

THE EFFECTS OF IONIZING RADIATION ON SAW RESONATORS

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Abstract - SAW resonators with frequencies ranging from 199 MHz to 746 MHz were fabricated and exposed to sequentially increasing total doses of various types of ionizing radiation, and the effects were observed. The substrates used were air-swept and as grown (non-swept) 40° Y-rotated quartz, LST-Quartz, and non-swept 40° Y-rotated quartz coated with a 400Å thick layer of SiO_x². The total doses used range from 1 kRad(Si) to 10 MRad(Si), and the radiation types tested were Co-60 gamma, high energy electron (β⁻), proton, and heavy ion (Si-28, Cl-35, Ge-74, and Au-197) radiation. The results of these measurements show a distinct difference in the radiation sensitivity of SAW device performance parameters based on the substrate used. The effects of the passivating SiO_x layer were also interesting since the coated devices exhibited significantly smaller radiation induced changes than those without the coating. A summary of experimental findings for the 199 MHz devices is presented; and some implications for the suitability of SAW devices for use in various radiation environments are discussed.

I. Introduction

SAW devices are currently used in many signal processing and communication system applications which include exposure to a radiation environment. The type and amount of radiation to which the devices are exposed varies with the application from tactical military to space radiation environments. It is therefore desirable to know what effects the various types of radiation found in these environments have on SAW device performance.

Very little has been published on the total dose effects of ionizing radiation on conventional SAW devices [1,2,3]. The extension of radiation effects observed in

bulk wave devices to SAW devices is not obvious, since the active region of the SAW device is restricted to a small portion of the crystal near the surface. However, if the interaction of radiation with the SAW substrate is considered, microscopic changes in crystal structure and material properties can be related to the effects seen in overall device performance.

The interaction of various types of radiation with quartz and vitreous silica has been investigated extensively [4,5,6], and some significant radiation induced changes in material properties have been found. Density, thermal conductivity, internal friction, and internal stress can all be affected by exposure to certain radiation environments. How changes in these material properties affect SAW resonator performance has not yet been determined.

II. Experimental approach

Prior experiments on lithium niobate (LiNbO₃) delay lines indicated that Co-60 gamma radiation caused no changes in operating characteristics up to a total dose of 400 MRad [1]. However, the researchers performing this study may have been unable to measure very small changes in performance accurately due to the broadband characteristics of the device under consideration and the performance parameters being measured. This may have caused this particular device to appear insensitive to radiation. It would be misleading, however, to interpret this result as indicative of the insensitivity of all SAW devices to total dose effects. Initial exposures of several types of devices on various substrates to 10 MRad(Si) Co-60 radiation showed that the performance of SAW resonators was significantly more sensitive to radiation than that of other device types tested. Although small changes in performance may have occurred for other types of devices, the ease with which accurate frequency measurements can be made on SAW resonators made small frequency changes in these devices easier to detect. Certain matching components used inside the SAW device package also proved to be sensitive to radiation. These preliminary findings led to the selection of a set of unmatched SAW resonators for these tests.

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² The coating mixture used is approximately SiO₂; however, the stoichiometry has not been checked for this process. The actual material deposited is therefore referred to as SiO_x throughout this paper.

Single pole 199 MHz SAW resonators were fabricated on air-swept 40° Y-rotated quartz and non-swept quartz. Some of the resonators on non-swept quartz were coated with a 400Å thick RF sputtered layer of SiO_x. These devices were all identical in structure except for their substrate and SiO_x coating. None had internal matching components, and all were spot mounted with epoxy in T-08 cans and thermosonically bonded using gold wire. This experimental approach was chosen to allow a direct comparison of the effect radiation has on swept and non-swept 40° Y-rotated quartz substrates without variations in operating frequency or device design creating ambiguities in the results. Two higher frequency devices were tested: a 746 MHz two pole in-line coupled SAW resonator filter (RFI) fabricated on 34.75° Y-rotated quartz and a 504 MHz RFI fabricated on -75.5° Y-rotated LST-Quartz, a relatively new leaky surface wave substrate. Results of measurements made on the higher frequency devices and a more complete treatment of the results of heavy ion bombardments on all devices will be discussed in a future paper.

Fifty (50) of each type of device were fabricated so that several devices of each type could be held without exposure to radiation as control units and many devices could be exposed to each type of radiation. Where possible, multiple devices were exposed and tested at each radiation level. Control devices were measured along with the test devices before and after irradiation. The results of the control tests served to verify that no drift was occurring in the measurement equipment and that the observed variations in irradiated device performance were actual radiation induced changes. Multiple test devices showed that the radiation induced changes were consistent from device to device and allowed statistical methods to be used in analyzing the data. In order to eliminate any possible bias due to expected results during data acquisition, the experiment was performed using a double-blind approach.

The resonator test devices of a type which have a high-Q, narrow passband response that will show clearly any small radiation induced changes in performance. While their amplitude varies only slightly across the passband, phase varies rapidly. Due to this rapid variation in phase with frequency, a small change in operating frequency which may not be apparent from amplitude considerations can be detected by measuring the frequency at which a predetermined insertion phase occurs. In addition to the frequency at which a given insertion phase occurs, nine other performance characteristics were measured before and after exposure to various types and levels of radiation. The nine additional quantities measured were minimum insertion loss, frequency at which minimum insertion loss occurs, phase corresponding to the frequency of minimum insertion loss, center frequency (measured at the -3 dB

point relative to the minimum insertion loss), 3 dB bandwidth, device Q, maximum group delay over the passband, frequency at which the maximum group delay occurs, and phase corresponding to the frequency of maximum group delay. The resolution of the network analyzer used for these measurements varied depending on the frequency range, number of measurement points, and the parameter to be measured; however, the measurement uncertainty based on resolution for frequency measurements on the 199 MHz devices was ±1.26 ppm.

Several samples of each type of resonator were exposed to different total doses of various types of ionizing radiation from 1 kRad(Si) to 10 MRad(Si). The radiation types tested were Co-60 gamma, high energy electron (β⁻), proton, and heavy ion (Si-28, Cl-35, Ge-74, and Au-197) radiation.

III. Experimental Procedure and Results

Co-60 γ Radiation

A Co-60 γ source at NRL was used to irradiate devices to 500 kRad(Si), 1 MRad(Si), and 5 MRad(Si) total dose levels. Nine of each type of device were placed in the Co-60 source, and three of each type of device were withdrawn at each total dose level for measurements.

The 199 MHz resonators fabricated on swept quartz showed a negative frequency shift which increased in magnitude linearly (in ppm) as the square root of the total dose as shown in Figure 1. A maximum observed change of -12 ppm occurred at a total dose of 5 MRad(Si). Several other performance parameters for the swept quartz devices showed small changes which correlated with radiation exposure levels. The 3 dB bandwidth increased with increasing total dose, while device Q and maximum group delay decreased with increasing total dose relative to the control units. These

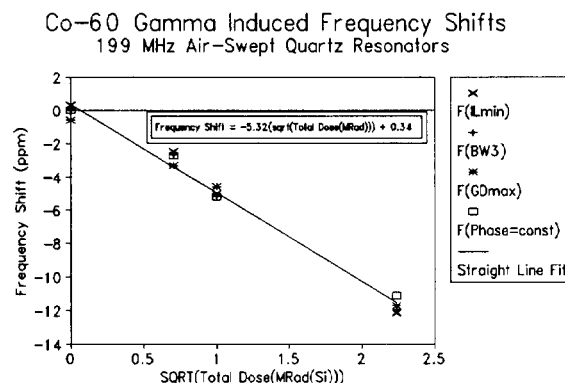


Figure 1: Frequency shifts for Co-60 gamma irradiation of swept quartz resonators.

results are self consistent, since a wider bandwidth implies a lower Q value, which corresponds to a smaller phase slope versus frequency across the passband and thereby decreased group delay. The changes in Q, bandwidth, and maximum group delay were quite small. The largest observed change was 0.25% and should not have a significant effect on most systems applications.

The 199 MHz resonators fabricated on non-swept 40° Y-rotated quartz showed positive frequency shifts significantly larger than the changes observed for the swept quartz devices. At a total dose level of 5 MRad, the frequency changed by +106.4 ppm, and once again the magnitude of the frequency shift was observed to be approximately proportional to the square root of the total dose (see Fig 2). Other parameters which were observed to change for the non-swept quartz devices were: insertion loss decreased by less than 3.3%, while device Q and maximum group delay increased and 3 dB bandwidth decreased by less than 1.9% relative to the changes seen in the control units. Although these changes are larger than those seen for swept quartz, they are still fairly small and may have a less significant effect on system performance than the observed variations in frequency.

The devices fabricated on non-swept quartz and coated with SiO_x showed frequency shifts substantially smaller than the uncoated non-swept quartz (see Fig. 2 and 3). A frequency shift of approximately +8 ppm was observed for the lowest total dose exposure used (500 kRad(Si)), and the frequency shift decreased with increasing total dose to a +3.4 ppm shift at 5 MRad(Si). This somewhat more complicated dependence on dose is in agreement with results for the variation in density of vitreous silica presented by Primak[5,6] for fast neutron radiation. For larger doses, the frequency shift becomes

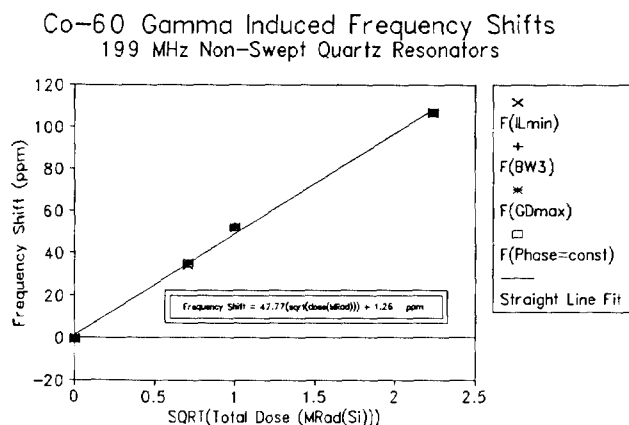


Figure 2: Frequency shifts for Co-60 gamma radiation of non-swept quartz resonators.

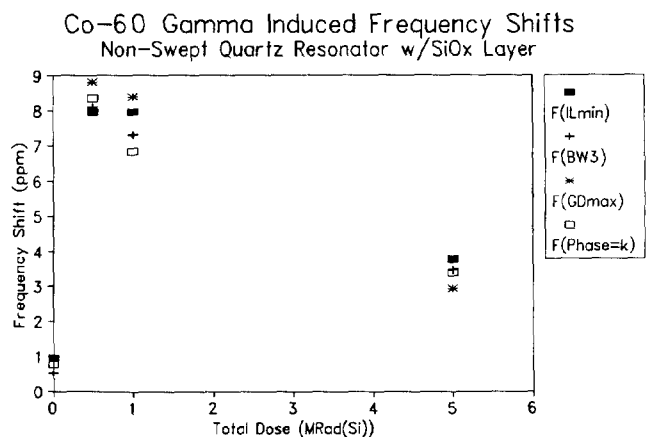


Figure 3: Frequency shifts for Co-60 gamma irradiation of non-swept quartz resonators coated with 400Å of SiO_x.

proportional to the square root of the total dose, as was the case for the swept quartz. Other parameters varied somewhat, but the behavior was more complicated than that of the devices without a coating, and no simple relationship between radiation levels and the parameter measurements has been found.

Figure 4 shows a comparison of the gamma radiation sensitivity of frequency for 199 MHz resonators fabricated on all three substrates. Notice that the swept quartz devices are substantially less sensitive to radiation induced frequency shifts than those devices fabricated on non-swept quartz. It is also interesting to note that the magnitude of the shifts observed for devices fabricated on non-swept quartz and coated with a layer of SiO_x were

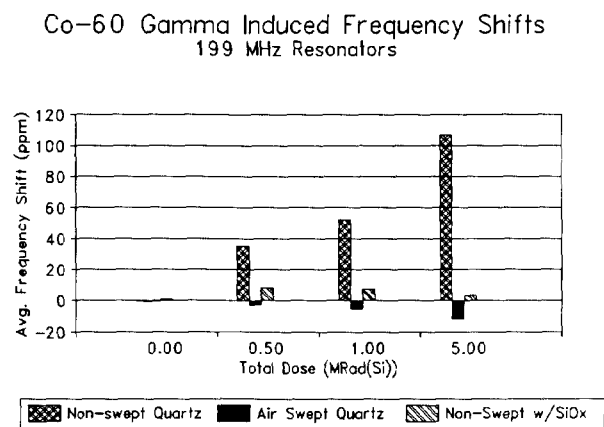


Figure 4: Comparison of frequency shifts for various substrates and gamma radiation.

much smaller than those observed for devices fabricated on non-swept quartz without this coating, and at higher total doses, the radiation induced frequency shift decreased to a value lower than that observed for devices built on air-swept quartz substrates. The effects of such a coating on devices fabricated on swept substrates would be interesting to investigate. The decreased susceptibility of a coated device to radiation has very interesting implications for improving the radiation hardness of SAW devices for use in space and other hostile radiation environments.

LINAC High Energy Electron (β^-) Radiation

The linear accelerator (LINAC) at the U. S. Naval Research Laboratory was used as a high energy pulsed electron source and delivered approximately 1 kRad(Si) of 40 MeV electrons per 1.0 μ sec pulse. The target devices were mounted ten inches from the LINAC gun, and TLDs were used to determine the dose per pulse. All measurements were made at room temperature, and enough time was allowed for any residual activity in the irradiated samples to die out prior to post irradiation measurements.

The 199 MHz resonators fabricated on swept 40° Y-rotated quartz showed no distinguishable changes in any of the measured parameters for doses ranging from 11.275 kRad(Si) to 100 kRad(Si). At 500 kRad(Si), small negative shifts in frequency were observed, with the magnitude of the shifts increasing in proportion to the square root of the total dose. The maximum observed shift was -14.6 ppm, which corresponded to a 10 MRad(Si) total dose. Variations in other measured parameters were of the same order of magnitude as changes observed for the control devices and could not be attributed to radiation exposure.

Two sets of measurements were performed on the 199 MHz resonators fabricated on non-swept 40° Y-rotated quartz. In each set of measurements four devices were exposed to high energy electron doses ranging from 1 kRad(Si) to 500 kRad(Si) or from 100 kRad(Si) to 10 MRad(Si). For these devices, positive frequency shifts were observed starting at a dose level of 11.275 kRad(Si) and increasing with increasing total dose to a maximum observed shift of + 121 ppm at 10 MRad(Si). Figure 5 shows the results of the two tests. The frequency shifts are generally proportional to (Total Dose)^{0.7}. However, if only the lower dose levels are considered (1 MRad(Si) and below), the data is proportional to the square root of total dose, as found previously. An explanation for this behavior is not offered yet, but the results are not inconsistent with prior work [5,6]. No significant changes in phase at minimum insertion loss and phase at maximum group delay were noticed for any radiation level tested. No changes in minimum insertion loss were observed at total doses up to 2 MRad(Si). At 5 MRad(Si)

LINAC Induced Frequency Shifts 199 MHz Non-Swept Quartz Resonators

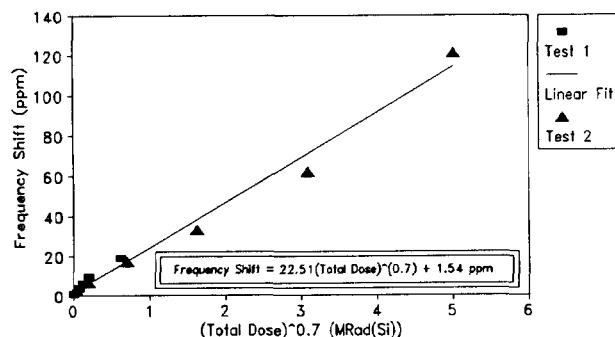


Figure 5: Frequency shifts for high energy electron radiation of non-swept quartz resonators.

and 10 MRad(Si), an increase of insertion loss was observed, along with increased variations in 3 dB bandwidth, Q, and maximum group delay. The behavior of the latter three quantities with dose level is interesting. At lower doses (up to 2 MRad(Si)), the 3 dB bandwidth increased slightly with increasing dose, while maximum group delay decreased with increasing dose. At higher levels, the 3 dB bandwidth decreased, while the maximum group delay increased. Device Q exhibited a dependence on radiation levels that was unclear at low doses, but an increase in Q was seen for total doses above 5 MRad(Si).

Devices fabricated on non-swept 40° Y-rotated quartz and coated with SiO_x again exhibited a more complicated behavior. Low total doses caused positive frequency shifts which increased as the total dose level was increased. However, above a certain total dose, the frequency shifts started to decrease, and eventually became negative (see Fig 6). No significant changes in minimum insertion loss were observed. Small variations in 3 dB bandwidth, Q, and maximum group delay were

LINAC Induced Frequency Shifts 199 MHz Non-Swept Quartz with SiO_x

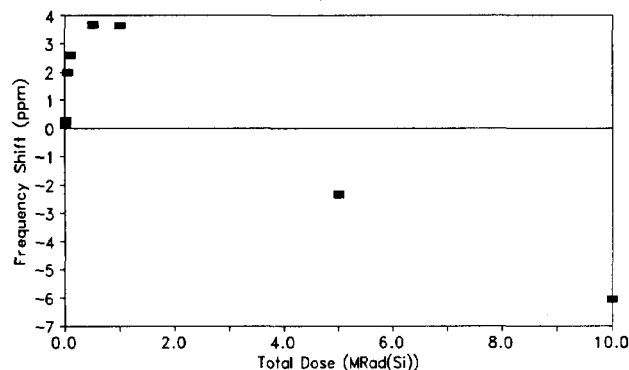


Figure 6: Frequency shifts for high energy electron radiation of non-swept quartz resonators with a 400Å coating of SiO_x.

observed for total doses of 5 MRad(Si) and above. The 3 dB bandwidth increased slightly with increasing exposure, while the maximum group delay and device Q decreased. In addition to the unusual behavior shown by the frequency shifts of the coated devices, it is interesting to note that the magnitude of the shifts observed for these devices were smaller than those observed for devices fabricated on air-swept quartz. Figure 7 shows a comparison of the frequency shifts caused by high energy electron radiation of devices fabricated on swept 40° Y-rotated quartz, non-swept 40° Y-rotated quartz, and non-swept 40° Y-rotated quartz coated with SiOx.

Proton Radiation

Proton irradiations were performed with a seventy-six inch cyclotron at the Crocker Nuclear Lab at the U. C. Davis NRL Proton Irradiation Facility. All three types of 199 MHz devices were exposed, with one device exposed at each of the following five total dose levels: 100 kRad(Si), 200 kRad(Si), 500 kRad(Si), 1MRad (Si), and 2 MRad(Si). Dose rates were roughly equal for these exposures, averaging approximately 3.8 kRad/sec.

The swept quartz devices showed a shift toward lower frequency which was linear with the square root of increasing total dose. A total dose of 2 MRad resulted in a frequency shift of -6.3 ppm. Other measured parameters did not change significantly for the radiated parts when compared to the observed variations in measurements of the control devices.

For the same device fabricated on non-swept quartz, an increasing positive frequency shift was observed with increasing total dose exposure. Once again, the increase was approximately linearly related to the square root of the total dose, and was significantly larger than that seen for the swept quartz case. Shifts of + 8 ppm with 100 kRad(Si) total dose and + 50 ppm with

2 MRad(Si) total dose were observed. In addition to the changes in frequency, several other parameters exhibited changes which were dependent on the total dose. Insertion loss decreased, the -3 dB bandwidth decreased, and the device Q increased with increasing total dose. The dependence of these quantities on total dose has not yet been fully examined, but it appears to be exponential.

The devices fabricated on non-swept quartz and coated with SiOx once again exhibited a different frequency behavior. The frequency shifts observed for these devices first increased, then decreased with increasing total dose, as was the case for exposure to high energy electron radiation. The maximum observed frequency shift was + 14 ppm. Other parameters measured for these devices did not change in a manner which could be correlated to their exposure to radiation. In this aspect, these devices performed very similarly to those fabricated on swept quartz.

Heavy Ion Bombardment

Heavy Ion bombardment experiments were conducted at the Tandem Van de Graff Single Event Upset Test Facility at Brookhaven National Labs. The ions and dose levels used for these measurements are listed in Table 1. All of the resonators tested, independent of substrate, exhibited a negative shift in frequency. For most of the combinations of radiation level and device substrate investigated, these frequency shifts were between -2.5 ppm and -20 ppm. It is interesting to note, however, that contrary to the previous findings the changes observed for the devices fabricated on swept quartz were somewhat greater than those fabricated on non-swept quartz. The observed changes in performance of the resonators upon irradiation by heavy ions did not exhibit a simple dependence upon total dose, as was the case for the other types of radiation tested. Nor was there a clear connection between ion mass or energy and variations in device performance. Work is currently underway to try to determine causative mechanism(s) for the observed changes.

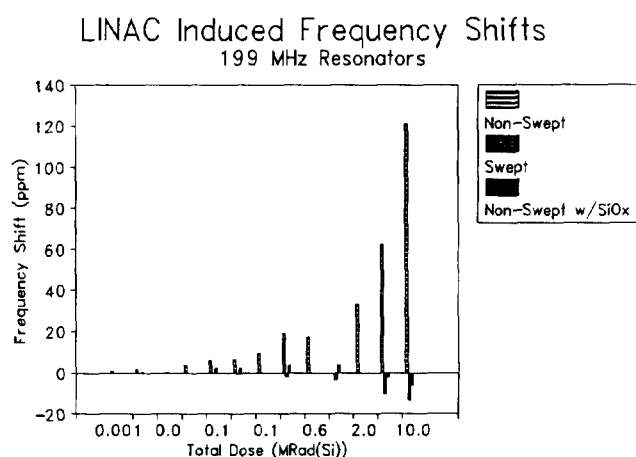


Figure 7: Comparison of frequency shifts for various substrates and high energy electron radiation.

Table 1: Ions used for SAW Bombardment

Ion	Energy (Mev)	Fluence (cm-2)
Si-28	190.88	$1 \times 10^6, 1 \times 10^8$
Cl-35	213.60	$1 \times 10^6, 1 \times 10^8$
Ge-74	190.46	1×10^8 at 0° 1×10^8 at -60°
Au-197	350.00	$1 \times 10^6, 1 \times 10^8$

IV. Discussion

An approximate dependence of frequency shift on the square root of dose was observed for all devices fabricated on both swept quartz and uncoated non-swept quartz when exposed to high enough levels of Co-60 gamma, high energy electron, and proton radiation. This relationship has not yet been fully explained, but it is in agreement with results obtained by Primak [5,6] for the variation of density of vitreous silica with dose for electron, gamma, and proton irradiations. Their experiments confirmed a reduced power dependence on dose (0.5-0.7) independent of the energy of irradiating particles, within experimental error. A model for how this density change translates into the observed macroscopic variations in SAW device performance has yet to be established. Why swept quartz undergoes a negative frequency shift and non-swept quartz undergoes a positive frequency shift is undetermined at present. How the observed changes depend on crystal cut angle (data for high frequency devices not presented here implies this) is also undetermined.

The shape of the more complicated dependence of frequency shift on total dose observed for devices coated with SiO_x is similar to the variation in density of vitreous silica observed upon irradiation by fast neutrons. It is also similar to the fractional changes in volume observed for electron bombardment of amorphous silica that had previously been compacted by neutron irradiation. The mechanism proposed [4,5,6] to explain this observation involves the electron radiation allowing stresses which had been imposed on the silica by the initial neutron compaction to be relieved. Thus, although electron radiation acting on a silica sample that had not been pre-stressed would cause compaction of the silica, an initial expansion was seen, followed by compaction at higher electron doses. It is proposed here that a similar mechanism is responsible for the observed dependence of frequency shift on total dose for SiO_x coated devices. During the process of coating the SAW resonators with SiO_x , stresses may be introduced into the silica layer and/or the crystal substrate. These stresses can be introduced in several ways, and may reside within each layer or may be concentrated at the interface. Initially, the electron radiation may allow for molecular reorientation, causing a relaxation of this intrinsic stress and leading to a frequency shift. At higher doses additional radiation compaction may occur causing the frequency shift to change direction. A possible alternative explanation for this behavior is that, since the density changes experienced by quartz when exposed to radiation are generally opposite those seen in amorphous silica, perhaps some sort of saturation is taking place in the silica layer initially, after which the changes taking place would be dominated by the behavior of the crystal substrate. More work needs to be done to determine

whether or not either of these proposed mechanisms explain the observed phenomena satisfactorily.

Conclusion

There are several areas which still require substantial investigation, not the least of which is the variation of device performance with heavy ion bombardment. However, several important results are evident from this study. First, the observed frequency shift of SAW resonators on non-coated substrates is approximately proportional to the square root of total dose. Further work is needed to refine this observation and obtain a useful model for prediction of such shifts. Second, substrate choice is significant if performance variations such as those observed in this experiment will impact system performance. Third, devices fabricated on swept quartz are quite resistant to radiation induced damage, exhibiting only small variations in performance even when exposed to relatively high total dose levels of gamma, high energy electron, and proton radiation. This result will be particularly significant to design engineers considering the use of SAW components in long-lived space applications. Last, but possibly most interesting, is the observation that utilizing a coating such as SiO_x can make devices fabricated on less pure materials behave as well or better than those fabricated on more costly high purity swept quartz. Whether this type of coating will reduce the sensitivity of devices fabricated on swept quartz even further is just one of the many fascinating unanswered questions the results of this study pose.

References

1. Berg, N., and Speulstra, J., "The Operation of Acoustic Surface Wave Delay Lines in a Nuclear Environment", *IEEE Trans. on Nucl. Sci.*, NS-20, No. 6, pp 137-143, 1973.
2. Berg, N., and Udelson, J., "Nuclear Radiation Effects on Surface Acoustic Wave Devices", *IEEE Trans. on Nucl. Sci.*, NS-21, pp. 141-148, 1974.
3. Berg, N., and Udelson, J., "The Effects of Pulsed Ionizing Radiation on the Operation of Surface Acoustic Wave Amplifiers and Convolver", *IEEE Trans. on Nucl. Sci.*, NS-22, No. 6, pp. 2503-2509, Dec. 1975.
4. Brückner, R., "Properties and Structure of Vitreous Silica. II.", *J. of Non-Cryst. Solids*, Vol. 5, pp. 177-216, 1971.
5. Primak, W., "Fast-Neutron-Induced Changes in Quartz and Vitreous Silica", *Phys. Rev.*, Vol. 110, No. 6, pp. 1240-1254, June 1958.
6. Primak, W., and Kampworth, R., "The Radiation Compaction of Vitreous Silica", *J. Applied Physics*, Vol. 39, No. 12, pp 5651-5658, Nov. 1968.

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