CHALLENGE 6

PUSHING THE LIMITS OF SPACE TECHNOLOGY

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1. INTRODUCTION AND GENERAL DESCRIPTION

Current technology ecosystem surrounding space-related activities is an adapting scenario. It is a response to the realities of worldwide commercial and highly competitive marketplace, on the one hand, while adds to the traditional public cooperative projects for global security, environmental protection, and space exploration programs, on the other. Technology challenges are identified for specific components and systems in each one of these sectors. In most cases, the main constraint is cost, similar to on-Earth applications. Yet, there is an increasing trend on also assessing their sustainability. For instance, Clean Space initiative consists in technical analyses to identify knowledge-gaps, such as introducing eco-design, green technologies, space debris remediation. However, baseline targets for technology evolution continue to be higher reliability of materials (systems lifetime, radiation hardness, thermal management, self-protection, self-healing...) or higher efficiency and capabilities of devices (sensitivity, processing power, data management power, frequency ranges...).

Today, numerous new projects and missions have already been scheduled by the different Space agencies and private companies. Space missions require huge, continuous development of a number of advanced technologies. For instance, the ESA-JAXA BepiColombo mission, launched in 2018, aims at a comprehensive study of Mercury, including the characterization of its magnetic field, magnetosphere, and both inner and surface structure. In this case, 80% of the technologies used to equip the whole spacecraft (including solar cells, electronic devices, shielding, antennae, scientific instrumentation…) had technology requirements specific to this mission. Yet, new developments are not always mission-exclusive, and e.g. part of BepiColombo technologies have been replicated for the Solar Orbiter mission launched in 2020. Without the large efforts done for developing their new technologies, these two missions would have not been possible.

Public research institutions, e.g. CSIC, can bring their expertise to carry out exploratory, high risk and longer-term investigations, for instance offering breakthrough technologies based on new materials or on novel devices and systems concepts. On one side, earth and deep space observation requires more and more sensitive and precise sensing systems. On the other hand, space missions shift more and more from orbital missions to in situ missions or colonization missions that need to cope with their related harsh environments. Novel technologies as well as a better understanding of the operation conditions are necessary to enable such missions to succeed. In this scenario, sensing, together with telecommunications and energy management are definitively three pillars of the future space science and development.

Consequently, the exploration of breakthrough sensing technologies for monitoring and instrumentation is needed for both public services like weather forecast, navigation, disaster management, and for space exploration, which includes deep space observation, planetology, astrophysics, among others. If we have a closer look to the currently planned Space missions of the different agencies for the next 10-15 years, we can identify a first set of technology requirements, as starting points. As an example, in Annex 1 are listed some of the scheduled scientific missions by ESA and other agencies, including the type of instrumentation planned to be integrated to the spacecraft. We can identify by this way which kind of materials and components technologies will be needed for instrumentation and anticipate longer term needs.

Novel space applications also require search for novel sensing, processing, communication and energy management technologies able to operate in harsh environment with a high reliability. Today's satellites have already got much smarter, and in space as on Earth, end-users are demanding more and more processing power. Space-borne applications related equipment (ground-based, satellites, spacecraft...) are mainly built with semiconductor-based electronics systems. It may represent up to 70% of the payload in satellites and un-crewed spacecraft. Satellites and Spacecraft use hundreds of microchips to control their navigation in space, and to be able to convert the signals measured by all the instruments on board into useful information. Complex integrated circuits act as the brains that process all the incoming and outgoing data in the spacecraft. Sophisticated circuit design tools and commercial manufacturing technologies used to produce microchips for terrestrial applications (inside home computers, mobile phones, etc.) have been adapted for their use in space applications. However, future space instrumentation requires increasing computing capabilities which need to cope with stringent requirements like reduced size, mass, power consumption and high tolerance to radiation. It involves the development of a new generation of digital processing units for space instrumentation. For instance, a new generation of Digital Processing Units (DPUs) based on powerful FPGA or ASIC devices and brand-new space processors can simplify the DPU designs without compromising on efficiency and increasing significantly its capabilities. Together with these new advanced developments, it is very important to carry out dedicated and optimized control software for the chosen architecture by balancing the design options for error protection and computing performance.

Clearly, the main obstacle for the reliable operation of the on-board electronic systems in a spacecraft is radiation. Electronics for space applications usually have very high functional safety requirements. In most missions, the involved cost is so high that failure is simply not an option. As a result, the electronic components that may end up in space have to undergo stringent qualification processes. These are expensive processes that verify the functional integrity of the components under pre-determined radiation and temperature scenarios, but also of all the mechanical bonds under severe vibrations. Moreover, with the advent of ultimately scaled CMOS integrated circuits, radiation failure anticipation will create a need for modelling effort. This requires the development of improved radiation-hardening strategies, both at low-level (from the circuit topology to its layout) and at high-level (with system-level approaches such as error-correcting codes, approximate computing, clever redundancy schemes, etc.).

Definitively, the fundamental study of radiation effects on equipment but also on humans is crucial for the future space missions. Outside Earth's protective atmosphere, radiation is everywhere: high-energy particles from the Sun, protons, electrons and ions are attracted by Earth's magnetic field and cosmic rays bombard us from beyond the Solar System. Radiation levels in space are up to 15 times higher than on Earth and radiation can have severe health consequences for humans. Effect of cosmic radiation on living cells is one of the main health hazards associated with space travel and exploration. In humans, overexposure to radiation can cause cancer, damage to the foetuses of pregnant women and heritable genetic disorders that can be passed onto future generations. Consequently, in the shorter term, radiation is going to be a crucial issue when it comes to planning the future human exploration, of the Moon and Mars. ESA experience of radiobiological effects in the space environment comes mostly from manned spaceflight in Low Earth Orbit (LEO). For long-duration interplanetary missions, most of the radiation dose will arise from cosmic rays, solar particle ions and secondary particles against which future spacionaute will need to be sheltered. This will probably be the most important challenge for the future crewed space missions.

In addition, in many future missions, the correct operation of the electronics on-board in Space environment must be also guaranteed at extreme temperatures and often for long mission durations, where on-board parts repair or replacement is not an option.

In this scenario, the emergence of novel dedicated materials and devices technologies for efficient sensing, data processing and energy management able to operate under harsh environment would have a significant impact on future Space applications.

2. IMPACT IN BASIC TECHNOLOGY PANORAMA AND POTENTIAL APPLICATIONS

The main sectors where next generation Space technologies are being pursued are:

- Public services, e.g. weather forecast, satellite-assisted navigation, disaster management.
- Commercial services, e.g. telecommunications, broadcasting and multimedia, traffic management, applications of earth observation.
- Space science, e.g. astrophysics, planets exploration, exoplanets search, deep space understanding.
- Low Earth Orbits and outer space transportation, e.g. future re-usable systems, small expandable launchers, balloons.
- Living in Space, e.g. life sustainability, space infrastructures, crew transportation, logistics.

Both Space Science and Public services require advanced technologies for optical surveillance and imaging science. Optical surveillance is the primary method for surveillance and tracking of objects and satellites in higher terrestrial orbits because this task does not require high temporal resolution in the image acquisition. However, surveillance of objects in low earth orbits requires sub-millisecond accuracy in the image acquisition. Optical surveillance in LEO regions has recently emerged thanks to the availability of high-resolution low-noise sensors, with global electronic shutter, that feature high temporal resolution (Żolnowski,2019). However, short exposure times translate in large amount of noise and the generation of huge amounts of mostly redundant data. This vaste amount of data demands very large communication bandwidth and power at the sensor output. Furthermore, these data must be further processed for object detection and tracking requiring high computation capabilities of the processing system.

Additionally, the discovery of habitable exoplanet candidates and most-distant galaxies require the development of new, sophisticated technology, which is definitively a challenge for optics and other research fields. In the case of optics devoted to the near and far infrared, there are scheduled missions, such as ESA's ARIEL, planned for 2028, where the observations of a set of exoplanets will be done in the wavelengths from 2 to 8 microns. In this case, the development of optics for such wavelengths, are basic for its success. Other missions such as Athene or Lisa will also require optical technologies which have yet to be developed, also for infrared observation. Briefly, the currently available CCD-based optical sensors are not well suited for neither far nor near infrared observations. Thus, new sensing devices, both sensor and also optics, should be developed for this wavelenght range. Along with this, stable mounts and compact designs will be required, such as photonic integration of the different optical components, which will be interesting for increasing accuracy and stability of the optical systems both in earth and in space missions.

Concerning Astronomy, ground-breaking discoveries in this field are usually linked to the development of state-of-the-art detectors. Particularly, the mm/sub-mm/Far-IR range is strongly constrained by the sensitivity and the size/number pixels of array detectors. For instance, radiation detectors based on superconductors display revolutionary performances, which are making them essential elements in a variety of next generation instrumentation, both in space and ground-based astronomy. Their key advantage is related to the much lower characteristic excitation energy, which is of the order of the meV for low temperature superconductors, three orders of magnitude below typical bandgaps in semiconductors. Thus, these cryogenic detectors can provide single photon detection combined with spectroscopic capabilities, low dark count rates and excellent sensitivity, over a wide energy range. These achievements are specially suited for photon-starved science cases. For instance, the Kinetic Inductance Detectors (KID) technology exhibits a huge potential for building very sensitive large cameras with more than 1000 pixels with a simple multiplexed readout, like in the ESA's NIKA2 and CORE instruments (de Bernardis, 2018). Besides, Transition Edge Sensors (TES) is another promising technology. Impact of TES in basic science can be evaluated from the fact that they are considered already essential to access new science, and thus incorporated in very complex and revolutionary instruments, such as X-IFU, the high resolution X-ray spectrometer onboard Athena, ESA's next X-ray telescope. TES arrays constitute the detectors of the HIRMES instrument on the stratospheric observatory SOFIA, and are under development for ground telescopes and other underground instruments, among them: ACTPol, BICEP2, CRESST, HOLMES, and are being considered for axion search (IAXO). They also start to be in use in materials science and security, and constitute one of the technologies in consideration for quantum communications.

Regarding solar physics, the technological development of harsh environment sensing and electronic systems would constitute the heart of the instrumentation that will contribute to solve scientific questions related to the magnetic field coupling of the different layers of the Solar atmosphere, to further investigate the magnetic field in both the chromosphere and in the corona or to understand the evolution of the solar structures. Another application field can be found in the space weather discipline where understanding the influence of the solar magnetic field is a key point. This knowledge will allow a better forecasting of some solar events that are crucial form life and security on Earth.

Besides, planetary science missions will continue to revolutionize our understanding of the origin and history of the Solar System. New instruments with more advanced and sensitive sensors will gather data to help scientists understand how the planets formed, what triggered different evolutionary paths among planets, what processes have occurred and are sill active, and how Earth among the planets became habitable.

All this current and future space instrumentation demand increasing computing capabilities and advanced data systems which need to cope with specifications like size, mass and power consumption and high tolerance to radiation. Hardware and software building blocks for control and data systems (fault-tolerant computers, support ASICs, standard interface controllers, etc.) are required for future exploration missions, as well as for the next generation of commercial satellites and spacecraft. In this sense, Digital Processing Units (DPUs) based on powerful Field Programmable Gate Arrays (FPGA) or Application Specific Integrated Circuit (ASIC) devices could play an important role in different scientific challenges based on instrumental development and novel spacecraft electronic management, which usually involves the execution of complicated algorithms on board. As mentioned before, applications can be found in several scientific cases for different areas like solar physics, asteroseismology, or planetary science missions.

However, current submicronic densely packed ICs generations used for Space component technologies are more and more sensitive to Space-environment effects (radiation, electrical discharges, temperature gradients...). Standard electronics developed for Earth applications is mainly based on silicon technology. This implies a typical operation temperature range between -55ºC and 125ºC, atmosphere pressure operation, a medium lifetime of 10 to 15 years, and basic cosmic ray protections, among other limitations. Radiation and temperature stresses are real issues for all the electronic systems designed for Space application with this silicon technology. A direct approach to reduce the performance gap between components used on Earth and those used in Space is to re-use components developed for Earth application (the so-called COTS, Components Of The Shelf) without other hardening process than extra shielding. With such a strategy, the burden is shifted from specific circuit development to qualification, with special emphasis in the analysis of radiation effects in the performance. Indeed, several candidates of similar performance must be qualified to have a chance of finding one that meets the specifications. The development of Rad-Hard Application-Specific Integrated Circuits will likely remain the preferred path for critical systems. That being said, the COTS strategy is gaining momentum, because some large volume markets (like for instance automotive) demand components with very high functional safety requirements. It has been reported that muon Single Event Effect may induce a non-negligible soft error rate at Earth surface in ultimately scaled CMOS. This may be good news for space applications since it would trigger a lot of effort in the development of state-of-the-art rad-hard circuits.

Another relevant part of a space equipment is the power system which is in charge of supplying energy to all the active systems of the satellite, spacecraft or ground based. The current power systems, typically developed for earth applications are heavy, bulky, not efficient enough and, due to their design/technology specificities have even more difficulties than low power electronics to operate in extreme environments. Advanced power electronics, with enhanced lifetime and reliability under extreme temperature ranges and radiation environment would have a considerable impact on high power robotics, crew electric propulsion missions and in-situ resources utilization missions, as well as nanosatellites and small planetary probes. It will enable novel missions to solar system planets like Mercury, Mars, Venus, Jupiter etc., and allow longer term near sun observation missions. Predictions from different electronics roadmaps indicate that in 2030, 80% of the consumed energy on earth will pass through power converters, and by essence, through power semiconductor electronics. The optimisation of these power devices is then fundamental to reduce energy losses in converters used everywhere. This is even more critical in space application, were energy consumption must be optimised as much as possible to ensure operation lifetime of the systems.

Importantly, all these technologies can also be derived to on-earth applications like human health, energy management, oceans exploration, exploration of the Earth's interior, transportation, telecommunications, among other.

3. KEY CHALLENGING POINTS

In this panorama, focusing on the harsh environment technologies required to build efficient sensing and data/energy processing space systems on one side, and the CSIC research groups competences on the other side, we can identify and evaluate the new challenges CSIC is fully prepared to face.

3.1. Challenge 1: Development of advanced optic, optical and image sensors to enable more precise and deeper observation imaging

As mentioned earlier, several issues are still present with conventional optical sensors when used for space surveillance: resolution, limited dynamic range, noise, large amount of data, etc. Despite the recent advances, there are still challenges to be tackled in the next 10-15 years. First, the current dynamic vision sensors are not optimized for space applications. Second, algorithms targeted and optimized for the detection of different object of interest in space, such as stars, satellites, debris objects, etc., using the output of the optimal sensors should be developed, such as neuromorphic sensors. In addition, low power neuromorphic processing hardware optimized for space use and for space objects detection and optimized for radiation tolerance are compulsory to meet future requirement of long life missions.

One direction to tackle these issues is to develop research on Dynamic vision sensors (DVSs). DVS are a new type of bioinspired vision sensing devices which are based on a different acquisition paradigm than conventional CCDs and CMOS Active Pixel Sensors (APS). In a DVS, each pixel detects the changes in the illumination impinging on that pixel in an asynchronous, continuous, and autonomous way. Each pixel adapts its response time to the local illumination conditions. Furthermore, as the sensor generates outputs only when there is a temporal change in the illumination, only the moving objects in the scene produce an output, while the static background parts remain silent. Thus, the sensor output information can be sparse and highly compressed compared to the output of conventional conventional image sensors. This information compression reduces the bandwidth and power consumption of the sensor communication output channel and allows output post-processing for real-time detection and tracking of target objects using low power embedded or neuromorphic processors (Mead, 1990). The high parallelism of neuromorphic computing systems promises to make them more resilience to local radiation events. These systems will be appropriate to develop smart and low power neuromorphic computation on-site systems reducing the amount of information communication.

Another direction is to use advanced optics technologies for IR observation with high stability and accuracy. Research on materials which can be used in this range, with improved performances, new concepts or tools to reach the desired wavelengths is necessary. For instance, the atmospheric transmission window called M-band is interesting for making observations for terrestrial exoplanets, but there are, to date, not integrated optic devices suited for this band or others at longer wavelengths. Additionally, observations for astrophysics, solar physics, and atmosphere physics communities at key spectral lines in the far and extreme ultraviolet (FUV, EUV) require challenging coating and optics developments. A promising option is to investigate on optical coatings for the FUV-EUV in the main wavelength range of 40-200 nm. Coatings include mirrors, filters, and polarizers. Also, lighter and cheaper medium diameter optical mirrors for space-borne and ground-based observatories would be desirable. New materials could be the way to mass-produce them.

3.2. Challenge 2: Define novel radiation detectors concepts and technologies for scientific instrumentation and safety control

Radiation detectors for electrons, protons, neutrons, X-ray, light ions and heavy ions will be a key technology in the future space exploration and manned missions. Again, current technologies based on Silicon are highly limited and other approaches are required. The accessibility of cryogenic temperatures and the potential advantages of low temperature electronics are likely to boost superconducting detectors and electronic devices as an alternative to Silicon. Cryogenic detectors with superconductors are a Key Enabling Technology which will see in the coming years a widening of their application range, for specific targets. The fabrication and readout (multiplexing) of large arrays is a crucial aspect for some applications.

Today, Transition Edge Sensors (TES) are the most mature cryogenic detectors technology: they constitute very versatile, ultra-sensitive radiation detectors, able to detect from gamma-rays to microwaves and particles with energy resolving power, very low dark count and efficiency close to 100% (Irwin, 2005). For instance, the search for biosignatures in exoplanets will require telescopes operating in the ultraviolet, visible, and near-infrared bands. Since biosignature detection is a photon-starved science, this requires detectors with nearly zero dark counts and moderate spectral resolution. TESs is a most interesting technology in this field because they meet these requirements and offer the prospect of non-dispersive imaging spectroscopy. In spite of the relative maturity and excellent performances achieved, there are still open questions regarding fundamental aspects of the operation of these devices. Fully understanding them should result in approaching their theoretical limits. In the range of visible-UV, of especial interest for planetary exploration, current research is focused on improving efficiency to values as close to 100% as possible (values >90% have been achieved by different groups). Also, for biosignature search, improvement of the spectral resolving power up to at least a value R=100, which is considered achievable.

On the other hand, Kinetic Inductance Detectors (KIDs) is another approach to be considered (Calvo, 2016). The main advantage of KIDs is their intrinsic multiplexing capability in frequencies due to the sensitive element to the radiation, the inductor. This allows to manufacture thousands of resonators with different resonance frequencies which can be readout in the frequency domain through a single line. Future space mission to study the Cosmic

Microwave Background (CMB) will require cameras with large number of detectors, very good sensitivity and polarization selectivity. KIDs are the ideal candidates to be used as they exhibit very good sensitivity and they are intrinsically multiplexable which allows the frequency multiplexing of thousands of pixels through a single transmission line. However, KIDs still need further key developments to fulfill all the requirements of future space missions. Among them, the development of new materials for the detection of low frequencies (50 to 100 GHz) and the design of new geometries for improving the polarization sensitivity and cross-polarization, are key requirements that should be improved to meet the mission baseline. KIDs intrinsic advantages will be also exploited outside the limits of millimetre astronomy and reach shorter wavelengths such as visible light and x rays, and particle detection through the so-called phonon mediated detection. The KID technology that is being developed will not only provide a dramatic increase in mapping speed for broad band imaging, but it could also enable novel applications in spectro-polarimetry and hyperspectral imaging. Additionally, future space science and Earth observation missions are limited by the availability of high sensitivity large imaging detector array technology for the mm-FIR wavelength range. KIDs can be used as alternative technology that still have some critical aspects that need to be demonstrated or optimized. Regarding the detector performance, the polarization response is at a very early stage of development, the beam shape on the sky still shows mid to high level side-lobes, and the best sensitivity achieved so far is below that required for a background limited spectroscopic space missions with a cold aperture (<10 K) in the FIR range. Design of new geometries for improving the polarization sensitivity and cross-polarization are key aspects that should be faced.

Additionally, it would be interesting to develop a new family of uncooled radiation semiconductor detectors as well. A new disruptive technology could be developed based on robust wide bandgap device/technology, and even combined with the versatility of novel 2D materials, such as graphene. Wide bandgap semiconductors typically have a better collection of charges induced by several types of radiation, making them attractive for detectors applications. Silicon Carbide (SiC) or SiC-2D technologies (graphene, WS_2, MoS_2...) could address two complementary issues: radiation tolerance and thermal management, while keeping excellent sensing performance or incorporating novel operation principles. For instance, it is foreseen that WBG microdosimeters can be further developed for space application, so that we might better understand the biological effects of space radiation and its effects on human cells in long range crewed mission for future space colonization.

3.3. Challenge 3: Development of a new generation of digital processing units (DPU) for space instrumentation and extreme radiation environment

As it has been pointed out in the previous sections, the development of Digital Processing Units (DPU) based on FPGAs, comprising hardware, firmware and software are a key technology to solve a wide variety of space science challenges. These challenging DPUs based on FPGAs must enable the execution of complex algorithms (image compression, image stabilization, etc.) in real time or almost real time. This is essential to solve some scientific problems which are required to be performed on board due to the limited storage resources as well as the reduced bandwidth available, which does not allow the data transmission to Earth to perform the calculations on ground. Additionally, these DPUs will be the perfect candidate for long-duration missions thanks to their adaptability and fault-tolerant capabilities that will allow them to work under very harsh environments. Despite the excellence reached with the already developed solutions, there is still a wide field to explore regarding innovative architectures and configurations for the new systems based on FPGAs. The computationally highly demanding algorithms to be implemented imply to squeeze at maximum the available resources and this task can only be undertaken by developing new technics for re-configurability and architecture optimization. This challenge is linked with the needs and specifications for control electronics and data treatments of sensing systems driven by challenges stated in Chapters 1 and 2.

It is now widely assumed that conventional CMOS scaling, the well-known Moore’s law, is coming to an end. However, it is also fairly clear that CMOS circuit will not disappear in the mid-term. One path to continue functional scaling is 3D integration, which poses significant challenges for concurrent errors due to a single cosmic ray traversing the stacked layers. Another path is that ultimately scaled CMOS platforms are likely to be complemented with some “exotic” technologies to increase application capabilities. As an example, Spin-Transfer-Torque Magnetic RAM (STT-MRAM) modules are readily produced on CMOS compatible processes and it is only a matter of time that an embedded version appears as an option in standard commercial processes. Other technologies like silicon photonics, memristors, graphene or other two-dimensional layers, may also be adapted for their use as a back-end CMOS process option. Roadmapping beyond short to midterm is quite challenging because the global semiconductor market is orders of magnitude larger than the space electronics market. Not all the possible technologies will make their way to mainstream production and space applications will have to take advantage of the global scale winners, even if others would have been more suitable. Anyhow, the inclusion of new "exotic" technologies will trigger a lot of research in qualification for space, developing appropriate models for temperature, radiation, magnetism, etc.

The variability of ultimately scaled CMOS and the advent of "exotic" technologies is also fostering the research of unconventional computing architectures that depart form Von Neumann's. In-memory computing, spiking neural networks, approximate computing, etc., are all interesting concepts that may find a perfect application in space. Indeed, these computing architectures are thorught to cope with the intrinsic high variability of the technologycal parameters of the devices and imperfect yield, taking advantage of massive parallelism rather than perfect matching. They could thus be inherently resilient to radiation impact or other environmentally induced drifts. Besides, AI applications, which also rely on these architectures, will be a hot topic for space missions in the coming years, be it for computer vision, smart sensing or control applications.

3.4. Challenge 4: Development of harsh environment electronics enabling future long range exploration missions

As already mentioned, two of the main constraints on current semiconductor microsystems employed in on-board electronic are their thermal operation limits and radiation hardness, which worsen to meet the reliability and compactness specifications required by the application. Creating KETs based on new emerging rad-hard materials for low and high temperatures is a requisite to enable these space technology demands. As a consequence, temperature and radiation hard Micro-/nano-technologies and the resulting microsystems are of strategic importance to European space exploration strategy, potentially impacting all areas of activity.

To achieve these goals, a first objective should be to target new family of Rad-hard, High-Reliability microsystems, focusing initially on cosmic radiation monitoring and on energy management of onboard electronic systems. These microsystems could integrate customized sensors for in-situ monitoring and protection, and control front-end electronic circuits by means of heterogeneous approaches. Such complexity requires novel concepts and tailored fabrication processing approaches, as well as specifically designed packages, involving new materials and architectures.

Additional measures for space applications concern energy management through power devices. The relevancy of the power system in a spacecraft is not negligible as it can represent up to 30% of the total mass. As a consequence, novel approaches must be found to reduce power systems mass and volume, increasing power density (reducing losses). One of the main targets would be a fourfold reduction of the system volume and mass, safely lasting over 30 years without replacement and being capable of operating in a vacuum in extreme temperatures and radiation fields. Another objective would be to break the 170ºC junction temperature barrier of current power devices. Overcoming this limit will expand the scientific mission span ambitioned by ESA and, therefore, will contribute to answer the main quests in space sciences. For this purpose, wide bandgap material-based power semiconductor devices for operation at high temperature and high power-density are the only candidates for the viability of future missions. These semiconductors are also more resistant to radiation. SiC MOSFETs, GaN High Electron Mobility Transistor (HEMT) and current limiters are identified in both ESA and H2020 roadmaps and should be our first targets for the short term (10 years). Such devices require novel concepts and fabrication processing approaches (e.g., thin-film-based technologies) to overcome their current thermal limits. Moreover, these semiconductor devices will provide their maximum potential only with a specifically designed package involving new materials and architectures to operate under the aforementioned conditions. Besides, development and validation of specific characterization and reliability tests adapted to the stringent space specifications are still needed and compulsory. For the longer term (15-30 years), other less mature WBGs like Diamond and Gallium Oxide should be explored.

In general, we need to acquire a fundamental understanding of radiation effects on humans, materials and equipment. The limitations of knowledge of the space radiation environment impact on the space science and exploration is affecting the design and operation of future missions and spacecraft. A more fundamental approach consisting in deeply studying the radiation effects on electronics systems and look for mitigation techniques at design and technology levels is compulsory. Space travellers will be irradiated with cosmic rays to a dose rate considerably higher than that received on Earth. In order to make sensible judgements about space exploration, the risks to health of such radiation need to be assessed. Part of the assessment of risk is to allow for the enhanced biological effectiveness of high LET radiations with respect to others. In order to meet these goals, radiation sources must be assessed in order to focus the studies on the worst-case radiation scenario (i.e. higher cosmic ray and solar particle events dose). Then, transfer trajectories minimizing interplanetary radiation should be identified and modelized. Shielding provides a way to prevent astronauts from being exposed to the harsh radiation environment of space. Beyond that, radiation doses can be mitigated by parallel methods such as accurate knowledge of transfer trajectories, definition of an acceptable effects dose threshold and space weather monitoring and warning systems. The development of solid state microdosimetry and nanodosimetry for space applications would allow a better understanding of the biological effect of space radiation and quantify microdose and LET in order to create a RBE model for long-duration space travels. Microsensors of the smallest effective volume developed in semiconductors will establish a new standard for the absorbed microdose measurements. For instance, diamond has some important advantages compared with the often-used silicon, e.g. a better radiation resistance and tissue equivalence. On the contrary, it is very difficult to get high quality material to be used as detector and the Micro-Electro-Mechanical System (MEMS) fabrication is a challenge.

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