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Radiation Tests of a Commercial Temperature Sensor for Monitoring System

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Abstract

An experimental study was conducted to evaluate the resiliency of the monitoring system based on the commercial DS18B20+ temperature sensors under the ionizing radiation exposure. These temperature sensors were irradiated with gamma rays till at least total ionizing dose of 680 Gy(Si). Several samples were exposed to irradiation at the different dose rate and various electrical modes. This work presents investigation results of the DS18B20+ temperature sensors measurement accuracy change under the influence of ionizing radiation. A good approximation of the temperature sensor measurement error was obtained numerically, using a power function. Experimental results allow modeling the radiation sensitivity of the monitoring system.

Keywords–temperature measurement accuracy, temperature sensor DS18B20+, ionizing radiation, dose rate, electrical mode

I. Introduction

Accurate temperature measurements are required in many measurement systems, for example, process control and instrumentation applications, for conducting studies and others. For this purpose thermocouple, resistive temperature sensors (platinum wire), thermistors (solid semiconductor material) and integrated circuit (IC) sensors can be used. Except for IC sensors, all temperature sensors have nonlinear transfer functions. Therefore, sensor nonlinearity correction is required. However, sensor output may be digitized directly by high resolution ADCs, hereupon linearization and calibration are performed digitally. The sensor output signal has to be properly conditioned and amplified before further processing if it is necessary. Moreover, temperature sensors with digital outputs have a number of advantages over those with analog outputs, especially for remote applications.

The DS18B20+ sensors from Maxim Integrated are programmable resolution 1-wire digital thermometer for high-precision temperature monitoring with minimal connections [1]. The basis of 1-Wire® technology is a serial protocol, using a single data line plus ground reference for communication [2]. The 1-Wire master initiates and controls the communication with one or more 1-Wire slave devices on the 1-Wire bus. Each 1-Wire slave device has a unique, unalterable, factory-programmed, 64-bit identification number, which serves as device address on the 1-Wire bus. This enables to connect up to 80 spatially distributed temperature sensors to a single wire bus. Thus, it is simple to use one microprocessor to control many DS18B20+s distributed over a large area. Most 1-Wire devices take their energy from the 1-Wire bus (parasitic power supply).

Preliminary studies have shown that the temperature sensors measurement accuracy is reduced under ionizing radiation exposure, and their measurement error depends on the dose rate and a power supply voltage [3]. Some irradiation tests have been already carried out on the Dallas (Maxim Integrated) DS18B20 temperature sensors at three high dose rates of 575, 50, and 5 krad(Si)/h up to 300 krad (Si) [4]. From this test, it can be observe that the measurement error is non-linear or “oscillating”. Also DS18B20 sensors were studied in a vacuum environment at temperature from -50 ℃ to 100 ℃ for the space measurement system [5].

Information about a total dose degradation of temperature sensors precision provides more accurate temperature data at testing of different objects under ionizing radiation. As a result of this study can be carried out modernization of the experimental equipment for monitoring in real time the research subject temperature or the local ambient temperature during radiation exposure experiments, using spatially distributed temperature sensors, connected to a single bus, as well as reducing the weight and dimensions of the temperature sensors simultaneously. For this purpose, the tests were carried out, using gamma rays from interim decay storage of research reactor. The DS18B20+ samples were irradiated up to at least total ionizing dose of 680 Gy(Si) at three dose rates: 10^{-4} Gy(Si)/s, 10^{-3} Gy(Si)/s, and 0.01 Gy(Si)/s. For example, the dose rate of 10^{-4} Gy(Si)/s and 10^{-3} Gy(Si)/s are low enough to carry out ground testing, simulating space environment.

II. Devices Under Test

The DS18B20+ digital thermometer is an IC temperature sensor with a bandgap-based thermal circuit [1]. The high accuracy of these sensors is specified by compensating for the offset and curvature of the device error characteristic. This technique does not work for Maxim's older thermal ICs, which have a dual-oscillator-based thermal measurement circuit.

The DS18B20+ temperature sensor provides 9-bit to 12-bit Celsius temperature measurements and has an alarm function with nonvolatile user-programmable upper and lower trigger points. The DS18B20+ communicates over a 1-Wire bus that by definition requires only one data line (and ground) for communication with a central microprocessor. It has an operating temperature range from -55 °C to +125 °C and is accurate to ± 0.5 °C over the range of -10 °C to +85 °C. The core functionality of the DS18B20+ is its direct-to-digital temperature sensor. The resolution of the temperature sensor is user-configurable to 9, 10, 11, or 12 bits, corresponding to increments of 0.5 °C, 0.25 °C, 0.125 °C, or 0.0625 °C, respectively. The default resolution at power-up is 12-bit.

The DS18B20+ can be powered by an external supply on the V_{DD} pin, or it can operate in “parasite power” mode, which allows the DS18B20+ to function without a local external supply. The DS18B20+ power supply range is from 3.0 V to 5.5 V. In the latter case, the DS18B20+ can derive power directly from the data line (“parasite power”). So the DS18B20+ is charged while the bus is high, and some of the charge is stored on the parasite power capacitor (C_{PP}) to provide power when the bus is low.

III. Test Setup

Developed software and test equipment have provided real-time monitoring of the measured temperature values of two DS18B20+ sensors (the one of them is the reference sensor) and displaying on the monitor screen two graphs of temperature versus time.

The 1-Wire bus system uses a single bus master to control one or more slave devices. Test equipment includes a specialized adaptor (1-Wire master), to which two slave adaptors are connected on the same wire. The temperature sensors are easy installed to slave adaptor. 1-Wire master enables communication between a USB host system and a 1-Wire bus, using a bridge chip. In this bus system, the master identifies and addresses devices on the bus, using each device’s unique 64-bit code.

1-Wire Software Developer's Kit for Windows has allowed developing software application for the Windows platform that requires communicating with hardware devices (adaptor) for sending and receiving information through the 1-Wire protocol. Software allows also setting resolution of the temperature sensors, the conversion time and saving the data to a file.

IV. Test Description

In total, 30 different DS18B20+ samples were tested. Six sets of devices, each consisting of 5 DS18B20+ temperature sensors, were irradiated at the room temperature (~22 °C), three dose rates and two electrical modes during radiation exposure, using a gamma ray source.

Samples were exposed to three different dose rates: 0.36 Gy(Si)/h, 3.6 Gy(Si)/h, and 36 Gy(Si)/h. The external power supply was equal to 5.0 V or 0 V at an active or a passive electrical mode during effects of ionizing radiation, respectively. All the studies were performed at the measurement accuracy of 0.0625 °C. The irradiated sets of all devices under test are individually identified according to Table I.

Within these studies it was assumed that the measurement error is a difference between the temperature values of irradiated sensors and the reference sensor that was not exposed to ionizing radiation.

Prior to radiation tests, the comparative evaluation was carried out in order to estimate the initial differences between the temperatures values of the reference sensor and sensors to be intended for radiation exposure.

The devices of each set were attached to one board, and the samples of A1, A2, A3-sets were continuously and simultaneously biased at 5.0 V. Using a gamma ray source, six sets of devices, each consisting of five DS18B20+ samples, were irradiated at three dose rates and two electrical modes.

Each sensor of all sets was passed a comparative evaluation between steps at the radiation exposure runs. The DS18B20+ measurement accuracy was determined by the results of the comparative evaluation. The temperature measurement error was increased during the influence of ionizing radiation.

TABLE I. IRRADIATED SETS AND DEVICES NUMBERS

Dose Rate [Gy(Si)/h]	Electrical Mode	
	Active	***Passive***
0.36	A1-1, A1-2 … A1-5 (Set A1)	P1-1, P1-2 … P1-5 (Set P1)
3.6	A2-1, A2-2 … A2-5 (Set A2)	P2-1, P2-2 … P2-5 (Set P2)
36	A1-3, A3-2 … A3-5 (Set A3)	P1-3, P3-2 … P3-5 (Set P3)

V. Results

The aim of the experimental research was to investigate the effect of gamma radiation on the DS18B20+ temperature sensors measurement accuracy. The devices measurement accuracy variations in consequence of radiation exposure are obtained.

The temperature measurement error of all A1, A2, A3-sets samples as a function of total ionizing dose (TID) are shown in Fig. 1, Fig. 2 and Fig. 3, respectively. On the other hand, the experimental data for all P1, P2, P3-sets samples can be observe in Fig. 4, Fig. 5 and Fig. 6, respectively. These figures let us observe that increasing temperature leads to the increase of the DS18B20+ measurement error for all combinations of electrical modes and dose rates. It can be seen that specific measurement error at various experiment conditions differs between samples of each set, and this variance increases with increasing TID.

The DS18B20+ average measurement error at the active and the passive electrical modes for all dose rates under ionizing radiation are depicted in Fig. 7 and Fig. 8, respectively. The average DS18B20+ accuracy degradation rates are different for each combination of electrical modes and dose rates. The measurement error of all samples irradiated at the active mode is greater than samples irradiated at the passive mode. Moreover, the measurement error decreases with increasing dose. Thus, the DS18B20+ temperature sensors measurement accuracy over the investigated dose range is minimal at the dose rate of 36 Gy(Si)/h.

A distinctive feature of the effects of ionizing radiation to DS18B20+ at the passive mode is that the measurement error increase at the dose rate of 0.36 Gy(Si)/h significantly exceeds the same one at the dose rate of 3.6 Gy(Si)/h and 36 Gy(Si)/h. Further, the measurement errors at dose rates of 3.6 Gy(Si)/h and 36 Gy(Si)/h are not much different from each other.

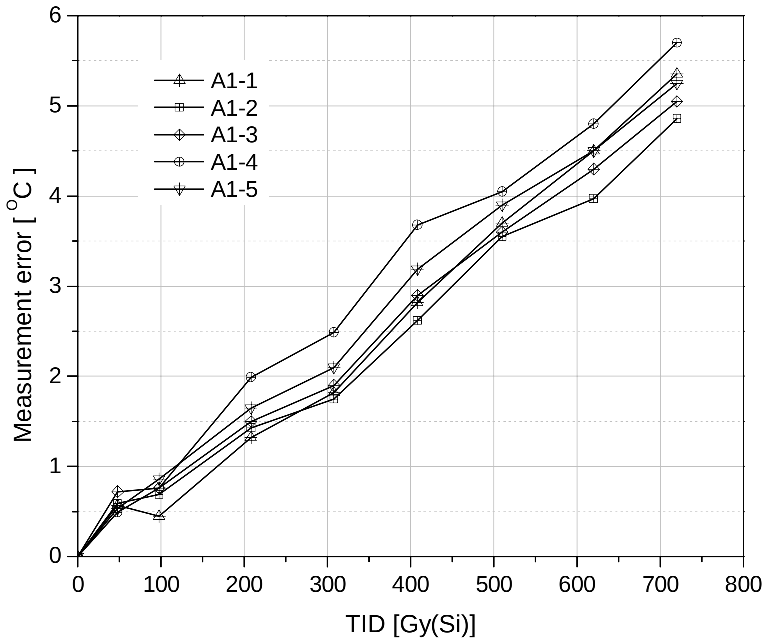

Fig. 1. Measurement error versus TID for the A1-set samples.

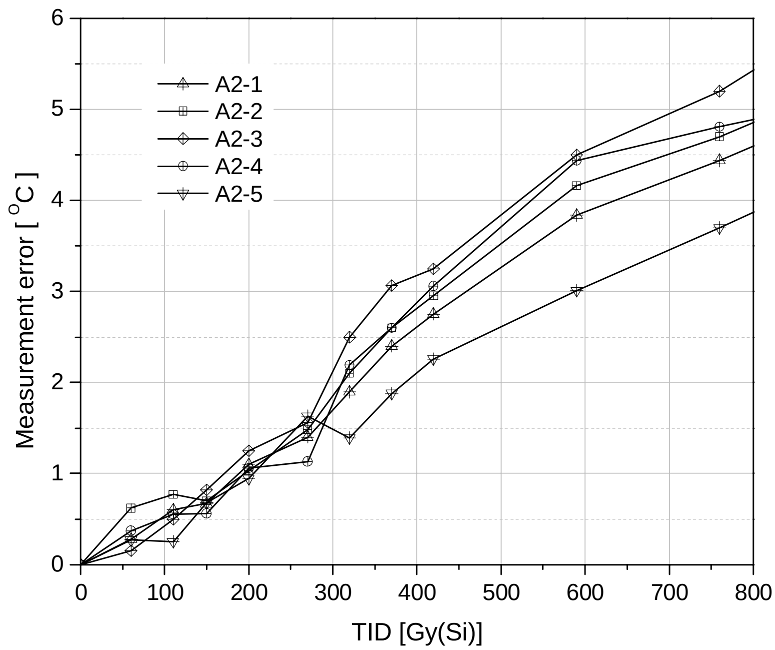

Fig. 2. Measurement error versus TID for the A2-set samples.

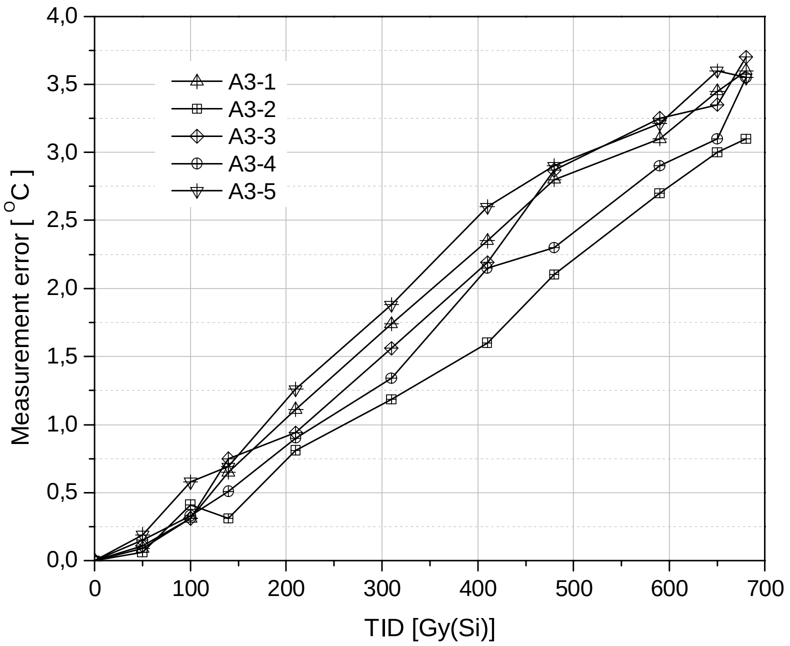

Fig. 3. Measurement error versus TID for the A3-set samples.

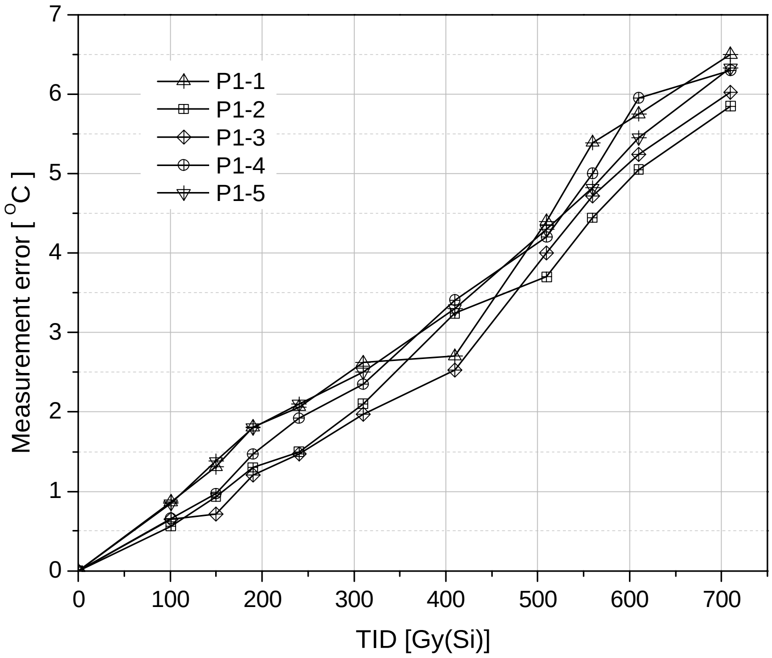

Fig. 4. Measurement error versus TID for the P1-set samples.

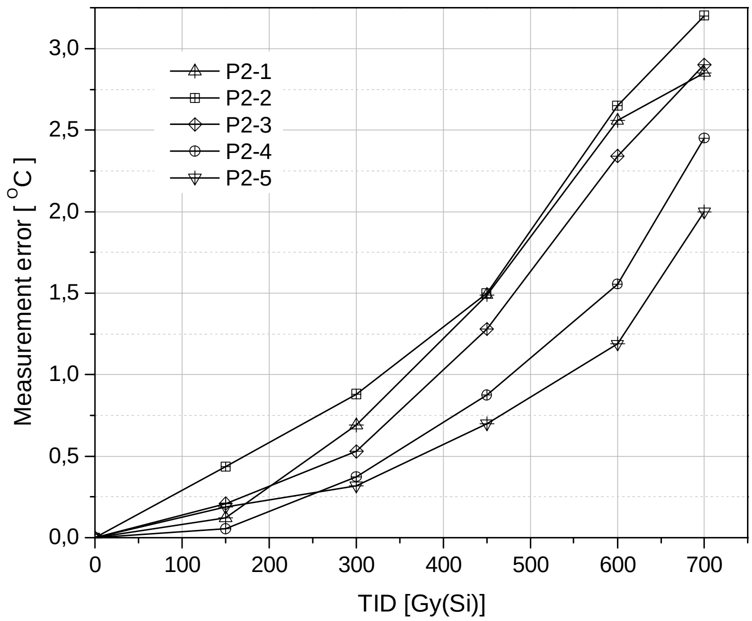

Fig. 5. Measurement error versus TID for the P2-set samples.

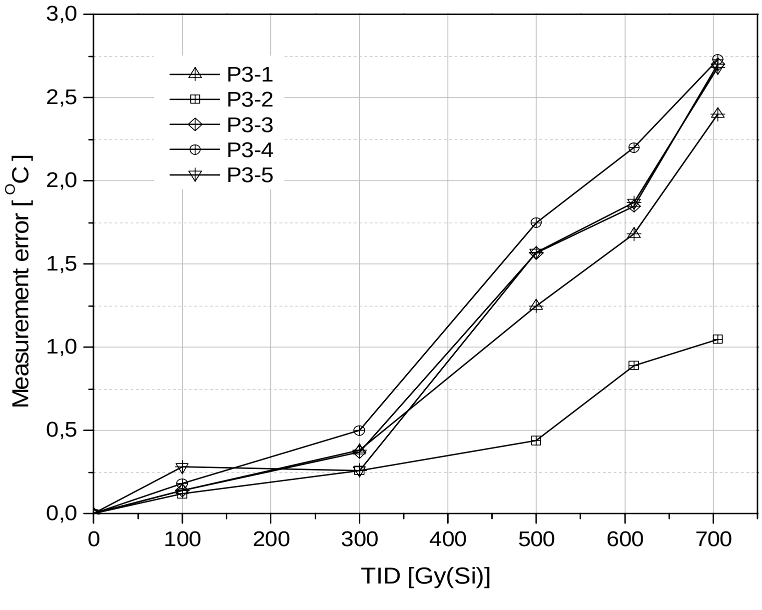

Fig. 6. Measurement error versus TID for the P3-set samples.

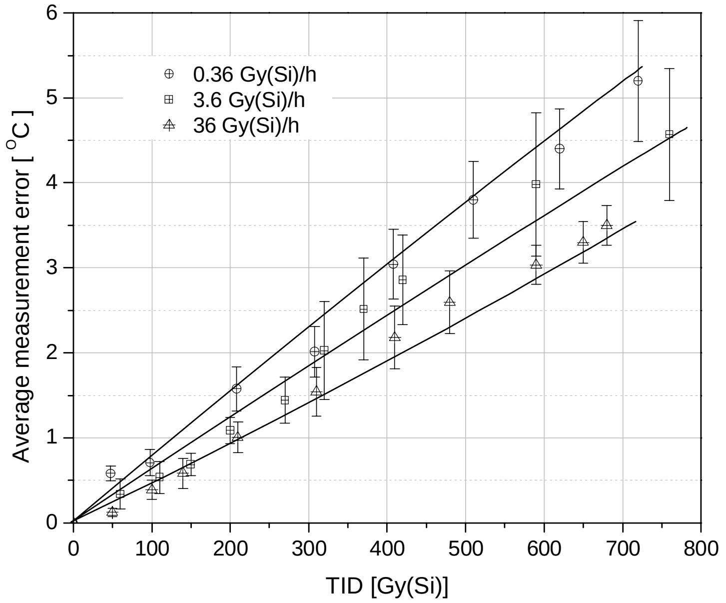

Fig. 7. Average temperature measurement error as function of the total ionizing dose at the active electrical mode at the dose rates of 0.36 Gy(Si)/h, 3.6 Gy(Si)/h, 36 Gy(Si)/h.

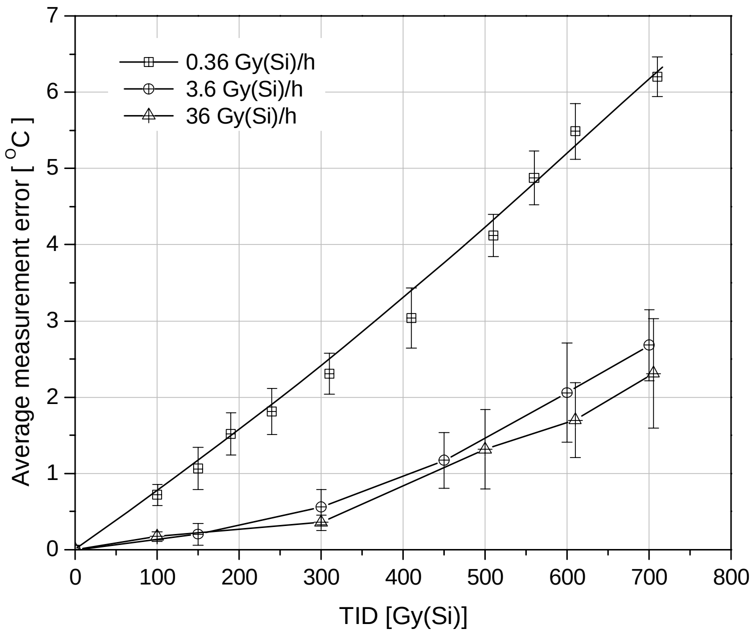

Fig. 8. Average temperature measurement error as function of the total ionizing dose at the passive electrical mode at the dose rates of 0.36 Gy(Si)/h, 3.6 Gy(Si)/h, 36 Gy(Si)/h.

VI. Relation Between Temperature Measurement Error and TID

It is possible to derive a mathematical expression for the dependence between the DS18B20+ temperature measurement error and TID for different dose rate and electrical modes, using the obtained results.

The experimental data has been fitted with the various power functions. The best accuracy has a fitted equation of the temperature sensors measurement error ΔT:

$$\Delta T = a \cdot D^b,$$

where a and b are the approximation coefficients.

The values of both coefficients for different working conditions of DS18B20+ temperature sensors are presented in Table II.

TABLE II. THE APPROXIMATION COEFFICIENTS

Electrical mode	**Dose rate [Gy/h]**	***a*** **[°C/(Gy)^b]**	***b***
Active	0.36	$3.9 \cdot 10^{-3}$	1.1
	3.6	$3.5 \cdot 10^{-3}$	
	36	$2.7 \cdot 10^{-3}$	
Passive	0.36	$3.3 \cdot 10^{-3}$	
	3.6	$3.8 \cdot 10^{-4}$	1.7
	36	$2.8 \cdot 10^{-5}$	

VII. Conclusions

The DS18B20+ temperature sensors were irradiated with gamma rays no less than 680 Gy(Si) at various combinations of dose rates (0.36 Gy(Si)/h, 3.6 Gy(Si)/h, 36 Gy(Si)/h) and electrical modes (from a power supply of 5.0 V or without external supply).

Acquired results have shown that the measurement accuracy degradation under the ionizing radiation exposure differs for samples of each set. Generally, the temperature measurement error is increasing during the ionizing radiation exposure. The results have also demonstrated that the measurement accuracy degradation trend is similar for all DS18B20+ digital thermometers at the different dose rates and both electrical modes during radiation exposure. The experimental data were fitted by different functions within the investigated total ionizing dose range up to 680 Gy(Si), an approximate solution with the best accuracy has been determined, and the approximation coefficients have been extracted for each dependency.

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