Design Analysis of Radiation Hardened Integrated Circuits Using Nanotechnology

Yihui Mu

{muyihui0103@163.com}

Chengdu College of University of Electronic Science and Technology of China, Chengdu, China

Abstract. As the manufacturing process of integrated circuits advances to the nanometer level, the integration and complexity of integrated circuits have been greatly improved. In various electronic devices, the working environment of integrated circuits is getting worse and worse. Radiation effect is one of the important factors affecting the function and reliability of integrated circuits, and it has strong pertinence. In recent years, as the volume of electronic equipment has become smaller and smaller, and the performance of integrated circuits has become higher and higher, the problem of failure caused by radiation effects has become more and more serious. In order to cope with the influence of various radiation effects, the article adopts the anti-radiation reinforcement technology of nanotechnology to design and analyze the integrated circuit. Firstly, this paper gives an overview of related technologies and theories, then analyzes the radiation effect under nanotechnology, and finally analyzes the design of integrated circuits. The research results show that the anti-radiation ability of the integrated circuit strengthened by nanotechnology can reach up to 89.9%.

Keywords: Nanotechnology, Radiation Hardening, Integrated Circuit, Particle Flipping Effect

1. Introduction

With the continuous development of integrated circuit manufacturing technology, the integration and complexity of integrated circuits have also been greatly improved. However, due to the shrinking of the process size, the change of the internal structure of the device, and the introduction of new process nodes, the reliability of the device is getting worse and worse. In electronic equipment, the problem of failure due to radiation effects is also becoming more and more serious. Compared with traditional semiconductor devices, integrated circuits need to be affected by high-energy particles (such as alpha particles, beta particles and gamma rays) in the space radiation environment during operation, and will cause damage to the internal circuit function and performance of the device.

In order to cope with the above-mentioned impacts, research institutions and enterprises at home and abroad are constantly launching radiation-resistant hardening designs and products. Chen Yurong designed a new NMOS

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(N-Metal-Oxide-Semiconductor) isolation tube SRAM (Static Random-Access Memory) memory cell layout structure using a 0.18μm bulk silicon process. According to the analysis results, under the premise of ensuring the function of the storage unit, the SRAM memory unit has the anti-total dose effect, and can realize the optimization of the unit area at the same time [1]. Xi Chengxian analyzed the effect of space radiation on the three-junction GaAs solar cell array, combined with the ground test results to design the anti-radiation solar cell array, and verified it on a satellite in an inclined geosynchronous orbit. The results show that the mathematical model of anti-radiation design can provide a reference for the design of solar cell arrays of other medium and high orbit satellites [2]. Yao Jin used 0.18μm CMOS (Complementary Metal Oxide Semiconductor) and other reinforcement technology to design circuits, and proved that the radiation-resistant circuit under the reinforcement technology platform has obvious advantages in radiation resistance performance and area [3]. The above studies have significantly improved the radiation-resistant design, but there is a lack of solutions that can be applied to different types of integrated circuits.

Based on the existing radiation-resistant hardening design schemes, this paper studies the design methods and development trends of different types of integrated circuits in different irradiation environments, and looks forward to the future radiation-resistant hardening design schemes.

2. Overview of Related Technologies and Theories

An integrated circuit is a highly integrated integrated circuit, and its development has gone through several important stages: 1) From the 1960s to the early 1980s, it was mainly carried out under conventional techniques; 2) From the early 1980s to the early 1990s, it was mainly carried out under the nanometer process; 3) From the late 1990s to the present, it was mainly carried out under the CMOS process [4]. At present, integrated circuits have been widely used in aviation, aerospace, national defense and other fields, and have become an indispensable part of electronic systems and equipment. Due to the complex working environment of electronic equipment, it is often affected by various radiation effects during operation, which causes problems such as integrated circuit performance degradation and device failure, which seriously affects the normal operation of electronic systems [5].

Physical reinforcement technology refers to the application of physical methods in integrated circuit design to improve circuit performance, reliability and radiation resistance. This technology mainly includes two aspects: one is to use specific physical effects for reinforcement; the other is to use structured design to optimize the circuit structure [6]. The physical reinforcement method is generally realized by adding anti-radiation units in the circuit. In different types of circuits, due to the different effects of radiation effects on circuit performance and reliability, different physical methods are used for reinforcement.

Chemical reinforcement refers to the method of adding anti-radiation units in integrated circuit design to improve the anti-radiation ability of circuits. There are three main methods of chemical reinforcement: One is to use materials with radiation resistance; the other is to use chemical reagents to change the circuit structure; the third is to use structural units with radiation resistance [7]. In different types of circuits, chemical reinforcement methods are different, such as using ion implantation for analog integrated circuits; using inverting diodes for digital integrated circuits; using inverters for analog-to-digital converters; using metal detectors for analog-to-digital converters wait. Various methods have their own characteristics, and should be selected according to the specific situation when applying [8].

3. Analysis of Radiation Effect Under Nanotechnology

As the process size continues to decrease, the channel width of the transistor decreases, resulting in a rapid decrease in its power consumption. However, due to its thermal effect and radiation effect, the current of the transistor will drift, causing the temperature inside the integrated circuit to rise continuously. Under the nanoscale process, after the size of the transistor is reduced to the nanometer level, the channel width is further reduced, causing the thermal effect inside the device to become more obvious. These include effects such as subthreshold current, threshold voltage drift, soft errors, and more. Therefore, these factors need to be considered in the design of radiation-resistant hardening under nanotechnology [9].

These factors need to be considered when designing radiation-resistant hardening under nanotechnology: (1) Ensuring the applicability of the radiation-resistant hardening design scheme, consider multiple schemes in the design, and make reasonable choices; (2) Ensuring that the radiation-resistant hardening design scheme will not affect the circuit function; (3) Ensuring that the radiation-resistant hardening design scheme can adapt to different application scenarios; (4) Ensuring that the radiation-resistant hardening design scheme has good scalability and maintainability [10].

When designing anti-radiation reinforcement under nanotechnology, in addition to considering the above factors, the following points need to be paid attention to: (1) The number and size of transistors in the circuit are different due to different device manufacturing processes; (2) The number and size of transistors in different types of integrated circuits are different; (3) The number and size of transistors in different types of integrated circuits are the same; (4) When the device manufacturing process is the same, there are differences in the radiation resistance of devices using different materials; (5) When different material devices are used, the radiation-resistant hardening design scheme and results may be different; (6) The radiation-resistant hardening design scheme may affect the circuit function [11].

4. Anti-Radiation Design Methods and Technologies

With the continuous improvement of integrated circuit technology level, anti-radiation design has become an important part of integrated circuit design. By strengthening the radiation environment simulation test, analyzing the error mechanism and failure mode, carrying out circuit-level radiation resistance reinforcement design, and verifying the performance and reliability of the circuit through radiation resistance, it is the main method to improve the radiation resistance of integrated circuits at present [12]. The article will analyze and study different types of integrated circuits, and adopt a radiation-resistant design scheme based on fault injection experiments and fault isolation technology in combination with existing design methods and technologies.

4.1 Anti-radiation Design Method Based on Fault Injection Experiment and Fault Isolation Technology

Fault injection experiment is to use electronic irradiation equipment to simulate the radiation environment, and to study whether the circuit will produce errors by applying different doses of radiation to the input end of the circuit. Currently commonly used irradiation equipment includes medical X-rays, electron accelerators, etc. Medical X-rays are mainly used in clinical medical research, and the radiation dose is very high. The electron accelerators widely used at present are mainly gamma rays, neutrons and protons [13]. Gamma rays will produce a large number of high-energy particles during the ionization process, causing serious damage to the human body; neutrons will produce high-energy particles during the ionization process, causing serious damage to the human body; protons will produce high-energy particles during the ionization process, causing serious damage to the human body. Therefore, it is very necessary to conduct radiation experiments on circuits. When designing a radiation-resistant circuit, it is necessary to evaluate whether the circuit will produce errors through injection experiments [14]. Typically, circuits can be simulated and analyzed using single event effect simulation software. When the input signal is a pulse, the signal cannot be recognized by any circuit; when the input signal is a sine wave, the signal can be recognized by any circuit; when the input signal is a square wave, the signal can be recognized by any circuit. Before the injection experiment, it is necessary to select the appropriate simulation software according to the function of the circuit and the operating environment.

Fault isolation technology is to isolate the normal working circuit from the circuit damaged by radiation, and it can still continue to work normally after being damaged by radiation. When it is damaged by radiation, it should be isolated from the source of the fault. When designing a radiation-resistant circuit, it is necessary to isolate the affected part first. If the fault occurs on the input side, it must be isolated; if the fault occurs on the output side, it must be isolated. Since different types of integrated circuits have different failure mechanisms and failure modes, it is necessary to deal with them according to specific conditions [15].

4.2 Anti-radiation Verification Technology

The anti-radiation verification technology is a technology to detect and analyze whether errors will occur in the circuit during actual operation. When an error occurs during the operation of the circuit, it can be judged whether there is an error by detecting and analyzing it in time. Commonly used methods include simulation experiments, hardware experiments, etc. [16]. Due to the different characteristics and purposes of integrated circuit radiation resistance design and verification, the corresponding design and verification work should be carried out according to the actual situation in the specific design process.

According to the anti-radiation hardening technology that has been researched so far, different types of integrated circuits use different hardening technologies:

(1) Realize radiation protection reinforcement based on logic gates: Logic gates are the most basic and important circuit units, through which the radiation protection of functional modules such as data level shifters, adder/subtractors, comparators, and oscillators can be implemented. For example: in the digital signal processor, the data adder/subtractor and the comparator adopt the anti-radiation hardening technology; in the analog signal processor, the comparator and the oscillator adopt the anti-radiation hardening technology; in the DSP, the comparator implements the hardening technology, etc. [17].

(2) Radiation-resistant hardening based on CMOS devices: CMOS devices are commonly used in the design of radiation-resistant circuits. When designing radiation-resistant hardened circuits, the protection of errors generated by CMOS devices can be achieved by adding auxiliary units and error injection circuits [18].

(3) Anti-radiation hardening based on microprocessor: Microprocessor is a special type of integrated circuit. The protection and analysis of errors generated by the chip can be realized by integrating components such as a microcontroller and a memory in the chip [19].

5. Design and Analysis of Nanotechnology Radiation-Resistant Hardened Integrated Circuits

As the manufacturing process of integrated circuits advances to the nanometer level, the process node of the nanometer level greatly reduces the cost of integrated circuits, and at the same time causes major changes in the manufacturing process of integrated circuits. In order to cope with various radiation effects, traditional anti-radiation design schemes are all aimed at design schemes such as static sequential circuits, gate arrays, multi-mode and multi-frequency, etc., and these schemes are all implemented based on traditional CMOS circuits. Due to the manufacturing process characteristics of CMOS circuits, these solutions are not suitable for integrated circuit design under nanometer process conditions.

Due to the greatly improved integration of integrated circuits under the nanometer process, the size of the device becomes smaller and the leakage current increases. At the same time, as the size of the device becomes smaller, the heat generated by the leakage current will cause the temperature of the device to rise. Due to the increase of leakage current and temperature rise, the circuit parameters and circuit functions will change, thereby degrading the circuit performance.

Table 1. Flip effect analysis table

	Anti-radiation ability	Power consumption	Efficiency	Reliability	Fault tolerance
Single particle flip effect	Low	Centre	High	Low	Low
Double particle flip effect	High	High	Centre	High	High

Therefore, in the design of anti-radiation hardened integrated circuits under nanotechnology, it is necessary to design corresponding anti-radiation hardening schemes for different types of circuits. However, due to the differences in the design schemes of different types of circuits, targeted analysis and design are required for radiation resistance hardening [20]. The article will analyze from two aspects of the single-event flipping effect and the double-event flipping effect, and the results are shown in Table 1.

6. Results and Discussion

The article compares and analyzes the integrated circuit with anti-radiation reinforcement of nanotechnology and the traditional integrated circuit. There are three main indicators used for comparative analysis - radiation resistance (Fig. 1), work efficiency (Fig. 2) and fault tolerance rate (Fig. 3).

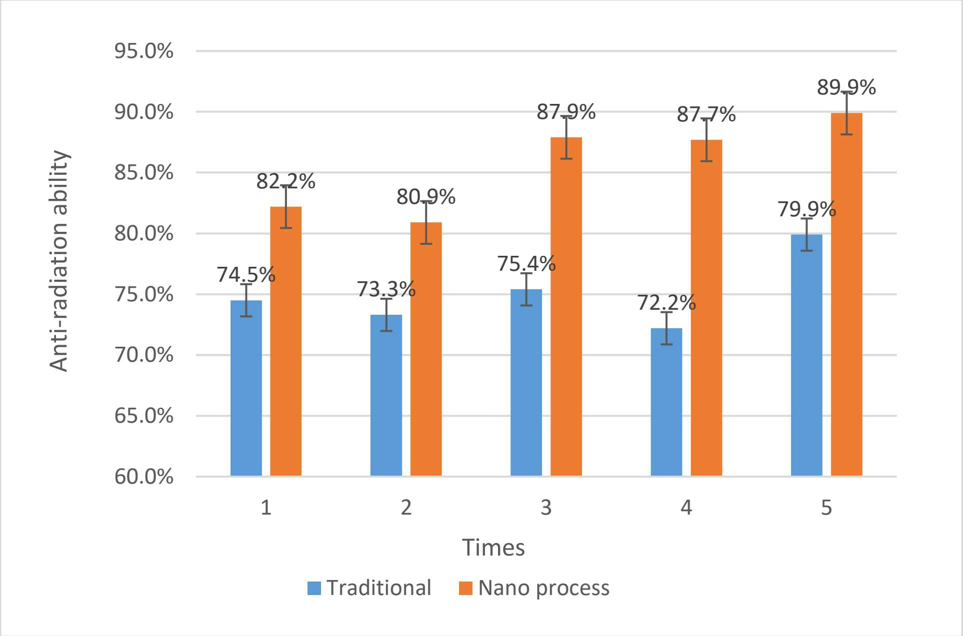

Figure 1. Radiation immunity

It can be seen from Fig. 1 that the highest radiation resistance of traditional integrated circuits is 79.9%, the lowest is 72.2%, and the calculated average radiation resistance is 75.06%; the highest anti-radiation ability of integrated circuits reinforced by nanotechnology is 89.9%, the lowest is 80.9%, and the calculated average anti-radiation ability is 85.72%. It can be seen that the anti-radiation hardened integrated circuit of the nanotechnology has a higher anti-radiation ability.

It can be seen from Fig. 2 that the highest efficiency of traditional integrated circuits is 79%, the lowest is 76.3%, and the average efficiency is calculated to be 78.16%; the efficiency of integrated circuits with radiation resistance hardened by nanotechnology is the highest at 89.5%, the lowest at 86%, and the average efficiency is 87.86%. It can be seen that the anti-radiation hardened integrated circuit with nano-technology has higher work efficiency.

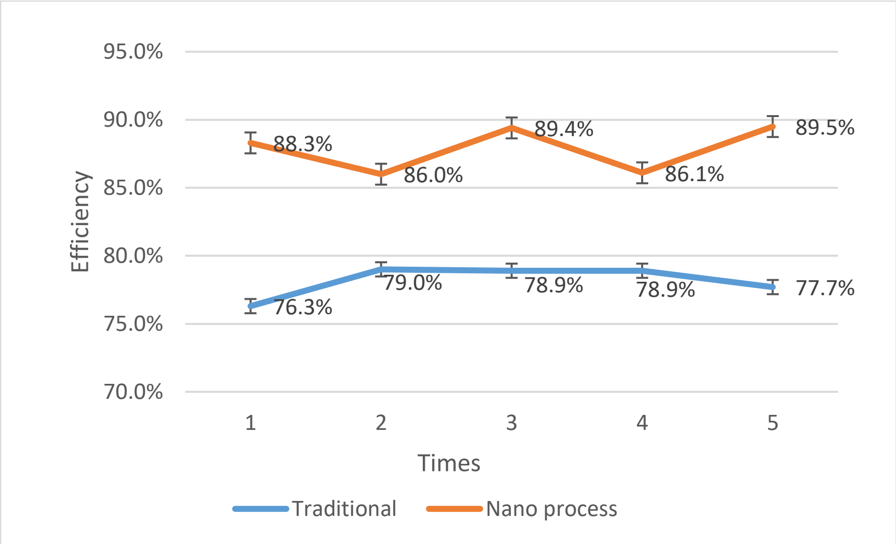

Figure 2. Efficiency

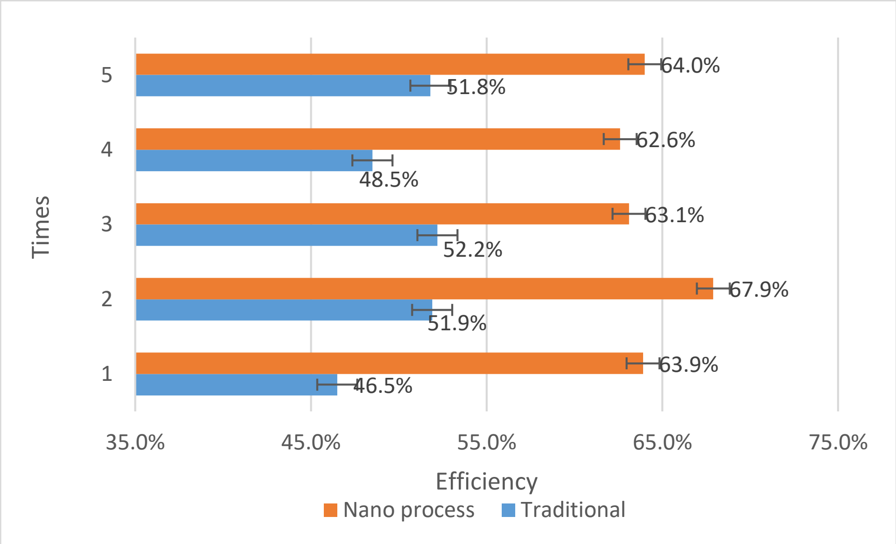

Figure 3. Tolerance rate

It can be seen from Fig. 3 that the fault tolerance rate of traditional integrated circuits is generally below 53%, the highest is 52.2%, the lowest is 46.5%, and the calculated average fault tolerance rate is 50.18%; the highest fault-tolerance rate of nano-technology radiation-hardened integrated circuits is 67.9%, the lowest is 62.6%, and the average fault-tolerance rate is 64.30%. It can be seen that the radiation-hardened integrated circuit with nanotechnology has a higher fault tolerance rate.

1) The research and application of anti-radiation hardening technology is a complex system engineering, which not only needs to consider factors such as process nodes, materials, and design methods, but also considers device structures and circuit functions, any problem in any link will affect the hardening effect. Therefore, the research on radiation-resistant hardening technology must first analyze the main influencing factors of radiation effects, and then combine device structure, circuit function and design methods to determine the research direction of radiation-resistant hardening technology.

2) At present, China's research on radiation resistance reinforcement under nanotechnology is relatively lagging behind. The research in this field in foreign countries started earlier, and the technology is relatively mature; while the research in this field in China is still in its infancy, and there is a big gap. At the same time, due to the different chip design and manufacturing processes, the radiation resistance capabilities of different types of integrated circuits are also different. Therefore, analysis and research should be carried out according to the actual situation, and a reasonable anti-radiation reinforcement technology should be adopted on the premise of ensuring the reliability of the chip.

3) For devices with the same function, their performance will also be different. Therefore, it is necessary to compare and analyze the performance of different devices when designing the circuit. In addition, in order to improve the anti-radiation hardening effect and chip reliability, methods such as multi-chip cascading and multi-circuit interconnection can also be used to improve the anti-radiation hardening effect.

7. Conclusions

With the advancement of semiconductor technology to the nanometer level, the manufacturing cost of integrated circuits has been decreasing, but its radiation resistance has not been significantly improved. The article adopts a method of anti-radiation hardening based on energy harvesting. This method first uses the energy harvesting device generated inside the integrated circuit to collect the energy generated inside the chip, then converts it into an electrical signal and transmits it to the peripheral circuit for processing, and finally achieves the anti-radiation hardening effect. Experimental results show that this method can effectively improve the radiation resistance of the chip. This article mainly analyzes the radiation-resistant hardening design schemes and products of different types of integrated circuits under nanotechnology, and provides a reference for further research on radiation-resistant hardening design methods and products. In the future, as the integrated circuit manufacturing process advances to the nanometer level, more electronic components and circuit modules may be introduced into the integrated circuit. Therefore, it is necessary to further study more radiation-resistant hardened designs and products of different types of integrated circuits.

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