CCRAD - CUBESAT'S COTS RADIATION DETECTOR

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***Keywords**: COTS, Cubesat, Diode, RadFET, Radiation*

Radiation detectors are measuring devices whose function is to establish the level of environmental radiation. These detectors can be of various types, depending on the mission objective, orbit, sensor, particle characteristics, energy level and other factors that should guide the project. For CubeSat, the availability of mass and energy is very restrictive; therefore, simplicity is a parameter that should define the complexity of the system design; therefore, a detection topology based on radfet is a good option, as it allows for a simpler circuit and has a well-known behavior.

Radfet is an electronic device, more precisely a CMOS transistor, which can be polarized by constant current and can be monitored by reading the output voltage which, with the action of radiation, undergoes a deviation in value proportional to the cumulative action of radiation in the device. This circuit does not allow the characterization of specific particles, but it can indicate the accumulation of radiation over time, together with auxiliary data such as the moment of reading, where it is possible to estimate the location and conditions of the space environment.

The voltage reading must be performed by a digital analog converter directly from the radfet, or through a conditioning circuit that defines that the maximum variation does not exceed the converter's input reading values.

With this circuit, its application is possible in numerous missions, contributing to the construction of a radiation database, helping in the environmental characterization of the operational orbit, especially in the region where Brazil is located, because in this area the South Atlantic anomaly occurs zone, area where INPE and partner missions will operate. This data is vital for mission projects, as it is one of the parameters for systems projects.

1. Introduction

Cubesats are being increasingly valued in the development of projects related to the space area due to several factors, mainly the fact that the cost of design and launch is significantly lower than that of conventional satellites. These satellites can be launched using smaller and cheaper launch vehicles, in addition to being able to be launched together. However, the space environment has a number of characteristics that the component must support, radiation being a critical factor [1].

From the point of view of on-board electronics, despite being internal, it also suffers from the wear and tear of this environment in several parameters such as thermal dissipation, energy availability, mechanical resistance, material used, electronic components and functional interference due to radiation action. After the launch, every problem presented is permanent, and from this point on, the tendency is to manage them. Mitigations such as shielding, redundancy, protection circuits, use of qualified components are options that must be carefully planned, as they bring consequences such as cost, mass, efficiency of operation and, according to adverse circumstances, may not present the expected results [1, 2, 3].

Rapid technological evolution processes lead to a reduction in systems, costs, new features and an increase in the use of COTS (Commercial-off-the-shelf) components. According to ESA, COTS is a commercial electronic component readily available and not manufactured, inspected or tested according to military, or space standards. These components do not have the same strength as components qualified for use in space. Despite this fact, if mitigation processes are well selected, it becomes feasible to reduce the satellite systems by allowing small circuits of low cost and mass, making the category of cubesats viable. These devices can operate in smaller orbits and for a reduced time and cost, increasing the interest for the commercial use of space to provide services [2,3,4].

The objective of this work is to demonstrate the main concepts necessary for research and development of low consumption electronic systems and small dimensions, using shelf components (COTS), which can be shipped on different missions. These systems must perform measurements and send environmental radiation data. This work aims to assist in the future formation of an environmental radiation database, to serve as another source of consultation and study of this environment. These orbits should be directly related to the needs of the missions in the regions with the greatest radiation effect in the context of Brazil, contributing to a better understanding of this environment and of the solutions for operating systems.

2. The effects of the Van Allen belt and the South Atlantic anomaly on Brazil

A particularity for space missions, directed mainly to a region where Brazil is affected by the influence of the South Atlantic Anomaly zone, a location that presents an increase in the test level at lower altitudes. Despite these known effects, do a better search and more studies, for this information that can help those interested in operating satellite systems in this region and carry out their projects within a specific database for these conditions. If we consider a mission in Earth's orbit, there are additional factors such as the residual atmosphere, an action of the soil's magnetic field and its interaction with these variables. It should also be noted the formation of filter belts known as the Van Allen Belt, presence of space debris, solar concealment by the planetary shadow, among other factors that influence the execution of a project for the present environment [2,3].

In the LEO (Low Earth Orbit), there is the inner belt of Van Allen, a region with a large concentration of protons captured by the Earth's magnetic field. To detect even more, to verify that above the inner belt there is a region without a great increase in gravity and, then, the outer belt with captured electrons (Figure 1). This device has a dynamic behavior, in addition to the temperature variations that exist in the storage filter and deep space that are deflected or lose their energy along the path to Earth, by the terrestrial magnetic field [1].

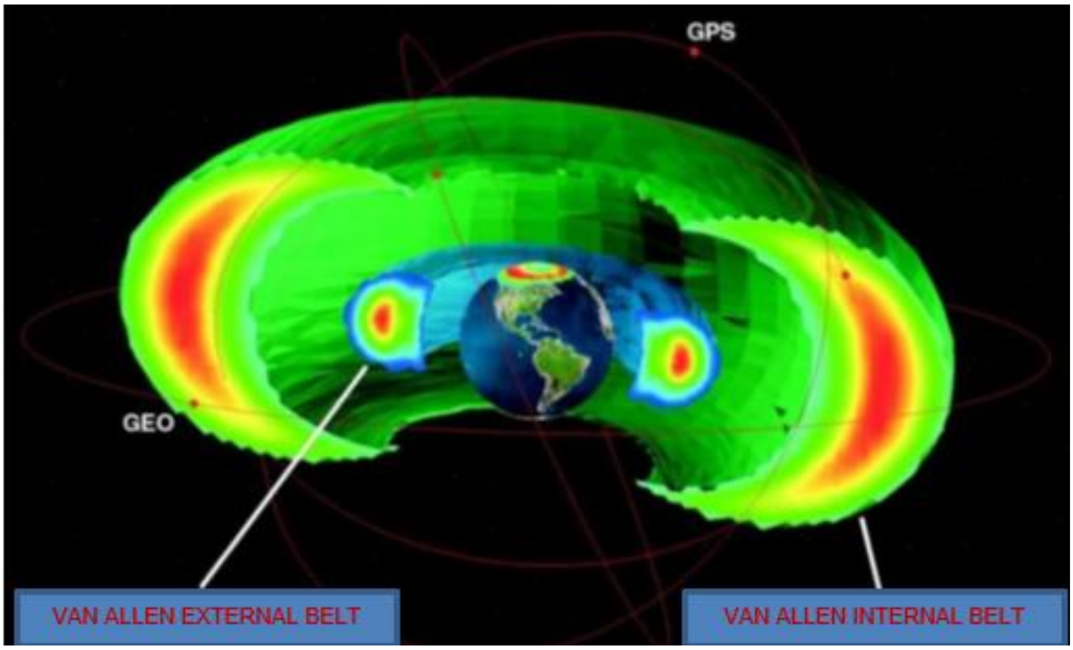

Figure 1 – Van Allen belt [1]

Specifically, in the region of Brazil in relation to the South Atlantic Ocean, there is an anomaly in which the belt approaches the Earth (Figure 2). The Figure represents the iintensity of the Earth's magnetic field as recorded by the European satellite SWARM, in 2015. The red areas represent places where the magnetic field is strongest, while the blue areas depict a decrease in intensity [5]

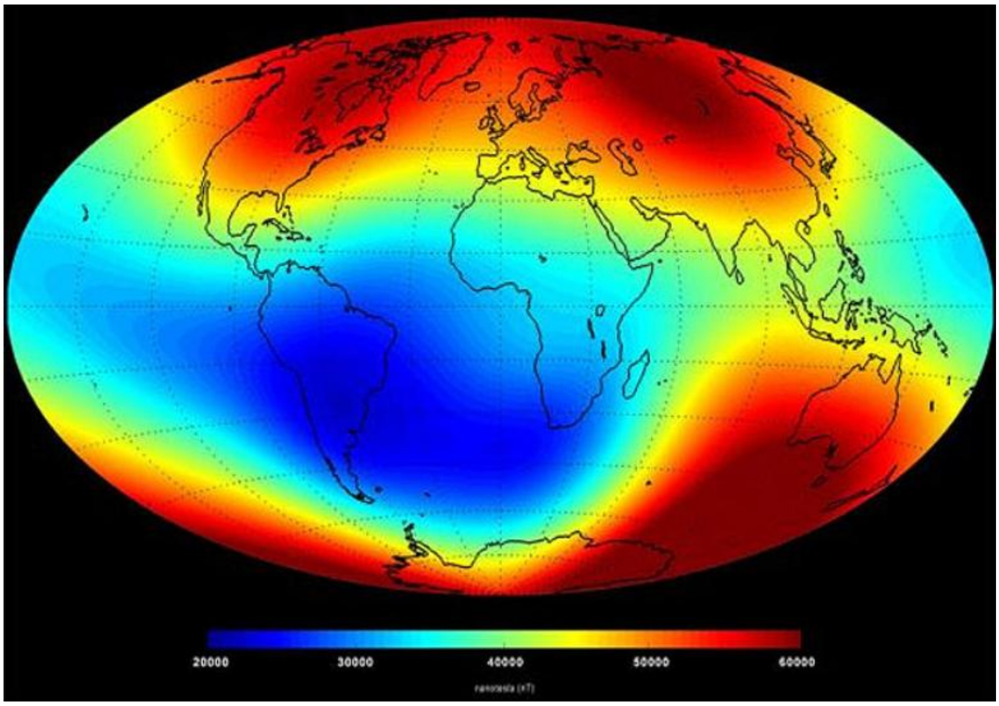

Figure 2 – South Atlantic anomaly [5]

In order to collect data on lightning considering the region of Brazil, it is feasible to use cubesats that can have semiconductor-based radiation detectors as their payload.

3. Main semiconductors used as radiation detectors

Metal-Oxide-Semiconductor Field Effect Transistors (MOSFET) have advantages such as the possibility of constant minimization, high operating speed and lower leakage current, in addition to being less noisy in the types of current-controlled transistors. The Figure 3 illustrates an example of a n-channel MOSFET transistor for o 0V gate bias and positive gate bias [6].

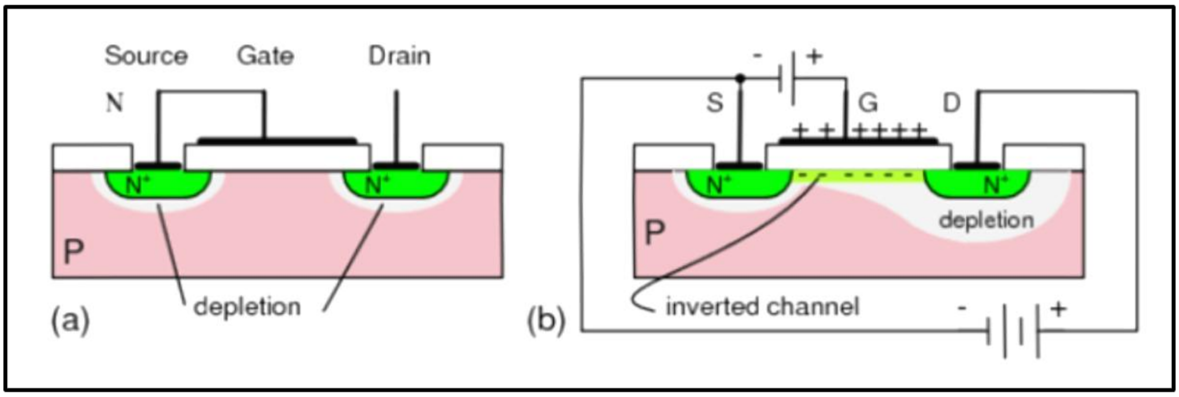

Figure 3: MOSFET example

The technology used to manufacture MOSFETs indirectly controls the energy barrier of the gate. A MOS transistor is manufactured from a doped semiconductor substrate, usually with silicon and doping type N or P, with four terminals (substrate, gate, source and drain). A thin layer of insulating material covers the central part of the structure, usually consisting of silicon dioxide (SiO_2). There is another layer (usually highly doped polycrystalline silicon) above the silicon dioxide, forming a low resistivity electrode (gate). At the ends, there are two symmetrical regions (source and drain) strongly doped in reverse of the substrate. Through the application of voltage at the gate, there is a control of the conduction between the source and the drain, configuring the normal operation of the device. This doped gate has an induced charge, behaving like an MOS capacitor. Charge carriers are attracted to the upper polarized plate, creating an inverted channel under the oxide. In this way, a depletion region isolates this channel from the volume of the silicon substrate, allowing to control high current outputs with low input power [6,7].

The emergence of new technologies in recent years has caused the CMOS (Complementary Metal Oxide Semiconductor) transistor channel to undergo a miniaturization process, increasing the effect of ionizing radiation on its functioning. However, as much as the technology advances, in the current context there are still no manufacturing processes that are completely immune to the effects of radiation. As previously explained, when a transistor receives the effects of radiation it ends up accumulating some charges in the oxide, on the entire surface of the circuit and not only in the area of the transistor. This effect changes the functioning of the circuit due to changes in the characteristics of your devices. Depending on the specific project, each particular circuit responds differently to the radiation load, according to its intrinsic characteristics (manufacturing technology) [8].

Considering the physical effects when a MOSFET is exposed to radiation, electron gap pairs are created in the matter. In this way, these pairs recombine quickly; in insulators, such as silicon oxide present in the device's gate. However, it is noteworthy that not all carriers recombine immediately. Some electrons and gaps are transported through the oxide in opposite directions, in the presence of an electric field. Due to greater mobility, electrons are transported more quickly through the gate's oxide. The gaps, in turn, are transported by a much slower process, consisting of successive jumps in the oxide towards the silicon substrate. In this way, positive charges are stored in the oxide after irradiation, considering the fact that part of these gaps are captured in these traps, remaining this way. It should also be considered that interface states are created in oxide-silicon that behave as traps for electrons due to the effects of radiation [9].

These two feats mentioned, the capture of charges in the oxide and the creation of interface states promote changes in the electrical characteristics of the device. The main effects, represented in Figure 4, can be synthesized in the variation of the threshold voltage, increase of the ramp factor (slope factor) and decrease of the mobility of the carriers of the channel. The supply of a circuit consisting of a P-channel transistor in series with a diode gave the graph in Figure 4. Said figure represents the device before and after the irradiation of 100 Gy (solid lines); the transistor at 0 Gy, showing a displacement of ∆VTH, is also represented (dotted line) [9].

Given the above, it appears that the dominant effect of ionizing radiation on MOS transistors is related to the deviation from the threshold voltage (threshold voltage). Synthetically, it is also found that the most sensitive part of a MOS transistor to ionizing radiation is silicon oxide (SiO_2), causing the possibility of migration of electron-gap pairs before recombination. Considering a positive polarization in an NMOS, the gaps tend to move towards the Si/SiO_2 area. Electrons that are removed from the oxide tend to migrate to the transistor gate. Total Ionizing Dose (TID) refers to these accumulations of charges, which can promote a population inversion under the substrate according to the amount of this accumulation [10].

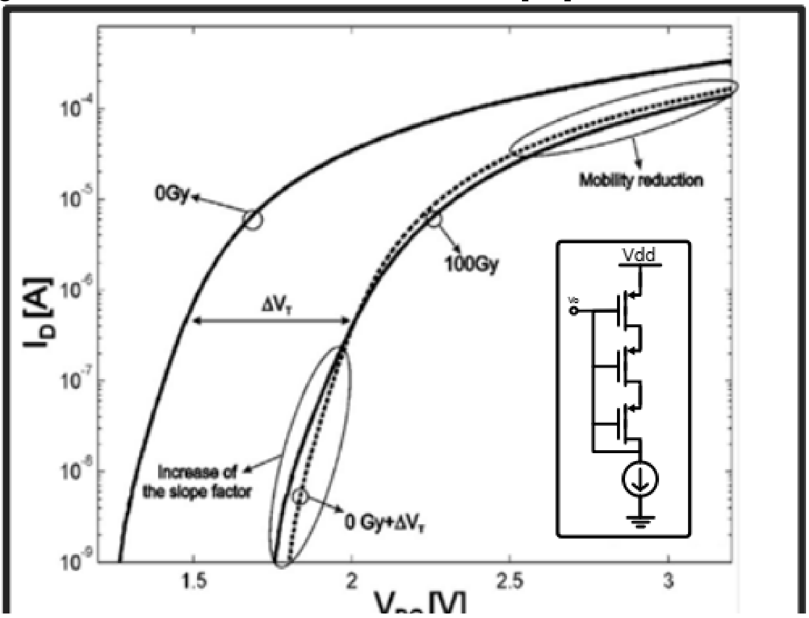

Figure 4: Main effects of ionizing radiation [9]

These electronic phenomena alter the characteristics of the device, one of the main effects being deviations from the threshold voltage. As exposed, these have a great relationship with the charges trapped in the oxide and in the Si/SiO_2 area, and the electrostatic effect of these charges creates an electric field on the substrate surface. In NMOS (nFET Metal Oxide Silicon) transistors, electrons attracted to the channel region result in a decrease in the threshold voltage; in PMOS (pFET Metal Oxide Silicon) the effect is the opposite. Figure 5 demonstrates the consequence of TID on the threshold voltage of a MOS transistor. The greater the accumulated dose of ionizing radiation, the greater the displacement of Vt and the change in the response of the circuit in which is the device [10].

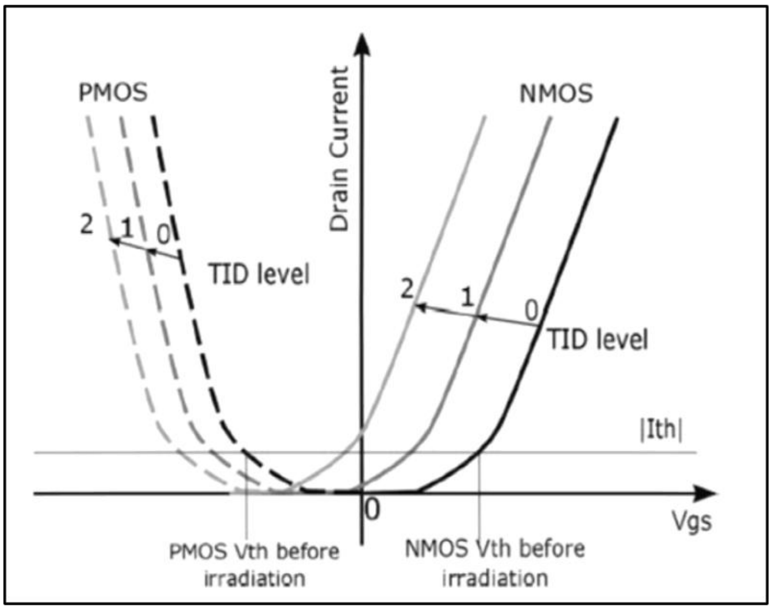

Figure 5: Effects of Vt variation on NMOS and PMOS devices [10]

RadFET (Radiation Sensing Field Effect Transistor) is a CMOS that can be polarized by constant current and monitored by reading the output voltage which, with the action of radiation, suffers a deviation in value proportional to the cumulative action of this radiation on the device. There are several studies on the application of RadFETS as meters of the absorbed radiation dose, with reference to the induced threshold voltage change. This circuit does not allow the characterization of specific particles, but it can indicate the accumulation of radiation over time, with auxiliary data such as the moment of reading, where it is possible to estimate the location and conditions of the space environment. RadFETs have a significant advantage over other dosimeters, although there are some limitations. This advantage is related to the fact of having the ability to operate in passive mode, being possible to read the information about the absorbed dose, using conventional electronic circuits. The voltage reading must be performed by a digital analog converter directly from the RadFET, or through a conditioning circuit that defines that the maximum variation does not exceed the converter's input reading values [11].

However, the limitation of RadFETs as offline dosimeters refers to the inherent fading effect (the limit stress decreases over time due to spontaneous annealing). The dose rate can be determined in RadFET-based applications by dividing the absorbed dose measured by the time elapsed from the beginning of an irradiation session until the measured absorbed dose is reached (average values). The RadFET is a specially designed P-channel MOSFET with a greater sensitivity to ionizing radiation. In the most common applications, the region of interest is the gate oxide (SiO_2 layer) for the monitoring of absorbed dose using RadFET, deducting the threshold voltage change caused by the accumulation of charge [11]. The Table 1 cites some examples of RadFETS cited in the literature.

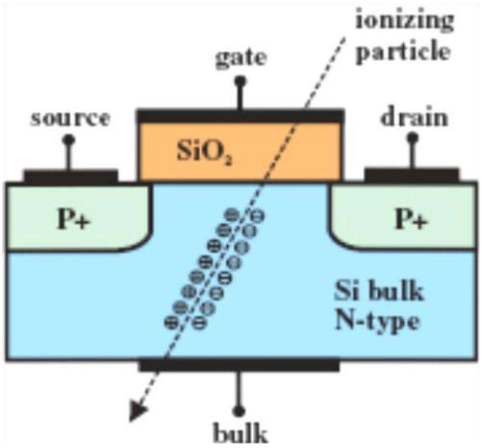

Figure 4: RadFET cross section [11]

In addition to RadFet, another radiation detector that causes the use of silicon PIN photodiodes (PN junction with an intrinsic layer), considering that it has a good sensitivity to various forms of radiation. PIN diodes have some important characteristics for this application, such as:

a) reduced size;

b) low energy consumption allowing measurements close to the sources of radiation; and

c) indicated for use on board aircraft and satellites as a dosimeter for ionizing damage, within the permitted limitations of the experimental device.

Table 1: Examples of RadFETs

RadFET	Characteristics
REM RFT300-CC10G1 [12]	• gate oxide with a thickness of 300 nm; • 1.5 mV / cGy sensitivity and an almost transparent radiation enclosure; and • suitable for many radiation beams and space.
TY1004 (chip) [13]	• manufactured by Tyndall National Institute; • incorporates two identical RadFETs with a 400 nm port oxide thickness; and • very small active area (gate oxide surface): 300 μm by 50 μm.
Transistor MOSFET LS 3N163 PMOS [14]	• can be used to design RADFETs to meet different design requirements, such as cost, sensitivity, linearity and and power; • in a typical application, it is operated in a non-polarized mode (power-off mode) and exposed to radiation; the change in threshold voltage is then measured and the corresponding radiation exposure level determined; • in another application, where higher levels of sensitivity are needed, it is operated in polarized mode (energy mode); and • has a sensitivity of 33 mV/Gy in non-polarized mode and 62 mV /Gy in polarized mode.
FGDOS (Chip) [15]	• dosimeter based on floating gate designed, developed and marketed by iC-Málaga; and • its high linearity and sensitivity response make it suitable for space applications.
VT01/VT02 (Chip)	• 400nm Varadis chip; • consists of two identical RadFETs that have individual port and

[16]	drain terminals, while the source and the substrate are connected; • has a large dynamic range, from 1 cGy (1 rad) to 1 kGy (100 krad); • form a set with two internal transistors, in addition to a protection diode; • operate with low polarization value (10uA recommended); and • VT01 has a plastic housing and VT02 ceramic.

As a working principle, photodiodes are semiconductor light sensors that generate a current or voltage when they are under the effects of light. The operation of Si-PIN photodiodes can be direct and indirect, with applications for different types of radiation. One of the most used ways to use high energy or the coupling of a scintillator. This device can be defined as material that flickers at a wavelength when subjected to violence. In addition to the mentioned advantages, Si-PIN photodiodes can be highlighted by other characteristics such as superior energy resolution, a relatively high response speed and small thickness, which can be variable, depending on the required application. However, these devices also have advantages such as size limitation and ease of violation-induced degradation. Next, Figure 5 shows a PIN diode when reversed polarized. It is noteworthy that the establishment of an electric current can only occur due to region incidents in the region between the PI and IN junctions of the PIN diode [17].

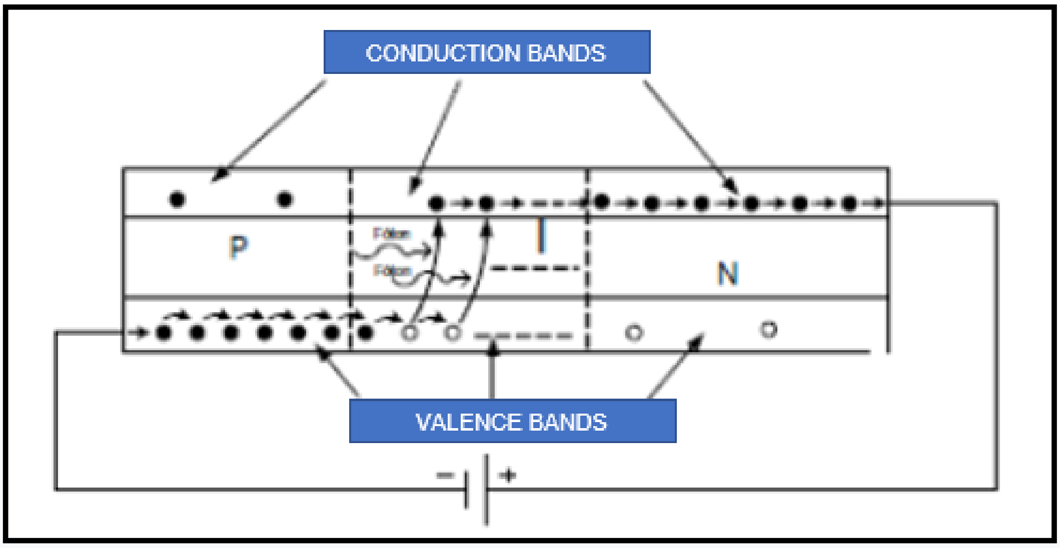

Figure 5 - Electron path in the PIN (reverse bias) [17]

3. Proposals for studies on radiation

Which studies of strategic radiation effects for the space area have been created for the CITAR Project (Circuitos Integrados Tolerantes à Radiação), by the Ministério da Ciência, Tecnologia, Inovações e Comunicações (MCTIC) of Brazil, or which is being carried by Renato Archer CTI (Centro de Tecnologia da Informação), INPE and other research institutions. This project is responsible for developing a technology for resistance to electronic components, developing systems for high-speed communication between satellite subsystems in environments subject to radiation, establishing the necessary infrastructure for testing alterations and other related activities [18].

The more pronounced effects of the anomaly of the South Atlantic and the Van Allen Belt in the region of Brazil, allow an opportunity to carry out more in-depth studies on the effects of radiation. With the increase in the incentive for the study and development of cubesats, it becomes more viable to send radiation detectors in this mission category, presenting the lowest costs and other advantages, already mentioned. It is also noteworthy that there is a growing demand for studies that affect the effects of radiation, due to the possibility of developing techniques that can perform a mitigation on COTS devices. INPE has a team of researchers related to the Radiation Engine- ering Sector and the CITAR Project, which are mainly responsible for activities related to this area.

This team decided to carry out studies and design activities, including a search in the market for components or commercial devices that may be candidates for applications such as application-to-application systems. To do this, check if the behavior of the parameter is adjusted in relation to the effects, characterizing these changes and ensuring the repetition of these results. With an initial selection of CMOS transistors and PIN diodes, as the main devices, circuits will be displayed that have a small size, low cost of execution, low energy consumption and those that will be shipped in any type of application, adding another way in the mission, without compromising the main function.

4. Conclusions

In this article, the main concepts necessary for research and development of electronic systems using commercial components were demonstrated, which are related to the future formation of an environmental radiation database in the context of Brazil. For this, INPE is part of the CITAR Project, which should use its researchers in the search for solutions to implement data collection. It appears that one of the most relevant opportunities is the use of cubesats with semiconductor-based radiation detectors, as payloads. Cubesats have several advantages such as lower project and launch costs than conventional satellites. One of the advantages of RadFETs is the possibility to measure the accumulation of radiation over time, operating passively. PINS diodes are small, have low energy consumption (measurements close to radiation sources) and are indicated for use on board aircraft and satellites.

With the technological evolution, other devices can compose a base of components to complement the radiation measurements, as the tests present favorable characteristics. The survey of environmental radiation data in space missions, specific to INPE or through partners, is part of a new joint effort to study particle radiation in different orbits in the region of Brazil. This area is of great interest for space exploration, mainly because of the greater incidence of effects related to the South Atlantic anomaly and the Van Allen belt.

The implementation of radiation detectors in cubesats will allow the community access to a database for academic or commercial use, contributing to the growth of knowledge in this area. Through future studies of the characteristics raised, this database should become an essential source of information in a globalized world, which depends more and more on scientific research. Collaboration between the sectors involved in this research should accelerate the development and use of scarce resources for the good of the entire society.

Acknowledgments

The authors would like to thank the CITAR Project, Radiation Engineering Sector, Institutional Training Program (PCI) and the Postgraduate Course in Space Engine-

ering and Technology / Engineering and Management of Space Systems (ETE / CSE).

References

[1] B. C. Junqueira, Use of COTS in Nano Satellites, Brazilian Journal of Development, Vol. 6, Nº 1, January (2020), pp. 1476-1490.
[2] C. Dyer, Radiation Effects on Spacecraft & Aircraft, In: Proceedings of the Second Solar Cycle and Space Weather Euroconference, Vico Equense, Italy, September 24 - 29, 2001, Paper number 92-9092-749-6, pp. 505 – 512.
[3] G. Pippin, Space environments and induced damage mechanisms in materials**,** Journal Progress in Organic Coatings, Vol. 47, Nº 3–4, September (2003), pp. 424-431.
[4] Europe Space Agency (ESA), ECSS-E-ST-00-01C, ECSS System: glossary of terms, Paris, France, 2012. 63 p.
[5] R. Leite, Anomalia Magnética do Atlântico Sul se desloca e cobre todo Brasil, 2019, available in https://www.apolo11.com/noticias.php?t=Anomalia_Magnetica_do_Atlantico_Sul_se_desloca_e_cobre_todo_Brasil&id=20161004-095452
[6] **D. P.** Magalhães, Study and Characterization via Monte Carlo Damage Simulation of Ionizing Radiation in Hybrid Pixel Detectors, M.Sc. Thesis, Gleb Wataghin Institute of Physics, University of Campinas (UNICAMP), 2018.
[7] V. C. D. Silva, M.Sc. Thesis, Radiation-resistant CMOS Structures using Conventional Manufacturing Processes, Instituto Militar de Engenharia (IME), 2005.
[8] S. Ghissoni, R. L. Reis**,** Optimization of Power Consumption and Delay for CMOS Circuits using SCCGs with Anti-radiation Topology, 2013, available in: https://www.researchgate.net/profile/Ricardo_Reis3/publication/237588180.
[9] J. C. Ribeiro, Integrated Radiation Sensor in High Voltage CMOS Technology, M.Sc. Thesis, Federal University of Santa Catarina (UFSC), 2017.
[10] B. B. C. Oliveira, L. A. Faria, Hardening / Hardening to Ionizing Radiation by unit Cell Circuit Design Techniques of Signal Conditioning Circuits (ROICs), in: Proceedings of the Simpósio de Aplicações Operacionais em Áreas de Defesa (SIGE), São José dos Campos, São Paulo, Brazil, September 24-26, 2019, Paper number 1983 7402.
[11] M. S. Andjelković, G. S. Ristić, A. B. Jakšić, Using RADFET for the Real-time Measurement of Gamma Radiation Dose Rate, 2015, available in: https://iopscience.iop.org/article/10.1088/0957-0233/26/2/025004/meta**.**
[12] A. G. H. Siedle, J. O. Goldsten, R. H. Maurer, RADFET Dosimeters in the Belt: The Van Allen Probes on day 365, In: Proceedings of the 14th European Conference on Radiation and Its Effects on Components and Systems (RADECS), Oxford, UK, USA, September 23-27, 2013, Paper number 978-1-4673-5057-0.
[13] N. Hubert, F. Dohou, D. Pédeau, RadFET Dose Monitor System for Soleil, In: Proceedings of 7th International Beam Instrumentation Conference (IBIC), Shanghai, China, 2018, Paper number 978-3-95450-201-1.
[14] M.S.M. García, J. T. Río, A. Jaksic, J. Banqueri, M. A. Carvajal, Response to Ionizing Radiation of different Biased and stacked PMOS Structures, Journal Sensors and Actuators A: Physical, Volume 252, December 1 (2016), Pages 67-75.
[15] R. Ferraro, S. Danzeca, M. Brucoli, A. Masi, M. Bruggera, L. Dililloc, Design of a Radiation Tolerant System for total Ionizing Dose Monitoring using Floating Gate and RadFET Dosimeters, in: Proceedings of the Topical Workshop on Electronics for Particle Physics, September 26–30, Karlsruhe, Germany, 2016.
[16] Varadis RADFET, Our Products (VT 01 and VT 02), 2020, available: varadis.com.
[17] S. F. L. Nogueira, Study of a semiconductor ionizing radiation detector of aerospace interest, based on a photodiode PIN, M.Sc. Thesis, Space Science and Technology Course, Physics and Mathematics Applied, Instituto Tecnológico de Aeronáutica (ITA), 2016.
[18] INPE, Projeto CITAR testa componente eletrônico tolerante à radiação para uso em sistemas espaciais, 2016, available: http://www.inpe.br/noticias/noticia.php?Cod_Noticia=4115