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SiC in Space: Potential High-Power Application Survey

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Abstract. The next space missions require power levels that current space qualified semiconductor technology cannot provide. The silicon carbide devices are considered to overcome these challenges, and provide the required technical performance. European space industry is asked in individual meetings about their specific needs and requirements, this information is gathered, classified and presented to the silicon carbide manufacturers. This work is the connection between the two industries to better understand the requirements and applications, and build a new business case for the SiC devices in space applications.

Introduction

The space exploration missions as well as the future development plans of the main space agencies in the world demand several orders of magnitude more power than what is currently available [1], [2]. The European Space Agency (ESA) is pushing for high-voltage (HV) systems to enable the high-power (HP) in space, but this transition is blocked by the operation of electrical, electronic, and electro-mechanical (EEE) components in space, forcing the engineers to apply deratings to the maximum rated values for reliability reasons [3].

On the one hand, the space qualified Si components show poor performance in HP systems, due to their limited blocking voltage and low current level. On the other hand, and even if the GaN devices show unmatched performance there are no available space qualified HV GaN devices yet. Following the trend in terrestrial HP applications, power distribution [4], [5], electric vehicles and traction [6], [7], [8] and aerospace applications[9], [10] for example, space engineers are looking to the SiC as an answer to the technical challenges presented by the new HP applications.

SiC has already been proposed for and tested in space applications with promising results. Improved efficiency and system level performance are achieved in a high input voltage power processing unit (PPU) [11] in a HP PPU [12], and in HV (100 V) distribution systems [13], [14]. Even if the reported results are positive, there is a wide gap on the space market to be covered by SiC, needing a clear effort from the SiC manufacturers to develop and test space qualified SiC components that could be used to achieve the technical figures required in the new HP space applications.

In this paper, the author tries to bridge the existing gap between the SiC manufacturers and the potential end users of their products, the space power industry. By gathering the needs of the main European companies of the space industry, presented firsthand to the author, the potential applications of SiC semiconductors in space are classified, also identifying the main technical drivers required in each one. By doing so, the author presents a new market and potential business case for the SiC manufacturers, guiding them to a better understanding of the needs the space power industry has, and helping the adoption of the SiC technology by the space industry, to finally overcome the challenges of the next HP systems in space.

Methodology

As it is mentioned in the introduction of the paper, this work is carried out in constant communication with the main European space power companies. The work is divided in 5 phases, needing the contribution of the industry in four of them. Fig. 1 summarizes the phases and the number of companies involved in each one of them.

Phase 1, First Contact. During the first phase of the project, the most important space power companies in Europe are identified, together with the key people inside the organizations to stablish the first contact by email. In the communication, the main idea of the project is explained, and the company is invited to an individual meeting with the author. The companies and the key people are selected using the expertise of the most experienced colleagues in ESA, which in some cases even participate in the first communication. The companies are offered to invite any individual colleague or advisor to the meeting, to ensure the information is transferred and received correctly, and most importantly, it reaches the right people inside the institutions. 12 companies are contacted in this first phase.

Phase 2, Individual Meetings. One-hour meetings are set with the companies during the second phase. The first half of the meeting is used by the author to present the project in detail. There, the background of the project, the terrestrial approach and the benefits of the SiC devices are explained. The author also presents the main terrestrial voltage standards and its applications, finishing the presentation with a review of the published radiation testing results and the existing SiC based space systems. A discussion and feedback opportunity opens right after.

In the end of the meeting, the author presents and shares a fill-in form specially designed for the project, which the companies are asked to fill-in and send back to the author. The form is divided in two categories, making a difference between the most urgent needs and future wishes the companies might have. In each category, the companies should name and describe the specific application benefiting from the required new semiconductor devices, explain the technical characteristics of the current solution, describe the main drivers to improve it and make comments on the needed or desired semiconductor characteristics.

The companies are then given time to discuss internally and fill-in the form gathering the needs from different internal departments. Out of the 12 initially contacted companies, 10 answered positively and went through meeting the author in the individual meetings and receiving the fill-in form.

Phase 3, Gathering, Classification and Redaction of the Information. The third phase consists of gathering the information in the filled-in forms, classifying the applications mentioned by all the companies, putting together all the common answers and writing a wide document with all this information. This work is done individually by the author, keeping the confidential status of all the answers.

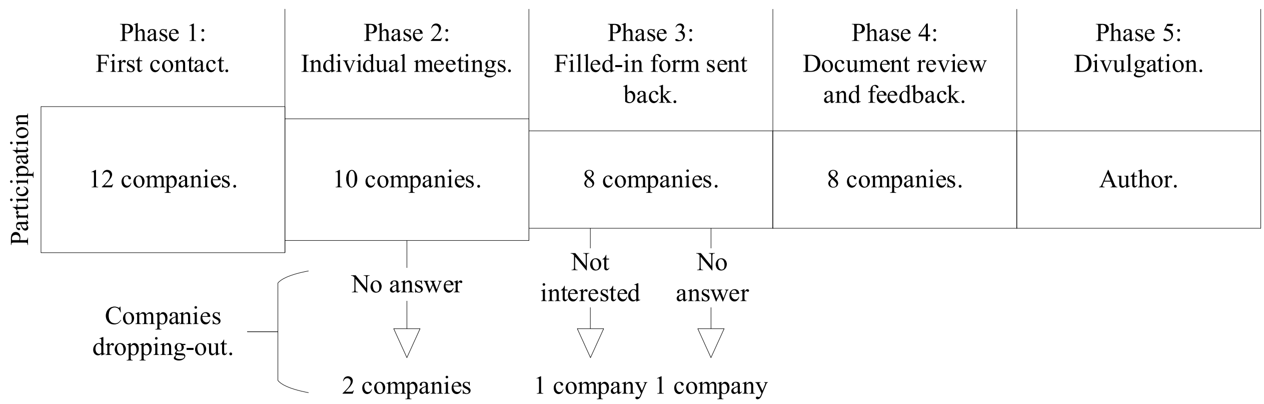

Fig. 1. Summary of the phases of the project, together with the number of companies participating in each phase.

Out of the 10 meetings, one company declined the offer to participate stating their focus is on the lower power spectrum, and the current technology satisfies their needs. Another company participated actively in the meeting, gave positive feedback and even participated in further information exchange during the following months. However, and even if their feedback is considered and used in the following stages of the project, they failed to deliver an organized answer by filling-in the form. The project continues with 8 formal answers out of the 10 meetings, gathering all the information in a document called technical specification document.

Phase 4, Review of the Technical Specification Document. All the 8 contributing companies receive the technical specification document and are asked to check and review it internally. All the companies agree on the content of the document, giving positive feedback to the author.

Phase 5, Divulgation of the Results. The final phase of the project is making the results public, writing technical papers such as this work, and presenting the project in specialized conferences. The main objective of the project, as mentioned in the introduction, is to connect both the SiC manufacturers and the space power industry, so the final phase of the project is equally important to achieve the main objective.

Results

Classification by Industry Requirements. The requirements of the industry clearly divide the applications in two types and are summarized in Fig. 2. In the first case, industry wants to increase the power of existing low-power systems, keeping the performance figures. These application type includes HP distribution, needing HP latching current limiters (LCL), HP DC-DC converters and rectification. A common desire is to increase the voltage of the application, but due to the complexity of the solution, and to be able to reach even higher power, increasing the current is also needed. The considered application voltage for these applications is above 100 V, the higher the better, up to 300 V. Systems up to 100 A are desired. The rectification stage, or the rectifying component in each system should also be considered.

The second application type is looking to improve the performance figures of already existing HP systems. In this application type, we can find HP motor drives, to drive pumps or use in vector thruster control in the launchers.

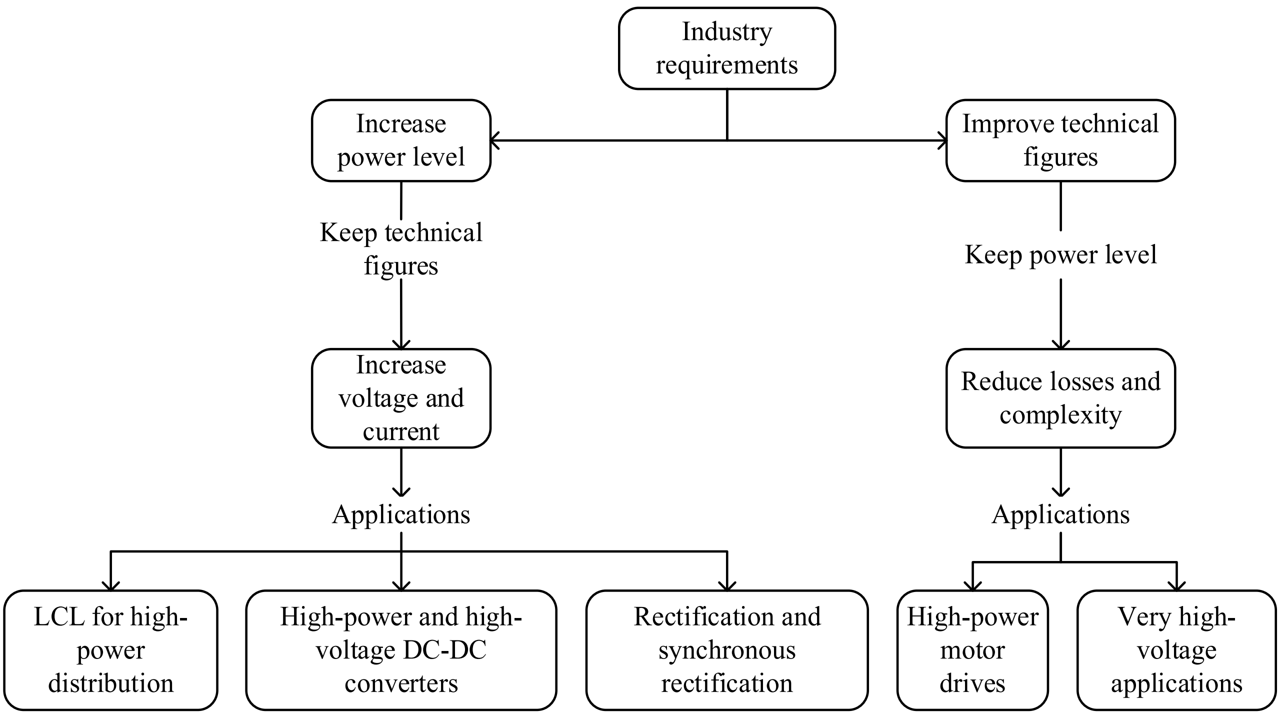

Fig. 2. Application classification by the industry requirements.

These are already existing applications, that operate at HP and in very demanding conditions. Reducing the losses and the complexity of these systems, by reducing the needed number of parallel devices for example is also a requirement for industry. HP motor drives operate at HV, over 100 V up to ideally 1 kV, and consume high-current, over 200 A. Even if industry mentioned the 200 A limit in these applications, further requirements are found to supply up to 400 A for electric motor drives. The final applications are the very HV applications. Covering switches, circuit breakers and diodes. These applications work at over 800 V, but limited current. As their development stage is still preliminary in most cases, the interest shown by industry is also reserved.

Classification by ESA Innovation Categories. ESA classifies innovations in three categories, according to the degree of innovation they bring when compared to the state-of-the-art. Each innovation category brings a different degree of risk for the industry, directly related to the time, cost and effort required for its development, and the possibility of its massive adoption by the end users. This section explains the three innovation categories, and classifies the applications presented before in each one of the categories, shown in Fig. 3.

The first category is called enhancing and refers to innovations which bring a substantial improvement to the state-of-the-art system. It is usually based on a technology replacement, keeping the same features, but improving the performance. In the case of the SiC, this kind of innovation would mean replacing the Si devices in an existing application and optimizing the system to get system-level benefits. Enhancing innovations represent low risk for manufacturers, and the development cost, time and effort should be low. The adoption of the innovation by industry should be straightforward and have high probability of success. Most of the applications mentioned by the industry fall in this category.

The second category is called enabling and refers to innovations which will allow a new feature, new application, or even a new mission. The technologies in the enabling innovation category are considered as critical technologies for a certain feature, application or mission. In the case of the SiC, this means that without the adoption of such devices, the new desired feature, application or mission is no longer possible, due to the limitations of the state-of-the-art technology. Enabling innovations represent medium-high risk for manufacturers, as their development cost and effort is higher, since this new feature, application or mission has never been done before. In addition, its adoption by industry is more challenging, and the probability of success is lower, because the new feature, application or mission in which this innovation is required might be delayed, suffer a significant variation, or even get cancelled in the worst-case scenario. Very HV applications fall in this category of innovation.

The last category is called game-changing and refers to innovations which promise to bring entirely new capabilities. With this kind of innovation, completely new missions could be considered in the future. Game-changing innovations represent high-risk high-reward scenarios for manufacturers, as they would be leading totally unexplored markets. However, the adoption by industry is not even considered yet, leading to high uncertainty in the future markets. Industry is asked to focus on the enhancing and enabling innovations during the meetings, because the main goal of the work is to develop a business case for an early, cost-effective and successful adoption of the SiC technology by the European space industry.

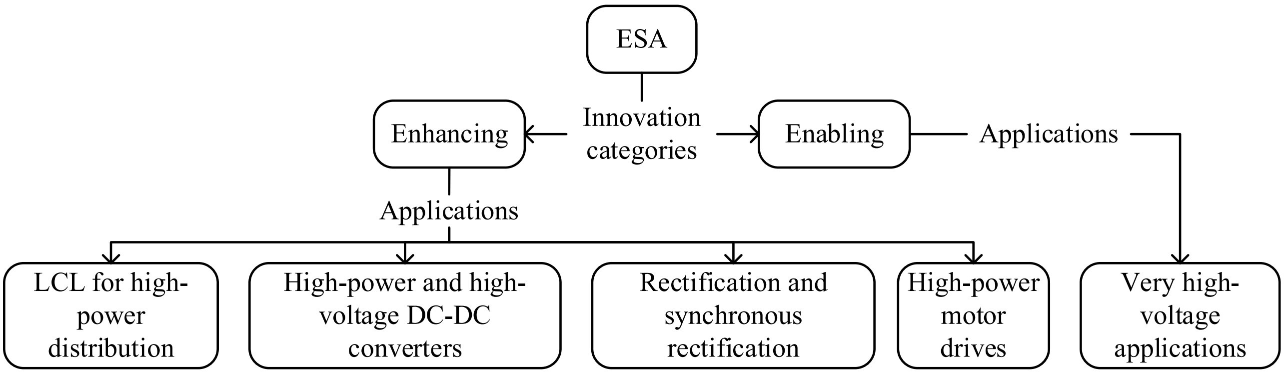

Fig. 3. Application classification by ESA innovation categories.

Main Drivers. Industry is asked to highlight the main technical drivers to optimize in each application. Each application has its own characteristics, so depending on the target application, SiC manufacturers should focus on one or another technical feature to optimize in their product. Fig. 4 shows the main drivers to consider in each application, highlighted in grey, together with the technical requirement to make an impact in each main driver.

Increased current and thermal performance is a main driver for the applications willing to increase the power. With the current level increment, the conduction characteristics gain relevance, being also a main driver for all the enhancing applications. This means industry is looking for devices that are rated at high current and can perform in severe thermal environments, with reduced conduction resistance when compared to the space qualified silicon devices.

For HV and HP DC-DC converters, the switching performance is equally important. The same main driver should also be considered in the rectification and synchronous rectification applications, by optimizing the reverse recovery of the diodes. Due to the limited space qualified drivers, switching frequencies are usually not high in these applications, but pushing to 100 kHz or above is a desire of the industry, if the device technology allows it. With better switching performance than the space qualified Si, this is where SiC becomes key for these switched applications. Even if HP motor drives are also switched applications, the lack of magnetic components such as high frequency transformers or inductors in the topology reduces the interest of increasing the switching frequency to the 100 kHz range. Although a reduction of the switching losses is welcome, the extremely high current of the applications makes the conduction performance more important than the switching in this application.

All the before mentioned improvements should come with a reliable and relatively high blocking voltage capability. Mostly for HP motor drives and very HV applications this is a challenging requirement. Finally, it is worth mentioning that the peripheral technology used in the application should follow the proposed improvements, and the new features should be achieved with space qualified technology. This includes space qualified driving devices for improved conduction and switched performance, and printed circuit boards (PCB) technology for the required high current. The device packaging and connectors are also equally important.

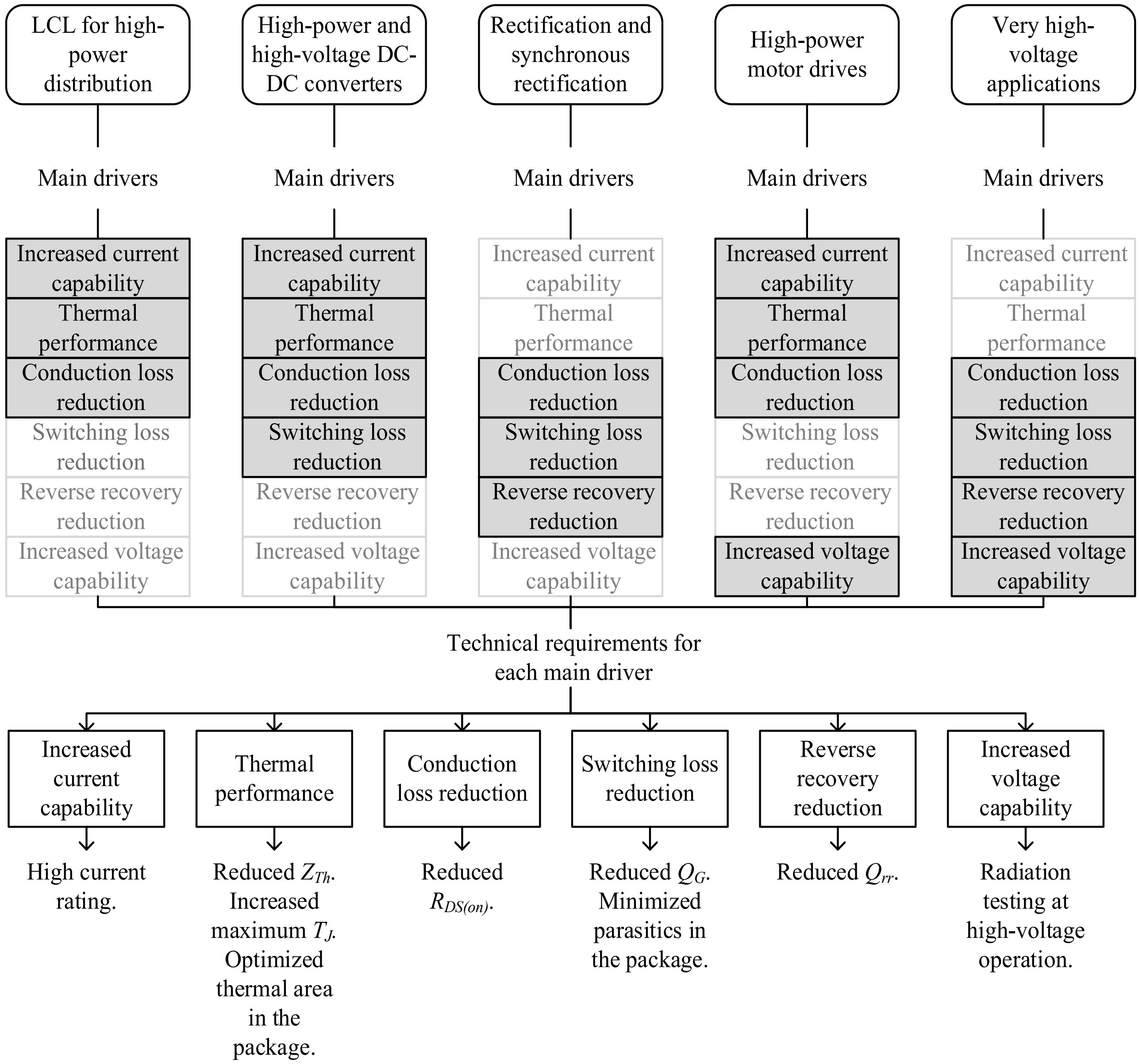

Fig. 4. Main drivers to optimize for each application, with the technical requirements for each main driver.

Radiation. The HV operation of SiC MOSFETs in space is fully connected to the radiation effects, mostly to single event effects (SEE). Extensive testing has shown SiC devices need to be derated in voltage to prevent single event burnouts (SEB), analyzing the phenomenon in detail and proposing several causes [15], [16], [17]. In addition, these MOSFETs can suffer degradation due to SE even at significantly lower blocking voltages [15], [18][19]. The last reported tests show the SEE free voltage limit depends on the nominal blocking voltage of the devices and is related to the epi layer thickness [17], [20].

Table 1 highlights the SEB voltage limit for the maximum tested linear energy transfer (LET) for different rated voltage SiC MOSFETs, based on the available results in the literature. The results show 1200 V SiC MOSFETs, a widely developed voltage standard for the automotive market, is promising to operate in most of the space application voltage levels. If the nominal blocking voltage is confirmed to be related to the SEB voltage limit, the imminent development of several kV SiC MOSFET also suggests very HV applications could be possible in space in the near future [21], [22]. However, and even if this literature review seems promising, the results should be validated by more extensive testing. It is also important to remember the fact that the data presented in Table 1 shows the SEB voltage limit, so more careful study is mandatory to obtain the real SE degradation limits that will meet mission specifications. This is why industry considers qualifying SiC MOSFETs for space applications is necessary to gain confidence and acceptance among the end users in the space market, as the HV capability is still not proven.

Table 1. SEB voltage limit for the maximum tested LET for different rated voltage SiC MOSFETs.

LET	Nominal voltage of the SiC MOSFET [V]				
[MeV-cm^2/mg]	650	900	1200	1700	3300
25		400			
45	300				
60				550	850
65			400		

Packaging. The final technical comment of the industry is regarding the packaging needed to provide the technical requirements. The first concern is regarding the fast switching and the switching performance, which directly relates to the parasitics in the packaging and connections to the PCB. Currently discrete components are used in space, but their interconnection to build most of the power converter topologies such as the buck, boost, isolated bridges and inverters require a half-bridge connection of two discrete devices. Packaging the half-bridge in a single package, optimizing the parasitics and taking the burden or designing a more complicated layout from the designers is considered beneficial by industry.

The second concern is the thermal management of the devices in HP systems. Most of the times, HP means needing to remove several watts from the device, and the thermal coupling of the devices is not always straightforward. Designing HP packages with optimized thermal coupling to the thermal plate of satellites or the cooling system in the module is another requirement from industry. This can separate SiC devices from the extremely miniaturized GaN devices for example and make them the evident choice for HP systems in space. Packaging SiC in space qualified half-bridge modules, with minimum parasitics and optimized thermal coupling is key for their adoption in HV and HP DC-DC converters, as well as for HP motor drives. Some companies also mention HP six-pack modules for three-phase motor drives. Fig. 5 summarizes the different applications mentioned during this work, together with the operation points and the required packages. The vertical arrow represents the switching frequency f_{sw} of each application. For distribution LCLs, for example, no switching is needed, so discrete packaging is preferred. If we advance in the f_{sw}, HP modules show up, some to optimize thermals, in very high current applications, others to optimize the parasitics, in higher f_{sw}. In high f_{sw}, GaN devices should be considered.

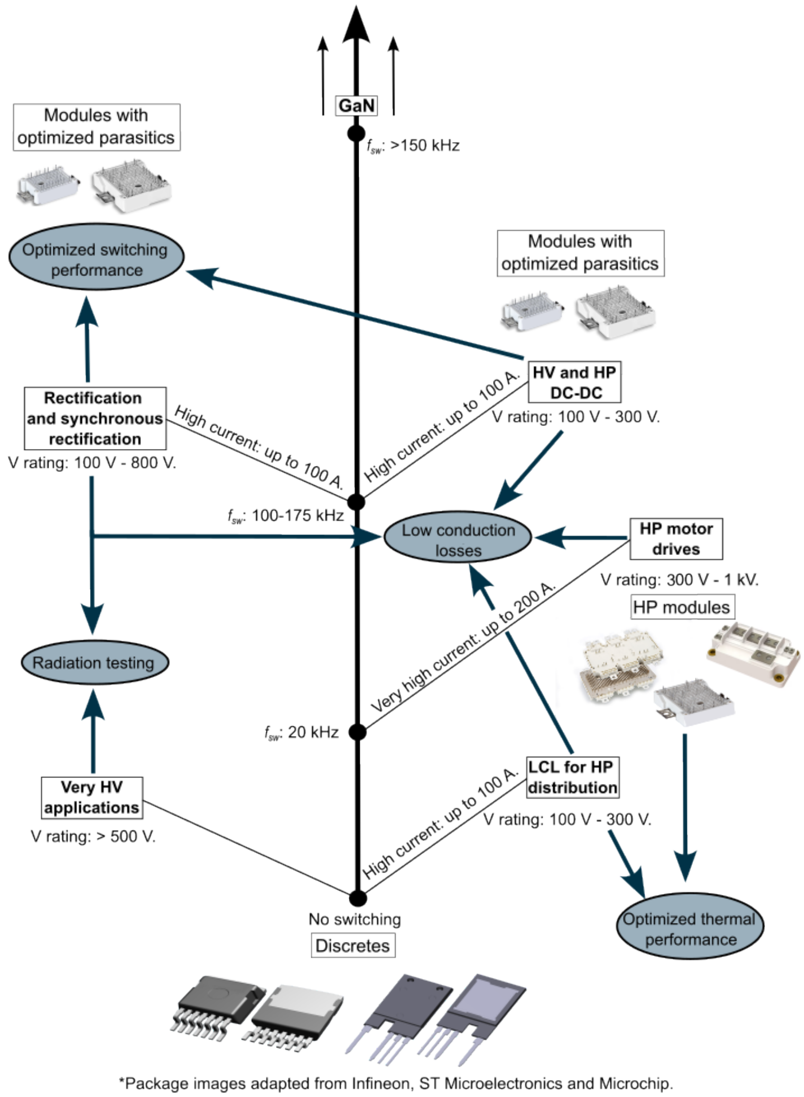

Fig. 5. Required packaging type for each application, depending on the operation characteristics. In blue, the most important technical requirement for each application.

Ongoing Work

As it has been shown in this work, there is interest on the SiC devices for several HP space applications, but industry still needs to find the answer to some technical questions. The operation conditions of the SiC devices in space applications will be very different from those in terrestrial applications. First of all, the voltage will be derated, using at least 1200 V SiC devices in 100 V or 150 V applications. In addition, there are no space qualified drivers optimized for SiC devices, and all the peripheral technology such as PCB connections and capacitor for example also need to be space qualified. The superior performance of the SiC devices in space conditions need to be tested.

This is a work the author is also doing inside ESA. Building conceptual prototypes, the space operation conditions are tested with commercial SiC. In the first prototype, the same space qualified drivers are used to compare the losses of a space qualified Si MOSFET and the losses on a 1200 V commercial SiC MOSFET is space operation conditions. This tests if the better physical characteristics of the SiC devices are still beneficial when severely derating the voltage, and using non optimized drivers. In addition, it tests if the one to one technological replacement will be beneficial in terms of losses, using already available and well known space qualified peripheral technology. The results are favorable and will be available soon.

The second conceptual test is done by using HP half-bridge SiC modules, again with space qualified peripheral technology and space operation conditions. A prove of concept 400 A inverter is designed and tested for motor drives, using 1200 V HP half-bridge commercial SiC modules, but driving them with space qualified drivers. In the design, the performance of the SiC modules with space technology and operation conditions is tested, but it also works as a technology demonstrator, providing a reference design to industry on how to design HP systems, up to 400 A with space technology on a PCB. In addition, the challenges of HP are combined with the challenges the high switching speed of the SiC brings, facing high di/dt and dV/dt rates, all tested in space operation conditions.

All this conceptual tests and demonstrator designs are supported by the launch of the EPOSiC project by ESA. In this project, Europe looks to support the development of space qualified SiC technology by funding the design, development, testing and qualification of a HP half-bridge SiC module, tested and qualified to switch 300 V and 50 A, together with an extended operation temperature range. The project intends to provide the technology requested by industry and gathered in this work.

Conclusion

This paper presents the work done together with the European space power industry, gathering their needs and requirements to tackle the next HP space missions. SiC technology is identified as a potential technology to overcome the HP challenges to come, so the most interesting applications for the SiC are listed, together with the main drivers to optimize in each one. The applications are classified according to the requirements of industry, but also following the ESA innovation categories. This provides SiC manufacturers a clear understanding of the potential applications as well as the development roadmap to follow when targeting a specific application. The author also presents the SiC technology demonstrators developed in ESA to answer the main technology and performance questions industry has.

This work is a connection between the SiC manufacturers and the potential end users of their products, the space power industry. It will help them to better understand the needs the space power industry has, and adapt their products to provide the most desirable technical features. If done, a new business case could open for the SiC devices. It also shows the involvement of the author and ESA in the matter, offering themselves to assist on the adoption of this technology, as well as on the development of roadmaps and product definitions.

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