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High Level Gamma Radiation Effects on Cernox™ Cryogenic Temperature Sensors

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Abstract. Cryogenic temperature sensors are used in high energy particle colliders to monitor the temperatures of superconducting magnets, superconducting RF cavities, and cryogen infrastructure. While not intentional, these components are irradiated by leakage radiation during operation of the collider. A common type of cryogenic thermometer used in these applications is the Cernox™ resistance thermometer (CxRT) manufactured by Lake Shore Cryotronics, Inc. This work examines the radiation-induced calibration offsets on CxRT models CX-1050-SD-HT and CX-1080-SD-HT resulting from exposure to very high levels of gamma radiation. Samples from two different wafers of each of the two models tested were subjected to a gamma radiation dose ranging from 10 kGy to 5 MGy. Data were analysed in terms of the temperature-equivalent resistance change between pre- and post-irradiation calibrations. The data show that the resistance of these devices decreased following irradiation resulting in positive temperature offsets across the 1.4 K to 330 K temperature range. Variations in response were observed between wafers of the same CxRT model. Overall, the offsets increased with increasing temperature and increasing gamma radiation dose. At 1.8 K, the average offset increased from 0 mK to +13 mK as total dose increased from 10 kGy to 5 MGy. At 4.2 K, the average offset increased from +4 mK to +33 mK as total dose increased from 10 kGy to 5 MGy. Equivalent temperature offset data are presented over the 1.4 K to 330 K temperature range by CxRT model, wafer, and total gamma dose.

1. Introduction

High energy physics projects including ITER and FCC are driving radiation hardness requirements to increasingly higher levels. While it is not the goal of these high energy projects to irradiate supporting infrastructure and electronic components, they are invariably irradiated by the leakage radiation from the performed experiment. High energy physics projects often require superconducting magnets to steer charged particles or confine plasmas, and these superconducting magnetic require a cryogenic supply system complete with temperature monitoring down to 4.2 K and below. A common cryogenic temperature sensor used in these applications is the Cernox™ resistance temperature sensor (CxRT) manufactured by Lake Shore Cryotronics, Inc. [1] CxRTs are a negative temperature coefficient (NTC) device, and at the cryogenic temperatures required for these high energy applications they provide high stability, high resolution, low magnetic-field induced offsets, and high radiation resistance. (Refer to [2] for device specifications.) To date, CxRTs have been tested to 10 kGy gamma radiation in both cryogenic and room temperature irradiations. [3, 4, 5] This paper details the gamma radiation induced offsets in CxRTs at gamma irradiation levels ranging from 10 kGy to 5 MGy.

2. Method

The CxRT sensing body is a conducting zirconium nitride embedded in a non-conducting zirconium oxide matrix and the electrical resistance of this combination is a strong function of temperature. By modifying the relative ratios of conducting to non-conducting material the temperature sensitivity of the resulting sensor can be tailored to optimize performance over different temperature ranges. Two common Cernox models widely used in high energy physics applications are the model CX-1050-SD covering the 1.4 K to 420 K temperature range and the model CX-1080-SD covering the 20 K to 420 K temperature range. These two models were chosen for investigation in this work.

A total of 80 sensors were tested in this experiment. These 80 devices were comprised of 20 sensors from each of two model CX-1050 wafers and two model CX-1080 wafers. The sensors were all packaged in Lake Shore's SD package which is a flat, hermetically sealed package, measuring roughly 2 mm wide × 3 mm long × 1 mm high with 33 mm copper leads extending from the package. Prior to irradiation all sensors were calibrated in Lake Shore's Temperature Calibration Facility. Approximately 84 calibration measurements spanning the 1.4 K – 325 K temperature range were taken for the model CX-1050-SD-HT devices and 52 calibration measurements spanning the 20-325 K taken for the model CX-1080-SD-HT devices. The uncertainty associated with these calibrations is given in Table 1, and only temperature shifts above twice the calibration accuracy were considered statistically significant.

Table 1. Uncertainty of Lake Shore Cryotronics' calibrations.

Temperature (K)	Uncertainty (± mK)	
	CX-1050-SD	CX-1080-SD
1.4	4	–
4.2	4	–
10	4	–
20	8	8
30	9	9
50	12	11
100	17	14
200	33	25
300	46	36

Following calibration, the sensors were divided equally into ten groups – nine groups for irradiation plus one group for a control group. Nine levels of total gamma irradiation dose were chosen for investigation: 10 kGy, 25KGy, 50 KGy, 100 KGy, 250 KGy, 500 kGy, 1 MGy, 2.5 MGy, and 5 MGy. The sensors for each individual irradiation level group were assembled together, collectively wrapped in a piece of aluminum foil, and then placed in a 5 cm wide × 7.5 cm long × 2.5 cm tall ESD protective box padded with ESD compliant foam. The aluminum foil prevented contamination of the sensors from disintegrating foam and leaching plasticizers from the boxes due to irradiation. The boxes were wired shut using standard copper wire to prevent them from accidentally opening during handling. Irradiations were performed at Sandia National Laboratory's Gamma Irradiation Facility [6] at a dose rate of about 10 Gy/sec. Previous irradiation work to 10 kGy had indicated that no thermal annealing would occur so the irradiation was performed at room temperature. [7] Sensors were unpowered during irradiation.

Following irradiation, the sensors were returned to Lake Shore for testing with recalibration occurring within approximately two weeks. The data were analyzed in terms of the equivalent temperature shift calculated as $\Delta T = \Delta R / S_T$ where ΔR is the resistance change calculated as ($R_{Final} - R_{Initial}$) and S_T is the temperature sensitivity in ohms/kelvin. The results of these recalibrations are presented in the following section.

3. Results

The data are initially presented in terms of calibration shift as a function of temperature and of total gamma dose. Sample data is shown in Figure 1 where the temperature offsets are plotted as a function of temperature and dose for devices exposed to four different total dose levels spanning the lowest to highest levels tested in this work. In the figure, data for four sensors (two from each wafer) are shown for each dose level with filled symbols representing the first wafer and open symbols representing the second. The results in this figure are typical of the overall results. Generally, the radiation-induced temperature offsets increased with both increasing temperature and with increasing dose. Also, for samples from a given wafer, the offsets were consistent at total gamma radiation dose levels of 1 MGy and below. At a dose level of 5 MGy, increased scatter was observed even between samples from a single wafer. Scatter between the samples from different wafers was also observed to increase as the total dose level increased. These effects are all demonstrated by the data shown in Figure 1.

Figures 2 shows the average offsets for each dose level as a function of temperature for the combined CX-1050 wafers while Figure 3 shows the equivalent data for the combined CX-1080 wafers. To aid the eye in following the irradiation level, alphanumeric symbols "A" through "J" are used in labelling each plot with "A" representing the control group and symbols "B" through "J" representing the irradiation level increasing from 10 kGy to 5 MGy respectively.

The CX-1050-SD-HT devices tested in this work had room temperature resistances on the order of 55 Ω with sensitivities on the order of -0.15 Ω/K while the CX-1080-SD-HT devices had room temperature resistances on the order of 225 Ω with room temperature sensitivities of about -1.1 Ω/K. With that in mind, the +1,600 mK average room temperature offset of the CX-1050-SD-HTs after exposure to 5 MGy gamma radiation (see Figure 2) only represents a change of -0.24 Ω from the original 55 Ω pre-irradiation resistance, or about -0.43%. Similarly, the +2,600 mK average room temperature offset of the CX-1080-SD-HTs after exposure to 5 MGy gamma radiation (see Figure 3) only represents a change of -2.86 Ω from the original 225 Ω pre-irradiation resistance, or about -1.3%. With regard to radiation hardness, these values would be quite good if used as a simple resistor, but the decreasing sensitivity near room temperature magnifies the resistance change when used as a temperature sensor.

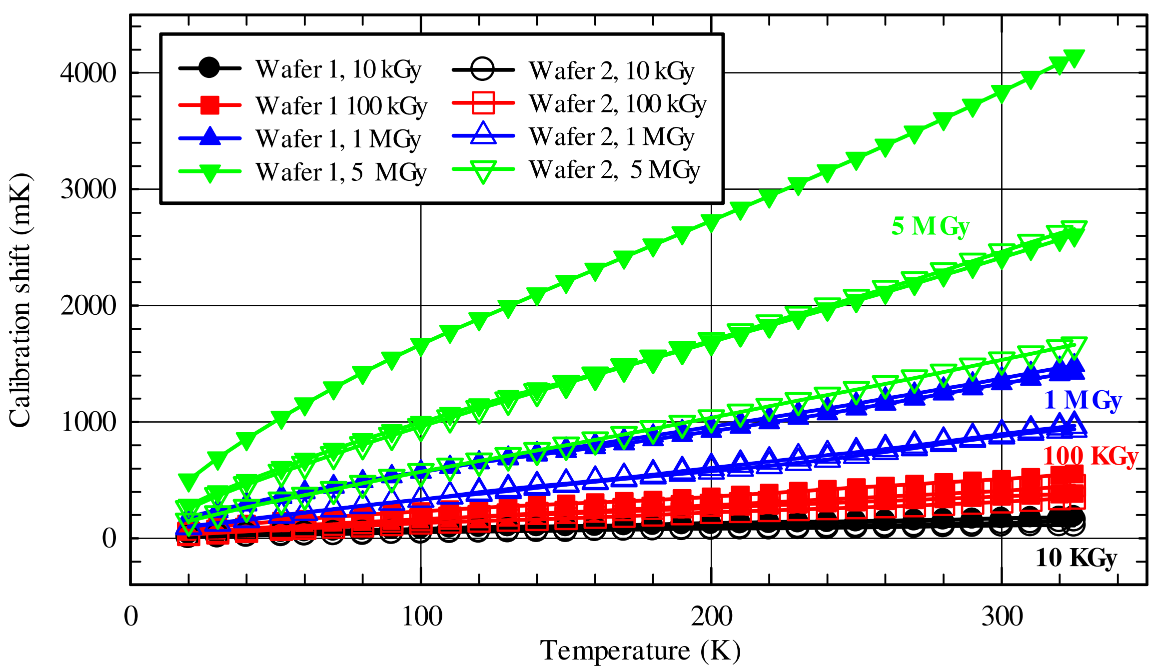

Figure 1. Typical calibration offset data as a function of temperature for sensors from the two tested CX-1080 wafers for four different total gamma radiation dose levels.

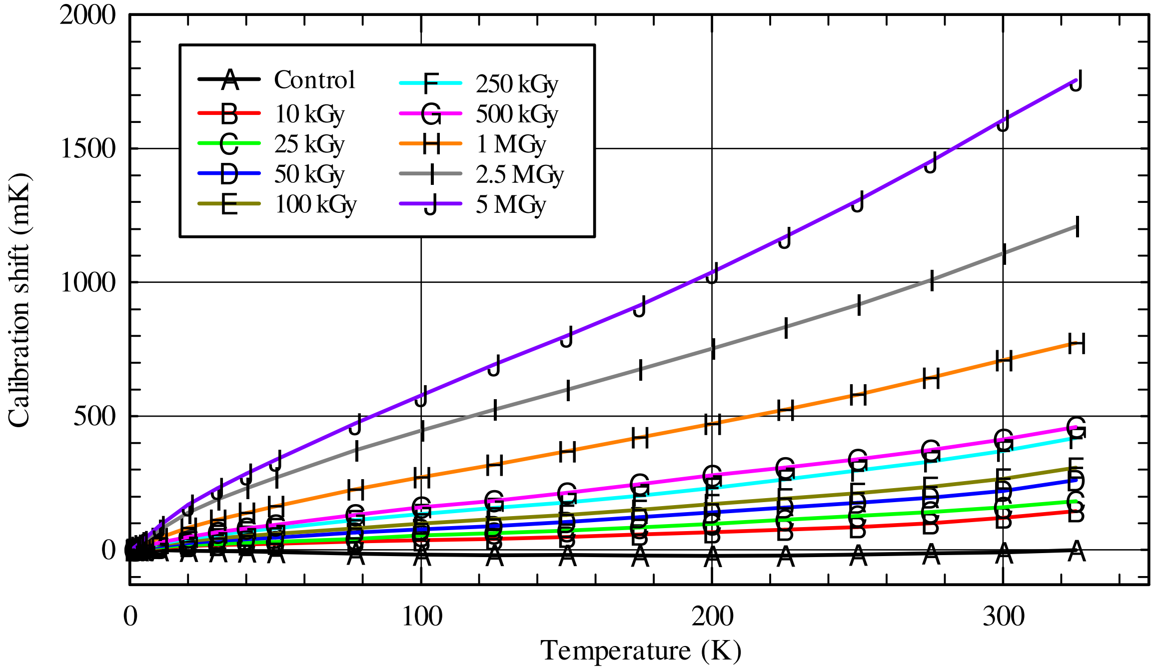

Figure 2. Summary of gamma radiation induced calibration shifts for CX-1050-SD-HT devices.

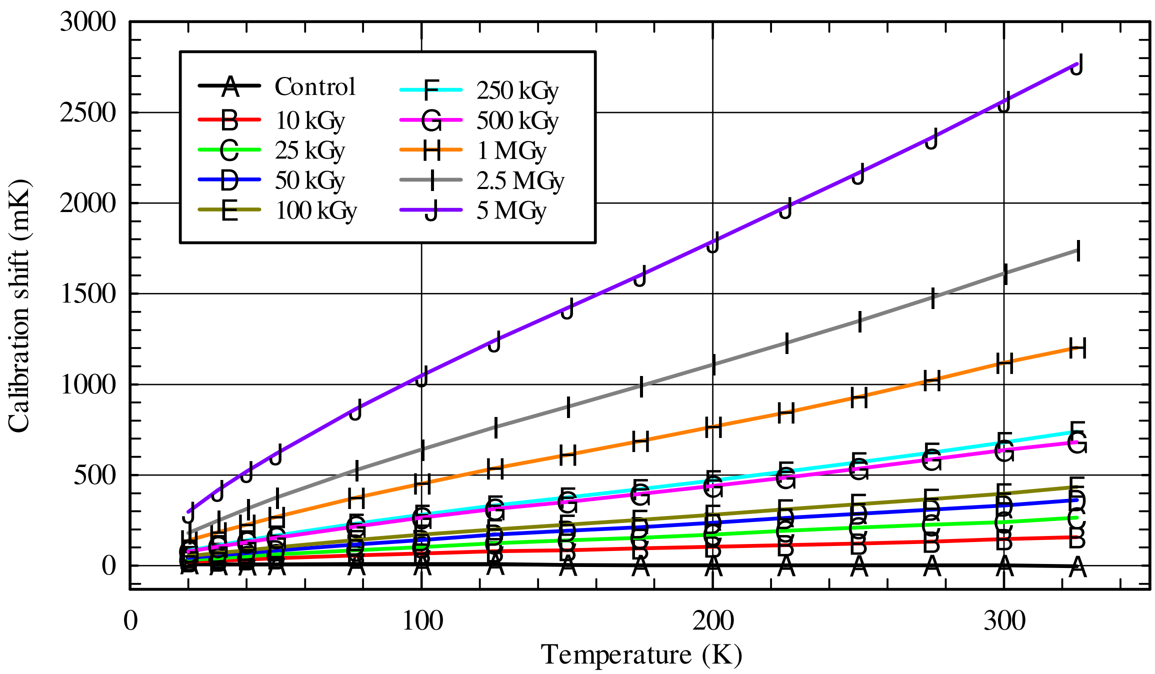

Figure 3. Summary of gamma radiation induced calibration shifts for CX-1080-SD-HT devices.

The wide range of calibration shifts in Figures 2 and 3 makes it difficult to discern the lower temperature offsets which is most often the region of interest. To better show the lower temperature data Figures 4 and 5 present the data as (ΔT/T) (%) as a function of temperature for the CX-1050-SD-HTs and CX-1080-SD-HTs respectively. The temperature scale has been converted to a log scale in these figures to provide even greater detail for the lower temperature data.

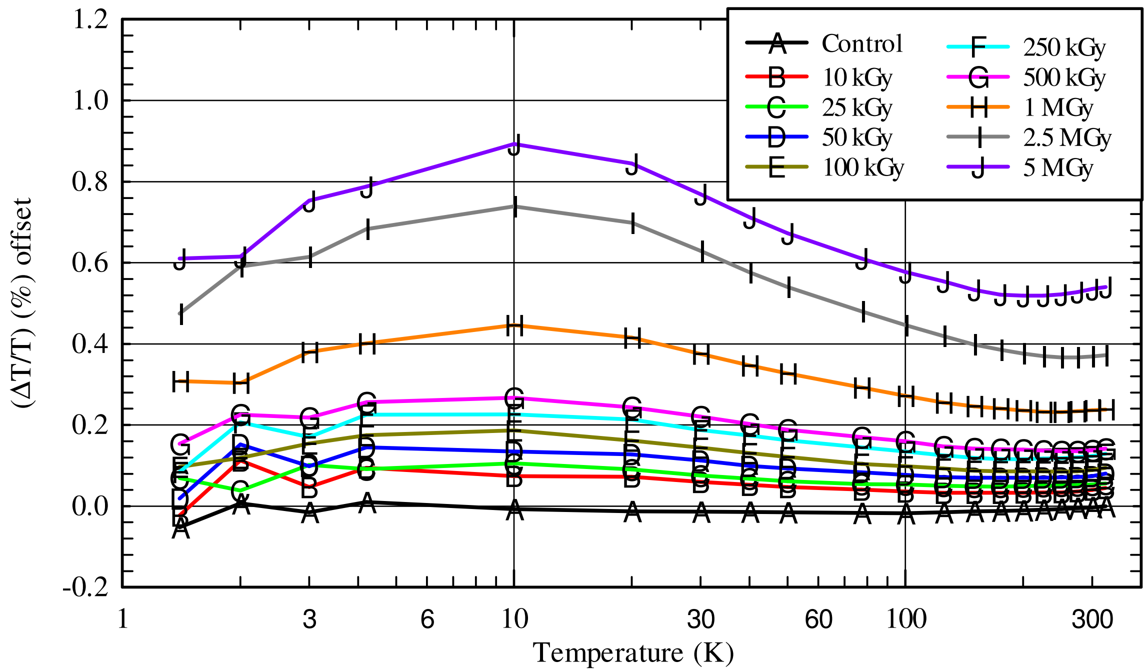

Figure 4. (ΔT/T) (%) as a function of temperature and total dose for combined CX-1050 wafers.

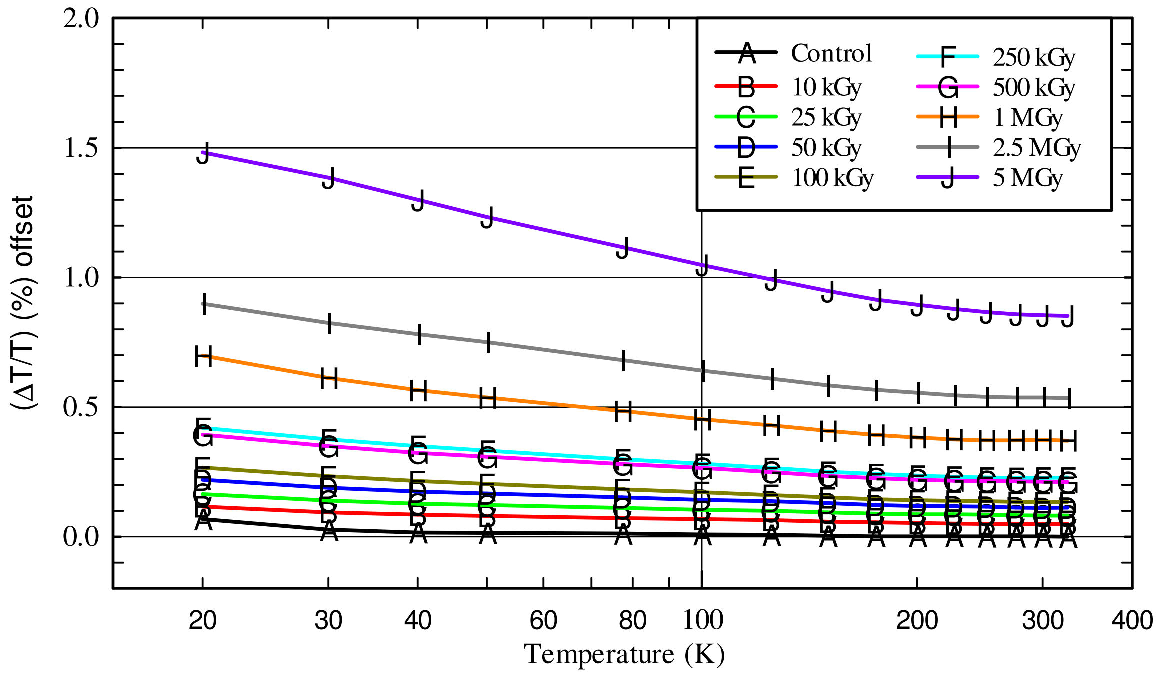

Figure 5. (ΔT/T) (%) as a function of temperature and total dose for combined CX-1080 wafers.

While the figures allow the overall trends to be quickly visualized, it's difficult to present the entirety of the data without making the plots unintelligible. For detailed results, these data have been summarized in Tables 2 and 3 for the CX-1050-SD-HT and CX-1080-SD-HT respectively.

Table 2. Average temperature offset and standard deviation of model CX-1050-SD sensors as a function of temperature and total gamma radiation dose.

Temp. (K)	Average offset (Standard Deviation) in millikelvin following irradiation at dose level									
	Control	10 kGy	25 kGy	50 KGy	100 kGy	250 kGy	500 kGy	1 MGy	2.5 MGy	5 MGy
1.4	-0.7 (1.3)	-0.3 (0.2)	1 (1.1)	0.3 (1.1)	1.4 (0.4)	1.2 (0.9)	2.1 (1.0)	4.3 (1.6)	6.6 (2.8)	8.5 (10)
2	0.1 (1.7)	2.3 (1.8)	0.8 (0.8)	3.1 (2.4)	2.4 (0.5)	4.1 (0.9)	4.5 (0.8)	6.1 (3.8)	12 (5.9)	12 (15)
3	-0.4 (1.3)	1.4 (0.6)	3.1 (1.6)	3 (1.1)	4.6 (1.0)	5.1 (1.3)	6.5 (1.3)	11 (4.4)	18 (7.4)	23 (26)
4.2	0.4 (1.2)	4 (2.4)	3.8 (0.9)	6.1 (1.9)	7.3 (1.5)	9.5 (1.3)	11 (1.4)	17 (7.9)	29 (12)	33 (38)
10	-0.7 (1.7)	7 (3.6)	11 (3.4)	14 (2.5)	19 (3.5)	23 (3.1)	27 (3.8)	45 (18)	74 (30)	89 (100)
20	-2.5 (2.8)	15 (7.1)	18 (3.7)	26 (6.6)	32 (6)	43 (6.3)	49 (7.6)	83 (33)	140 (58)	169 (186)
30	-4.1 (1.4)	18 (9.9)	23 (5.3)	34 (9.1)	43 (8.6)	56 (7.5)	66 (8.4)	113 (47)	189 (78)	231 (250)
50	-7.8 (3.7)	23 (13)	31 (6.6)	46 (13)	61 (11)	81 (11)	94 (13)	164 (67)	270 (111)	336 (354)
77.35	-13.1 (5.4)	32 (13)	42 (4.6)	65 (19)	81 (15)	112 (16)	131 (17)	226 (91)	371 (151)	472 (471)
100	-17.8 (6.2)	36 (16)	54 (14)	77 (22)	98 (21)	134 (22)	160 (20)	272 (103)	446 (181)	577 (556)
150	-18.8 (0.8)	49 (16)	73 (13)	105 (27)	131 (28)	178 (32)	213 (25)	369 (139)	598 (238)	800 (715)
200	-21.7 (3.1)	67 (23)	98 (22)	140 (36)	172 (39)	232 (39)	278 (28)	472 (174)	753 (294)	1037 (867)
250	-16.7 (8.1)	85 (14)	127 (25)	177 (40)	213 (50)	296 (50)	339 (38)	580 (217)	916 (358)	1306 (1015)
300	-8.8 (8)	121 (24)	160 (39)	222 (53)	266 (58)	371 (60)	413 (44)	709 (265)	1108 (420)	1607 (1177)
325	-0.8 (2.6)	145 (38)	182 (32)	261 (58)	307 (69)	419 (74)	460 (41)	774 (291)	1209 (465)	1757 (1275)

4. Discussion

The results of this work were consistent with previous investigations of CxRTs up to the 10 kGy level [3, 4, 5] and show the trend of positive temperature offsets (i.e. resistance decreases) continuing up to the 5 MGy level. No catastrophic failures resulted from the irradiation, and the offsets were sufficiently small that the devices remain quite useful after irradiation to even 5 MGy, especially at the lower temperatures of greatest interest in high energy physics. Although consistent with earlier results, the resistance decrease is somewhat unexpected. Co-60 gamma radiation with energies of 1.173 MeV and 1.332 MeV is expected to interact with matter mainly through the Compton Effect which could create defects in the material which would lead to an increase in resistance following irradiation. [8] Cleland, Crawford, and Holmes [9] observed displacement of atoms in germanium, another common cryogenic sensing material, when irradiated by Co-60, and these displacements resulted in an increase in the resistivity. More recently, Mitin et al. also observed a resistance increase in Ge on Ga-As films used as NTC cryogenic thermometers after toom temperature gamma irradiation to 7.6 MGy. [10] However, carbon resistors, which are also sometimes used as NTC cryogenic thermometers, have been observed to decrease in resistance in both bulk and film resistor form which was attributed to the creation of additional carriers in the material. [11, 12]

Table 3. Average temperature offset and standard deviation of model CX-1080-SD sensors as a function of temperature and total gamma radiation dose.

Temp. (K)	Average offset (Standard Deviation) in millikelvin following irradiation at dose level									
	Control	10 kGy	25 kGy	50 KGy	100 kGy	250 kGy	500 kGy	1 MGy	2.5 MGy	5 MGy
20	13 (3)	23 (13)	33 (14)	44 (6)	53 (22)	84 (22)	79 (62)	140 (47)	180 (36)	296 (148)
30	8 (3)	28 (10)	42 (12)	57 (6)	70 (23)	112 (22)	105 (80)	184 (63)	247 (51)	416 (200)
50	7 (4)	40 (11)	61 (14)	83 (10)	102 (29)	166 (27)	154 (114)	268 (90)	375 (69)	617 (288)
77.35	9 (3)	56 (14)	86 (19)	116 (17)	142 (39)	231 (34)	216 (156)	375 (119)	527 (91)	864 (386)
100	9 (4)	67 (16)	103 (21)	142 (20)	171 (42)	280 (37)	265 (188)	452 (137)	640 (109)	1048 (453)
150	5 (4)	86 (19)	140 (28)	192 (29)	226 (52)	375 (42)	352 (249)	612 (169)	875 (135)	1422 (581)
200	2 (4)	105 (23)	172 (28)	237 (41)	281 (57)	470 (49)	440 (305)	765 (202)	1109 (160)	1788 (700)
250	2 (2)	122 (26)	210 (31)	287 (53)	339 (73)	570 (48)	535 (365)	930 (238)	1348 (186)	2165 (821)
300	2 (6)	146 (30)	241 (41)	331 (61)	398 (83)	680 (56)	637 (431)	1119 (270)	1611 (212)	2563 (953)
325	-3 (11)	157 (34)	265 (39)	362 (72)	435 (90)	741 (71)	683 (474)	1203 (292)	1739 (232)	2768 (1027)

Metal oxide films are generally considered radiation hard, but the CxRT sensing film is a conducting ZrN embedded in a non-conducting ZrO matrix which complicates the behaviour. It's possible that the decrease in resistance is due to the creation of additional carriers within the ZrN/ZrO film, but it's also possible that the gamma radiation causes an interaction between the CxRT sensing film and the contact metallization used for electrical connection. The CxRT sensing film is a high resistivity material and the commercial devices utilize a metallization pattern with an interdigitated finger pattern that places multiple segments of the CxRT sensing film in parallel to reduce the overall resistance. That requires placing the metallization (gold over molybdenum) directly over the sensing film as shown in Figure 6. In this pattern, the V+ and I+ connections share a common electrical contact as do the V- and I- connections. This makes the device an inherently two-lead device and resistance changes due to changes in metallization are indistinguishable from changes in the actual sensing film. Differentiating between the radiation effect on the actual sensing film and that on the sensing film-contact metallization interface will require a metallization pattern that separates the voltage and current contacts and moves the voltage contacts out of the active area of the sensing film. Figure 7 shows one possible design that accomplishes these requirements.

5. Conclusions

In this work, a total of 80 sample CxRT cryogenic temperature sensors from two model CX-1050 and two model CX-1080A were irradiated to nine irradiation levels ranging from 10 kGy to 5 MGy using a Co-60 gamma radiation source in order to determine the effects of high level gamma radiation on their temperature response. For the nine irradiation levels tested, the data show a positive temperature calibration offset for the CxRTs that increases with both temperature and total dose. Sample devices from the same wafer showed consistent behaviour for radiation levels up to 1 MGy but showed variation at higher levels. Variations were also observed between samples from different wafers of the same model. No failures resulted from the radiation exposure, and, overall, the CxRT radiation hardness is quite good. In the region of interest to high energy experiments below 4.2 K, the induced offsets were small. At 1.8 K, the average offset increased from 0 mK to +13 mK as total dose increased from 10 kGy to 5 MGy. At 4.2 K, the average offset increased from +4 mK to +33 mK as total dose increased from 10 kGy to 5 MGy. These small offsets at 4.2 K and below for gamma radiation exposures up to 5 MGy make CxRTs a suitable cryogenic thermometer for high energy physics experiments where increasingly higher radiation levels are expected.

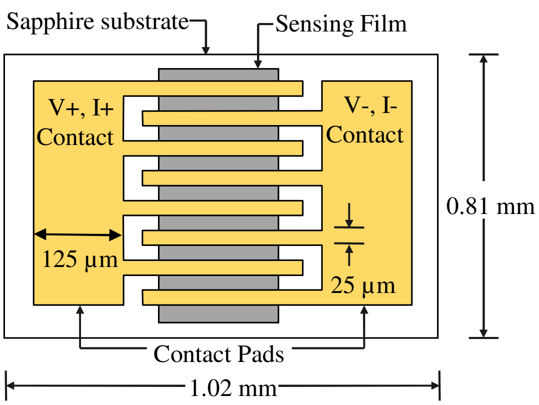

Figure 6. Current metallization pattern used for CxRT devices tested in this work.

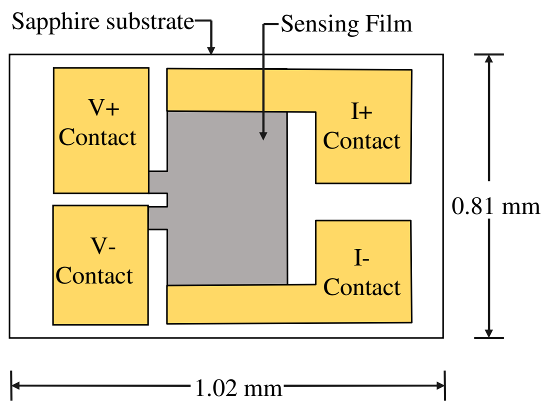

Figure 7. Mask pattern design to remove voltage contact metallization out of the active area of the sensing film to eliminate interface effects. .

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