Discover Materials

Review

Radiation-induced degradation in optoelectronic devices for satellite applications: a review

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Abstract
Optoelectronic devices play a crucial role in the functionality of satellite systems, particularly in optical communication. However, these devices face significant challenges due to radiation-induced degradation, which can compromise their performance and reliability in the harsh space environment. This review provides a comprehensive analysis of the impacts of various types of radiation, including protons, electrons, gamma, and neutrons, on optoelectronic components used in satellite applications. The review discusses the mechanisms through which radiation interacts with semiconductor materials, leading to phenomena such as ionization and charge build-up, which can result in the deterioration of key performance parameters such as optical efficiency, signal integrity, and operational lifespan. The review delves into the specific effects of radiation on critical optoelectronic components, including photodetectors, light-emitting diodes (LEDs), and laser diodes, with a particular focus on inter-satellite optical wireless communication systems. By analyzing the existing literature, this review traces the evolution of research on radiation effects, highlighting trends in understanding and mitigating radiation-induced damage. It also identifies gaps in current knowledge and suggests areas for future investigation to enhance the resilience of optoelectronic devices against radiation. This effort provides valuable insights that can inform the design and development of more robust optoelectronic systems capable of maintaining reliable operation in radiation-rich environments, thereby contributing to the advancement of satellite communication technologies.

Keywords Radiation · Space · Optoelectronics devices · Performance · Degradation · Inter-satellite

Abbreviations

CME	Coronal mass ejection
CMOS	Complementary metal oxide semiconductor
COTS	Commercial off-the-shelf
DBR	Distributed Bragg reflector
DCNU	Dark current non-uniformity
DD	Displacement damage
DDD	Displacement damage dose
DFB	Distributed feedback
FP	Fabry–Perot
GaAs	Gallium arsenide

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GaN	Gallium nitride
GCR	Galactic cosmic ray
InGaAs	Indium gallium arsenide
InGaAsP	Indium gallium arsenide phosphide
IsOWC	Inter-satellite optical wireless communication
L-I	Light power vs current
L-I-V	Light power vs current vs voltage
LED	Light emitting diode
LEO	Low earth orbit
LET	Linear energy transfer
NIEL	Non-ionizing energy loss
OMERE	Orbitography and radiation environment
PIN	Positive-intrinsic-negative
SBD	Schottky barrier diode
SEE	Single event effect
SEU	Single event upset
SPE	Solar particle event
SRH	Shockley read-hall
TID	Total ionizing dose
UV	Ultraviolet
VCSEL	Vertical surface emitting laser

1 Introduction

In recent years, the reliability and performance of optoelectronic devices in satellite applications have become critical due to the increasing demands for high efficiency and durability in harsh space environments. The space environment is characterized by a continuous influx of high-energy charged particles, solar radiation, plasma, and cosmic rays [1], which pose significant challenges to the functionality of optical communication systems. These radiation sources can induce various forms of damage, including ionization [2, 3] defect formation [4–6] and annealing [7–10] , leading to performance degradation in semiconductor materials which can have an impact on both the efficiency and dependability of the electrical components of the optical communication systems [6–9].

Notably, solar particles are the most prevalent radiation particles encountered in space, and their interactions with optoelectronic components can result in catastrophic failures. Radiation could cause a variety of damage effects in optical transceivers, including degradation of the electro-optical properties of the electrical components, and single event effects (SEEs) [3, 8, 11–14]. SEEs are events in which a single high-energy particle can cause a significant change in the state of a device [7, 15, 16]. Ongoing research is focused on developing radiation-resistant optical communication systems to ensure their reliable operation in space and other harsh environments [17–19].

Understanding the mechanisms of radiation-induced degradation is essential for developing robust optical communication systems capable of withstanding these harsh conditions. While substantial research has been conducted on the effects of radiation on various semiconductor devices [20–22] , there remains a notable gap in the literature regarding the specific impacts on optoelectronic devices used in satellite systems. This paper aims to provide a comprehensive review of the radiation-induced degradation in optoelectronic devices, focusing on key performance metrics such as responsivity, dark current, threshold current, and slope efficiency. The findings will contribute to a better understanding of the challenges faced by these devices in space and highlight potential avenues for future research and development.

The paper is organized as follows: Section 2 introduces the sources of space radiation and their effects on optoelectronic devices, discussing the mechanisms of radiation damage. It highlights the presence of high-energy charged particles, solar radiation, and cosmic rays, which can lead to ionization, defect formation, and other detrimental effects on semiconductor materials. Section 3 reviews recent studies on the performance degradation of optical transmitters, focusing on key metrics such as threshold current, slope efficiency, and output power under various radiation exposures. Section 4 examines the performance degradation of optical receivers, detailing how radiation impacts responsivity, dark current, and overall device reliability. Finally, Section 5 concludes with recommendations for enhancing the radiation resilience of these critical components, emphasizing the need for ongoing research and development to improve the robustness of optoelectronic devices in harsh space environments.

1.1 Sources of space radiation

With the knowledge gathered from space missions over the years, space radiation sources such as solar-based charged particles, galactic cosmic rays, and earth radiation belts have been uncovered and elucidated. From the beginning of the space era to these days, many operational failures have taken place on satellite systems. The different sources of radiation can have different effects on spacecraft and their components. For example, cosmic rays can cause ionization damage to materials, while solar radiation can cause both ionization damage and annealing. Radiation impacts can also be affected by the intensity of the radiation, the type of substance that is being irradiated, and the duration of the exposure.

Space radiation presents a significant challenge to the reliability and performance of optoelectronic devices used in satellite applications. The primary sources of space radiation include solar radiation, cosmic rays, the Van Allen radiation belts, solar flares, geomagnetic storms, micrometeoroids, and space debris, as referred to Fig. 1. Each of these sources contributes to the degradation of semiconductor materials through mechanisms such as ionization, defect formation, annealing, and other effects on materials and devices in spacecraft. The specific sources of radiation that affect a particular spacecraft will depend on its orbit and the time of year.

The sources of radiation in the space environment present significant challenges to the reliable operation of optical satellite communication systems [2, 22, 23]. Proton bombardment and other radiation effects can impact on the performance and functionality of optical terminals, necessitating a thorough understanding of these sources and their effects. By comprehensively addressing these issues, researchers and engineers can develop robust optical communication systems capable of withstanding the harsh conditions of space. Beyond the Earth's magnetosphere, the space radiation environment includes solar wind, galactic cosmic rays (GCRs), and solar particle events (SPEs). The solar wind [23–25] is made up of electrons and protons with a high fluence rate (10^{10} cm^2 s^{-1}) but low energy (0.5 to 2 keV). SPEs mostly produce protons with time-varying fluence rates (10 to 10^3 cm^{-2} s^{-1}) and medium energies (10 MeV to 1 GeV). GCRs are made up of extremely high energy (100 MeV to 1 TeV+) nuclei from hydrogen ($Z = 1$) to iron ($Z = 26$) with a lower fluence rate (10^{-5} to 1 cm^{-2} s^{-1}) [26–28].

Solar radiation, particularly during solar flares and coronal mass ejections, releases high-energy particles, including protons and electrons, which can penetrate satellite systems and induce ionization damage. This ionization leads to the generation of electron-hole pairs within semiconductor materials, potentially causing shifts in electrical characteristics and increasing the likelihood of single-event effects (SEEs). The intense energy from solar events can also result in annealing, a process that can temporarily heal some radiation-induced defects but may also lead to further material degradation over time.

Cosmic rays, composed of high-energy protons and heavy ions, originate from outside the solar system and pose a continuous threat to spacecraft. These particles can penetrate deep into materials, causing displacement damage by

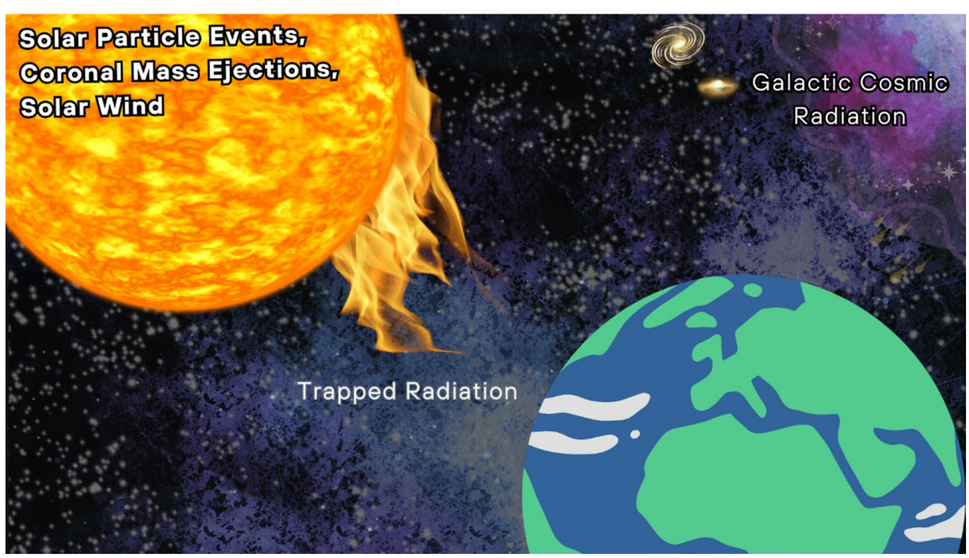


Fig. 1 Sources of space radiation from solar, intergalactic nuclei, trapped radiation between the Earth's atmosphere and outer space

knocking atoms out of their lattice positions, leading to defect formation. Such defects can act as recombination centers, reducing carrier lifetimes and degrading the performance of optoelectronic devices [20].

The Van Allen radiation belts, which encircle the Earth, are regions of trapped charged particles, primarily electrons and protons. These belts are particularly hazardous for satellites in low Earth orbit (LEO) as they can cause significant ionization and displacement damage. The high-energy particles in these belts can lead to the formation of defects in semiconductor materials, resulting in increased dark current and reduced responsivity in photodetectors, as well as threshold current shifts in laser diodes [3, 8, 15–17].

According to extensive assessments of these failures, the primary causes of these anomalies are space radiation environment, problems based on electronics, design faults, lack of quality, and problems owing to unknown causes. Twenty percent of spacecraft problems with known causes are attributed to space radiation, according to [20, 21]. It is worth noting that around one-third of the causes of satellite malfunctions remain unidentified. However, the space environment presents various challenges brought by the presence of various kinds of particles and fields. This section focuses on discussing the sources of radiation that can impact optical terminals and their vulnerability to solar radiation bombardment.

1.1.1 High-energy charged particles

Interstellar gaps between planets do not constitute a pure vacuum, containing approximately 10 energetic atoms per cubic centimeter (atom/cm^3) combined with galactic and solar radiation. Predominantly, the sun is the source of most of these particles; with the solar wind extending outward at velocities between 300 and 1000 kilometers per second, directed towards the atmosphere of the Earth. High-energy particles that are charged, such as cosmic rays and galactic cosmic rays, have been prevalent in the space environment [13, 15, 16]. These particles pose a significant threat to the functionality of optical terminals in space. When these charged particles interact with optical components, they can cause ionization, leading to potential disruptions and performance degradation.

The radiation belts provide a principal source of cosmic energy particles. The earth's surface makes up one among the several celestial bodies within the solar system we live in, therefore it consists of a magnetic field. Because of the Lorentz Force, the resulting magnetic flux creates magnetic belts that capture charged particles and cause them to travel almost regularly in certain regions. These radiation belts are also referred to as the Van Allen Belts [20, 21], after J. Van Allen found them in the end of the 1950s, a period marking the beginning of the cosmic age. The Van Allen Belts originate given that the Earth's atmosphere ceases, because the atmosphere destroys trapped particles.

The aforementioned are two doughnut-shaped charged particle zones that surround the Earth. The inner belt is 1,000 to 6,000 kilometers above the Earth, whereas the outer belt is 15,000 to 60,000 kilometers above the Earth. The Van Allen radiation belts are largely made up of protons and electrons and can be rather powerful. As described by [29], radiation belts are mostly made up of electrons and protons with energies ranging from 1 keV - 7 MeV to 1 keV - 300 MeV. There are no less than two radiation bands that circle the Earth, known as the inner and outer belts, while there have been more than two belts in the past. The outer layer is mostly made up of electrons, while the inner layer is made up of a combination of protons and electrons. Particles are denser in some places, as illustrated in Fig. 2.

1.1.2 Solar radiation

Solar radiation, comprising solar flares and solar energetic particles, is another crucial source of radiation in space. The intense energy released during solar events can impact optical terminals, potentially causing temporary malfunctions or even permanent damage. Understanding the effects of solar radiation on optical communication systems is essential for ensuring their reliability in the harsh space environment.

Another major source of ionized radiation particles is the sun. Periodical cycles of solar activity normally last eleven years. The solar period's eleven years are separated into two groups, solar maximum, and solar minimum, accordingly. Solar activity is at its peak during a solar maximum period, that spans about seven years. Solar activity is relatively low throughout the span of four years of the solar minimum period. Conversely, the galactic cosmic ray and trapped proton fluxes are maximal during the solar minimum period. These are sudden and intense eruptions of energy from the Sun. Solar flares can emit a variety of radiation, including protons, electrons, and X-rays. Solar flares can cause significant damage to spacecraft and their components. One of the major phenomena caused by solar activity includes geomagnetic storms which trigger significant fluctuations within the Earth's magnetic field arising from solar activity. Geomagnetic storms can increase the level of radiation reaching the Earth's atmosphere, and they can also cause the Van Allen radiation belts to expand.

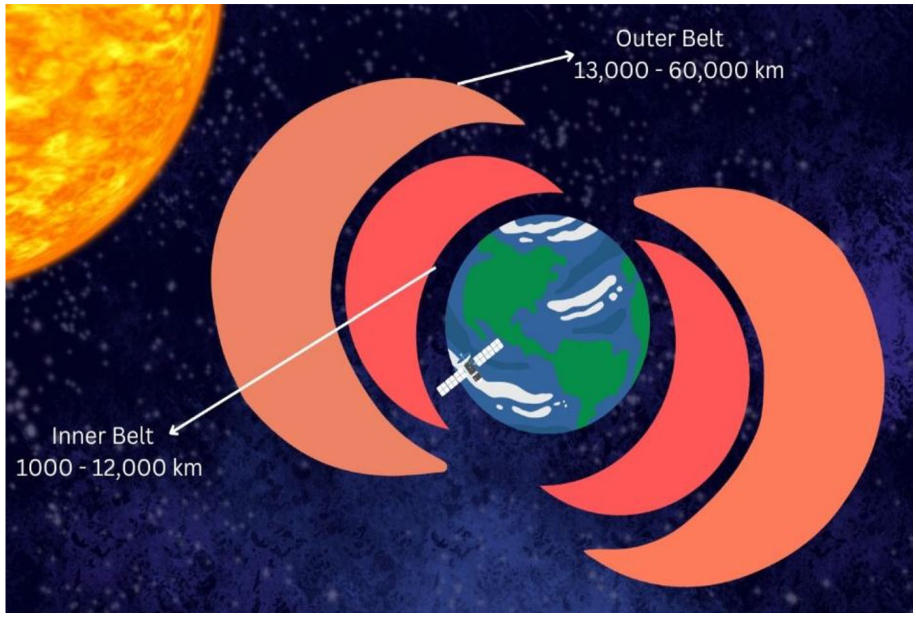


Fig. 2 Radiation belts around Earth

Referring to Fig. 3, SPE are streams of particles generated on the solar surface right through a coronal mass ejection. The release in terms of energy during these occurrences triggers a magnetohydrodynamic resonance to emerge then spread out of the sun across the interstellar boundary, resulting in particle acceleration. The flow amount of energy from radiation released is significantly influenced by solar activity, resulting in lower discharges throughout low solar activity times and larger impulses, more frequently occurring during high solar activity periods. Solar particles are classified into two types: solar flares and coronal mass ejections (CMEs). The former appears to be likely to develop into an electron-rich environment, whereas the one that follows is likely to be proton-intensive. It is to note that the extreme high-energy hadrons emitted by CMEs comprising protons (96.4%), alpha (3.5%), and heavy ions (0.1%) with energies as high as 1 GeV. Protons from Coronal Mass Ejections (CMEs) are the primary cause of Total Ionising Dose (TID) and Displacement Damage (DD) effects. In addition, these particles, which include heavy ions, protons, and alpha particles, can produce transient or permanent Single Event Effects (SEEs).

1.2 Types of existing radiation

During the last 50 years of space exploration, radiation-hard electronics, which form the backbone of the space program, have enabled advancements in satellite launches and space station construction. It is generally known

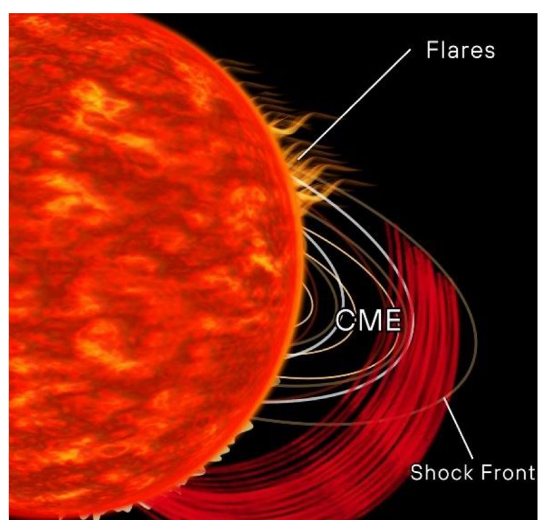


Fig. 3 The sun's coronal mass ejection

that very energetic particles in the radiation environment destroy microelectronic components, causing faults in the electronics [14]. Ionizing and particle radiation are the two major types of radiation that could potentially be present in hazardous circumstances where laser diodes are used. Ionizing radiation includes high-energy photons such as gamma rays and X-rays, while particle radiation includes energetic neutrons [23, 30, 31]. Through complete ionization and displacement, these energetic particles caused damage to materials employed in electronic devices [1, 32–36], which would have an impact on the dependability of the devices.

The space environment in which spacecraft are located while in orbit is extremely complicated, including charged particles, micrometeoroids, atomic oxygen, and space debris [35]. The electronic systems of spacecraft are subject to various comprehensive factors, including displacement damage effects, ionization effects, and charge-discharge effects caused by high-energy charged particles such as protons, electrons, and heavy ions [27]. These effects can have a negative impact on the spacecraft's performance and on-orbit lifetime.

Strong radiation is discernible in space, originating mostly from galactic cosmic rays and solar cosmic, as well as other radiation belts. High-energy photons and particle radiation come from a variety of natural sources in the solar system as well as artificial ones found in everyday places like nuclear power plants and particle accelerators [37, 38]. The space radiation environment comprises three different types of radiation particles. These include solar particle events (SPE), galactic cosmic rays (GCR), and the van Allen belt [26], where protons are the most prevalent species [36, 39]. These positively charged radiation particles are especially problematic because they can initiate nuclear reactions that produce high-energy recoil nuclei, capable of causing significant degradation. This is particularly relevant for near-Earth space missions where high proton fluxes are encountered [26].

Since it depends on the type of radiation, its energy, and the length of exposure, there can be different impacts on satellites and their components. SPE, for example, can induce ionization damage to materials, resulting in changes in the electrical characteristics of materials and devices. GCR can induce ionization damage as well as annealing. One high-energy particle can have a substantial impact on a device's state through single-event effects, particularly those brought on by the Van Allen radiation belts [16, 40].

1.3 Radiation effects on electronic devices for satellite applications

Radiation effects on semiconductor devices are among the areas that are actively studied by researchers worldwide [8, 41, 42]. To suit the needs of industry, researchers have been studying the damaging effects of radiation on semiconductors since the early twentieth century. These industries were fueled by a diverse variety of electronic device applications that necessitate knowledge of radiation effects such as displacement damage and ionization [1]. Nowadays, innovations in the semiconductor sector, such as diodes, are primarily motivated by space incorporation [20, 21] along with radiation hardness [4, 11]. The prolonged exposure of these appliances to harsh conditions could result in irreparable radiation damage [30, 31]. To improve the performance of these devices, essential knowledge of these devices, such as the radiation damage process and rate of deterioration, must be acquired.

Figure 4 provides a comprehensive overview of how various types of radiation impact electronic components, and categorizes these effects into several key areas, such as the direct impact on electronics, types of radiation, and interactions with components. This highlights the potential damage to components, influence on performance, and charge disruptions that can occur. The importance of testing and mitigation strategies, such as experimental tests and design aspects, to manage these effects, needs to be taken into consideration. Additionally, this addresses the interaction mechanisms like photon interactions and Compton scattering, emphasizing the need for robust solutions to protect satellite electronics from radiation-induced challenges.

Surface damage, ionization damage, and also displacement damage are considered the three main types of damage that space radiation causes when it impacts semiconductor materials. The ionization damage is generally caused by γ radiation, and the ionizing radiation makes superfluous electron-hole pairs leading to the conduction increase [43, 44]. Surface damage is generated by the ionization of the surface oxidation layer that results from ionizing radiation, which generates a positively charged environment affecting the surface state.

Displacement Damage Dose (DDD) and Non-Ionizing Energy Loss (NIEL) are critical metrics used to assess radiation damage in semiconductor devices, particularly in the context of space applications. DDD quantifies the extent of damage caused by radiation-induced atomic displacements within a material [9]. It is a function of the incident radiation fluence and the material's susceptibility to damage, as characterized by the NIEL parameter. NIEL represents the energy

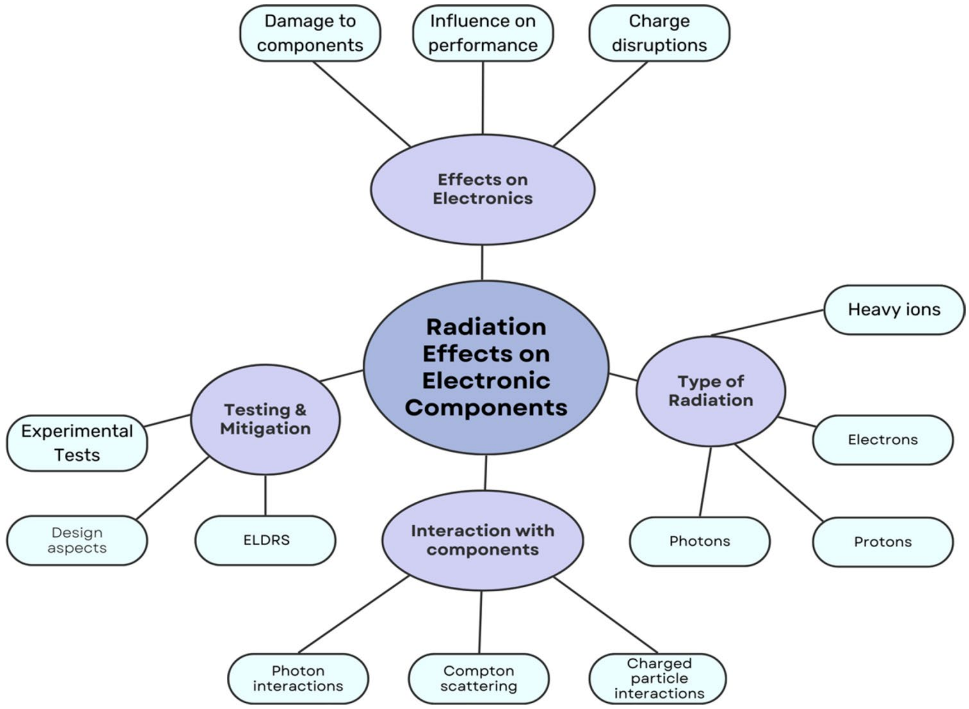


Fig. 4 Radiation Effects on Electronic Components

lost by radiation as it traverses a material, which does not result in ionization but instead causes atomic displacements, leading to defects in the crystal lattice.

The accuracy of DDD calculations is heavily dependent on the precision of the NIEL parameter. NIEL provides a theoretical estimate of the number of defects that may be produced per unit path length of an incident particle, making it a fundamental component in predicting the degradation of electronic devices under radiation exposure. However, deviations from the NIEL scaling approach have been observed, particularly in materials like silicon and GaAs. These deviations can limit the accuracy of degradation predictions, as the experimentally measured damage levels may differ significantly from those predicted by NIEL-based models [45].

Such discrepancies highlight the need for improved understanding and modeling of radiation interactions with materials. The observed deviations suggest that the NIEL parameter may not fully capture the complexity of damage mechanisms, especially for different types of radiation and materials. This has implications for the reliability of radiation risk assessments and underscores the importance of refining NIEL calculations to enhance the predictive accuracy of DDD models. Addressing these challenges is crucial for developing more robust radiation-hardened components for space applications.

A radiation environment for spacecraft components is mission-dependent. For example, if the spacecraft is to function in Low Earth Orbit (LEO), the engineers must account for trapped particles, solar particles, and GCR. If it is an interstellar trip, they may choose not to consider trapped particles. On the other hand, possible consequences are based on the radiation environment, which is determined by orbit profile, component technologies, and design parameters like voltage threshold, frequency, duty cycle, temperature, redundancy philosophy, and so on [28]. The impact of radiation-induced degradation on satellite applications is significant. It can lead to the failure of critical systems, resulting in the loss of valuable data and potentially catastrophic mission failures [46, 47].

Semiconductor devices of satellites in LEO encounter mostly proton and electron particles trapped in the Van Allen belts, which travel across the region numerous times every day [33–35]. Likewise, the research in [43] has studied the displacement damage mechanism that has been observed after proton irradiation subjected to VCSEL lasers within 3 to 10 MeV. The following table presents a comprehensive review of other past studies that are significant in investigating radiation-induced degradation on main electronic devices used in satellite communications systems. In the case of the Schottky Barrier Diode (SBD), its reverse leakage current is the most sensitive parameter to proton irradiation, even at low energy [48].

The impact of ionizing radiation on light-emitting diodes (LEDs) becomes particularly noteworthy because LEDs are extensively used as lighting sources in space missions [2, 6, 10, 14, 36]. LEDs are highly flexible, robust, compact, and energy-efficient, rendering them well-suited for use in challenging scenarios with limited power resources. For instance, in space, LEDs provide artificial daylight for astronauts and plants while also providing light sources for space cameras.

Gallium Nitride (GaN)-based LEDs are particularly well-suited for illumination in imaging and mapping applications within environments that are heavily exposed to radiation. Their use extends to nuclear reactors and space, where they must withstand high levels of radiation. Research has identified the primary cause of leakage current, which is often associated with the degradation of optical power in LEDs. Minimizing leakage current is a key goal in the LED industry, as it directly impacts the performance and longevity of these devices.

Waveguide-integrated Germanium-on-Silicon (Ge-on-Si) photodiodes are essential components in silicon photonics, particularly in high-radiation environments such as those encountered in space and high-energy physics experiments [44]. These photodiodes, when subjected to high fluence neutron and proton irradiation, demonstrate minimal losses in responsivity and moderate increases in dark current and capacitance, indicating their robustness in extreme conditions. The ability of Ge-on-Si photodiodes to maintain performance under such conditions is crucial for their application in optical communication systems used in space missions. Furthermore, silicon photonic devices, such as micro-ring resonators (MRRs) and Mach-Zehnder interferometers (MZIs), are crucial in high-radiation environments like space due to their potential in optical communication and sensing applications. These devices, when exposed to high-energy neutron and gamma-ray irradiation, exhibit changes in their optical properties, such as wavelength shifts, which are critical for maintaining their performance in space missions. The presence of a SiO_2 cladding layer significantly enhances the radiation tolerance of these devices, reducing the impact of radiation-induced refractive index changes [50].

In the context of space applications, the resilience of GaAs-based photodiodes to radiation damage is comparable to the durability required for other photonic devices [49], such as silicon photonic passive devices, which are used for optical interconnects and sensing. The study of radiation effects on main optoelectronics devices such as laser diodes. photodiodes and amplifiers [51–57] provide valuable insights into the mechanisms of radiation-induced degradation, which are also relevant for understanding the behavior of other photonic devices under similar conditions. This study highlights the critical role of material and structural design in developing radiation-resistant photodiodes suitable for space missions (Table 1).

1.3.1 Radiation interactions with matter

The kinetic energy of the particles that the nucleus emits is known as radiation. Particle radiation, such as alpha (α), beta (β), and neutron (n), whereas electromagnetic radiation, which consists of electromagnetic waves of energy such as gamma rays, are two types of radiation. Particle radiation contains electrically charged particles that can trigger ionization.

For electronics used in radiation environments, increasing radiation hardness and reliability are essential. Efforts have been undertaken in the past to get a better understanding of radiation degradation in semiconductor materials. Many articles on radiation effects offered experimental, theoretical, and software modeling data. Ionization and displacement damage are two types of radiation impacts [1, 2]. Ionization happens due to electron, proton, and gamma-ray environments, while displacement damage is usually produced by fast neutron radiation. Table 2 lists the typical Linear Energy Transfer (LET) values of various radiations.

In outer space, the primary form of radiation consists of high-energy protons. Despite this, due to their single electric charge, most of these protons lack the high LET necessary to directly cause single-event upsets (SEUs) through ionization. However, SEUs induced by protons are typically the result of secondary particles produced from proton-nuclei collisions within or near sensitive areas of semiconductor devices. These secondary particles can be either nuclei recoils from elastic collisions or nuclear fragments from inelastic collisions. It is these heavy-ion secondary products that often serve as the mechanism for proton-induced SEUs. Consequently, accurately simulating the effects of proton-induced radiation involves not only nuclear physics modeling but also calculations related to particle transport and energy deposition.

In turn, TID damage produces electron-hole pairs within the semiconductor materials and confines holes near the interface region, reducing hole migration; the expelled particles' DD impacts change the lattice's atom locations. SEE effects formed electron-hole (e-h) pairs along its knocking path in the device, causing the current behavior to vary [13, 32].

There are two primary ways that the electromagnetic radiation particle and the electronic component can interact, as shown in Fig. 5. According to [28], nuclear contact must be realized by the radiation source directly interacting with the atomic nucleus. Only protons among the radiation particles are capable of nuclear interaction. The more energy that is transferred during nuclear interaction, the simpler it is to displace, split up into little fragments, or detonate the atom. The effects of nuclear contacts are more severe than those of electronic interactions, yet the likelihood of nuclear reactions occurring is lower than that of electronic reactions. In electronic interaction, on the other hand, an incoming

Table 1 Comprehensive review of the impact of various radiation on electronic devices for satellite applications

References	Type of radiation	Energy	Dose	Device
[8]	Neutron	20 MeV	up to 10^{16} n/cm^2	Laser, photodiode
[9]	Electron, Proton, Neutron	up to 1.5 MeV (electron), up to 170 MeV (proton)	up to 2.5×10^{12} ecm^{-2}, up to 6.3×10^{11} pcm^{-2}, up to 10^{13} pcm^{-2}	Photodiode
[11]	Gamma, proton,	30 MeV (Proton)	up to 50 krad (Gamma), up to 1×10^{12} pcm^{-2}	Photodiode
[21]	Electron	3 MeV	up to 200 kGy	Laser diode, photodiode
[30]	Neutron	20 MeV	3×10^{16} pcm^{-2}	Mach-zender modulator
[31]	Neutron, X-ray	2015	1.2×10^{15} ncm^{-2}, 1.3 MGy	Modulator
[33]	Proton	105 MeV	2.55 X 10^{11} pcm^{-2}	Photodiode
[34]	Proton	50 MeV	6.3×10^{11} pcm^{-2}	Laser, photodiode
[35]	Proton	50 MeV	1×10^{12}—3×10^{13} pcm^{-2}	Laser diode
[43]	Proton, Gamma	–	3×10^{13} pcm^{-2}; 10 MGy	Laser, photodiode
[44]	Neutron, Proton	23 MeV, 24 GeV	up to 3×10^{16} ncm^{-2}, up to 4.1×10^{16} pcm^{-2}	Photodiode
[46]	Gamma	–	up to 10 krad	Laser, Modulator, EDFA, Photodiode
[47]	Gamma	–	1 MGy	Laser, Modulator, Amplifier, Coupler, Detector (Degradation performance of each device taken from other literatures for simulation)
[49]	Proton	49.7 MeV	–	Photodiode
[50]	Neutron	–	1×10^{12} ncm^{-2}	Mach-Zender Interferometer, Coupler
[51]	Proton	3 MeV, 10 MeV	6.7×10^{12}—1.6×10^{14} pcm^{-2}	Laser
[52]	Electron	1 MeV	3×10^{17} ecm^{-2}	Laser
[53]	Proton, Neutron	24 GeV, 20 MeV	up to 1.1×10^{16} pcm^{-2}, up to 1.1×10^{16} ncm^{-2}	Photodiode
[54]	Electron	3 MeV	up to 250 kGy	Low Noise Amplifier
[55]	Proton	3 MeV	3×10^{12} pcm^{-2}	Laser Diode
[56]	Proton	10—60 MeV	up to 2.5×10^{12} pcm^{-2}	Photodiode
[57]	Proton	63 MeV	2×10^{12} pcm^{-2}	Photodiode

Table 2 Typical LET values of various radiation

Type of radiation	LET (keV/μm)
Gamma radiation (Cobalt-60)	0.3
250 kVp X-ray	2
10 MeV protons	4.7
150 MeV protons	0.5
Recoil protons from fission neutrons	45
14 MeV neutrons	12
2.5 MeV alpha particles	166
2 GeV Fe Nuclei	1000

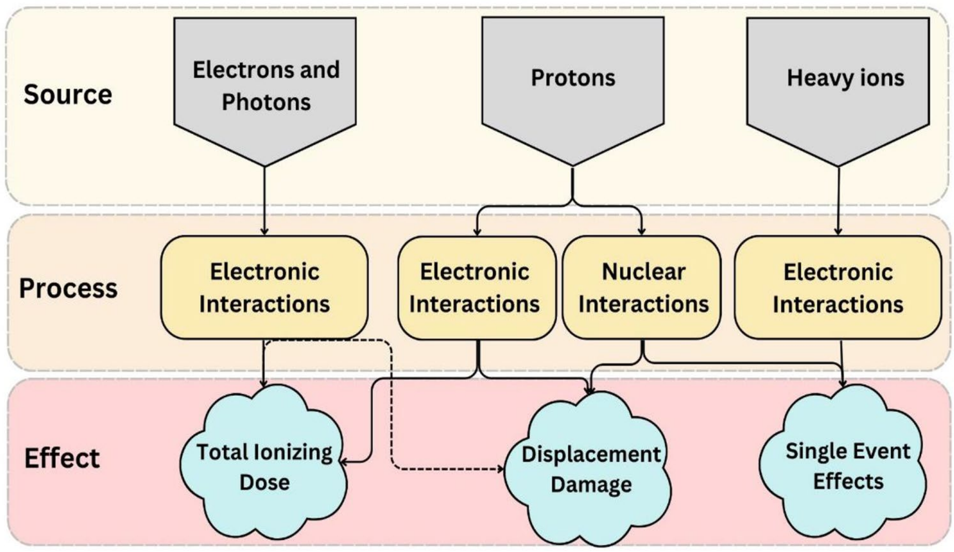


Fig. 5 Radiation effects on optoelectronic devices

particle comes into contact with the electrons that are orbiting the atom. This interaction transfers the energy of radiation particles to the atom. Higher energy atoms encounter ionization of excited electrons.

In the case of semiconductor materials exposed to space radiation; displacement damage dose, and total ionizing dose are the two principal radiation impacts. The displacement damage dosage induces flaws in semiconductor materials, reducing the lifetime of minority charge carriers, whereas the total ionizing dose produces extra electron-hole pairs and causes surface damage. The two damaging effects interact to create a loss in quantum efficiency, surface recombination, velocity increase, and generation current rise in the PIN photodetector, resulting in a decrease in photocurrent and an increase in dark current [9, 11, 38, 46, 50, 53–57]. In addition, the findings presented in [59] have demonstrated displacement damage is the major effect of proton irradiation on VCSELs. Also, DD has been found to be the primary cause of degradation in PIN photodiodes based on the findings in [44, 49]. One of the key aspects of displacement damage is the creation of defects in the semiconductor lattice, specifically through the formation of Frenkel pairs. The formation of Frenkel pairs is a significant concern because these defects can become electrically active, altering the electrical properties of the semiconductor material. They can increase the recombination rate of charge carriers, reduce carrier mobility, and ultimately degrade the performance of optoelectronic devices [9, 26, 51, 60].

Essentially, radiation-induced bandgap levels can initiate several processes such as type conversion, generation, recombination, trapping, compensation, tunneling, scattering, and field improvement of carrier generation effectiveness. In theory, any combination of these processes, or all of them, can occur at the same level. The role that a specific level plays is determined by parameters including carrier concentration, temperature, and the device region in which it exists (for example, in a depletion region).

Solar radiation, particularly gamma radiation, can indeed degrade semiconductor materials over time, significantly impacting their electronic properties and leading to reduced efficiency and performance. Prolonged exposure to this radiation can alter the bandgap of semiconductors, affecting their electrical conductivity and optical properties. This degradation is compounded by high-energy particles from solar radiation, such as electrons and protons, which can introduce defects in the crystal lattice of semiconductor materials. These defects can act as recombination centers or trap states, impairing charge carrier mobility and lifetime, which are critical for the performance of optoelectronic devices. These ionization effects result from the interaction of radiation with the electronic structure of the material, leading to the generation of electron-hole pairs.

As emphasized in Section 2.0.2, it is important to note that protons, as a significant component of solar radiation, contribute to both Total Ionizing Dose (TID) and Displacement Damage (DD) effects. TID effects arise from the ionization caused by these high-energy particles, leading to the generation of electron-hole pairs and surface damage, which can further degrade the performance of semiconductor devices. On the other hand, DD effects result from the displacement of atoms in the crystal lattice, creating defects that can trap charge carriers and reduce their mobility. The degradation of dark current in photodiodes is primarily dominated by Total Ionizing Dose (TID) effects, which are responsible for increasing the surface recombination current. TID effects damage the surface of the photodiode, leading to the development of interface states in the semiconductor material. These interface states increase the rate of surface recombination, thereby elevating the dark current. This phenomenon is particularly pronounced in InGaAs photodiodes, where the intrinsic epilayer is susceptible to defect formation, resulting in deep acceptor levels in the material bandgap [5].

Moreover, solar particles can also induce Single Event Effects (SEE), where a single high-energy particle can cause significant disruptions in the operation of semiconductor devices. These combined effects of TID, DD, and SEE from solar radiation highlight the critical need for understanding and mitigating the impacts of radiation on optoelectronic devices, ensuring their reliability and performance in the harsh conditions of space. These also give rise to thermal effects, leading to an increase in the operating temperature of semiconductor devices. Elevated temperatures can accelerate the diffusion of dopants and other impurities, which alters the electrical characteristics of the semiconductor. This alteration can lead to increased leakage currents and reduced breakdown voltage, further compromising the performance and longevity of these devices in space applications. Understanding these interactions is vital for developing robust optical communication systems that can withstand the challenges posed by the space environment [61, 62].

The displacement damage effect and the ionizing effect have a significant impact on laser diodes exposed to space radiation. While the ionizing effect can be somewhat overlooked due to the effective conduction of semiconductors when forward-biased, it nonetheless introduces interface traps that lead to material deterioration. This aligns with findings that displacement damage is the primary impact on laser diodes, as supported by various studies [14, 51, 52].

High-energy particles such as protons, electrons, neutrons, and heavy ions are prevalent in outer space and can cause irreparable damage to the materials of optoelectronic devices. This damage can lead to a significant reduction in performance or even complete malfunction [30, 36, 54, 61, 63]. For instance, the Razak Sat 1 satellite, launched into Near Equatorial Low Earth Orbit in 2010, experienced communication failures believed to be caused by radiation damage to its high-resolution camera, which was intended for forestry and resource management [24]. Furthermore, many communication systems, including CubeSats, utilize commercial off-the-shelf (COTS) optoelectronic components, which may be particularly vulnerable to these radiation effects [51, 53, 61]. Understanding these interactions is crucial for developing robust optical communication systems capable of withstanding the harsh conditions of space.

1.4 Recent work on radiation-induced effects in Optical Transmitters

1.4.1 Threshold current

The threshold current of an optical transmitter is one of the major characteristics to evaluate any degree of degradation since it determines the minimum value of current required to turn on the transmitter. This characteristic is mainly dependent on the type of semiconductor material and the design of the optical transmitter [30, 54]. In addition, the threshold current damage factor also can be used to characterize the degradation rate of the threshold current [52, 55, 64]. The relationship between both can be derived as follows:

$$\frac{I_{th}}{I_{th(0)}} = 1 + K_I\,\Phi \tag{1}$$

where $I_{th(0)}$ is the pre-radiation threshold current, I_{th} is the threshold current measured after irradiation, K_I is the damage factor of the measured threshold current and Φ is the radiation fluence (#/cm^2).

In [21], they investigated the effects of 3 MeV electron irradiation on the performance of transceivers of inter-satellite optical wireless communication (IsOWC) system. The findings demonstrate that even after the first radiation dose of 50 kGy, the threshold current of GaAs distributed feedback (DFB) laser diode has shown the same degradation rate as the last dose of electron irradiation (up to 200 kGy). The high energy from that irradiation produces non-radiative recombination centers which results in an increase of the threshold current. This is due to the decreased minority carrier lifetime as the electron dose hits 50 kGy. The findings in [26] have shown that GaAs-based lasers exhibit a consistent increase in threshold current after exposure to various types of radiation, including electron and proton radiation. This increase is primarily due to the formation of non-radiative recombination centers, which reduce the optical gain of the lasers. From [21], 3 MeV electron irradiation also has been observed to cause significant degradation in GaAs distributed feedback (DFB) laser diodes, with the threshold current increasing consistently with radiation dose. However, the slope efficiency remains unchanged after irradiation [55, 65]. Similarly, as stated in [65], proton radiation also leads to the formation of non-radiative recombination centers in GaAs-based lasers. This results in increased recombination rates, which cause a rise in threshold current and consequently lower the optical gain of the lasers. These effects are characteristic of semiconductor materials like GaAs, irrespective of whether the radiation source is electrons or protons, as both types of radiation induce similar degradation in laser performance [26].

In [59], they also noted that the study of threshold current degradation is crucial, especially in vertical-cavity surface-emitting lasers (VCSELs). In the study, it is found that displacement damage is the contributing factor to the increased threshold current of VCSELs. It is believed that spontaneous emission and stimulated radiation are impacted by the competitive behavior between radiative recombination and non-radiative recombination after 3 MeV electron irradiation. Interestingly, the increase in normalized threshold current by 3 MeV exceeds the degradation by 10 MeV. This occurrence is owing to lower energy radiation having a larger Non-ionising Energy Loss (NIEL) value. In contrast, a higher degradation effect is observed on VCSELs that are irradiated by 10 MeV compared to a lower radiation energy of 3 MeV when the fluence is converted to Displacement Damage Dose (DDD), which proves it is necessary to use DDD equivalent displacement damage within a certain range [52].

According to [51], commercial VCSELs exposed to 3 MeV proton generated underlying defects due to the existence of aforementioned non-radiative centers within the active region of the lasers which also contributed to a significant increase of internal optical losses and threshold current. This can be observed in Fig. 6, in which the result suggested that, after 3 MeV proton irradiation with the highest fluence of 10^{16} p/cm^2, the threshold current decreases with 19.32 mA (16.85%), 21.68 mA (19.08%) and 25.37 mA (19.58%) for temperatures of 10°C, 20°C, and 30°C, respectively. A similar trend of threshold current degradation can be seen when proton irradiated two models of VCSELs (Lumex and Honeywell) at high energy of 50 MeV from 1 x 10^{12} pcm^{-2} to 3 x 10^{13} pcm^{-2} in fluence [35]. The radiation-induced defects due to bulk recombination are the dominant mechanism of the shift of the threshold current. These defects can trap carriers and prevent them from recombining, which is necessary to produce light [60]. In [52], the study believes that low energy (1 MeV) electron radiation may induce displacement damage in VCSELs which becomes the pivotal factor

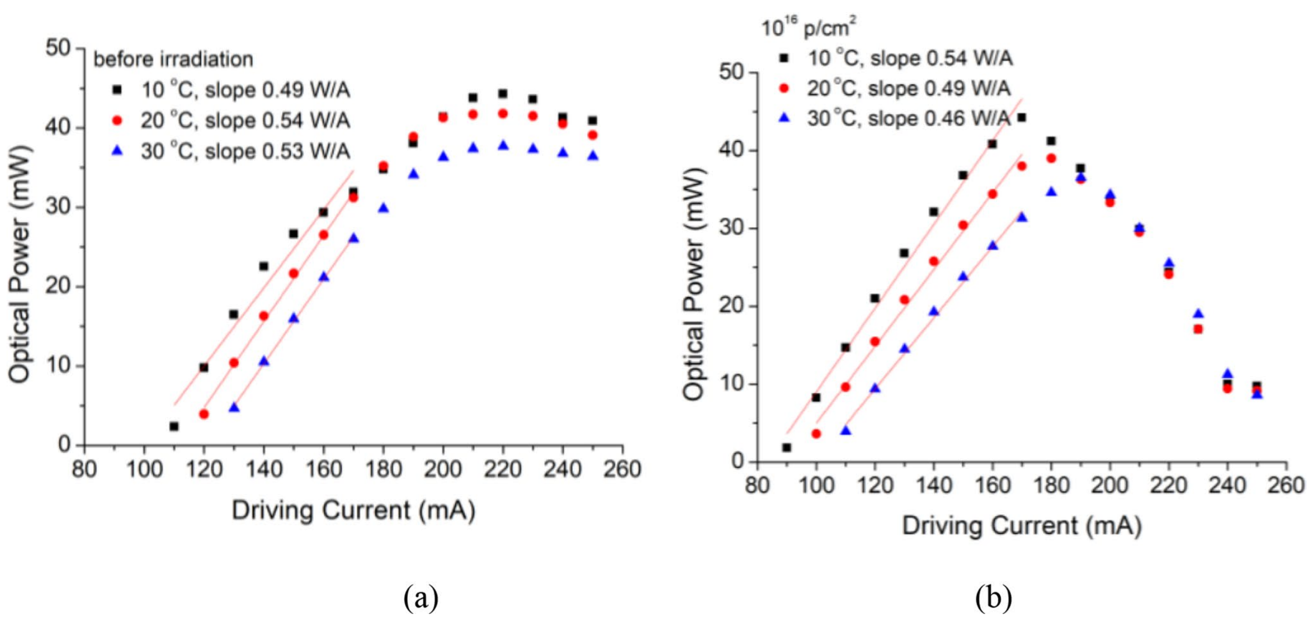


Fig. 6 The emitted optical power vs. the driving current for three case temperatures (**a**) before irradiation and (**b**) after 10^{16} p/cm.^{2} irradiation [66]

to the cause of threshold current degradation. In the case of low-energy proton radiation, the optical power vs. driving current graphs in Fig. 6a and b illustrate the degradation of lasers' performance after irradiation, showing a decrease in emitted optical power at various driving currents compared to pre-irradiation conditions. Specifically, after exposure to a proton fluence of 10^{16} p/cm^2, the optical power values increased only slightly, indicating a degradation in the device's efficiency [66]. Thus, the impact of radiation on threshold current is further influenced by temperature. As temperature varies, the behavior of these non-radiative recombination centers can change, affecting the overall degradation rate. Higher temperatures may exacerbate the effects of radiation-induced defects, leading to a more pronounced increase in threshold current. This temperature-dependent nature of degradation highlights the need for careful thermal management in space applications where temperature fluctuations are common [26].

The research in [8] found that VCSELs are among the most radiation-hard laser structures due to having smaller active volumes. The findings show that other single-mode laser structures (Fabry-Perot) have stopped lasing when 20 MeV neutron reaches the highest fluence of the test (2 x 10^{15} ncm^{-2}), while VCSELs and Quantum Dot lasers still survive. This suggests that there is a critical degradation in the threshold current of neutron-irradiated VCSELs. A similar result on VCSEL was demonstrated in [55] which the normalized threshold current shifted positively to the increasing fluence of 2 MeV proton radiation and the same trend observed in [34] under 50 MeV proton radiation.

It is found most of the research shows a positive shift in threshold current after irradiation. This effect can cause a transmitter to have higher resistance since it requires a higher current to reach its original operating point. Besides, the material properties of the transceiver can be affected too, such as the bandgap of the semiconductor material used. The radiation-induced effects are responsible for the formation of traps, which can limit the efficiency of the device and degrade the overall performance of a transceiver system in a satellite. Table 3 provides the summary of threshold current degradation under different radiation.

1.4.2 Slope efficiency

The ratio of the output power of an optical transmitter to its input current is known as its slope efficiency. It measures the amount of light output produced by the transmitter per unit increase in drive current within a linear region above threshold current (I_{th}). This characteristic can be influenced by a variety of factors, including the type of semiconductor material employed, the design of the transmitter, and the amount of radiation exposure. In [8], the study presented the cause of the observed drop in laser slope efficiency after 20 MeV neutron irradiation. This study believes that the difference between carrier lifetime above threshold and carrier lifetime at threshold can give more insight into further slope efficiency degradation studies [35]. A decrease in internal quantum efficiency indicates a reduction in slope efficiency. After VCSELs are irradiated with 1 MeV electron, the results in [52] find that the decreased slope efficiency is due to the radiation-induced defects that impact the optical absorption [34]. This means more affected carriers from non-radiative recombination centers reduce the number of photons generated by lasers per unit of time.

It also indicates a significant change in the slope efficiency of VCSELs after 50 MeV proton at a fluence of 1 x 10^{12} pcm^{-2} is irradiated [42]. The study also demonstrates a different trend of degradation for an irradiated strained quantum-well laser. As the device reaches the threshold current, its slope efficiency becomes relatively higher, then the value declines soon after the forward current applied is higher than the threshold current. In [36], they suggest that the differences in mode structure within lasers cause the substructure change in the slope efficiency.

A lowered slope efficiency of a transmitter indicates a decrease in the conversion of input power to the desired output power which can deteriorate the efficiency of the device. In the long term, this may cause an optical transceiver to be

Table 3 List of past works on threshold current degradation of transmitters due to Proton, Electron, and Neutron radiation

References	Type of radiation	Finding
[8]	Neutron	The threshold current shifted to higher value after irradiation
[21]	Electron	The threshold current increased with radiation dose
[35]	Proton	The threshold current increased linearly with radiation fluence, provided the relative increase is less than about 40%
[52]	Electron	The degradation of threshold current was observed in all two models of VCSELs
[55]	Proton	The threshold currents for all two models of laser diodes increased
[59]	Proton	The threshold current exhibited degradation

Table 4 List of past works on slope efficiency degradation of transmitters due to Proton, Electron, and Neutron radiation

References	Type of radiation	Finding
[8]	Neutron	Slope efficiency of FP lasers decreased with increasing fluence
[35]	Proton	A significant change in slope efficiency occurred even after the first radiation level
[52]	Electron	The degradation of threshold current was observed in all two models of VCSELs

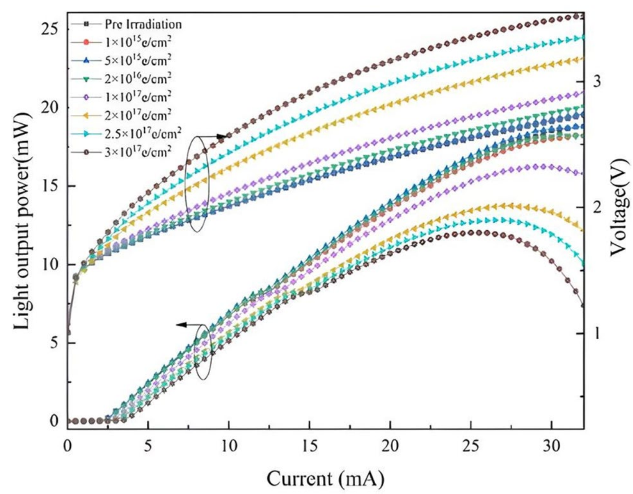


Fig. 7 L–I–V characteristics of 850 nm VCSEL after irradiation with a range of fluences and at a constant heat sink temperature of 30 °C [52]

less sensitive to the incoming signal since it needs more power for proper conversion which risks the performance of devices used in space missions. Table 4 provides a summary of slope efficiency degradation under different radiations.

1.4.3 Output power

Output power is a measuring characteristic that quantifies how much light a transmitter can generate. It is dictated by the properties of the semiconductor material, the structural design, and the amount of current passing through it. The findings in [35] show that the optical power characteristics of a typical VSCEL experience a negative shift after 50 MeV proton irradiation (up to 15 mA of applied forward current). The study believes the specific geometry of a transmitter may have a pronounced impact on the output power characteristics and its measurement over a wide range of currents can provide avenues into damage mechanisms of the device. 80% degradation in optical power of a VCSEL is seen in [52] due to 1 MeV electron (up to a fluence of 2.5 x 10^{17} ecm^{-2}) which demonstrates that the output power degradation (up to 30 mA of applied forward current) is worse than the degradation of its threshold current. The study states the temperature increase in the resonant cavity of the junction interrupts the device stability which is caused by a large number of radiation-induced defects and the appearance of defective energy levels in the quantum wells, as presented in Fig. 7.

Output power is the key parameter to evaluate the degradation effect of most LEDs, as emphasized in [10]. Significant degradation is observed on 50 MeV proton irradiated LEDs as its output power decreased by a factor of two from 2 x 10^{10} pcm^{-2} to 3 x 10^{10} pcm^{-2}. Both amphoterically doped and double-heterojunction LEDs experience a decrease in light output which the degradation relates to the simple power law based on lifetime damage. In the case of LEDs, another important practical parameter is the angular dependence of the light output since this device comes in different package types. Certain LEDs consist of internal lenses to reduce angular light output. Thus, radiation-induced degradation characterization of LEDs is more challenging than other electronic devices [10, 26].

The study presented in [26] highlights that the output power of LEDs decreases after irradiation, with the extent of this decrease being contingent upon the material composition of the LED. The findings indicate that InGaAsP LEDs are among the most sensitive to displacement damage dose (DDD), showing a substantial reduction in output power post-irradiation. Specifically, these LEDs retain less than 20% of their original output power after exposure to a DDD of 8 MeV/g. In contrast, AlGaN devices demonstrate greater resilience, with only a 20% power loss after nearly a DDD of 10 MeV/g. This material-dependent response underscores the importance of selecting appropriate materials for LEDs used in radiation-rich environments, such as space.

The research in [26] also notes that the degradation in optical power does not appear to be significantly influenced by bias conditions, except potentially in InGaAlP materials, where a bias effect might be observed. Additionally, discrepancies in degradation levels when comparing different types of irradiations, such as varying proton energies, may arise due to inaccuracies in the Non-Ionizing Energy Loss (NIEL) evaluation. These findings emphasize the need for precise NIEL assessments to predict and mitigate radiation effects on optoelectronic devices accurately.

In [67], they observed the output power performance of the FP laser under high doses of gamma radiation as seen in Fig. 8 and they found that the insubstantial degradation is correlated with the minimal degradation of the threshold current. In [64], the study looked into how gamma radiation affects the optical characteristics of DFB laser diodes and optical modulators. The study finds a slight degradation of the output power of DFB lasers at 30 krad. These findings demonstrate the relative insensitivity of DFB lasers to ionizing radiation, which agrees with the results in [3, 8] and [21].

A similar degradation was seen in [68] in which the light intensities of visible lasers degraded slightly at a cumulative gamma radiation dose of 10 kGy-Si. The irradiation effect of modulators is relatively the same as the lasers as only a 0.06% reduction of output signal is observed. In [64], they introduced the experimental degradation results into a simulative measurement to derive the performance of the communication terminal. The normalized output power is measured to degrade to 20% of its operating point at the same dose of 30 krad. This rapid decrease trend is because of the increase of TID on the lasers. This relates to the decrease of quantum efficiency which implies the effect of the formation of non-radiative combination centers that disrupt the radiative recombination sites and impact the lifetime of minority carriers [21]. Quantum efficiency refers to the probability that a photon will be emitted when an electron and hole recombine [32]. Under 3 MeV electrons, the output power of DFB lasers degrades significantly by more than 40% with the increasing dose (up to 200 kGy). Because of the high carrier density and high resistance of the DBR mirrors, which generate excessive heating, the optical power plot exhibits a rollover after the peak power [69]. The same pattern observed in [70] under a total dose of 30 krad of gamma radiation. Table 5 provides a summary of the output power degradation of optical transmitters under different radiation.

1.5 Radiation-induced effects on optical receivers

1.5.1 Dark current

When light is not present, the unwanted electrical current that still flows through a receiver is called dark current. It acts essentially as a leakage current in the reverse bias. This characteristic may arise from various internal mechanisms even in the absence of external light stimulation. Dark current is a vital parameter to ensure optimal performance and sensitivity of the device. An increase in dark current is related to the number of defects that may increase the noise level of the signal received [46, 70].

In the case of radiation-induced degradation, the growth of dark current is proportional to the fluence and energy of incident radiation. Thus, the ratio of a dark current increase to the incident fluence which is defined as dark current damage factor, may vary depending on the type of radiation applied. Three models of InGaAs photodiodes were irradiated with neutron (spectrum), proton (60–170 MeV), electron (0.5 – 1.5 MeV), and gamma (1.25 MeV) in [9]. The findings show that all photodiodes share the same trend of increased dark current with fluence. The study concludes that the dark

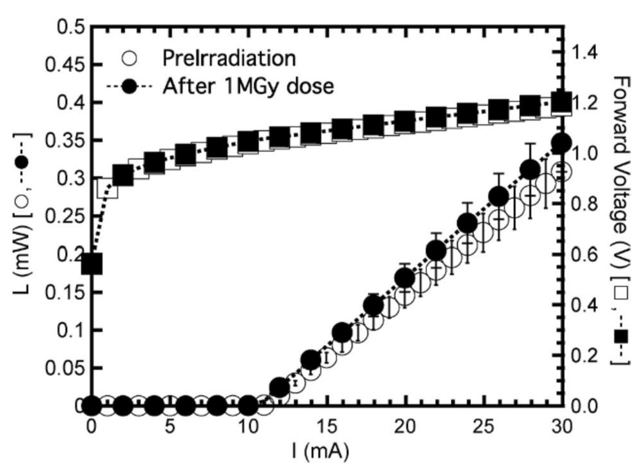


Fig. 8 L-I curve of FP laser diode pre and post-irradiation [67]

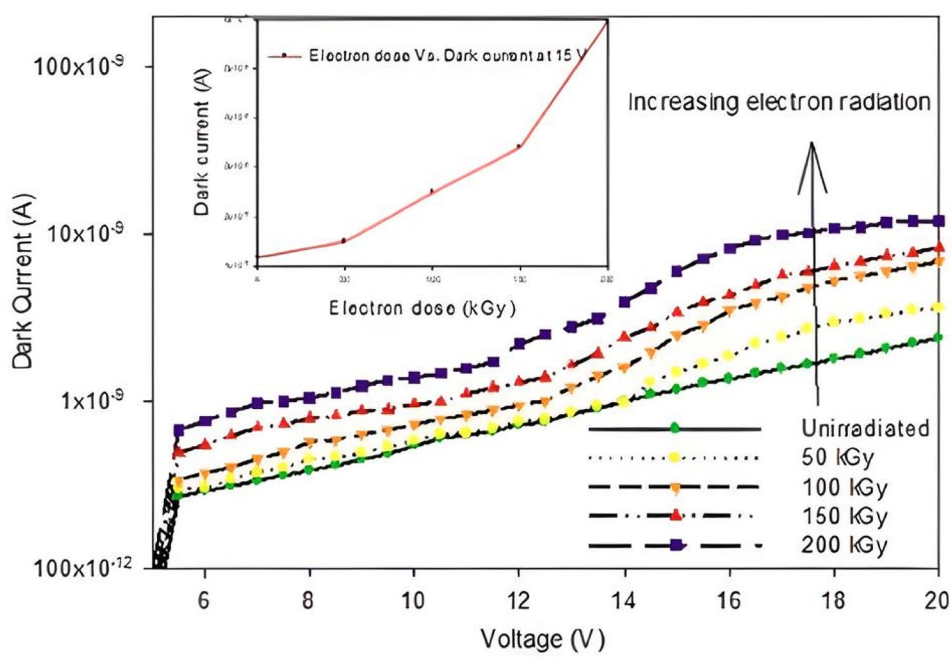
Table 5 List of past works on output power degradation of transmitters due to Proton, Electron, Gamma radiation

References	Type of radiation	Finding
[10]	Proton	Output power of LEDs is more severely degraded after higher dose of irradiation
[21]	Electron	The output power of DFB lasers decreased by more than 40% from the original value
[35]	Proton	Light output power degraded for both Mitsubishi and Lumex laser diodes
[52]	Electron	Degradation of optical power of VCSELs is more severe than the degradation of its threshold current
[64]	Gamma	The normalized output power measured from simulation exhibited 80% degradation at 30 krad
[70]	Gamma	Only a small degradation of output power of DFB lasers reported after gamma irradiation

current degradation of the photodiodes is dominated by TID effect. The TID effect is the primary cause of the increase in surface recombination current. The TID effect damages the surface of the PIN photodetector, causing interface states to develop in the semiconductor material. As a result, when interface states are present, the rate of surface recombination rises leading to the increased dark current. The dark current of PIN photodiodes is highly sensitive to ionizing radiation, which [33, 56, 67] have also tested photodiodes under gamma radiation. The results show an increment of dark current that is linear to the radiation fluence (up to 30 krad). Based on the finding in Fig. 9 below, the dark current of photodiodes is found to be seriously degraded under 1 MeV electron exposure as the dark current of photodiodes is reported to keep increasing until it reaches 40 nA after the fluence level of 200 kGy (at 20 V) [21]. The result is due to the defect formation in the intrinsic epilayer of PIN photodiodes that is responsible for forming deep acceptor levels in the material bandgap [54, 60].

Based on the study of dark current density under 24 MeV and 24 GeV proton by [53] and [71], the findings demonstrate that the sensitivity of InGaAs photodiodes to displacement damage is higher than silicon-based photodiodes by more than 3 orders of magnitude. Hence, [53] presented a drastic increase in the dark current of InGaAs photodiodes after irradiation by proton fluence of 1 x 10^{15} pcm^{-2} (24 GeV). This degradation is believed to be due to displacement damage in the active area of photodiodes [53, 72]. A simulation finding on dark current degradation of InGaAs photodiodes is presented by [33]. The OMERE radiation environment modeling program is utilized to simulate expected trapped radiation particle flux for a 1-year mission under 105 MeV proton and the degradation result is significant. Experimentally, the dark current values of all the tested photodiodes also exhibit a consistently increasing trend with displacement damage with proton fluences ranging from 5.0 x 10^9 pcm^{-2} to 2.55 x 10^{11} pcm^{-2}. The same trend is also observed on Germanium-on-Silicon photodiodes under high energy neutron in [44].

Fig. 9 Dark current degradation on InGaAs photodiodes under electron irradiation [21]



Dark current is generated by the thermal generation of charge carriers within the sensor's material and can vary significantly across the sensor array. The variation in dark current from pixel to pixel is known as DCNU, and it can lead to significant challenges in image processing and analysis. The generation centers for dark current are statistically distributed throughout the sensor's array. This distribution results in pixel-to-pixel variations, which are referred to as Dark Current Non-Uniformity (DCNU). Some pixels, known as "hot pixels," exhibit significantly higher dark current levels compared to others. These hot pixels can be problematic, especially in applications like star trackers, where they may be mistaken for actual stars, thus interfering with the system's accuracy and reliability [73]. The dark current non-uniformity has been measured experimentally on different CMOS Image Sensors (CIS), and these measurements are in good agreement with the simulations performed using the Monte Carlo toolkit. The results from [26] emphasizes the reliability of the model in predicting DCNU and highlights the importance of considering statistical effects in radiation test standards.

In regard to radiation-induced degradation, this critical point warrants further emphasis: the growth of dark current is closely related to the fluence and energy of the incident radiation. As previously stated, the dark current damage factor is defined as the ratio of dark current increase to the incident fluence, varies depending on the type of radiation applied. Studies have shown that InGaAs photodiodes exhibit a higher sensitivity to displacement damage compared to silicon-based photodiodes. It is worth reiterating that, this is aforementioned evident from the findings that demonstrate a drastic increase in dark current for InGaAs photodiodes after exposure to proton fluence, indicating a sensitivity more than three orders of magnitude higher than that of silicon-based photodiodes. These positive nuclei are capable of generating high levels of degradation, leading to increased dark current and DCNU. This is especially relevant for near-Earth space missions, where satellites encounter high proton fluxes [9, 26].

The current generated by PIN photodiodes is attributed to three different mechanisms including diffusion, band-to-band tunneling, and Shockley-Read-Hall (SRH) generation. However, [5] states that diffusion is not significant under reverse bias operation. The second mechanism generates band-to-band tunneling currents that depend strongly on the bandgap of semiconductor material, while trap-assisted tunneling currents produced from the SRH generation mechanism are influenced by both band gap and trap levels. According to [71] and [74], irradiation triggers new deep-level traps in the bandgap of photodiodes and the trap density increases linearly with fluence which is responsible for the dark current activation energies [11, 44, 57]. Table 6 provides a summary of the dark current degradation of optical transmitters under different radiation.

1.5.2 Responsivity

The efficiency of the photocurrent generation process is quantified by a parameter known as "responsivity" or "photosensitivity". This characteristic evaluates the amount of photocurrent produced; thus, it is calculated as the ratio of generated photocurrent to input optical power and is commonly measured in amperes per watt (A/W). Responsivity varies with several factors including wavelength, material, and applied bias voltage. A loss in photodiode responsivity is the most critical mechanism causing link performance degradation [53]. The reduced responsivity is related to the equal reduced sensitivity of the receiver. Thus, the responsivity loss of GaAs photodiodes matches the sensitivity loss up to 2 x 10^{15} p/cm^2 during the first irradiation test of 20 MeV proton. Furthermore, they investigate that, at a total fluence of 1 x 10^{15} p/cm^2, the GaAs photodiodes degrade around 70% to 80% in responsivity while InGaAs photodiodes only lost around 30%. This is due to similar displacement damage that caused the photo-generated carriers to recombine before photocurrent

Table 6 List of past works on dark current degradation of transmitters due to Proton, Electron, Gamma, and Neutron radiation

References	Type of radiation	Finding
[9]	Electron, Proton, Neutron	The dark current increased linearly with fluence for all samples after irradiation
[11]	Gamma, Proton	The dark current increased for both radiations
[21]	Electron	The dark current of PIN photodiodes kept increasing with higher electron radiation dose
[33]	Proton	The photodiodes exhibited increased dark current with increasing dose
[44]	Neutron, Proton	The dark current increased moderately under both neutron and proton radiation
[46]	Gamma	The dark current of PIN photodiodes increased and reported to be sensitive to ionizing radiation
[53]	Neutron. Proton	The dark current of photodiodes increased from nA to hundreds of mA under proton radiation
[70]	Gamma	A serious increase in dark current of PIN photodiodes

generation. The two most widely used photodiode materials in wireless communication are Gallium Arsenide (GaAs) and Indium Gallium Arsenide (InGaAs).

A 30% degradation in responsivity of 50 MeV proton-irradiated photodiodes (up to 2.5 x 10^{12} pcm^{-2}) is observed in [56]. There is a similar relation between dark current increment and responsivity degradation under proton irradiation despite the devices being of different manufacturers. 20 MeV neutron caused a decrease in responsivity in all tested photodiodes [8].

The devices experienced severe degradation (50%–70%) around the fluence of 10^{16} n/cm^2 which the abnormal change in responsivity is seen. This phenomenon is impacted by radiation-induced compensation of the lightly doped intrinsic region of the PIN structure [75]. Table 7 provides a summary of the responsivity degradation of optical transmitters under different radiation.

1.5.3 Capacitance

Capacitance gives valuable insights into the charge storage capability of a photodiode. This parameter plays a crucial role in the modulation of light signals in most receivers. Lower capacitance allows for faster discharge that directly enables the device to respond more quickly to the change in signal intensity. This is desirable for applications like optical communications. Having higher capacitance can be detrimental to high-frequency signals as the charge accumulation may lag behind the rapid changes of the incoming light [76]. Plus, the increase in doping concentration would result in a reduction of the depletion region width, consequently leading to an increase in capacitance. It is found in [67] that gamma radiation caused no observable effect on the capacitance of InGaAs because of the passive packaging components which were unaffected by the radiation.

When high data rates are involved (several Gb/s), the increased capacitance can be the major cause of radiation-induced performance degradation of the receiver. The capacitance of InGaAs photodiodes is observed to increase significantly after 10^{15} pcm^{-2} of 24 GeV proton. The increase is simulated by the appearance of deep-level traps in the band gap which increases the space charge density. In [77], they described the increase of heterojunction capacitance due to the traps induced by 3 MeV proton (up to 5 x 10^{12} pcm^{-2}) that are responsible for the formation of interface energy levels. The findings in [49] elaborate that proton bombardment leads to a rise in the effective doping concentration inside the intrinsic or p-type sections of photodiodes, resulting in capacitance increase.

In [44], the capacitance dependability of deep-level density and energy follow the same behaviours as the current. Traps that result from process of radiation at the heterointerface induce interface energy levels, thereby are subsequently followed with a rise in heterojunction capacitance [50]. Eventually, it builds up the electrical field across the depletion zone, hence the width narrows, resulting in an increase in terms of capacitance [8, 44, 61, 74]. Table 8 provides a summary of the capacitance degradation of optical transmitters under different radiation.

1.6 Conclusion

This review provides a comprehensive overview of the existing literature on radiation-induced degradation in optoelectronic devices, particularly focusing on their essential roles in satellite applications, specifically within transmitter and receiver subsystems. The literature consistently demonstrates that radiation exposure leads to significant alterations in the key properties of optoelectronic devices designed for space applications.

The review highlights the significant impact of radiation on the performance of optical transceivers in satellite systems, categorizing various forms of radiation damage such as Total Ionizing Dose (TID), Displacement Damage Dose (DDD), and Single Event Effects (SEE). These forms of damage can severely impair functionality, affecting critical performance metrics like responsivity, photocurrent, dark current, threshold current, and slope efficiency. Threshold

Table 7 List of past works on responsivity degradation of transmitters due to Proton and Neutron radiation

References	Type of radiation	Finding
[8]	Neutron	A drastic drop in responsivity in all GaAs-based photodiodes
[53]	Neutron. Proton	The photodiodes lost around 70% to 80% of their responsivity at a proton fluence of 1×10^{15} pcm^{-2}. Degradation from proton was more severe than neutron radiation
[56]	Proton	A decrease in responsivity of all photodiode samples was observed

Table 8 List of past works on capacitance degradation of transmitters due to Proton and Neutron radiation

References	Type of radiation	Finding
[44]	Neutron, Proton	The study revealed moderate increases in dark current and capacitance
[53]	Neutron. Proton	The capacitance of photodiodes, in contrast, only increased at the highest measured fluence level
[67]	Gamma	No observable degradation due to the radiation hardness properties of passive packaging

current degradation in optoelectronic devices, particularly GaAs-based lasers, is a critical issue when these devices are exposed to radiation. For instance, the threshold current of GaAs-based lasers increases after radiation exposure due to the formation of non-radiative recombination centers, which reduce optical gain. Studies show that after 3 MeV electron irradiation, GaAs distributed feedback (DFB) laser diodes exhibit consistent degradation, indicating cumulative damage. In the case of Vertical-Cavity Surface-Emitting Lasers (VCSELs), displacement damage from lower energy proton irradiation has a more pronounced effect than from higher energy radiation. Additionally, threshold current degradation is temperature-dependent and typically shows a linear relationship with radiation fluence, with increases generally under 40%. Overall, VCSELs are particularly sensitive to displacement damage, underscoring their vulnerability to radiation effects. Furthermore, GaAs photodiodes can experience a 70% to 80% degradation in responsivity after exposure to proton fluence of 1×10^{15} p/cm^2, while InGaAs photodiodes show only about 30% loss, indicating variable responses to radiation among different materials.

Despite these challenges, it is noteworthy that certain optoelectronic devices, such as Vertical-Cavity Surface-Emitting Lasers (VCSELs), exhibit a relatively high degree of radiation hardness. This characteristic makes them suitable for applications in environments characterized by elevated radiation levels, such as space missions. Furthermore, the review summarizes the current limitations of radiation-based studies on satellite optical transceiver performance and emphasizes the need for future research directions aimed at enhancing the resilience of these devices against radiation-induced degradation. The insights gained from past research underscore the importance of developing radiation-hardened components and implementing effective mitigation strategies to enhance the reliability and performance of optoelectronic devices in the harsh conditions of space.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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