the average frequency shift, ΔF_{avg} , in ppm as a function of total dose, Φ , in Mrad(Si) from each radiation.

RADIATION	AIR-SWEPT		NON-SWEPT	
	C_1	C_0	C_1	C_0
^{60}Co GAMMA	-5.32	0.34	44.43	6.76
40 MeV ELECTRON	-4.66	0.74	34.77	-4.02
60 MeV PROTON	-4.41	2.19	34.26	1.42

Equation 1. The fitted parameters, C_1 and C_0 , are shown in Table 1. Each of these fits agrees extremely well with the data and can be used to estimate the average frequency shift for the uncoated resonators versus total dose due to lightly ionizing spacelike radiation. No suitable theoretical explanation has been given as yet for this square root dependence with total dose.

The non-swept, SiO_x coated devices showed more complicated frequency shifts. Initially, the trend in each frequency shift was positive up to a total dose of approximately 0.6 Mrad(Si). Frequency shifts at larger doses went negative and actually crossed zero at approximately 2.5 Mrad(Si) for the 40 MeV electron data. Clearly, the 400 Å SiO_x layer has a large influence in the frequency parameter shifts. This rise and fall of the frequency shift can possibly be attributed to a radiation stress release followed by a radiation compression mechanism suggested in previous work on quartz and vitreous silica materials.[4,5,6] Stresses are introduced into the quartz surface and/or substrate by the addition of the SiO_x layer. The initial radiation relaxes this stress causing the positive frequency shifts up to a total dose near 1 Mrad(Si). After this, subsequent radiation damage causes compression of the quartz material causing the frequency shifts to go negative.

A second practical parameterization was applied which fits the frequency shift data well for the uncoated devices over the full total dose range for each radiation and fits the data well for the coated (SiO_x) devices up to approximately 2.5 Mrad(Si) for each radiation. This was an exponential parameterization and is given by the following

$$\Delta F_{\text{avg}} = A \exp(B\Phi) (1 - C \exp(-D\Phi)) \quad (2)$$

Equation 2. Table 2 gives a summary of the best fit parameters, A, B, C, and D, for the frequency shifts, ΔF_{avg} in ppm, as a function of total dose, Φ in Mrad(Si). The dashed curves in Figures 3, 4, and 5 are the fitted results given by the parameters in Table 2.

There is some intuitive physical interpretation to this parameterization of the frequency shift response. The incident radiation causes displacement and ionization damage to the surface material of the substrate crystal which carries the surface waves of the device. Consequently, the device surface wave properties, such as group and phase velocity, are altered in some way by the damage which is in turn dependent on the amount of radiation, or total dose. Simultaneously, that is, as damage is incurred by the radiation, the surface material must undergo some recovery due to normal annealing and re-structuring by subsequent radiation. In the scheme of Equation 2, the first term represents a generalized exponential damage term and the second term represents a generalized recovery term which is proportional to the amount of damage up to a given dose. Equation 2 fits the data quite well in all cases.

Table 2. Fitted parameters A, B, C, and D from Equation (2), for the average frequency shift, ΔF_{avg} , in ppm as a function of total dose, Φ , in Mrad(Si) from each radiation.

RADIATION & RESONATOR	A	B	C	D
^{60}Co γ AIR-swept	13.44	-0.470	1.004	-0.463
^{60}Co γ NON-swept	64.30	0.102	0.868	1.174
^{60}Co γ NON-swept & SiO_x	9.33	-0.203	0.998	8.277
e^- AIR-swept	10.49	-0.406	0.988	-0.435
e^- NON-swept	32.03	0.133	0.797	1.043
e^- NON-swept & SiO_x	201.20	-1.509	0.993	0.075
p AIR-swept	26.84	-0.515	0.922	-0.228
p NON-swept	800.20	-0.461	0.994	0.079
p NON-swept & SiO_x	442.90	-1.130	0.995	0.120

Results for the insertion loss shift, ΔIL , and the Q shift, ΔQ , both in %, versus total dose from each radiation are shown in Figures 6 through 11. The uncoated non-swept devices showed the largest changes for both insertion loss and Q in each radiation except for the ^{60}Co gamma insertion loss shift shown in Figure 6. No suitable explanation has been given as yet. These shifts are probably not as critical to SAW resonator system applications as the frequency shifts indicated in Figures 3 through 5.

SYSTEM IMPLICATIONS

Compared to many semiconductor technologies, which may experience single event upsets and catastrophic failures when exposed to sufficiently high levels of radiation, the lack of a drastic failure mechanism in SAW devices indicates that they are relatively radiation hard. However, the observed shifts or variations in device performance upon exposure to radiation may be large enough to have measurable effect on overall system performance.

One common application of SAW resonators is as a frequency control element. Considering the various radiation induced changes in the resonators tested, the only one large enough to be significant is the shift in device center frequency. The specific effects of center frequency shifts are circuit dependent. For a fixed frequency oscillator, the frequency of the oscillator will move as the center frequency of the SAW resonator changes. The largest

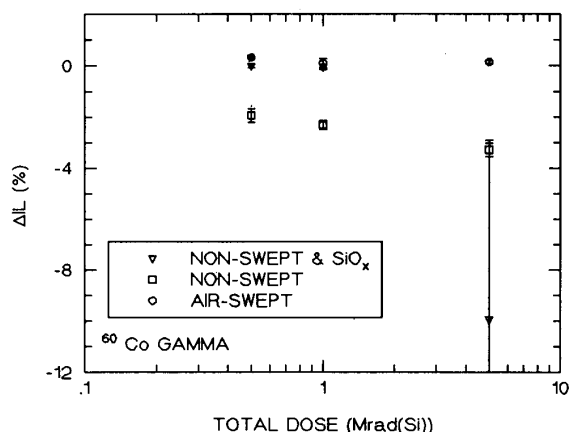


Figure 6. Insertion loss shift versus total dose from ^{60}Co gamma radiation.

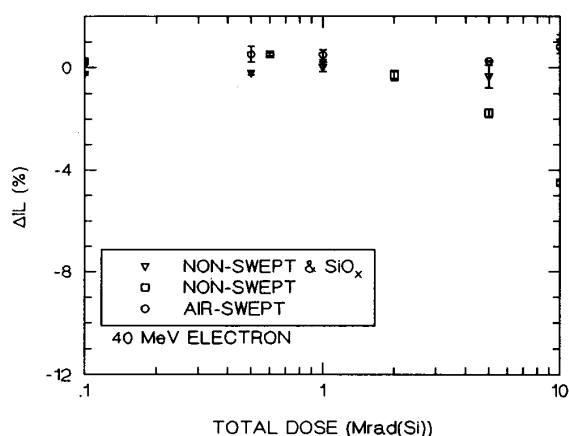


Figure 7. Insertion loss shift versus total dose from 40 MeV electron radiation.

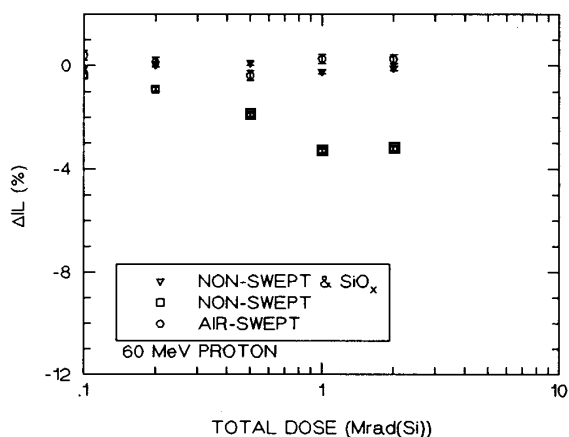


Figure 8. Insertion loss shift versus total dose from 60 MeV proton radiation.

frequency shifts observed in this experiment, which were on the order of 100 - 200 ppm, are comparable to the shifts caused by temperature fluctuations, i.e. approximately 60 ppm over the military temperature range (-50°C to 125°C). Also, these changes are usually significantly smaller than those caused by radiation exposure of the active devices in such an oscillator. The result of a center frequency shift in a resonator used in a voltage controlled oscillator (VCO) would again be a shift in frequency. If the VCO is used in a phase locked loop (PLL) application, however, it is possible that the center frequency of the resonator could change enough that the tuning range of the VCO could be exceeded and the loop could lose phase lock. Once again, although active device degradation would almost certainly be more significant than errors induced by SAW device frequency shifts, these shifts should be included in the design error budget. In addition, the reduction in radiation sensitivity observed when swept quartz is used as a substrate is worth considering during system design.

Another application for SAW resonators and narrowband filters is in channelizers or filter banks (often utilized in electronic countermeasure systems), or as pre-selector or IF filters in communication systems. This type of system is generally designed such that the passbands are wide enough to allow for frequency shifts that would be introduced by temperature variations, so that the signal is not distorted by center frequency shifts. However, in many cases the adjacent channels are so close that it is not possible to widen a given channel bandwidth enough to compensate for the observed radiation induced shifts (in addition to other shifts already occurring without corrupting the signal passed by that channel with information from an adjacent channel. In such cases, the radiation induced frequency shifts can cause serious degradation of the desired signals, as signals and noise from outside of the desired bandwidth is included in the signal passed, and part of the desired signal is not passed by the frequency shifted filter. In addition, if tracking between channels is critical, variations in the materials used for the different SAW filters and/or the amounts of radiation each SAW die is exposed to (due to differences in shielding) could cause the frequency shifts of different SAW devices within the same unit to vary. This could throw off tracking between channels.

Radar systems using SAW expander/compressor pairs can also be affected by radiation induced frequency shifts. For linear FM, a frequency shift would appear as a Doppler shift. In non-linear FM, sidelobe suppression would be degraded.

All of the above mentioned system effects of radiation induced changes in SAW resonators are secondary in nature to the changes that would occur to active devices due to radiation, and comparable or secondary to changes that occur in the SAW frequency due to ambient temperature fluctuations. However, given tight tolerances of

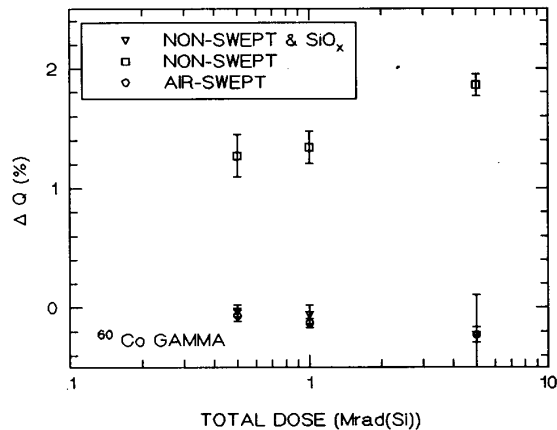


Figure 9. Q shift versus total dose from ^{60}Co gamma radiation.

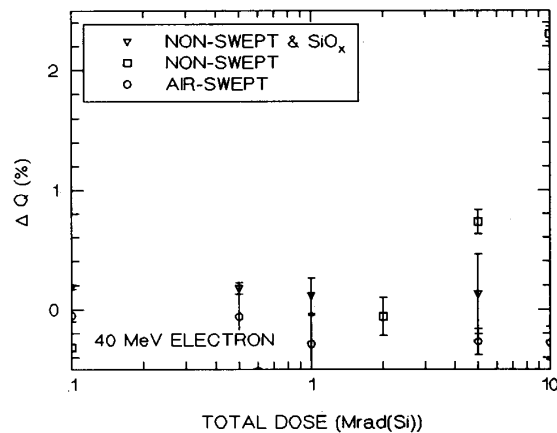


Figure 10. Q shift versus total dose from 40 MeV electron radiation.

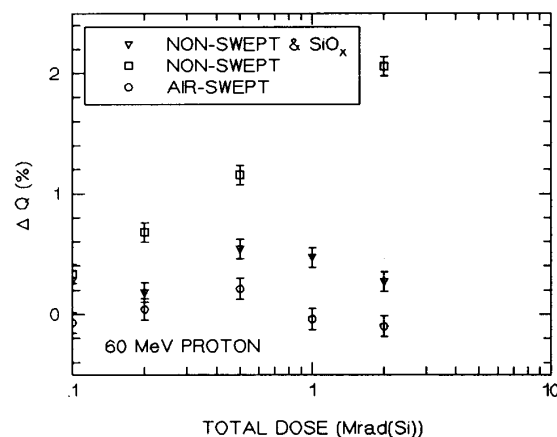


Figure 11. Q shift versus total dose from 60 MeV proton radiation.

many space based systems, the radiation induced changes should be taken into account during the design process. In particular, it should be noted that the effects of radiation on SAW devices can be reduced substantially (up to factors of 10) simply by utilizing a pure swept quartz substrate rather than a less pure material. Also, the results in this work indicate that the coated (SiO_2) non-swept quartz substrate showed little significant parameter change with total dose. The increase in cost of parts built on swept quartz or built on non-swept quartz and SiO_2 may be worthwhile considering their apparent immunity to radiation. When choosing between these two options, however, one should take into account the fact that coating these devices with SiO_2 can cause slightly higher insertion losses, frequency shifts, and spurious responses. The latter two effects can be compensated for in the device design process.

CONCLUSIONS

The data and analysis of this study are new and unique. They have significance especially in the area of space based signal processing and communications systems using SAW devices. SAW devices are typically "rad-hard" devices, i.e. they show no catastrophic functional failure for large total doses up to 10 Mrad(Si) compared to other Silicon device technologies. However, for narrowband SAW devices, it can be important to understand how the output frequency shifts as a function of total dose in order to accurately assess system performance. We have seen that the choice of substrate is important to system design engineers in selecting SAW components for long term space applications. The relatively impure uncoated non-swept substrates suffer larger parameter shifts due to dose from ionizing radiation while the more pure air-swept substrates and the coated (SiO_2) non-swept substrates show little parameter shift up to large doses.

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