Radiation Resilient Logic Circuit Study based on Wide Bandgap Devices

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**Concept of Operations**

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Concept of Operations

for

Radiation Resilient Logic Circuit Study based on WBG Devices

Team 1

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# Executive Summary

This report details the concept of operations for a study regarding radiation resilient logic circuits using wide-bandgap devices sponsored by Sandia National Laboratories. Radiation has significant effects on the functionality of electronic components and circuits, and it is important to use the various materials and design ideas to try and mitigate those effects in order to create robust circuits that function optimally in radiation environments. Radiation hardening techniques, both by design and by process, are used to make these circuits radiation resilient, though this report only focuses on concepts associated with radiation hardening by design specifically through usage of wide-bandgap materials and modified circuit layouts.

As described in the operation concept section, there are three logic circuits to be designed and tested: a 7 stage ring oscillator, a 4-bit static RAM memory cell array, and a 4:1 multiplexer. These three circuits will use gallium nitride as the wide-bandgap material, and after each individual circuit is built with radiation hardening by design, they will be integrated into a single, large logic circuit system with various applications detailed later in the report. The ring oscillator will provide a clock signal for the 4-bit SRAM array, whose output will feed into the 4:1 multiplexer, resulting in a 1-bit output. The primary application for this single integrated circuit is as control circuitry for power supplies, although there are other uses for it as well as each of the three individual circuits, which are detailed in the scenarios section of the report.

There is also further analysis of the advantages and disadvantages of the proposed improvements, potential limitations, and alternatives regarding the material and design considerations. Finally, the report also considers the project’s impact regarding advancements in aerospace applications, environmental efficiency of transistors, and ethical concerns related to radiation testing safety.

# Introduction

Logic circuits must be able to maintain functionality in radiation environments to guarantee reliable performance in critical situations. Logic circuits can be made robust by using radiation hardening techniques, including both radiation hardening by process and radiation hardening by design. These techniques can be used individually or in combination, depending on the type of logic circuit being developed. Materials such as silicon carbide and gallium nitride are often used in the design of circuits that are intended to be radiation resilient. Due to their wide band gap, these materials make the circuit more resistive to ionizing in radiation. By collaborating with Sandia National Laboratories, we will utilize radiation hardening by design to create a logic circuit which will be able to function in a radiation environment.

## Background

Logic circuits are used for a wide range of applications in modern technology. Employing these circuits is crucial for situations involving digital systems, data processing, automation, and much more. While standard logic circuits may operate effectively in typical environments, they will be insufficient in radiation harsh environments, such as space. Ensuring the dependable performance of these devices in radiation environments is essential for reliability in critical conditions. We will enhance existing logic circuits by implementing radiating hardening by design techniques, therefore allowing these circuits to be functional in the presence of radiation.

## Overview

We will construct a radiation resilient logic circuit which will be composed of a ring oscillator, a SRAM, and a multiplexer. Each of these circuits will be made radiation resilient by employing radiation hardening by design techniques. The main application of our project will be for space power systems and logic control systems. The use of ring oscillators, SRAMs, and multiplexers in space power/logic control systems is increasing. By analyzing how these circuits perform in radiation as a whole, it will provide information about how the individual circuits react in a radiation environment when connected to a bigger circuit. The use of wide band-gap devices such as silicon carbide (SiC) and gallium nitride (GaN) in logic circuits enhances their resilience to radiation. Since Silicon carbide has had significantly more research and usage in power electronics, our circuit will employ Gallium nitride as the wide band-gap device to promote further research on this material. By choosing Gallium nitride as our wide band-gap device, the implementation and testing of this project will provide more information on the effects of GaN in a radiation environment.

## Referenced Documents and Standards

*Electrical, Electronic, and Electromechanical (EEE) Parts Assurance Standard*. NASA. Accessed: Sep. 12, 2023. [Online]. Available: https://standards.nasa.gov/sites/default/files/standards/NASA/Baseline/0/nasa-std-873910.pdf

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# Operating Concept

## Scope

The logic circuit for our project will be composed of three individual logic circuits, which will be integrated to construct the final circuit. The individual circuits will consist of a ring oscillator, a SRAM, and a multiplexer. A seven-stage ring oscillator will produce an oscillating clock signal with a frequency of 100kHz. This signal will be connected to the input of a 4-bit SRAM which will retain data in memory. The SRAM will then provide input to a 4x1 multiplexer which will select the output data from one of the four binary inputs. A DC power supply will provide input power to the circuit, which will be 3V. The three individual circuits will be built on a transistor level, utilizing Gallium nitride (GaN) as the wide band-gap material. The goal of our project is for our final circuit to maintain functionality in a radiation environment. To achieve this, we will focus on implementing radiation hardening by design on the three individual circuits. Radiation hardening by design focuses on the design of the circuit itself, rather than the manufacturing process of the circuit components. Our final circuit will be tested in a radiation environment to observe the effect of radiation on the output data. Our circuit should maintain consistent in a radiation or non-radiation environment.

## Operational Description and Constraints

The main application of this logic circuit would be as a control circuit for power supplies. In radiation environments, power electronics are particularly important to radiation harden as they connect to all other parts of an electrical system, so radiation effects in a power circuit could be detrimental to the rest of the system. The entire circuit would yield a single bit output that would be used to switch power on and off to other circuits. Individually, these logic circuits can be used for a variety of applications in radiation environments.

## System Description

The proposed system has three major subsystems: a seven-stage ring oscillator, a 4-bit SRAM memory cell array, and a 4-to-1 multiplexer.

### 7 Stage Ring Oscillator

The seven-stage ring oscillator will receive power from a DC power supply and produce an alternating signal output at a desired frequency. It is capable of producing an oscillating output without a connection to an external function generator. The ring oscillator will consist of seven inverters arranged in a ring. The internal design of these inverters will be composed of transistors with a wide band-gap material so that the circuit will be functional in a radiation environment. The design of the ring oscillator will also include a feedback connection from the Vout pin to the first input pin. It will also include capacitors connected in parallel between each inverter. As the signal passes through each inverter, it will be delayed which decreases the frequency. The capacitance of the capacitors between each inverter will be chosen so that the output frequency of the ring oscillator is 100kHz. The output signal produced from the oscillator will serve as the input signal for the 4-bit SRAM.

### 4-bit SRAM Memory Cell Array

An SRAM memory cell array is a logic circuit that stores bits of data, 4 bits in this layout. SRAM is a kind of volatile memory that retains data as long as it has a power supply, and it’s commonly used in computer systems for its fast access times and simple design. Each cell consists of at least four storage transistors connected in a feedback loop to form a bistable flip flop circuit, and these transistors maintain the stability of the stored data until intentionally changed by a write operation. Two additional access transistors can be added to control read and write operations, and they act as switches that allow or block dataflow between storage nodes and read/write lines. These access transistors allow the cell to be read and written to without affecting the other cells in the array. It consumes little power, so it’s powered by a simple, low DC power supply. The cells can be arranged in different configurations, like a 2x2 or a 4x1/1x4 array, and each has its advantages and disadvantages which are detailed in Section 4.2. The behavior of memory cells in radiation environments is important to consider, as total ionizing dosage has significant effects on data storage. Single Event Upsets (SEUs) can flip the state of a memory cell bit, effectively corrupting the data. Radiation can lead to temporary data corruption, soft errors, or even complete data loss, which can be combatted by error detection and correction techniques that add redundancies to stored data and correct errors as they occur. This array will be radiation-hardened by design using wide bandgap transistors, like gallium nitride, and other methods to ensure that the entire circuit is radiation resilient.

### 4-to-1 Multiplexer

The 4-to-1 Multiplexer, or 4:1 MUX for short, is a logical circuit that receives four binary values as the input, and outputs one of those four values depending on the state of two additional selection bits. By controlling the selection bits, the user can select which of the four inputs the 4:1 MUX will use as the output. For our system, the 4:1 MUX will be selecting between the four binary values stored in the 4-bit SRAM cell array. This will allow the user to efficiently read out any of the four values stored, to determine whether or not they’ve been affected by radiation. The logic inside the MUX is conducted using numerous transistors that are themselves susceptible to radiation. Because of this, the use of wide-band gap transistors, namely gallium nitride, will be implemented along with other methods of radiation hardening by design to make the entire system radiation resilient.

A diagram of a computer system

Description automatically generated

Figure : Subsystem Block Diagram

## Modes of Operations

**Active**

The system is in the active mode of operation when power is connected to the system causing the ring oscillator to run and produce an oscillating output signal. This output signal is then routed to the input of the SRAM array where the binary values are stored. Lastly, the 4:1 MUX is connected to the SRAM array to select which of the four SRAM bits to read out as the output. The selecting of values from the SRAM array utilizing the MUX is what constitutes the system as active.

**Idle**

The system is in the idle mode of operation when power is once again connected to the system causing the ring oscillator to oscillate. This output signal will continue to input binary values into the SRAM array. However, in this mode of operation, the 4:1 MUX is not being utilized to select between the four bits of the SRAM array.

**Off**

The system is in the off mode of operation when the system is not connected to the power supply. This means the ring oscillator will not oscillate, the SRAM array will not store values, and the 4:1 MUX will not select values from the array.

## Users

The primary users of the system will be different disciplines of engineers depending on the application. For example, during the testing process, radiation test engineers and radiation hardness assurance engineers would be the primary users of the system. The user manual mentioned in the following section will guide the test engineers through the set up and operation of the system. After testing, the system can be utilized by power or system engineers to help with the control of power circuitry, as mentioned in section 4.

## Support

Support for operating the individual subsystems and the total system will be provided in a detailed user manual. This document will provide support for setting up and running the circuits for both typical and radiation testing, as well as steps for troubleshooting any common problems. The user manual will include the electrical schematics of all three subsystems, as well as how the circuitry integrates together.

# Scenario(s)

## Control Circuitry for Power Supply

This comprehensive circuit is best used as a control circuit for a power supply. As the output is 1 bit, it is a simple switch for on/off power control to a load. It can be used to implement control logic in a system where multiple power supplies or voltage sources need to be on or off based on user inputs or certain conditions. The ring oscillator provides a clock signal for the 4-bit SRAM array to store or modify bits related to configuration data or power supply management control signals, which each correspond to one of the four mux inputs. Depending on what the mux selector bit is, a certain power supply configuration from the 4 bit input is chosen. It is important to note that additional circuitry would be needed to translate the selected data configuration into actual control of multiple power supplies.

## 7-Stage Ring Oscillator

Ring oscillators have applications which can prove useful in many different scenarios:

* Ring oscillators are most commonly used as clock generators for electronic circuits. The oscillating output signal they produce serves as a clock signal for logic circuits.
* Ring oscillators can be used for timing purposes in a circuit. They can be implemented to produce controlled delays for a signal that is present in a circuit by adjusting resistor and capacitor values.
* In some applications ring oscillators can be used as voltage-controlled oscillators (VCOs) by incorporating a controlled input that will determine the frequency of oscillation. VCOs are commonly used for applications such as phase locked loops and frequency modulation.
* Ring oscillators are sensitive to temperature variations. This makes them suitable for use as temperature sensors since a change in temperature affects the frequency of oscillation.

## 4-bit SRAM Memory Cell Array

SRAM memory cell arrays have a multitude of applications for various scenarios:

* Their suitability for harsh environments makes them ideal for navigation, communications, and guidance systems in the military and aerospace industry.
* They’re most commonly used as cache memory in computer systems, and a 4-bit SRAM in particular could be used as a small, high-speed cache to store frequently accessed data efficiently.
* They can be used as registers within a CPU or microprocessor to perform arithmetic or logical operations, as well as a temporary storage for data during processing.
* SRAM is used as buffer storage in data communication, networking equipment, and storage devices to help manage data flow and provides temporary storage for smoother data transfer.

The arrangement of cells also determines how effective the SRAM cell array is in certain scenarios:

* A 1x4 or 4x1 array is more space efficient as its just a single row, and it has shorter access time because of the simpler structure and minimal bitline length. It typically consumes less power as it has fewer transistors and shorter bitlines, and it’s best suited for size-efficient applications that require a small, efficient memory structure.
* A 2x2 array might require more layout space as it’s a square grid, and it would have longer access times because of the additional bitline routing. It would also consume more power than a 4x1 array and it’s best suited for applications that require more organization due to the ease of managing a grid layout.

## 4-to-1 Multiplexer

Multiplexers are an incredibly practical device that can be utilized in many different types of applications. There are many scenarios where multiple input signals enter a device, and the user would like the ability to select which of the inputs should be read out as the output. Because of this, multiplexers are useful in a variety of applications.

* Multiplexers are heavily utilized in communication systems, as they allow for the transmission of multiple different input signals (audio or video) along one singular transmission line. This greatly reduces cost and increases efficiency.
* Considering the radiation environment, multiplexers are utilized in satellite and deep space flight systems to transmit data from the onboard computer systems back to the ground station, using GPS.
* An application similar to the one proposed would be utilizing multiplexers in the memory of a computer. Multiplexers are scattered throughout the architecture of a computer, meaning radiation resilient multiplexers would enhance the overall efficiency of computing in space.

# Analysis

## Summary of Proposed Improvements

* Wide-bandgap transistors
  + Greater breakdown voltage
  + Higher current limitations
  + Faster switching speeds
  + Extreme temperatures
  + More efficient and power dense
* Radiation hardening by design
  + Radiation resilient transistors
  + Modified layout design may be more compact and less expensive

## Disadvantages and Limitations

* Wide-bandgap semiconductor devices are expensive
* Size as a limiting factor
* Availability of parts
* Less research information on Gallium nitride transistors

## Alternatives

Below are alternative materials for wide bandgap devices that make up these logic circuits:

* Silicon carbide ()
  + SiC transistors would allow for more power to be delivered through the system, however, for the application, the higher switching frequency of GaN proves more beneficial.
* Gallium Oxide ()
  + Gallium Oxide has a high electron/hole mobility, similar to GaN, making it a viable alternative. However, the difficulties of cost and research increase drastically as gallium oxide is the newest and not yet as widely used.
* Radiation Hardening by Process
  + Traditional Silicon transistors could be utilized, with the design adjustments being made in the actual fabrication of the components, such as radiation shielding. This is not a viable alternative for this project since it would not be possible to fabricate custom components.

Below are alternatives for layouts for each of the subsystem circuits:

* >7- Stage Ring Oscillator
  + Adding more stages would yield lower frequency ranges.
* 4-bit SRAM Memory Cell – 4x1 or 2x2 array
  + There are many advantages and disadvantages to either array layout depending on user need and system design, which are detailed in Section 4.3.
* Multiplexers
  + The multiplexer can be edited to contain however many inputs and outputs are required. Alternative designs could have included two 2:1 MUXs or one 4:2 MUX in order to read two outputs at once.

## Impact

* Space exploration for the benefit of humankind
* More efficient transistors result in less waste in the environment
* Ethics concerning safety with radiation testing