D3.1 - Selection of Switching-Cell Main Power Semiconductor Devices

SWITCHING-CELL-ARRAY-BASED POWER ELECTRONICS CONVERSION FOR FUTURE ELECTRIC VEHICLES

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Description: Candidate references to be used in the implementation of the SCs. Literature review of WBG power devices state-of-the-art and future trends.

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Executive Summary

This deliverable reports the selection of the optimum power devices for implementing the SCAPE high-voltage switching cells, after a literature review and commercial availability check. In addition to suitable electrical characteristics, the selection of candidates considered the suitability and availability of bare-die components for their subsequent chip embedding process. Two SiC MOSFET references have been selected and samples have been obtained for an initial test campaign (GeneSiC G4R12MT07. 750V – 12 mΩ and Wolfspeed CPM3-0650-0015A. 650V – 15 mΩ). For the development of the low-voltage switching cells of the auxiliary SCAPE converters, GaN HEMTs from EPC will be selected. The deliverable also includes a prospective and literature review about power device emerging technologies.

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Document History

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1. Introduction

The description of the SCAPE deliverable D3.1 ("Selection of switching-cell main power semiconductor devices") stated in the proposal is the following: *Report on the literature review of WBG power devices state-of-the-art, suitable for EV power conversion, as well as on comprehensive review about future trends based on emerging technologies such as diamond or Ga_2O_3. The report will determine the candidate references to be used in the implementation of the SCs (switching-cells)*.

This description was defined taking into account:

- The need for determining the most suitable power devices for the high voltage (HV) SCs to be developed
- Relevant aspects already defined in the project call such as putting the focus on wide band-gap (WBG) semiconductors and performing a research on semiconductor emerging technologies.

It is also worth pointing out that, due to the specificities of the SCAPE project involving new converter concepts and integration solutions, it was foreseen that the main power semiconductor device selection must consider simultaneously (see task T3.1 description of work):

- SC requirements (electrical performances).
- Implementation needs and constraints (chip dimensions and top-side terminal patterns).
- Commercial availability of the parts.

Although D3.1 clearly concerns the high-voltage semiconductor devices to be used in the main SCs (traction inverter, battery charger), SCAPE also involves low-voltage SCs used in the EV auxiliary converters. Although these converters will not involve chip-embedding processes and their selection is not as critical as for the HV components, one section of D3.1 deals with this topic.

2. Switching cell requirements

The development of Task 3.1 ("Design of the converter switching cells") has provided the essential requirements for the main semiconductor switch characteristics. The basic block diagram of the considered SC developed by partners UPC and IREC is shown in Figure 1.a. As it can be observed, the power stage is configured with two transistors in series. S_m operates as the main switch while S_{iF} operates as an "intelligent fuse" (a protection device which is mainly operating in on-state and it is switched-off when a S_m failure is detected). This feature improves the overall robustness and provides additional fault tolerance to the converter.

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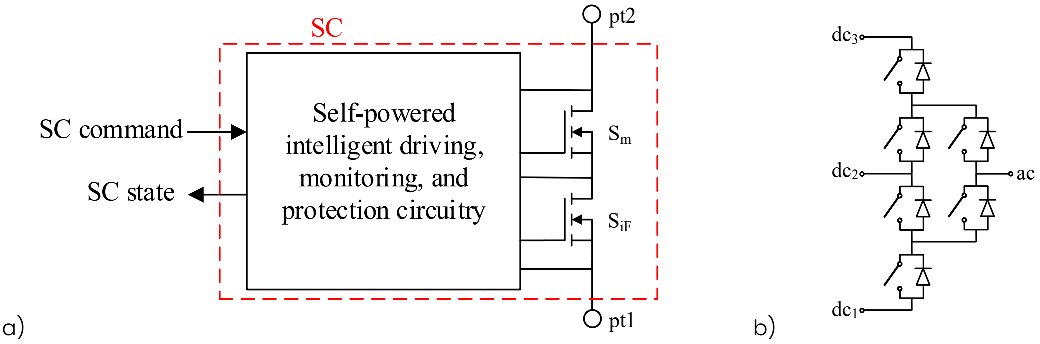

Figure 1. a) Block diagram of a switching cell based on MOSFETs. b) An example of a three-level leg multilevel ANPC topology.

In the project proposal, **SiC MOSFETs** were already considered as the first choice for the HV SCs (main switch). The precise selection of this device and possible alternatives are discussed in detail further on. In any case, due to the complexity of the proposed integration technology (power chip embedding) and due to the present day difficulties for obtaining semiconductors in reasonable delivery times, it has been decided to **use the same device reference for S_m and for S_{iF}**. Although the conduction losses are increased, this drawback can be assumed as present SiC devices show low on-state resistance (R_{on}) values (few tens of mΩ) and, as stated before, the system significantly improves its global performances at a reasonable cost.

Concerning the voltage rating required to the devices, the foreseen battery voltage is in the range of the 400 V for each converter level. Consequently, the most reasonable transistor **voltage rating is the 650 V commercial family** (depending on the different manufacturers, the voltage ratings for our application are in the 600 V up to 750 V range). The **current rating** of the SC could be easily scaled-up by **paralleling the transistors**, although for simplifying the development of the prototypes, a single die solution with enough current capability is preferable.

Finally, as it can be inferred from the three-level leg multilevel ANPC topology shown in Figure 1.b as an example, the SCs must show a freewheeling path represented by the anti-parallel diode connected across the switch. This diode will act at least during the dead-time between switching-on and –off of complementary transistors in the converter legs. SiC MOSFETs allow in general the use of their intrinsic body diodes and in such conditions the problem is solved by using this kind of devices. Nevertheless, special care will be paid to the operation of the MOSFET body diodes in our application in order to prevent or to mitigate possible degradation phenomena due to the bipolar current conduction through the SiC junction, or excessive power losses in the diode. In this sense, the possibility of allowing reverse current conduction through the MOSFET channel or including additional antiparallel SiC JBS (Junction Barrier Schottky) diodes can be always considered as options. The selection of JBS SiC diodes is not as critical as it is the case of the main switch.

3. WBG semiconductors: SiC devices

WGB semiconductor devices and SiC in particular, have reached their technological maturity in many power electronic converter application scenarios [Baliga 2018] [Millan 2014] and are replacing Si-based devices in an increasing number of industrial applications [She 2017].

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The relevance and suitability of SiC devices for EV applications has also been widely reported and demonstrated in commercial products [Matallana 2019]. After an initial period where SiC JFETs and even BJTs where proposed by different manufacturers, now the SiC MOSFET technology is commercialized (mainly in the 1200V range) by different companies. Trench gate-structures are also generalized among the main manufacturers.

Less than ten years ago, the 600V breakdown voltage range was clearly dominated by Si IGBTs, Super-Junction MOSFETs and GaN HEMT transistors due to their superior R_{on} figures [Kaminsky2014]. Recently, new 650V rated voltage SiC MOSFET have been developed and commercialized by several companies, directly competing not only with GaN HEMTs, but also with 600V IGBTs and Super-Junction (CoolMOS) families due to outstanding conduction performances (low R_{on}) and fast-switching capability and low switching losses [Ortiz 2019]. Consequently, t**he selection of 650V SiC MOSFETs seems to be the most logical choice for the SCAPE HV SCs**.

Although lateral GaN-on-Si HEMT transistors could also be considered for the HV SCs in SCAPE, these devices show a more critical thermal management and lower current rating for the nominal powers foreseen in SCAPE potential applications [Roccaforte 2018]. In addition, there is a lack of commercially available 600-650 V GaN bare dies for their integration in an embedding process.

It is also interesting to consider that 600 V Si IGBTs can be foreseen for the SCAPE application. Concerning the static characteristics, last generation Si IGBTs show similar voltage drops than 650V SiC MOSFETs at high current (Figure 2). In case that the required switching frequency is not very high (few tens of kHz), the Si option could be considered [Yuan 2020]. Probably, in this scenario the most limiting factor is the Si-based freewheel diode and its associated reverse-recovery losses and the higher conduction power losses at low currents. The idea of using Si IGBTs in a multilevel traction converter for electric trucks was presented as a good option by Infineon at EPE-ECCE 2022 conference, reinforcing the sense of this approach [Afonso 2022]. The hybrid combination of Si-IGBTs + SiC-JBS diodes could also be a reasonable choice for the SCAPE SCs (e.g. Infineon CoolSiC Hybrid discrete).

In the framework of SCAPE, it is interesting considering these Si-based options as they can be considered as mitigation solutions in case that the selected optimum SiC MOSFET devices cannot be finally acquired.

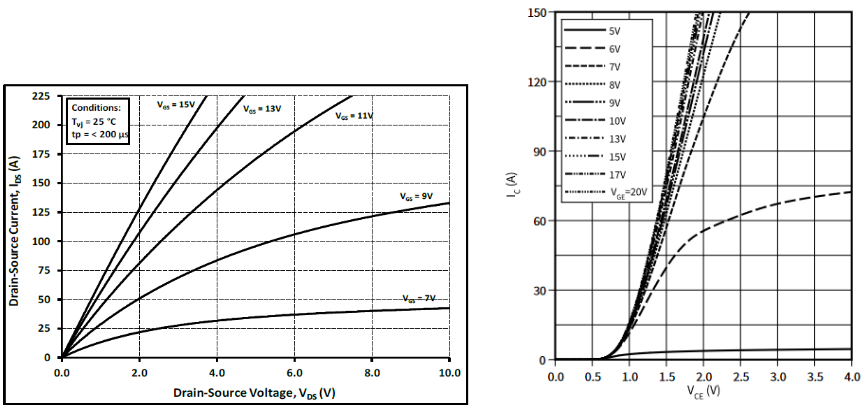

Figure 2. Comparison of two I-V curves for a 650V Wolfspeed SiC MOSFET (left) and an Infineon Si IGBT (right). Their voltage drop at high currents are similar.

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4. Evaluation of candidate samples for the HV SC

The SCAPE partners CSIC and DeepConcept (involved in the integration and embedding tasks of WP4), have looked for SiC MOSFETs bare-die samples in the region of the 650 V in order to verify their suitability and availability for the project.

The main SiC MOSFET manufacturers have been identified and the availability of the interesting references identified from their websites have been checked by online/email contact or direct contact in conferences (such as IWIPS, EPE-ECCE or CAS 2022). A list of the identified manufacturers is shown below, with the URL to their website SiC MOSFET catalog.

Infineon:

https://www.infineon.com/cms/en/product/power/mosfet/

Rohm:

https://www.rohm.com/products/sic-power-devices/sic-mosfet-bare-die

ST:

https://www.st.com/content/st_com/en/campaigns/scth90n65g2v-7-sic-mosfet-650v.html

GeneSiC:

https://genesicsemi.com/es/sic-mosfet/

Wolfspeed/CREE:

https://www.wolfspeed.com/650v-silicon-carbide-mosfets/

On-Semi:

https://www.onsemi.com/products/discrete-power-modules/silicon-carbide-sic

Mitsubishi:

https://www.mitsubishielectric.com/semiconductors/products/powermod/sicmosfet/index.html

Toshiba:

https://toshiba.semicon-storage.com/eu/semiconductor/product/mosfets/sic-mosfets.html

Fuji Electric:

https://www.fujielectric.com/products/semiconductor/model/sic/

Basic Semiconductor:

https://www.basicsemi.com/en/

Other companies such as TT Electronics and Powerex, were also initially considered but soon discarded because they proposed devices for very specific applications outside the SCAPE scope (e.g., high temperature or military applications). Finally, only two SiC MOSFET references revealed to be accessible for evaluation and subsequent purchase:

- GeneSiC **G4R12MT07-CAU.** 750V – 12 mΩ
- Wolfspeed **CPM3-0650-0015A**. 650V – 15 mΩ

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Both references show similar electrical characteristics, described in their respective datasheets, although these ratings are obtained under different conditions, hindering a direct performance comparison. For this reason, in order to undergo an experimental characterization campaign of both references under the same conditions, 4 samples per reference have been packaged in discrete ceramic substrates with the same dimensions and outline than the standard TO-247 package (Figure 3.a). It is worth pointing out that the GeneSiC samples were obtained under an NDA and specific details about their Mechanical Parameters and Chip Dimensions are confidential and cannot be publicly revealed (Figure 3.b).

a) b)

Figure 3. a) CPM3-0650-0015A SiC MOSFET packaged in ceramic substrates for evaluation at CSIC facilities. b) Public G4R12MT07-CAU datasheet section claiming for chip mechanical parameters confidentiality.

Static and dynamic switching tests have been performed for both MOSFET references using a standard curve tracer (250 µs test pulse) and a double pulse test (DPT) set-up respectively.

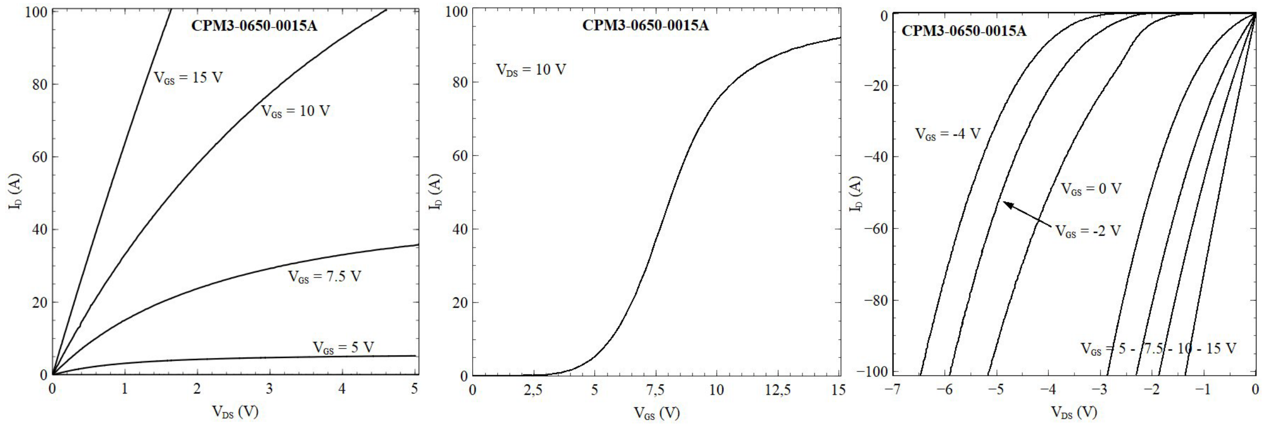

Figure 4. Static I-V curves at 25°C for the CPM3-0650-0015A SiC MOSFET packaged in a ceramic test substrate.

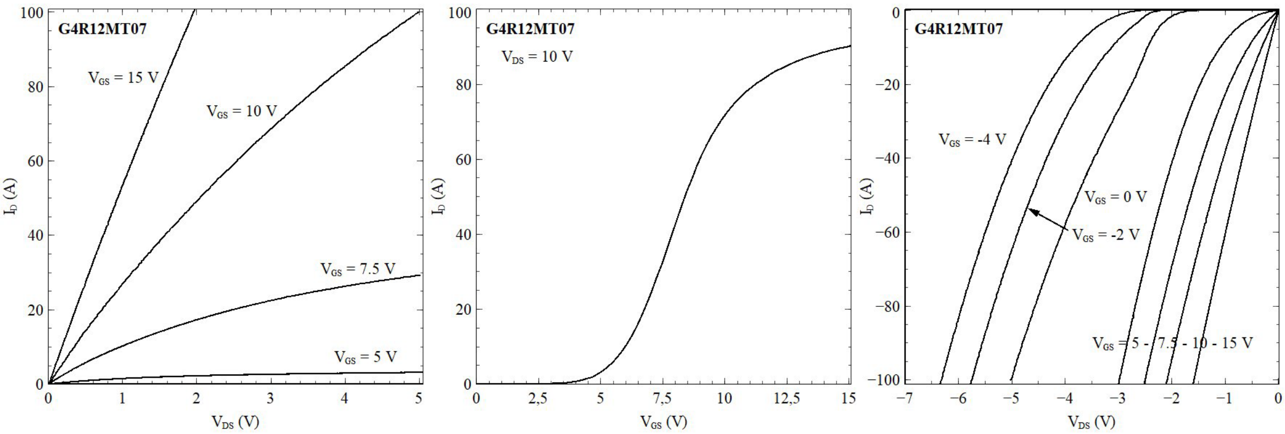

Figure 5. Static I-V curves at 25°C for the G4R12MT07 SiC MOSFET packaged in a ceramic test substrate.

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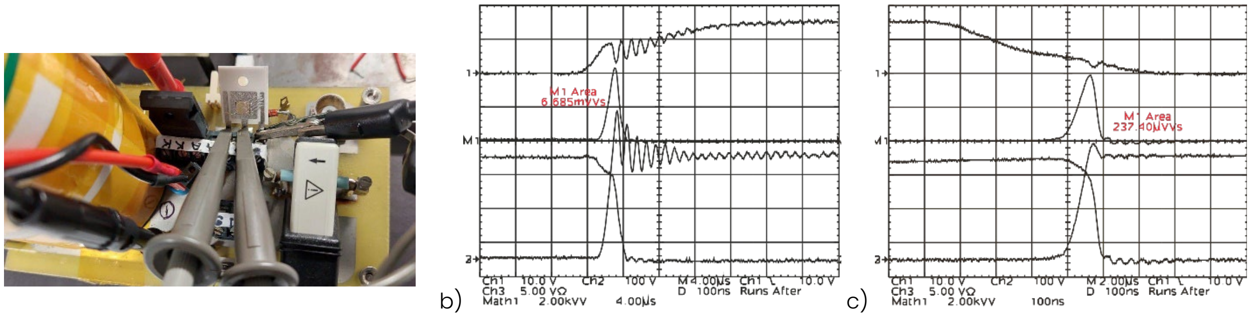

a) b) c)

Figure 6. DPT results for the CPM3-0650-0015A and for V_{BUS} = 300 V, I_D = 15 A, R_G = 10 Ω, V_{GSon} = 15 V, V_{GSoff} = 0 V. a) DPT test setup. b) Turn-on switching processes; from top to bottom, V_{GS}, instantaneous power loss, V_{DS} and I_D. c) Turn-off switching processes; from top to bottom, V_{GS}, instantaneous power loss, I_D and V_{DS}.

The static characterization results performed at 25ºC and shown in Figures 4 and 5 reveal that the two selected references show similar electrical performances, allowing currents high enough for the SCAPE prototypes using single chip SCs. The final thermal resistance of the packaging implementation using the chip embedding approach will limit the maximum current. The R_{on} values obtained for the packaged devices are around 16 mΩ, very low values for transistors in the 650 V range. Finally, it has been verified that the MOSFETs can be operated in the I_D-V_{DS} third quadrant, allowing the reverse current conduction through the channel and bypassing the body diode. This fact allows the reduction of the freewheeling conduction power losses.

In a similar way, the switching tests have shown similar behavior for the two evaluated SiC MOSFETs including the turn-on and turn-off switching losses. One of the most critical analyzed aspects concerned the turn-off behavior of the MOSFETs at V_{GSoff} = 0 V. This feature is critical for multilevel converters implementation where the gate-driving requirements can be alleviated using a unipolar voltage power supply that ensures a turn-on gate-to-source voltage in the 15 V range and a zero turn-off gate-to-source voltage. Figure 6.a shows a picture of the DPT setup used for the switching tests and Figure 6.b shows the turn-on and –off waveforms obtained for the CPM3-0650-0015A (similar results for the G4R12MT07). The dynamic behavior of both MOSFET candidates was suitable for the project purposes, including the turn-off performance at zero gate-to-source voltage.

For the initial assessment of the SiC MOSFET candidates involved in the deliverable D3.1, the measurements carried out have been sufficient to confirm the suitability of the two selected references from Wolfspeed and GeneSiC. A more in depth analysis including additional static and dynamic tests at different temperatures will continue in order to have a full comprehension and modelling of the used devices. This test campaign will be also linked with the robustness tests of Task T5.1.

Finally, regarding the chip dimensions and mechanical characteristics, both devices show suitable features for their subsequent Cu metallization and embedding process: die-size, die-thickness, topside pads patterns and dimensions, materials, etc.

5. Emerging technologies

Among the different emerging power device technologies, perhaps the one that could efficiently replace SiC and GaN-on-Si in the shorter term is based on vertical GaN devices (using bulk monocrystalline GaN wafers). This technology is very promising and will directly compete with SiC

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MOSFETs. Many technological fabrication processes must be still solved (such as p-type implantation) [Oka 2019] [Gupta 2022] [Amano 2018].

Ultra Wide Band Gap (UWBG) semiconductors (with band-gap energies E_g > 4 eV, higher than SiC or GaN E_g values) are in general very suitable materials for developing power devices. At present, the most relevant UWBG materials are diamond, Gallium oxide (Ga_2O_3) and AlGaN and related nitrides. AlGaN is mainly oriented to lower power applications than diamond and Ga_2O_3 [Higashiwaki 2021].

Diamond is sometimes considered as the ultimate semiconductor due to its outstanding physical characteristics (critical field, thermal conductivity, E_g, mobility, etc.). Nevertheless, although big research efforts have been devoted for years, there are still many technological and manufacturing challenges to be solved, such as good quality p-doped material, dielectrics, etc. Another critical limitation for diamond is the low availability and high cost of commercial (large area) and high quality substrates. Diamond potential seems to be promising for very high voltage and power applications (grid) in the long/medium term [Donato 2020] [Geis 2018] [Masante 2021].

Another promising UWBG semiconductor is Ga_2O_3. One of its main advantages is that single-crystal bulk substrates can be synthesized using several standard melt growth methods, in a more cost-effective process than diamond, SiC and GaN. Low thermal conductivity is a serious potential weakness of Ga_2O_3 and will be one of the most important research challenges to address. Vertical transistors and diodes operating at the voltage range of higher than 3 kV will be the main target for Ga_2O_3 power devices [Higashiwaki 2017].

6. Low-voltage SC: GaN devices

As stated before, SCAPE will develop optimum low-voltage auxiliary converters requiring low-voltage power devices (below 100 V breakdown voltage). In this application range and considering mainly the optimization of performances (high power density, efficiency, etc.) and any other aspect (such as cost), GaN-on-Silicon HEMTs are the best option [Musumeci 2021]. Although GaN HEMTs technology experienced significant improvements in recent years, the research efforts have been mainly addressed to increase breakdown voltages, and to improve the reliability of the devices [Flak 2016] [Amano 2018]. During all these years, the US based company EPC consolidated a catalogue of stable and efficient "low voltage" normally-off GaN HEMTs in the 15 V to 300 V range which have become in practice the natural choice for highly-compact highly-efficient power converters. In the framework of the low voltage SC of SCAPE, once definitive breakdown voltage and current ratings are defined, the selection of the optimum devices will focus on the EPC catalogue (https://epc-co.com/epc/).

7. Conclusions

The target of this deliverable was the selection of the optimum power devices for implementing the SCAPE SCs, after a literature review and commercial availability check. Additional to suitable electrical characteristics, the selection of candidates considered the suitability of bare-die components for their subsequent chip embedding process and their availability. Two SiC MOSFET references have been selected and samples obtained for an initial test campaign (GeneSiC G4R12MT07. 750V – 12 mΩ and Wolfspeed CPM3-0650-0015A. 650V – 15 mΩ). For the development of the low-voltage SCs of the auxiliary SCAPE converters, GaN HEMTs from EPC will be selected. The

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deliverable includes also a prospective and literature review about next power device emerging technologies.

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