Investigating the causation of bit flips

What are the underlying physical and computational mechanisms that govern the interaction of high-energy particles with semiconductor materials causing Single-Event-Effects and to what extent are current mitigation techniques useful in their prevention ?

World Studies

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Introduction

The aim of this World Studies EE is to evaluate and answer the following question: **What are the underlying physical and computational mechanisms that govern the interaction of high-energy particles with semiconductor materials causing bitflips and to what extent are current mitigation techniques useful in their prevention ?**

In today's world, the components used to build processors, memory and other hardware, are built on a submicroscopic scale. Because processors have shrunk and grown more energy-efficient, cosmic bit flipping is becoming more common: as a result of this efficiency it has become easier to set a bit purposefully, and thus, the less energy it takes to set a bit accidentally.[1]

When highly energetic particles, like cosmic rays, strike a device, they can unleash a shower of charged particles in the semiconductor, causing some bits to flip from 0 to 1 or vice versa. These bit flips are caused by Single-Event Effects(SEEs). They are unpredictable and can have dire social and economic impacts depending on their context. Consider the precariousness of a single bit flip and the chaotic disruption it can wreak. In a space mission, where success is hinged on a precise and finely tuned system, a bit flip could plunge the entire mission into disarray. Even potentially putting the lives of astronauts at risk and endangering the success of the mission. Similarly, a nuclear power plant relies on accurate and reliable data to prevent catastrophic accidents, a single bit flip in this context could have devastating consequences, sending shockwaves throughout society and the economy, with far-reaching and potentially incalculable costs. But even beyond these life-or-death scenarios, the ripple effects of bit flips can be profound. In our increasingly data-dependent society, even small errors can have big

1 John (2020)

consequences. Bit flips in financial transactions, for instance, could result in incorrect balances and misallocated funds. In communication systems, bit flips could disrupt vital information, leading to lost data and missed opportunities. The potential for chaos and disruption is endless, and the consequences can be felt throughout society and the economy. [2] [3] [4] [5]

This essay will be divided into two categories : Computer Science and Physics. By delving into this topic, the essay aims to provide a deeper understanding of the of the factors that can lead up to bitflips, and ways in which these errors can be prevented in order to ensure the reliability and integrity of computer systems.

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2 Jones, A., Smith, B., and Brown, C. (2021)
3 Shen, X., Lee, J., & Du, D. (2017)
4 Kim, J., & Lee, Y. (2017)
5 Chikalov, I., & Tal, I. (2012)

Interdisciplinary Approach

An interdisciplinary approach would offer valuable insights into the perplexing world of SEEs. Such an approach would require drawing upon the intricate principles and theories from both the field of physics and computer science to better grasp the causes and effects of SEUs, as well as evaluate strategies for preventing and mitigating their impacts. The physics aspect of this interdisciplinary approach would delve into the mysterious behavior of charged particles in relation to SEEs, and examine the forces at play between them, which are described by Coulomb's law. It would involve scrutinizing the complexities of the environment in which these particles interact with electronic circuits, and the intricate ways in which these interactions can trigger the onset of bitflips. On the other hand, the computer science component of this approach would concentrate on the design and operation of electronic circuits and systems, and the various strategies that can be employed to prevent or alleviate the effects of SEEs. With an interdisciplinary approach that integrates the knowledge and techniques from both the field of physics and computer science, we can begin to unravel the complex and unpredictable nature of bitflips and discuss effective strategies to prevent and mitigate their impacts. However, considering the topic of SEEs is very broad, this research will be focused only on two types of SEEs: Single-Event-Upsets and Single-Event-Transients.

Physics Related Factors

Radiation

1. Radiation

Radiation refers to the emission of energy in the form of waves or particles. There are many types of radiation, including electromagnetic radiation such as light and radio waves, particle radiation such as alpha and beta particles, and nuclear radiation such as gamma rays and neutrons.[6] [7]

2. Cosmic Rays

Cosmic rays are high-energy particles that originate from outside the Earth's atmosphere. They are composed of various subatomic particles, such as protons, electrons, and nuclei of heavier elements. Cosmic rays are constantly bombarding the Earth from all directions, and they are a major source of ionizing radiation.[8] [9]

6 Bosser, A. L. (2017)
7 The Editors of Encyclopaedia Britannica (2022)
8 Gaisser, T. K., Engel, R. and Resconi, E. (2016)
9 The Editors of Encyclopaedia Britannica (2022)

Computer Science Related Factors

Memory

1. Memory is a key component of computer systems that is used to store data and instructions. It comes in various forms, including volatile and non-volatile memory, each with its own characteristics and uses. Memory is a crucial resource for a computer system, and it is essential for the system to be able to perform useful tasks.[10] [11]

Background

Historical background

The first report on soft errors in space applications was published in 1975 by Binder et al. Four "anomalies" in satellite electronics that had happened throughout a 17-year operational span were examined by the authors. They concluded from their investigation that these four abnormalities could not be a result of the satellite being charged by the solar wind. The abnormalities had really been brought on by flip-flop circuits being triggered. This article defined "soft errors" as random, non-repeating single-bit faults in memory components that aren't brought on by electromagnetic interference or electrical noise but rather by radiation. In the study, soft mistakes in the Intel 2107-series 16-kb DRAM were concluded to have been brought on by alpha particles released by the radioactive decay of uranium and thorium impurities in the package materials. It was the first report of soft faults in electronic devices caused by radiation that occurred at sea level.[12]

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10 Hemmendinger , D. (1998)
11 The Editors of Encyclopaedia Britannica (2022)
12 Nicolaidis, M. ed., 2010. Soft errors in modern electronic systems, Springer.

Real World Incidents of SEUs

Voting Incident

On May 18th, 2003, voters in Belgium went to the polls, for an ordinary vote. In many regions, however, voting was done on a computer, something Belgium was experimenting with for over a decade. The system worked by inserting a magnetic card into the computer and then choosing the person they chose to vote for, their vote was then both saved on the computer, and on the magnetic card, which was then dropped into a box for redundancy. Later than night, when officials, one of the election officials detected a problem with the results from Schaerbeek, a municipality in central Brussels. One candidate had received more votes than what was mathematically possible, and so they recounted the magnetic cards again, and after several hours, after every vote had been recounted, all the votes were identical except for that one candidate, where the recounted number of votes was short of 4096 votes. After months of investigations and testing their software, the company concluded that there was only one possible cause for the sudden flip in bits: cosmic rays. They came up with that conclusion because of the number of extra votes the candidate got: 4096. Which is exactly 2^12, representing the 13th bit in a 16-bit register.[13] This however is a highly debated occurrence of an SEU, as some argue that we will never acquire enough evidence to conclude that it was in fact caused by an SEU, such as Mr. Paco Hope, who wrote an article titled *"Cosmic Rays Did Not Change Election Results"* in 2017, on his personal blog. Although it is not the most credible source of information he does make a point that *"Absence of Evidence is not Evidence of Absence"*.[14]

13 YouTube. (2021). The Universe is Hostile to Computers. YouTube.
14 (Hope, 2017)

The Super Mario Incident

Back in 2013, during a speedrun(which is when a player tries to finish the game in the shortest possible amount of time while fulfilling some criterions) through the 'Tick Tock Clock' level of Super Mario 64, user “DOTA_Teabag”'s character shot suddenly upward through the floor and onto a higher platform. Even after a $1,000 bounty was put out by *pannenkoek2012*, a famous speedrunner, no one managed to replicate the apparent glitch. That is, until the same user came out 6 years later with proof that placed cosmic rays at the first position of the potential causes of such an occurence. With a single bit flip that swapped a one to a zero in Mario's vertical position coordinate switched.[15]

Figure 1 - Actual picture of the streamed speedrun, displaying 2 images at a 1s interval, before and after the bitflip[16]

15 [16]
16 (Lewin Day, 2021)

Moore’s Law

Moore's Law was created Intel co-founder Gordon Moore in 1965. It states that the number of transistors on a microprocessor chip doubles approximately every two years. This trend has continued for over five decades, and it has led to a rapid increase in the processing power and capabilities of microprocessors. As the size of these components decreases, they become more susceptible to damage from high-energy particles, such as cosmic rays and ions. This can result in more frequent SEUs.[17] [18] [19] This graph shows the trend that Moore predicted, with the x-axis representing years, and y-axis representing the transistor count.

[20]

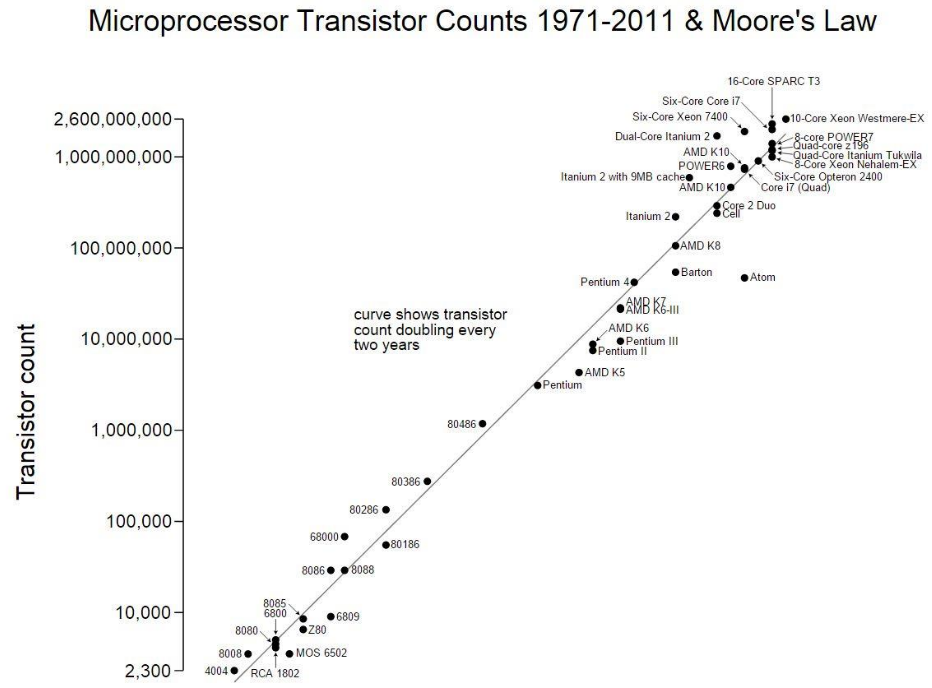

Figure 2 - Graph of Moore's Law, showing an increase in the transistors in microprocessors

17 Gregersen. E. (2011)
18 [9]
19 Moore, G. (1965)
20 phys.org(2015)

Single Event Effects

Soft Errors

SEEs can be categorized in two categories : Soft and Hard errors. As their name suggests, hard errors often result in a hardware failure, while soft errors usually result in non-permanent software issues. As mentioned in the introduction, this is a very broad field of study, and I will only be focusing on two out three of the soft errors that exist: Single Event Upsets, and Single Even Transients, which are ultimately quite similar.

SEUs

The genesis of SEUs lies in the occurrence of perturbations in device functioning that result in an alteration in the bit value, also known as a bitflip, caused by a high-energy particle. These SEUs have the potential to lead to inaccuracies in computational and data processing. However, it is worth noting that SEUs are generally not associated with persistent harm to the operational integrity of a given system.[21] [22] Nasa defines SEUs as such : *"Radiation-induced errors in microelectronic circuits caused when charged particles (usually from the radiation belts or from cosmic rays) lose energy by ionizing the medium through which they pass, leaving behind a wake of electron-hole pairs"*.[23]

21 Wang and Agrawal(2008)
22 Garshelis, D. (2000)
23 (Scientific and Technical Information Program, n.d.)

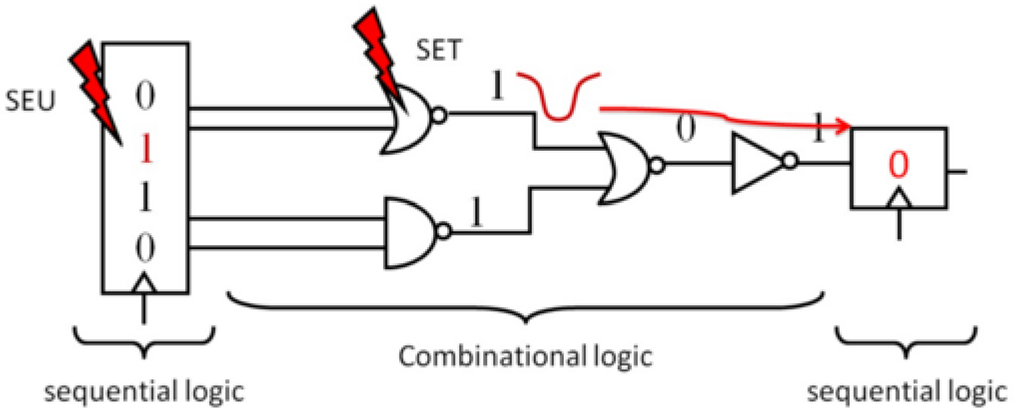

Figure 3 - Visualization of SEUs and SETs in a logical Boolean circuit, using logic gates[24]

This diagram illustrates both an SEU and an SET. As mentioned in their respective explanations, SETs are caused by temporary changes in the output signals of a device's logic circuitry, illustrated in the diagram by the red bolt which changes the logic gate. While an SEU causes a bit flip. Although both virtually cause bitflips, as the final output will be different in both cases, their processes are different.

SETs

In stark contrast to SEUs, the genesis of SETs can be traced back to a momentary surge in the current flow through a device, culminating in a rapid escalation in power consumption that, in turn, has the potential to trigger substantial harm to the device.[25] In fact, SETs are relatively infrequent, albeit considerably more destructive, in that they can produce irreversible damage to a system. SETs are often precipitated by high-energy particles like cosmic rays, which induce an abrupt rise in the circuit's voltage, which causes a change in the logic circuitry of a semiconductor. It is crucial to note that SETs are not typically associated with bitflips, as opposed to SEUs, which are directly tied to bit value alterations. [26] [27] [28] [29] [30] [31]

24 (José Rodrigo Azambuja, Kastensmidt and Becker, 2014)
25 JEDEC (no date)
26 Jones, J. (2020)
27 Shen, X., Lee, J., & Du, D. (2017)
28 Kim, J., & Lee, Y. (2017)
29 Chikalov, I., & Tal, I. (2012)
30 Langton, C. (2010)
31 [22]

Memory Cells

In order to comprehend the overall causes of such events, it is important to first understand how memory components work.

This section will discuss the current design of memory components, and their relationship with SEEs.

Memory design

The physical layout and design of memory components can affect their susceptibility to SEUs in several ways.

First, the density of memory components can affect their susceptibility to SEUs. Memory components that are densely packed and have small feature sizes are more susceptible to SEUs than larger, more spaced-out components. This is because high-energy particles are more likely to strike and cause errors in smaller, more densely packed components.

Second, the materials used in the construction of memory components can affect their susceptibility to SEUs. Certain materials, such as silicon, are more resistant to SEEs than others, and they can be used to reduce the susceptibility of memory components to SEEs.[32]

32 [13]

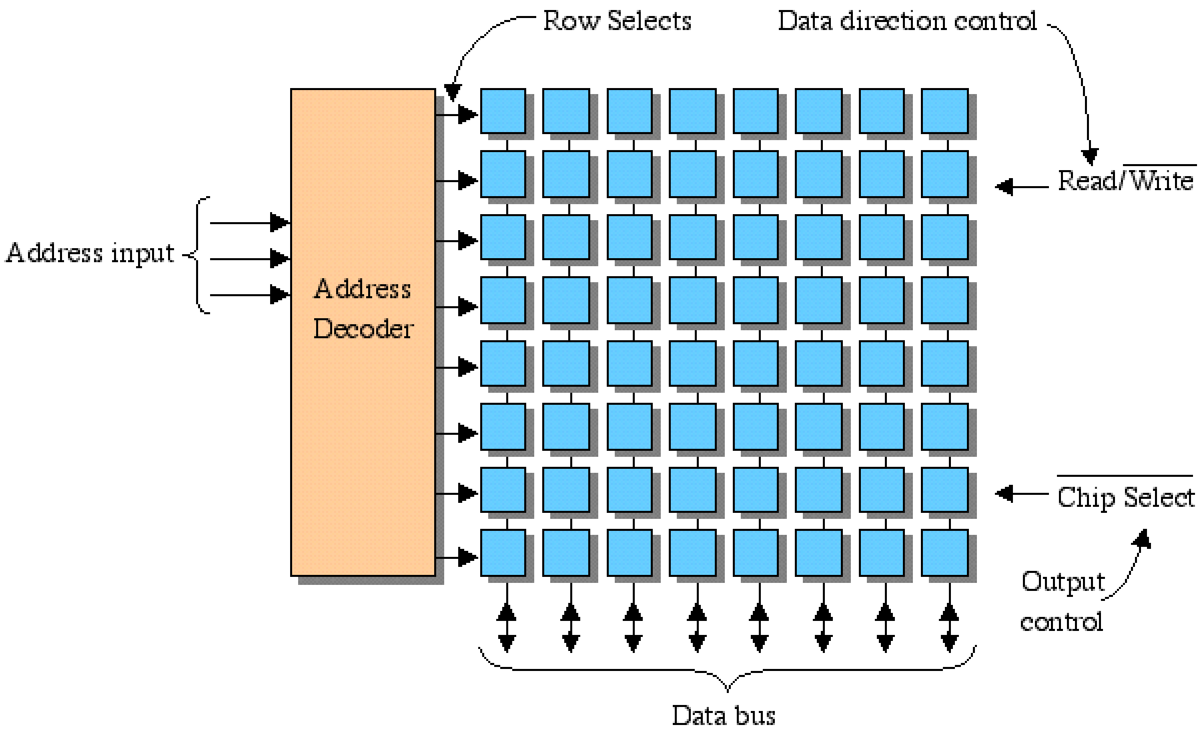

Figure 4 - Design of a memory cell[33]

To perform an operation on the memory, a command must be sent by setting its control inputs at specific values according to a pre-established timing.

Third, the physical structure of memory components can affect the way that SEEs are detected and corrected. For example, some memory components are designed with redundant circuits that can provide backup copies of data. This can help to prevent SEEs from causing significant problems in systems that use memory components.[34] [35]

33 (Tarnoff, n.d.)
34 [14]
35 [13]

The Determination of the Output (0 or 1)

The operational output of a memory cell hinges on the state of its storage elements, which are typically transistors or capacitors. In general, when a memory cell is accessed, the storage elements' state is read and translated into a binary value, either 1 or 0. The design of memory cells can vary in their methodology for ascertaining the state of storage elements, with some employing a charge or magnetic field presence or absence, among other determinants.

Nonetheless, several other factors can impact the output of a memory cell, including the voltage applied to the cell, the operational temperature, and external interferences like electromagnetic field. These factors have the potential to initiate changes in the storage elements' state, which may in turn lead to alterations in the memory cell's output.[36] [37]

36 [14]
37 [6]

Physics

This section will discuss physical implications of SEUs and SETs in relation with the Physics. The discussion will be spanned on two sub-topics: the sources of radiation and Coulomb's Law.

Sources of radiation

The principal sources of radiation that can cause SEUs are high-energy particles, such as cosmic rays and ions. Cosmic rays are particles, such as protons and atomic nuclei, that originate from outside of the solar system and travel through space at high speeds, on the other hand, ions are atoms that have gained or lost electrons, consequently giving them a net positive or negative charge. Both cosmic rays and ions can have high energies(1GeV per nucleon), and when they pass through a circuit, they can cause single events by interacting with the materials that make up the circuit.[38] [39]

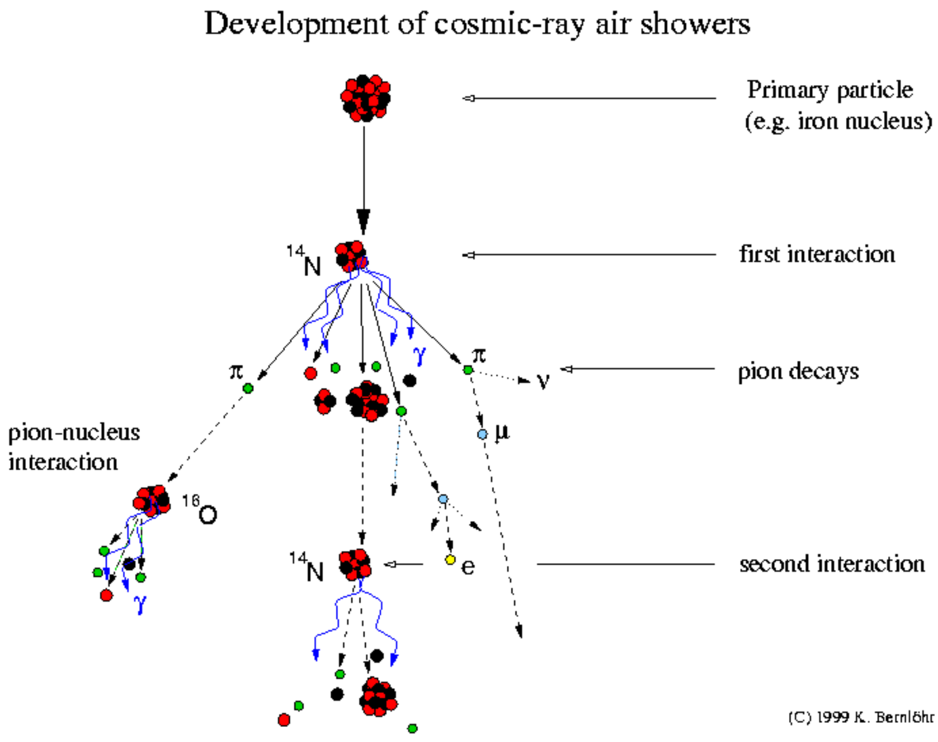

Figure 5- Development of cosmic-ray air showers (K.Bernlohr, 1999)

38 Smith, J. (2018)
39 Johnson, M. (2019)

Although some charged particles get deflected by the Earth's magnetic field, with the proper angle of incidence and sufficient rigidity, which refers to the particles' ability to maintain their trajectory through a magnetic field, charged particles have the potential to penetrate the Earth's magnetic field and make their way into the upper atmosphere. As a result of nuclear interactions with the atmosphere, these high-energy ions create reaction products such as muons, pions, gamma photons, and lighter nuclei, as shown in the figure above. These reaction products, in turn, induce further nuclear reactions with the atmosphere or decay into alternative products. After numerous steps, a cascade of secondary particles emerges, known as a "cosmic ray shower." These showers of cosmic rays occur more frequently at higher magnetic latitudes since the geomagnetic shielding effect is less powerful near the poles.[40] Nuclear interactions degrade the cosmic ray spectrum until about 15 km of altitude, at which point virtually all primary cosmic rays have interacted and turned into secondary particles.

SEES are caused by the interaction of ionizing particles with the semiconductor materials used in electronic circuits. When an ionizing particle passes through a semiconductor, it can knock electrons out of their orbits, creating a cloud of free electrons and positive ions; indeed, this cloud of charged particles is known as a Coulomb explosion, and it can cause a sudden increase in the electric field in the semiconductor material, which is directly proportional to the voltage applied to the semiconductor. When the electric field increases due to a Coulomb explosion, the voltage across the material also increases, this can cause a voltage spike or a current surge in the circuit, leading to SETs and SEUs.[41]
42

40 [6]
41 Lee, C. (2020)
42 Park, J. (2021)

Coulomb's law(will be explored in more depth below) describes the interaction between charged particles. It states that they will attract or repel each other based on the magnitude and sign of their charges; with the force being inversely proportional to the square of the distance between them, when a charged particle travels through matter, an electrostatic force is experienced from the surrounding electrons, causing the particle to decelerate. This process is called electronic stopping. Conversely, the charged particle will also exert an electrostatic force on the electrons, which may be strong enough to dislodge them from their atoms, leaving an ionized trail along the particle's path.

The maximum amount of energy which can be transferred to an electron in a single non-relativistic(less than the speed of light) collision, W_{max}, is given by the following formula:

$$W_{max} = \frac{2mev^2}{1 + \left(\frac{me}{M}\right)^2}$$ [43]

In this formula, m_e is the mass of an electron, v the velocity of the incident particle, and M the mass of the incident particle. In the case of low-energy charged ions, $m_e \ll M$, so we can make the approximation $W_{max} = 2m_e v^2$. This is the defining formulae of SEEs when describing them in Physics.

[43] [6]

The average rate of energy loss through electronic stopping for the incident particle is given by the following formula[44]:

$$\frac{-dE}{dx_{elec}} = \frac{1}{4\pi\varepsilon_0}\frac{Z_1^2 e^4}{m_e v^2} N Z_2 L$$

With : Z_1 being the charge number of the incident particle, Z_2 the atomic number of the target atoms, N the atomic density of the target material, ε_0 the vacuum permittivity, e the elementary charge, and L is a dimensionless quantity called the stopping number. which depends on the properties of the target material and the incident particle. It takes into account the details of the interaction between the incident particle and the electrons in the material, such as the screening of the Coulomb potential by the electrons.

44 (Ibid)

Coulomb's Law

Coulomb's law is a fundamental law of physics that describes the electrostatic force between two charged particles. The law states that *"the magnitude of the electrostatic force between two charged particles is directly proportional to the product of their charges and inversely proportional to the square of the distance between them."*[45] This relationship is described by the following equation[46]:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$$

Where F is the electrostatic force between the two particles, K($\frac{1}{4\pi\varepsilon_0}$) is the electricity constant, q_1 and q_2 are the charge of the particles, while r is the distance between them.[47]

The fundamental principle governing SEEs is Coulomb's law, which describes the electrostatic force between two charged particles. When high-energy particles collide with semiconductor materials, they can displace electrons from their atomic orbitals, creating a temporary surplus of charge. [48]

This charge surge can lead to a voltage spike, which, if it surpasses the maximum operating voltage of the circuit, can result in an SEU.[49]

Moreover, the behavior of charged particles in a magnetic field can further complicate the problem of predicting and mitigating SEUs. Cosmic rays, for instance, can be deflected by magnetic fields, altering their trajectory and the location within the circuit at which they cause an SEU. [50] [51] [52]

45 The Editors of Encyclopaedia Britannica (2022)
46 Coulomb, C.-A. de (1785)
47 [41]
48[32].
49 [40]
49 Jones, J. (2020).
51 Brown, M. (2019)
52 Lee, C. (2018)

Prevention Methods

Shielding

Shielding involves enclosing the memory circuit in a protective material, such as aluminum or copper, that can absorb the energy of high-energy particles. This can effectively block particles from reaching the memory circuit and prevent SEUs. Shielding is a relatively simple and straightforward method for preventing SEUs, and it can provide a high degree of protection for the memory circuit. However, shielding can also add weight and cost to the memory system, and it may not be practical for certain applications.[53]

Modular Redundancy

Redundancy involves storing multiple copies of the same data in different locations in the memory system, so that if an SEU occurs in one location, the data can be retrieved from another location. Scrubbing involves periodically reading and re-writing the data in memory to detect and correct errors caused by SEUs. Jones (2021) argues that modular redundancy can improve the reliability of a system, however it is usually more expensive to implement, and it adds complexity to a system, which makes it harder to manage [54] [55] [56]

53 Green, G. (2011)
54 Sengupta, A. (2021)
55 Brown, B. (2010)
56 [6]

Error Correction Codes (ECCs)

ECCs are algorithms that can detect and correct errors in data by adding redundant information to the data. When data is stored in memory, the ECC algorithm can be used to add additional bits to the data, which can be used to detect and correct errors that occur during storage and retrieval. This can help to prevent SEUs from causing data corruption and can improve the reliability of the memory system. ECCs are a powerful tool for preventing SEUs, and they can provide a high level of protection with minimal overhead. However, ECCs can also increase the amount of memory required to store the data, which can be a disadvantage in some situations.[57] [58] [59]

Scrubbing

Scrubbing involves periodically reading and re-writing the data in memory to detect and correct errors caused by SEUs. This can help to prevent SEUs by identifying and correcting errors before they cause data corruption. Scrubbing can be an effective method for preventing SEUs, but it can also increase the workload of the memory system and reduce its performance, as it necessitates high-speed access to memory.[60] [61]

57 [13]
58 Jones, J. (2020)
59 White, W. (2008)
60 Jones, J. (2020)
61 [6]

Evaluation of Methods

Overall, different prevention methods for SEUs have different advantages and disadvantages. Shielding, ECCs, redundancy, and scrubbing are all effective methods for preventing SEUs, but they may not be suitable for all applications. However, the paper titled "Software-implemented EDAC protection against SEUs"[62] written by *Philip Shirvani, Nirmal Saxena, Edward J. McCluskey*, argue that ensuring complete protection of both the code and data memory in software may not be practically or economically feasible. Nonetheless, this study showcases that implementing Error Detection and Correction (EDAC) in software can be a cost-effective solution that offers protection for code segments. Furthermore, the implementation of EDAC can substantially improve system availability in a space environment where radiation levels are low.

Conclusion

To conclude this research the question **"What are the underlying physical and computational mechanisms that govern the interaction of high-energy particles with semiconductor materials causing Single-Event-Effects and to what extent are current mitigation techniques useful in their prevention ?"** was answered effectively and accurately with a wide range of references that were often evaluated and assessed on their credibility. SEUs and SETs were explained, in hand with the help of real-life scenarios. The physical aspect of the research question was also explained in depth with the help of Coulomb's Law, and formulae were referenced, and their context explained in relation with the research question. The extent to which mitigation techniques are useful was also evaluated, and a

62 (Shirvani, Saxena and McCluskey, 2000)

conclusion was reached that software EDAC was the most appropriate and efficient method of mitigating these events.

In the long term, further research and development is needed to better understand and address the issue of SEUs. This could include improving the design of memory components and systems to reduce the likelihood and impact of SEUs and developing new materials and technologies that are more resistant to SEUs. By continuing to study and address the issue of SEUs, it is possible to reduce their impact on society and to improve the reliability and performance of electronic systems.[63] [64]

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63 [8]
64 [3]

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