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Understanding Radiation Damage on Semiconductor Devices: Mechanisms, Effects, and Mitigation Strategies

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Abstract: ***In modern electronics, semiconductor-based devices are crucial in energizing from a small domestic product to a High-end Industrial. Some industrial developments require precise results for a long time of uninterruptable operation, but these semiconductor devices have some limitations when working in high radiation areas. Due to high radiation, semiconductor material has damaged its structure, which results in degraded performance and reliability in Crucial nuclear reactor core environments. The paper suggests a broad perspective on radiation damage in atomic reactor environments on semiconductor devices. To make the precise mechanism that underlies and explores possible effects on the device efficiency and performance to mitigate the radiation-induced degradation. The damage to the semiconductor device can be mitigated via various techniques, engineering skills, and design changes to withstand high environmental radiation. The research will also be helpful to many semiconductor industries in building radiation electronics for nuclear and space sectors to control systems with the help of semiconducting materials.***

Keywords: Radiation, Damages, Semiconductor Devices, Mechanism, Effects, and Mitigation

1. Introduction

Overview of Semiconductor Devices

In the era of technology, Semiconductors are the base of advanced electronics that the world lives in today. The devices are made with conducting and insulating materials, allowing electricity to pass through them in certain conditions. The semiconductor devices are pivotal to enabling and controlling the various switching devices. In recent developments, a single small system is controlled by chips or semiconducting devices made of semiconductors. Wide semiconductor devices are made of silicon and germanium to make a small, fast, reliable, and efficient electronic system. Recent developments in semiconductor devices are growing insanely, and innovations in nano-transistors and computing technology are thriving. The development will also lead to new possibilities for future electronic systems and their applications [1].

Semiconductor devices are of foremost importance in electronic devices for several reasons. In every semiconductor device, elementary systems have transistors that play a gigantic role in electronic signal switching. Transistors allow the current control facility to create logical gates for modern electronics and computing systems. Millions of Transistors are Integrated to make Integrated Circuits (ICs) on a single chip that allows complex multi-functional operations. Recent developments have resulted in nanometer-sized transistors that offer high precision, efficiency, and long-performance capacity for compact technological device manufacturing. Some components operate at lower voltages, which makes them energy-efficient devices [1].

Additionally, these devices are used for quick response in on-and-off applications compared to older available technologies that make semiconductor devices flexible to operate in a wide range of applications. The semiconductor device has versatility and offers highly reliable and durable solutions in renewable energy, medical, telecommunications, and automotive systems, which limits unwanted mechanical failures in operations over harsh environmental conditions. Also, the devices have high reliability in operations, making them essential for use in critical military, space, and industrial systems. Semiconductors are made of silicon and germanium, making them Cost-Effective for mass production to manufacture cheap and affordable electronic devices [1][2].

In short, semiconductor devices are revolutionary systems in the field of electronics that enable a wide scope of development and applications, driving technological innovations for multiple industrial applications.

Overview of radiation damage

There are two main types of radiation: ionizing and non-ionizing radiation. Three ionizing radiation types are widely known: alpha, beta, and gamma rays. The fourth radiation type is electromagnetic waves, which directly correlate with semiconductor device damage study. There are two types of radiation damage: ionizing and non-ionizing. Electromagnetic- type radiation damage can be sub-categorized into direct and indirect ionizing radiation associated with radiation damage on Semiconductor devices. Ionizing radiation can be generated with x-rays, gamma-rays, and other lower electromagnetic wavelength spectrum. The other type is non-ionizing radiation from microwaves, radiowaves, and Infrared from the electromagnetic wavelength spectrum. The direct and indirect ionizing radiation correlation with the electromagnetic spectrum and its size comparison is illustrated in Figure 1 for better understanding [2].

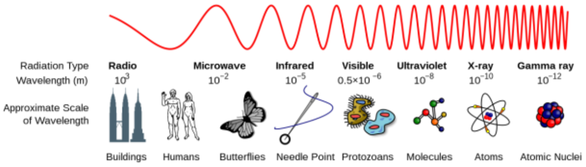

Figure 1: Electromagnetic Spectrum

The preliminary scope of this research aims to suggest new strategies, mechanisms, and techniques to mitigate radiation damage to semiconductor devices in space and nuclear environments and explore their capabilities in harsh environments [3].

Space and Nuclear technologies are partially connected with the unseen radiation damages in materials, which allows us to pursue research in these domains to explore reliable and efficient semiconductor devices to use in the technology. Exposure to cosmic radiation in space and neutron radiation of nuclear power plants are the critical damage that causes radiation-induced semiconductor material degradation, malfunctions, and failures. It is essential to explore the damage caused by radiation in order to design and develop robust semiconductor devices for space missions and nuclear power plants to protect the high associated investments [4]. Understanding radiation damage on semiconductor devices is essential to ensure their reliability and efficiency in such critical applications and to bring new developments in material, shields, and other mathematical modeling. It will also suggest and enable the development of radiation-hardened devices to withstand such harsh radiation environments for more extended functionality [5].

1.1 Mechanism and Effects of Radiation Damage on Semiconductor Devices

Mechanisms

Semiconductor devices used in space and nuclear power plants have critical environmental issues uncommon in traditional semiconductor device operations. Radiation damage due to ionizing radiation is typical in these devices, allowing us to research and find the mechanism. Earlier studies describe radiation-induced damage well, but how it is a phenomenon associated with this research is explained to understand the precise damage mechanism [4].
It has been observed that ionizing radiation from heavily charged alpha, beta particles, gamma, or neutrons strikes the atomic structure of the semiconductor material, creating damage to its structure. The Ionising radiation knocks the orbital electron and creates an electron-hole pair that leads to charge accumulation in a device that alters the electrical property of the semiconductor devices. Long charge traps in semiconductor devices have various elemental effects on the device's operation, including non-switching conditions, fluctuating values, lower voltage, and other temporary and permanent damages. Ionizing radiation and external process parameters like pressure and temperature induce annealing effects in which device properties can induce permanent defects in semiconductor devices[5].

Learning of these radiation damage mechanisms is essential to designing and developing radiation-hardened semiconductor devices to protect them in the harsh radiation environment. The development will also suggest improvements in the operational capabilities of the semiconductor material to improve its reliability and efficiency and minimize radiation damage.

Effects

A semiconductor device has various radiation effects on the semiconductor material. Depending on the intensity of the radiation source and the time in which the semiconductor material was placed near the radiation source, radiation damage on the semiconductor material can be characterized [6].

A few radiation damage types that are observed on electronics are as follows. Single Event Effect (SEE), Total Ionizing Dose (TID), and Displacement Damage (DD). Single Event Effect (SEE) is caused by a single heavy charged proton impact on the sensitive semiconductor material. It leads to and results in damage to critical memory systems of a semiconductor device. Total Ionizing Dose (TID) is the total accumulated ionizing radiation over a period that causes defects and damages in the semiconductor materials. It is frequently observed that TID results in leakage and degradation in device performance power shifts, and Displacement Damage (DD) occurs due to High-energy neutrons colliding with an atom of the lattice of the semiconductor materials, which displace another atom from its lattice position [7]. This atomic displacement produces defects in the semiconductor material that lead to damage and degradation of semiconductor devices. In some critical space and nuclear applications, this radiation damage is protected by various shields and techniques to improve their stability and reliability for a longer time [6][7].

It is crucial to find and understand the radiation effects in the semiconductor material. Mitigation techniques can be identified depending on the specific environmental conditions and applications in space and nuclear technology. The mitigation techniques can be radiation hardening of the material, shielding of the device, and controlling system code change to employ error correction for further enhancement of the radiation resistance of the semiconductor devices in harsh radiation environments [8].

1.2 Mitigation Strategies

High-charged energy particles like alpha, beta, gamma, and electromagnetic waves, along with prolonged exposure, can induce ionizing radiation that has several effects on the semiconductor device. This ionizing radiation exposure can initiate degradation and damage to the semiconductor material, leading to device malfunction, dynamic electrical output, degraded lifespan, and failure. Several techniques are used to mitigate these radiation damages [9]. Some of the Mitigation strategies are as follows:

Radiation Resistive Material: The first and foremost change is choosing the material that can withstand and resistive in such a harsh radiation environment [9]. The preliminary semiconductor material used in the semiconductor material must be updated with radiation-resistive materials like silicon carbide and gallium nitride to make the semiconductor device radiation tolerant. These semiconductor devices are widely used in various space applications [10].

Radiation Hardening and Hardened Packaging: To mitigate the radiation damage in the semiconductor device, the semiconductor material package design should add radiation tolerance semiconductor materials and develop similar device features to make a more radiation-resistive package. This primary mitigation strategy involves the radiation-resistive material that is inherently safe in the device structure-induced radiation defects to create a radiation device. Some specialized radiation-hardening encapsulations with traditional semiconductor material can also be used for specific sensitive applications of nuclear power plants [11].
Process, Material, and Shielding Improvement: There will always be continuous technological developments in the fields that require developments in the process, its material, and its techniques. In shielding, lead or tungsten manufacturers manufacture semiconductor material with radiation hardening capacity. Continuous research in the material will improve the fabrication facility for such radiation-resistive semiconductor devices [12][13].

Error Calibration, Operation, and Testing: Once devices are packed in the radiation hardern package, they can be found sensitive to some radiation and process parameters like temperature and pressure collaborative applications. These applications introduce profound errors and can be mitigated by improving the codes and algorithms [13]. Once it works fine in the radiation area, they are sent to the testing facility to evaluate their performance in real-time harsh radiation scenarios [13][15].

Introducing all such strategies in the material selection, hardening, process, and manufacturing of semiconductor materials with low radiation effects enhances their precision and efficiency in the harsh radiation environment of space and nuclear power plants [14].

2. Challenges & Future Directions

Plenty of challenges are in harsh radiation environments. Learning from the earlier knowledge of radiation types and their effects on semiconductor material is necessary to develop reliable and efficient semiconductor devices for the radiation environment area critically demanded in space and nuclear power plant applications. Also, radiation damage in the semiconductor material can cause specific device performance issues to be reduced in future developments in these fields.

The preliminary challenge of radiation damage on the semiconductor device is identifying the effects of radiation and exposure time during the operation. Only then can the device identify which type of radiation damage occurs in the semiconductor material. No tools are available to locate the inducted damages and predict its behavior in such a radiation environment. There is also a scope to research and develop such codes for future calculation and modeling [15].

Certain radiation-resistive materials are known and can be used in the future but still are in the research phase to be used in the semiconductor device package [15]. To select such radiation tolerance semiconductor materials, there are specific techniques to characterize them for further improvement in the manufacturing process [16]. All these processes are of the traditional available semiconductor devices, but there isn't any available knowledge on nanosecondary devices and their application in these environments [16] [17].

In the future, if all these semiconductor devices are integrated with nano transistor-based devices, then identifying radiation damages in the semiconductor material will be challenging and will require various real-time and earlier semiconductor device assessments and research in this field and find novel material that can be used in these systems [17]. This learning can also be used to develop software to analyze such systems for space and nuclear power plant applications. This will also require a collaborative effort from researchers, industries, and various agencies to accelerate this research in semiconductor device and material developments and its damage experiments [18].

3. Conclusion

Prolonged exposure to radiation on the semiconductor material can introduce radiation damage to the semiconductor material that is used in various space and nuclear power plant applications. It has been seen that several electromagnetic ionizing radiation exposures accumulate total ionizing dose and displacement damage in the semiconductor materials, which creates electron-hole pairs. The generated electron-hole pairs make a transportable layer that creates leakage in the semiconductor material. There are several impacts on the semiconductor devices, from a small error generation to permanent device damage.

Various radiation mechanisms and effects that impact the semiconductor device are described to understand the radiation damage on the semiconductor materials structures and atoms. Identifying the radiation damage on the semiconductor materials is explored in the research. A few radiation mitigation strategies like radiation hardening, shielding, process, materials, and other relevant improvements are proposed for harsh space and nuclear power plant environments to reduce the radiation effects on the semiconductor device.

Reliability and efficiency improvements are considered for more extended radiation exposure applications of semiconductor devices to make more reliable semiconductor devices for space and nuclear power plants. Adjustments in radiation-resistive semiconductor materials can mitigate the effects of the semiconductor material and proposed devices to reduce radiation damage and achieve high performance in harsh radiation environments. These radiation-hardened, shielded materials and error code integrations are also considered for the new semiconductor device design, testing, and analyses for real-time applications.

Moreover, semiconductor materials and futuristic applications can be crucial in various space and nuclear power plant applications. Further research and collaborations are suggested to develop safe, reliable, precise, and efficient semiconductor devices and mitigation strategies for their manufacturing, processing, and research applications.

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