Design of Radiation Hardened RADFET Readout System for Space Applications

Marko Andjelkovic[1], Aleksandar Simevski[1], Junchao Chen[1],
Oliver Schrape[1], Zoran Stamenkovic[1], Milos Krstic[1, 2]
[1] IHP – Leibniz-Institut für innovative Mikroelektronik
Frankfurt Oder, Germany
[2] University of Potsdam, Potsdam, Germany
{andjelkovic, simevski, chen, schrape, stamenko, krstic}@
ihp-microelectronics.com

Stefan Ilic, Luka Spahic, Laza Kostic, Goran Ristic
Faculty of Electronic Engineering, University of Nis
Nis, Serbia
stefan.kocanac@gmail.com, luka.spahic@gmail.com,
lazakostic@rocketmail.com, goran.ristic@elfak.ni.ac.rs

Aleksandar Jaksic
Tyndall National Institute
Cork, Ireland
aleksandar.jaksic@tyndall.ie

Alberto J. Palma, Antonio Lallena, Miguel Angel Carvajal
University of Granada
Granada, Spain
{ajpalma, lallena, carvajal}@ugr.es

Abstract**—Measurement of absorbed dose and dose rate is a common task in radiation environments such as space. This is accomplished with the specialized instruments known as radiation dosimeters. Among the most commonly used radiation dosimeters in space missions are those based on the Radiation Sensitive Field Effect Transistors (RADFETs). In this paper, we propose a design concept for a radiation hardened readout system for the real-time measurement of absorbed dose and dose rate with RADFET. The successive switching between the absorbed dose and dose rate readout modes, as well as the subsequent data processing, are performed by the self-adaptive fault-tolerant Multiprocessing System-on-Chip (MPSoC). The integrated framework controller and the real-time monitoring of particle flux with the embedded Static Random Access Memory (SRAM) enable the autonomous selection of operating and fault-tolerant modes, thus achieving the optimal performance under variable radiation conditions.**

Keywords—RADFET readout, radiation hardness, self-adaptive multiprocessing system-on-chip (MPSoC)

I. INTRODUCTION

The space environment is characterized by intense radiation originating from three main sources: galactic cosmic rays, solar particle events and radiation trapped in the Earth's magnetic field. The radiation intensity (flux) may increase by several orders of magnitude during a period of few hours or days (e.g. during the solar particle events) [1]. Such intense radiation may be lethal for humans, but is also a main source of temporary and permanent failures in electronic devices, circuits and systems. Therefore, the real-time monitoring of radiation intensity and the use of radiation hardened electronic instrumentation are the major requirements for space missions.

Monitoring of ionizing radiation exposure is accomplished with the specialized radiation dosimeters which provide the real-time measurement of the total absorbed dose and the dose rate under radiation exposure. A radiation dosimeter is composed of at least one radiation sensor and data processing electronics. The operating principle is based on measuring the radiation-induced change of the sensor's electrical parameters (i.e. the change of current flowing through the sensor or the voltage across the sensor). Due to their miniature geometry, inherent sensitivity to ionizing radiation and compatibility with the Complementary Metal Oxide Semiconductor (CMOS) technologies, the semiconductor electronic and optoelectronic devices such as diodes, transistors, photodiodes and phototransistors are usually used as radiation sensors.

In general, either custom-designed or commercial semiconductor devices can serve as radiation sensors. Because of their low price and wide availability, various commercial components have been investigated for dosimetry applications [2 – 8]. However, the custom-designed radiation sensors provide higher sensitivity, accuracy and resolution, and are thus more suitable for critical applications such as space missions. One of the most common radiation sensors employed in space are the Radiation Sensitive Field Effect Transistors (RADFETs). In comparison to other dosimetric solutions, RADFETs offer the advantages in terms of the possibility of operation without voltage bias and the ability to store the dosimetric information.

For acquisition of the signal from a radiation sensor and subsequent computation of absorbed dose and dose rate, the mixed-signal processing is required. Depending on the application requirements, the processing can be implemented with standard microcontrollers, Field Programmable Gate Arrays (FPGAs) or custom-designed Application Specific Integrated Circuits (ASICs). However, modern electronic systems are inherently sensitive to the high energy particles which can cause the Single Event Effects (SEEs) and subsequently result in soft (temporary) or hard (permanent) errors. Therefore, the design of electronic systems for radiation environment requires efficient and cost-effective radiation hardening measures.

In this paper, a design concept for a radiation hardened readout system combining a RADFET and a self-adaptive multiprocessor platform is proposed. The basis of the proposed design is a quad-core processing platform with the custom-designed framework controller and the Static Random Access Memory

(SRAM) which acts as a data storage unit and a particle detector. Such solution allows for dynamic selection of the operating and fault tolerant modes according to the application requirements and the measured radiation intensity. As a result, higher integration level and flexibility than the state-of-the-art solutions can be achieved.

The rest of the paper is organized as follows. The related work on RADFET dosimetry and the contributions of this work are elaborated in Section II. The overall design of the readout system is introduced in Section III. The preliminary design specifications of the analog and digital subsystems are discussed in Sections IV and V, respectively.

II. RELATED WORK AND PAPER CONTRIBUTION

A. Fundamentals of RADFET Dosimetry

The RADFET, also known as the MOSFET or pMOS dosimeter, is the p-channel MOS transistor specially designed for high sensitivity to ionizing radiation. It is mainly used for the absorbed dose measurement, but is also suitable for measuring the dose rate. The readout circuits for absorbed dose and dose rate measurement are illustrated in Figure 1.

For the absorbed dose measurement, the operating principle is based on the threshold voltage shift, ΔV_T, resulting from the radiation-induced charge accumulation in the gate oxide. As the volume of the oxide is finite, the amount of charge that can be accumulated is also finite. Based on this reasoning, a rational equation for calculating the absorbed dose D in terms of ΔV_T has been proposed by *Ristic et al.* [9],

$$\Delta V_T = a - \frac{a}{1 + b \cdot D^c} \qquad (1)$$

where a, b and c are constants for a given RADFET obtained by fitting the experimental results.

In principle, ΔV_T is equivalent to the difference between the threshold voltage before irradiation and the threshold voltage after certain period of irradiation. The threshold voltage V_T is measured by the so-called "one-point" method illustrated in Figure 1 (a), i.e. V_T is equal to the gate/drain voltage for a given drain current I_D, where I_D is typically around 10 µA.

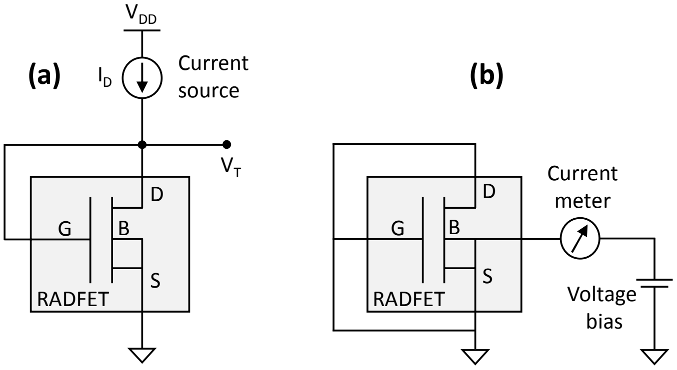

Figure 1: Readout configuration for: (a) dose measurement, and (b) dose rate measurement

The feasibility of the real-time dose rate measurement with RADFET has been demonstrated experimentally, with the Co^{60} gamma irradiation, by *Andjelkovic et al.* [10]. In contrast to the absorbed dose measurement approach where the gate oxide is the sensitive area, for the dose rate measurement the substrate (bulk) is the sensing region. The main idea is to measure the direct current induced by the radiation.

The measurement of dose rate with RADFET [10] employs similar concept as for *pn* diodes, i.e. a RADFET is configured as a diode and the reverse bias voltage is applied at the bulk, as illustrated in Figure 1 (b). Previous experimental results have shown that with the reverse bias voltage from 10 to 30 V, the current induced by gamma radiation is stable during the fixed dose rate exposure, for the dose rates from 0.65 to 32 Gy/h [10]. Depending on the reverse bias voltage, the induced current varies from around 200 pA to almost 4 nA in the investigated dose rate range, which can be measured very accurately with the standard current-to-voltage conversion techniques.

The mean value of the radiation-induced direct current as a function of dose rate and bias voltage can be expressed with the power relation [10],

$$I = k \cdot V_{BIAS} \cdot \dot{D}^m \qquad (2)$$

where I is the mean effective radiation-induced current in nA, $\dot{D}$ is the dose rate in Gy/h, V_{BIAS} is the reverse bias voltage in V, and k and m are the fitting coefficients.

Recently, *Kulhar et al.* [11] have shown that RADFETs can be also operated in the pulsed current mode, enabling to measure lower dose rates than those reported in our previous work [10]. At lower dose rates, the radiation generates current pulses in the RADFET which can be converted to voltage pulses, whereby the pulse count rate is proportional to the dose rate. As reported in [11], this approach allows for measuring the dose rates down to 0.5 mGy/h.

B. RADFET Readout Solutions for Space

Various RADFET readout systems have been reported in literature [12 – 15]. However, in these solutions RADFETs are used only for the absorbed dose measurement. In addition, in all cases a single processing core in the form of a commercial microcontroller or FPGA is used. The radiation hardness is achieved either through the hardware redundancy within FPGA or by replicating the microcontroller chips on the board. These approaches have two important shortcomings in the context of emerging space applications. First, measuring only the dose is not sufficient and hence would be necessary to use additional sensors (e.g. *pn* or *pin* diodes) for the dose rate measurement, which increases the overall cost of the implementation. Second, the static hardening measures produce significant overhead in terms of power consumption which is not acceptable for long-term space missions due to the restricted power budget.

C. Paper Contribution

Considering the aforementioned limitations of the existing RADFET readout solutions, this work introduces the following original contributions:

- The concept of simultaneous measurement of absorbed dose and dose rate with a single RADFET.
- The use of self-adaptive quad-core processing platform as a basis for radiation hardened RADFET readout system.

By measuring simultaneously the absorbed dose and dose rate with RADFET, the complete information on the radiation exposure can be obtained in real time with a single radiation sensor. Such concept eliminates the need for additional sensors for dose rate monitoring as in the case of previous solutions. Thus, the overall implementation cost can be minimized, while leveraging the unique benefits of the RADFET dosimetry.

With the readout system based on the self-adaptive multicore processing platform, the functionality is not limited only to monitoring of one or more RADFETs but is also possible to monitor other types of sensors within a spacecraft or a satellite. Moreover, the same platform can perform other mission-critical tasks (e.g. navigation, image processing, communication). Such hybrid concept is crucial in modern space applications which require high level of integration and fault tolerance with minimum power consumption.

III. READOUT SYSTEM DESIGN

Although it is possible to integrate the complete processing electronics on the same chip, in this initial design stage the analog and digital subsystems will be viewed as separate units. This approach has been chosen because the digital section, including the analog-to-digital converter (ADC), has been fully verified through different ICs developed at IHP. Moreover, at this initial design stage would be challenging to plan the on-chip integration of the highly sensitive analog circuitry for measuring very low currents in the picoampere range. It could also be possible to integrate the RADFET with the processing electronics, but the disadvantage of such approach is that it would not be possible to replace the RADFET and thus the whole system will have limited lifetime determined by the lifetime of the RADFET.

The proposed readout platform is composed of two separate units: an Analog Signal Conditioner (ASC) and a self-adaptive Multiprocessor System-on-Chip (MPSoC). The ASC is envisioned as a fully analog unit based on commercially available components. On the other hand, the MPSoC is intended to be implemented on a single chip, leveraging the IHP's commercial space-grade 130 nm SiGe BiCMOS technology. The block diagram of the readout system is illustrated in Figure 2.

Regarding the absorbed dose and dose rate measurement, three readout modes are supported:

1) ***No readout***: All pins are grounded and RADFET is operated as a passive absorbed dose meter, with or without bias applied to the gate terminal. Dose rate monitoring is not possible in this mode.

2) ***Absorbed Dose Readout***: The voltage measurement circuit is connected to RADFET and absorbed dose is calculated based on the threshold voltage shift.

3) ***Dose Rate Readout***: The current measurement circuit is connected to RADFET and the dose rate is calculated from the measured current.

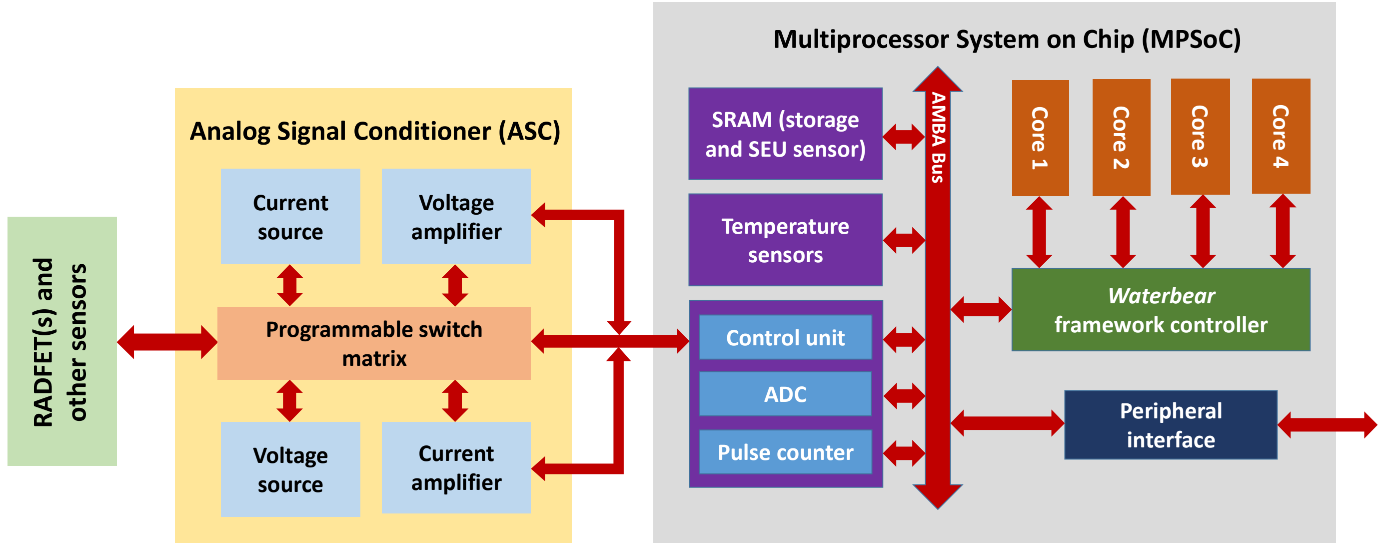

Figure 2: Proposed readout system design

IV. ANALOG SIGNAL CONDITIONER (ASC)

The Analog Signal Conditioner (ASC) processes the analog signals generated by the RADFET in the Absorbed Dose and Dose Rate Readout modes. The switching between the operating modes is controlled by the MPSoC. The ASC is composed of two acquisition channels: (i) voltage readout channel for absorbed dose measurement, and (ii) current readout channel for dose rate measurement. At this conceptual design stage, the idea is to implement the ASC subsystem with commercially available components suitable for space applications.

A. Voltage Readout Channel

The voltage readout channel measures the threshold voltage in the Absorbed Dose Readout mode, according to the setup depicted in Figure 1 (a). A current source provides the constant current bias at the RADFET's drain terminal, and a voltage source is employed to optionally bias the RADFET's gate terminal and thus control the sensitivity to radiation. A multi-range voltage amplifier is utilized to convert the voltage from the RADFET to the voltage range supported by the ADC integrated in MPSoC.

B. Current Readout Channel

The current readout channel combines the direct and pulsed current measurement in the Dose Rate Readout mode. For this purpose, the setup illustrated in Figure 1 (b) is used. It consists of a voltage source for biasing the RADFET's bulk terminal, a current measuring unit for direct current measurement and a charge measuring unit for pulsed current measurement. The direct current induced in the RADFET at medium and high dose rates is measured by the transimpedance amplifier, and a current integrator is used for measuring the pulsed current at low dose rates. Due to the wide range of current that can be induced in RADFET during the radiation exposure, the multi-range transimpedance amplifier with autonomous gain switching is required. As the lowest radiation-induced current can be in the range of tens of pA, it is required to use a very low input bias current operational amplifiers in the transimpedance and current integrating stages.

C. Programmable Switching Matrix

The switching matrix enables to select one of the three readout modes (no readout, absorbed dose measurement mode or dose rate measurement mode). It is based on analog switches used to successively implement the readout circuits given in Figure 1. For this purpose, eleven switches are required. The control signals and the switching pattern are defined in the program executed by the MPSoC.

D. Hardening of Analog Circuitry

The analog circuitry may be sensitive to Total Ionizing Dose (TID) and SEEs. Hence, the analog components have to be chosen to comply with the required TID and SEE limits. This is performed through the exhaustive irradiation tests or by employing the commercial rad-hard components. The TID tolerance can be improved with appropriate shielding while the SEE tolerance can be enhanced with special design techniques. In analog circuits, the most critical SEEs are the Single Event Transients (SETs) and the Single Event Latchup (SEL). The SET duration in analogic circuits is typically in the range of microseconds. To minimize the SET effects, the passive filters have to be inserted at the output of all analog integrated circuits. On the other side, the SEL is mitigated by monitoring the power supply current with appropriate current sensors, and resetting the power supply when the excessive current flow is detected.

V. SELF-ADAPTIVE MULTI-PROCESSOR SYSTEM-ON-CHIP (MPSOC)

The processing platform is a self-adaptive Multi-processing System-on-Chip (MPSoC) with four cores. It performs two main functions: (i) switching of readout modes for absorbed dose and dose rate measurement, (ii) processing of the data from ASC to determine the absorbed dose and dose rate. To enable the high level of flexibility, the platform supports the autonomous selection of the operating modes and fault-tolerant mechanisms during the runtime.

A. Waterbear Framework Controller

The basis of the self-adaptive MPSoC is the *Waterbear* framework controller, proposed by *Simevski et al.* [16]. It enables the adaptive switching of the operating modes, thus providing the optimal utilization of the system resources and a trade-off between performance, power consumption and fault tolerance. The functionality of the *Waterbear* framework has been verified on several chips developed at IHP, among which the most representative example is the PISA (Power-robust Microprocessor for Space) chip [16].

The *Waterbear* framework controller sets the multiprocessor in one of the three operating modes according to the requirements for fault tolerance and performance [16]:

- ***De-stress mode***: a single core is operating while the other cores are clocked- or powered-off to reduce aging and save power. This is done with the help of special aging sensors embedded in each core.
- ***Fault-tolerant (rad-hard) mode***: the cores can be coupled into various fault-tolerant modes such as Dual Modular Redundancy (DMR), Triple Modular Redundancy (TMR) or Quadruple Modular Redundancy (QMR). The coupled cores are executing each instruction simultaneously. The fault-tolerant modes are selected based on the current tasks of the system and the radiation intensity (particle flux) measured with the SRAM-based particle monitor.
- ***High-performance mode***: the multiprocessor operates as a common multiprocessor (each core executes its own task).

B. Processing Cores

In this case, four LEON2 cores have been chosen for data processing. The LEON2 processor is based on 32-bit SPARC architecture and AMBA 2.0 interconnection. It is highly configurable, allowing the user to customize it for a particular application. The advanced fault tolerant versions denoted as LEON3FT and LEON4FT, with integrated radiation hardening mechanisms within the cores, are also available [17].

C. Readout Interface

The MPSoC is interfaced to the ASC through the readout interface composed of an ADC, a pulse counter and a control unit. A 12-bit ADC has been selected for measuring the voltage from the voltage readout channel in the Absorbed Dose Readout mode. The pulse counter measures the radiation-induced pulses from the current readout channel when the Dose Rate Readout mode is active. The control unit provides the control signals, via the General Purpose Input/Output (GPIO) pins, for managing the operation of ADC, programming the switching matrix and selecting the measurement ranges in the current and voltage readout channels in ASC.

D. SRAM as Data Storage Medium and SEU Monitor

To enable the *Waterbear* framework to autonomously select different fault tolerant modes, the on-line monitoring of high energy particle flux is necessary. As the soft error rate (SER) of the entire system increases linearly with flux, the appropriate hardening configurations (DMR, TMR or QMR) can be applied to protect the system when high flux is detected. In this application, a 16 Mbit SRAM embedded in the MPSoC is intended to act both as a data storage unit and a particle monitor. This unique concept has been initially proposed by *Chen et al.* [18]. The standard error detection and correction (EDAC) and scrubbing techniques are employed to detect the single/double bit errors as well as permanent faults in each memory word. The 8-bit counters are used to count the single/double bit errors and permanent faults.

E. *Aging Sensors*

Aging effects lead to the long-term degradation of transistors' characteristics, eventually resulting in permanent errors. A typical consequence is the increase of the input-output delay. To alleviate these effects and increase the system lifetime, the aging monitor proposed by *Simevski et al.* [19] was chosen. The aging information from the sensor is used for controlling the de-stressing of the cores, thus allowing to extend their lifetime. The main advantages of this monitor over other solutions is the simple design, based on digital standard logic cells and storing of aging information in the form of digital code.

F. *Temperature Sensors*

Temperature monitoring is important for controlling the operation of digital logic and for calibration of the RADFET's response. As the RADFET's voltage response is temperature-dependent, it is necessary to track the ambient temperature variations in order to correct the voltage measurements. For this purpose, the Proportional To Absolute Temperature (PTAT) sensors have been chosen.

G. *Peripheral Interface*

Besides the readout interface for acquisition of data from the RADFET, several standard peripheral units are included for interfacing with other external hardware. The peripheral interface includes: Interrupt Request (IRQ) Controller, Timers, Universal Asynchronous Receiver Transmitter (UART), and GPIO port.

H. *Preliminary MPSoC Design Evaluation*

The main design requirement for the MPSoC is related to the radiation hardness. The IHP's 130 nm technology has been verified with extensive radiation tests which have proven its robustness to total doses beyond 100 krad, while the rad-hard library showed no latch-up for a Linear Energy Transfer (LET) up to 67 MeVcm^2/mg [20]. However, like any CMOS technology, it is sensitive to single event transients (SETs) and single event upsets (SEUs) induced by energetic particles. To achieve high robustness to SETs and SEUs, the selective gate- and circuit-level redundancy have to be applied together with the described self-adaptive fault-tolerance at the system level.

As the proposed MPSoC design is largely based on previous designs [16, 18], the preliminary evaluation of the chip area has been done considering the results from [16, 18]. Most of the chip area would be occupied by four LEON2 cores and SRAM. As the area of a single core is 5.22 mm^2 and the SRAM with supporting logic has the area of 14 mm^2, the total area of four cores and SRAM would be around 35 mm^2. The estimated area of additional on-chip hardware would not exceed 20 mm^2. The estimated operating frequency is around 50 MHz, which is sufficient for the target dosimetry application.

VI. CONCLUSION

This work introduces a design concept for a radiation hardened RADFET readout system, combining the simultaneous monitoring of absorbed dose and dose rate and the fault-tolerant platform based on the self-adaptive 4-core processor. The multi-core platform enables to control multiple radiation sensors or other types of sensors, as well as to perform additional tasks on the same chip. In comparison to existing RADFET dosimeters that have been employed in various space missions, our solution brings higher level of integration with more efficient utilization of available resources.

ACKNOWLEDGMENT

This work was conducted in the framework of ELICSIR project funded by the European Union H2020 Programme, under the grant agreement No. 857558.

REFERENCES

[1] R. Glein et al., "Detection of Solar Particle Events inside FPGAs," in Proc. European Conference on Radiation Effects on Components and Systems (RADECS), 2016.

[2] M. A. Carvajal et al. "A Compact and Low Cost Dosimetry System Based on MOSFET for In Vivo Radiotherapy," Sensors and Actuators A: Physical, 2012.

[3] R. Phurailatpam et al., "Characterization of Commercial MOSFET Detectors and their Feasibility for In-vivo HDR Brachytherapy," Physica Medica, 2016.

[4] M. Andjelkovic, G. Ristic, "Feasibility Study of a Current Mode Gamma Radiation Dosimeter Based on a Commercial PIN Photodiode and a Custom Made Auto-Ranging Electrometer", Nuclear Technology and Radiation Protection, 2013.

[5] C. N. Oliveira, H. J. Khoury, E. J. P. Santos, "PIN Photodiode Performance Comparison for Dosimetry in Radiology Applications," Physica Medica, 2016.

[6] M. Andjelkovic, G. Ristic, "Current Mode Response of Phototransistors to Gamma Radiation," Radiation Measurements, 2015.

[7] J. Roman-Raya et al., "Light-Dependent Resistors as Dosimetric Sensors in Radiotherapy," Sensors, 2020.

[8] S. Ilic, A. Jeftic, S. Stankovic, G. Ristic, "Floating-Gate MOS Transistor with Dynamic Biasing as a Radiation Sensor," Sensors, 2020.

[9] G. Ristic, N. Vasovic, M. Kovacevic, A. Jaksic, "The Sensitivity of 100 nm RADFETs with Zero Gate Bias up to Dose of 230 Gy(Si)," Nuclear Instruments and Methods in Physics Reasearch B, 2011.

[10] M. Andjelkovic, G. Ristic, A. Jaksic, "Using RADFET for the Real-Time Measurement of Gamma Radiation Dose Rate," Measurement Science and Technology, 2015.

[11] M. Kulhar, K. Dhoot, A. Pandya, "Gamma Dose Rate Measurement Using RADFET," IEEE Transactions on Nuclear Science, 2019.

[12] J. Seon, S. J. Kim, B. Sung, S. Al-Mari, S. H. Lee, "A Small Space Radiation Monitor Capable of Measuring Multiple ISD-VGS Values of MOSFET," Journal of Nuclear Science and Technology, 2010.

[13] R. Ferraro et al., "Design of a Radiation Tolerant System for Total Ionizing Dose Monitoring Using Floating Gate and RADFET Dosimeters," Journal of Instrumentation, 2017.

[14] J. O. Goldsten et al., "The Engineering Radiation Monitor for Radiation Belt Storm Probes Mission," Space Science Review, 2013.

[15] B. Teylor et al., "The Micro Radiation Environment Monitor (MuREM) and SSTL Radiation Monitor (SSTL RM) on TechDemoSat-1," in Proc. European Conference on Radiation Effects on Components and Systems (RADECS), 2011.

[16] A. Simevski, et al., "PISA: Power-robust Microprocessor Design for Space Applications," in Proc. IEEE International Symposium on Online Testing and Robust System Design (IOLTS), 2020.

[17] J. Andersson et al., "LEON Processor Devices for Space Missions: First 20 Years of LEON in Space," in Proc. International Conference on Space Mission Challenges for Information Technology (SMC-IT), 2017.

[18] J. Chen et al., "Design of SRAM-Based Low-Cost SEU Monitor for Self-Adaptive Multiprocessing System," in Proc. Euromicro Conference on Digital System Design (DSD), 2019.

[19] A. Simevski, R. Kraemer, M. Krstic, "Low-Complexity Integrated Circuit Aging Monitor," in Proc. IEEE Symposium on Design and Diagnostics of Electronic Circuits and Systems (DDECS), 2011.

[20] A. Simevski et al., "A Scalable and Configurable Multi-Chip SRAM for Space Applications," in Proc. IEEE International Symsposium on Defect and Fault Tolerance in VLSI and Nanotechnology Systems (DFT), 2019.