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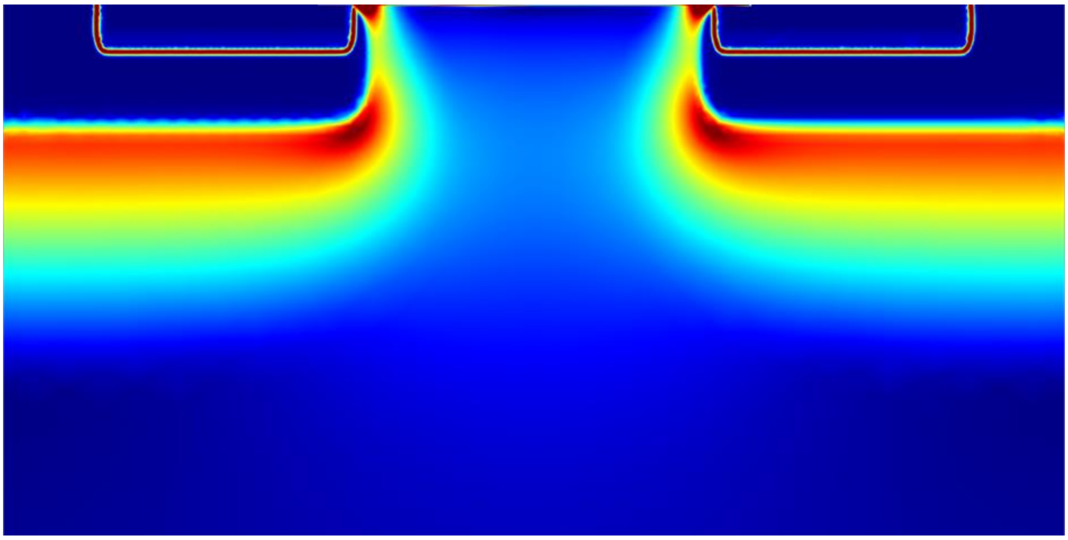
New power electronic materials and devices and its impact on the energy efficiency

Assessment Study for 4E Annex preparation



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The author of this report bears the entire responsibility for the content and for the conclusions drawn therefrom.

Context of this report

In the beginning of 2017, a new Annex to the IEA 4E TCP (Technology Collaboration Program of Energy Efficient End-Use Equipment) has been planned. The Power Electronic Conversion Technology Annex (PECTA) is designed as a platform to assess the efficiency benefit of using the emerging WBG technology. The overall goal includes collecting and analysing information about the new WBG-based power devices and electronics, coordinating internationally acceptable approaches that promote the WBG-based power electronics and developing greater understanding and action amongst governments.

This report is part of the PECTA preparation and by no means a technical publication. Based on this report the documents for PECTA have been elaborated and submitted to the 4E Executive Committee (ExCo).

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1 Technical Background

1.1 Power Electronics and its Applications

Terminology

The term “power electronics” is frequently used as an umbrella term for a system providing connection between power generation and power consumption. Depending on the specific case, “power electronics” may refer to the systemic interfaces, such as dc/dc converters, rectifiers, inverters, or to the components of such systems, namely semiconductor switches and rectifiers, auxiliary components, such as inductors and capacitors or transformers and control units. Within this report, the term is used as a synonym for systems being capable of flexibly and efficiently controlling the actual consumption of electrical energy in applications while specifically using semiconductor technology for such transmission in contrast to systems merely transmitting or consuming electrical energy using transformers or fixed frequency motors, for example. “Power electronic devices” in the context of this study is reserved for the active semiconductor components, such as semiconductor switches.

Introduction to Power Electronics

The main task of power electronics is control and conversion of electrical power from one form to another with high efficiency, high availability, small size, light weight, and low cost by operating power semiconductor devices in switching mode. With the requirements for handling a wide range of powers, from milliwatts to gigawatts, with minimized energy waste, power electronics systems have a huge impact on modern society in many aspects from the living standard, industrial revolution, to the reduction of greenhouse gas emission.

Power electronics is a multi-disciplinary field constituting of a set of sub-technologies: power semiconductors, packaging, passive components, power switching networks, electromagnetic design, cooling concepts, manufacturing, sensor/control technology, and physical environmental impact technology[1]. Over the years, the improvements in these constitute technologies have led to more advanced power electronics[2]. The power switching network technology including converter topologies and switching strategies has been developing continuously since the beginning of power electronics era, which can be related to the invention of vacuum tubes operating as electronically variable resistances[3,4]. Nowadays, power semiconductor switches, such as metal-oxide semiconductor field-effect transistors (MOSFETs), power diodes, and insulate gate bipolar transistors (IGBTs), represent the basic elements of power converter systems, and hence, directly influence the efficiency of energy conversion within the soft and/or hard switching operation[5]. In addition, many types of dc-to-dc, dc-to-ac, ac-to-dc, and ac-to-ac converter systems have been developed, and adopted as classical power converter topologies for various low-, medium and high-power applications ranging from consumer

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[1] J. D. van Wyk ; F. C. Lee, On a Future for Power Electronics, IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 1, no. 2, pp. 59-72, 2013.

[2] J. W. Kolar et al., Performance trends and limitations of power electronic systems, Proc. of 6th International Conference on Integrated Power Electronics Systems (CIPS), 2010.

[3] H.J. van der Bijl, The Thermionic Vacuum Tube and its Applications. New York, NY, USA, McGraw-Hill, 1920.

[4] E.D. Owen, Origins of the Inverter, IEEE Industry Applications Magazine, vol. 2, no. 1, 1996.

[5] R. W. Erickson and D. Maksimovic, Fundamentals of Power Electronics (Second Edition), New York, US, Kluwer Academic Publishers, 2004.

electronics[6] , electrical vehicles[7] , industrial applications as e.g. variable speed drives[8] , ac and dc current transmission systems[9] , space applications[10] , and power-grid applications[11] . As an example of power electronic system, a block diagram of a switched-mode power supply for ac-dc rectifier applications is shown in Fig. 1. The switching frequency typically in the range from 10 − 20 kHz up to hundreds kHz [12].

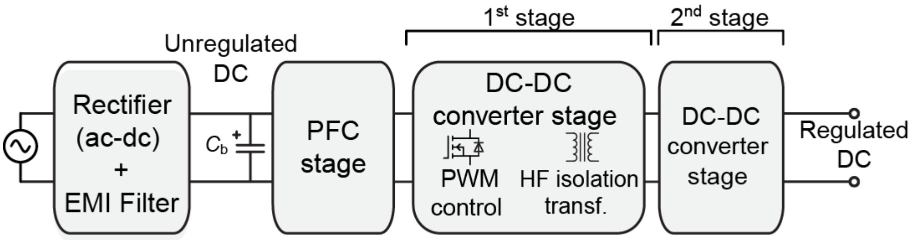

Fig. 1 Block diagram of switched mode power supply in ac-dc rectifier applications with power factor correction (PFC) stage: the AC voltage is rectified to unregulated DC voltage directly off the AC power line with no isolation transformer, then filtered via a balk capacitor C_b and processed with a DC-DC converter to a regulated DC output voltage (load), i.e. “chopped“ by a power semiconductor switch operating at a fast switching rate. An isolating DC-DC converter stage, e.g. flyback, forward, push-pull, etc., is used to provide isolation between the AC power line and the load.

Together with reducing the switching and conduction losses of power semiconductor devices, another challenge of controlling the energy flow by the switching operation of power devices is the generation of voltage and current signals consisting of not only the selected frequency component but a spectrum of unwanted frequency components. This is in turn characterized by power quality factor (total harmonic distortion factor) and/or the levels of generated electromagnetic interference (EMI). As a result, special techniques have been employed to reduce the unwanted signals flowing on the source-converter-load path. Besides the switching control strategies, converter topologies and filters, the electromagnetic design including the selection of components, their placement and circuit parasitics is of high importance for achieving a desired signal quality and compliance with the electromagnetic compatibility (EMC) standards. Furthermore with the existing trends towards higher power density and higher efficiency, both electromagnetic and thermal designs become more difficult, with increased

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[6] S. Mishra, Power Converter Systems for Consumer Electronics Devices, Proc. of IEEE International Symposium on Nanoelectronic and Information Systems (iNIS), 2016.

[7] C. C. Chan and K. T. Chau, An Overview of Power Electronics in Electric Vehicles, IEEE Transaction on Industrial Electronics, vol.44, no. 1, pp. 3- 13, 1997.

[8] B. K. Bose, Variable frequency drives-technology and applications, Proc. of IEEE International Symposium on Industrial Electronics Conference Proceedings, 1993.

[9] J. M. Maza-Ortega et al., Overview of power electronics technology and applications in power generation transmission and distribution, Journal of Modern Power Systems and Clean Energy, vol. 5, no. 4, pp. 499-514, 2017.

[10] M.D. Kankam, A Survey of Power Electronics Applications in Aerospace Technologies, 36th Intersociety Energy Conversion Engineering Conference, 2001.

[11] M. Claus, K. Uecker, and D. Retzman, Power Electronics for Enhancement of Grid Efficiency, Special reprint from BWK – Das Energie-Fachmagazin, vol. 60, no. 11, pp. 6-13, 2008.

[12] T. Reimann and M. Scherf, Frequency Optimum of Semiconductor Technologies and State-of-the-Art Magnetic Components on SMPS, Proc. Of 10th International Conference on Integrated Power Electronics Systems (CIPS), 2018.

electromagnetic and thermal coupling effects. There, virtual prototyping based on accurate and computationally efficient modelling tools is seen as a disruptive technology, which will enable engineers to consider simultaneously electromagnetic, thermal and mechanical aspects before expensive hardware prototyping of power converters[13].

While industry typically strives for the most cost effective solutions, long-term reliability can be another driving factor in the applications where the maintenance and replacement imply high costs or safety is affected, as e.g. power supplies of space stations, satellite power systems, and more-electric aircrafts. The application requirements in terms of functionality, efficiency, power quality, EMI/EMC, reliability, and cost, determine the power electronic system design. For example, the modular multi-level converter (MMC) topologies become more attractive in medium- and high-voltage high power applications, such as e.g. motor drives. MMCs enable high voltage blocking capability with excellent harmonic performance (i.e. low total harmonic distortion - THD) by stacking modular power building blocks consisting of power devices and capacitors. Higher number of levels within the output voltage waveform generated by MMCs leads to lower THD factor and reduced dv/dt stress on the motor windings insulation in motor-side converters. The output filter requirements for the attenuation of the motor windings insulation stress are greatly reduced; however, a high number of power devices and capacitors can potentially lead to reduced overall reliability and system efficiency. Finally, the total system costs and reliability have to be analyzed to evaluate the trade-off between good harmonic performance, and the reduced cost and size of the output filter, versus the increased control complexity, cost and volume of power devices and capacitors in the selected MMC topology[14]. Accordingly, the full utilization of both mature and developing technologies in power electronics can be only achieved by multi-objective system optimization, identifying the Pareto front of power converter systems with optimized performances based on the parameter space of existing topologies, available power semiconductor devices, energy storage components, etc.[15].

Nowadays, the huge potential of power electronics is recognized in highly efficient exploitation of renewable energy resources that will allow meeting ever-increasing global energy needs, and decreasing the global warming effects. Following the stringent environmental regulations, the application of power electronics has been spreading very fast, from the automotive and traction applications, uninterruptible power supply (UPS) systems, photo-voltaic (PV) and wind-power converters, motor drives, more-electric aircrafts, to high-voltage direct current (HVDC) transmission systems and smart-grids. The on-going technological change from silicon to wide-bandgap semiconductor devices in 21st century, new integration and packaging technologies, more advanced cooling mechanisms and optimized topologies, will shape power electronics in the future[16].

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[13] J. Biela et al. Towards Virtual Prototyping and Comprehensive Multi-Objective Optimisation in Power Electronics, Proc. of Power Electronics Technology Conference (PCIM), 2010.

[14] H. Abu-Rub et al., Medium-Voltage Multilevel Converters—State of the Art, Challenges, and Requirements in Industrial Applications, IEEE Tran. On Industrial Electronics, vol. 57, no. 8, pp. 2581-2596, 2010.

[15] R. Burkart, Advanced Modeling and Multi-Objective Optimization of Power Electronic Converter Systems, Diss. ETH No. 23209, ETH Zurich, 2016.

[16] ECPE Position Paper on Next Generation Power Electronics based on Wide Bandgap Devices - Challenges and Opportunities for Europe, 2016.

Power Electronic Applications

Traditionally, systems such as motor drives have been limited to a fixed frequency. With the introduction of the first power electronic systems, motor drives have been developed towards variable speed drives, capable of adjusting the motor speed to the needs in the application and the current load condition. With this capability, the motor itself can be operated more efficiently and, hence, requires less overall energy

.

Frequently discussed applications for such variable speed motor drives are heating, ventilation and air conditioning (HVAC) systems, machinery in factories (commonly referred to as industrial drives), motor drives for mobility applications (from bicycles to vehicles such as cars, locomotives, planes), or wind turbine motors for generation of electrical power.

In building technology, power electronics plays an increasing role for lighting and energy-efficient home appliances.

Charging is a vastly increasing field of activity – while most consumer electronics has become more mobile with domestic voltage levels (220 and 110V converted to 5 … 20V) being used for charging of laptops or cell phones, charging of personal vehicles (electrical vehicles) is now being one major emerging application space.

On the power generation side, power electronics is instrumental when connecting photo-voltaic or wind power installations to an electrical grid or directly to a site of consumption. As the generation of electrical power is fluctuating, the connecting power electronic systems needs to be capable of following these fluctuations.

With the development of the electrical grid towards inclusion of renewable energy sources on the one hand and the more elaborate use of electrical energy on the other hand (more efficient and specific consumption leads to less steady consumption levels), there are new challenges for the actual design and operation of electrical grids. The frequently used term “smart grid” refers to the capability of measuring and actively controlling grid operations – a capability which is closely tied to power electronic systems being utilized in the interfaces of the different grid units.

Power electronic applications can be summarized in at least two ways – one more descriptive showing the path of power from generation to consumption and one more on the technical level, grouping the applications dependent on their power and current/voltage ratings and the operating frequency. In Figure 2, power electronics applications are being depicted depending on their position within the path of electrical energy[17].

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[17] F. Blaabjerg, D. M.Ionel, Renewable energy devices and systems—state-of-the-art technology, research and development, challenges and future trends. Electr. Power Compon. Syst. 43(12):1319–1328, 2015.

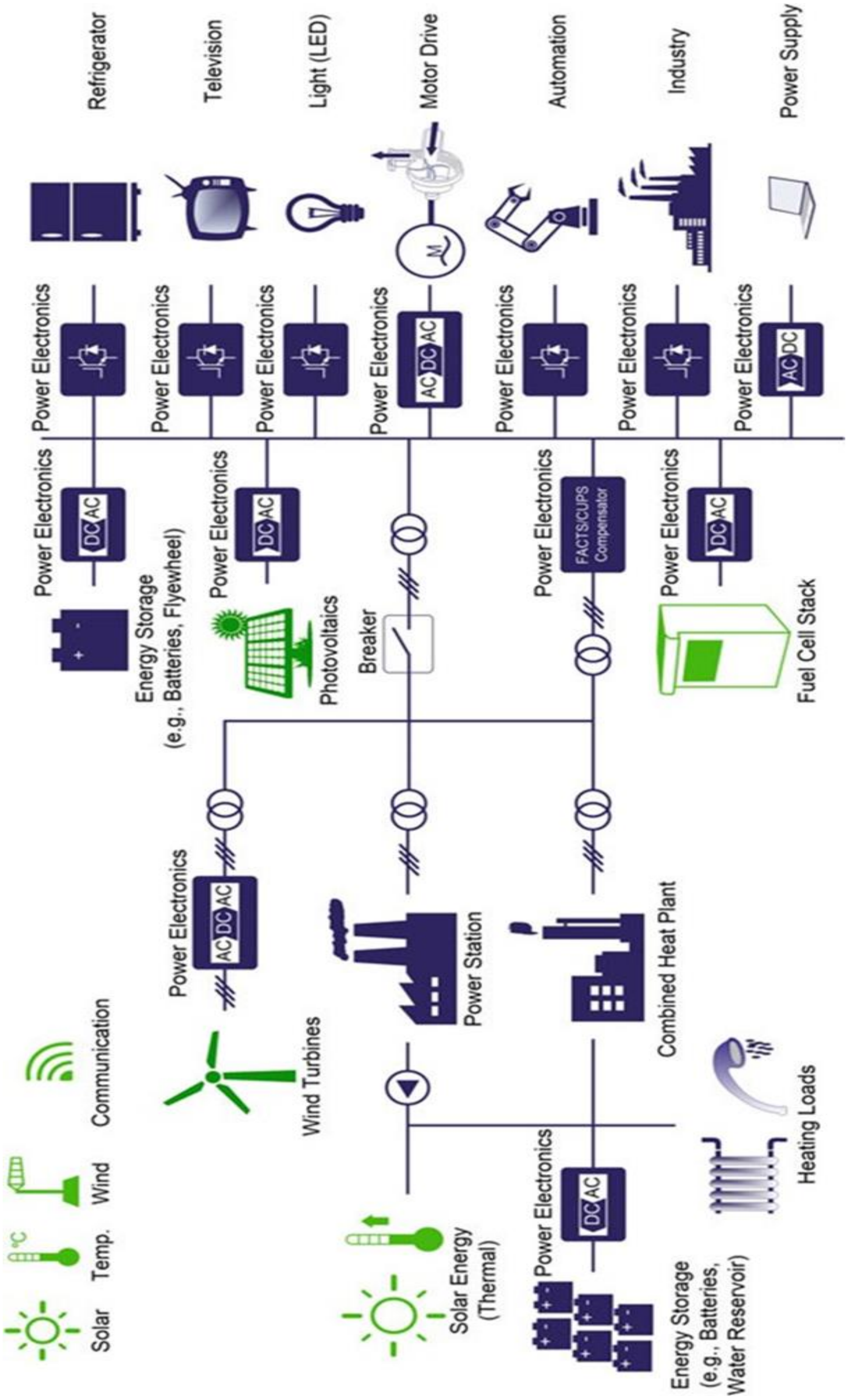

Fig. 2 Schematic representation of a modern energy system, which incorporates renewable energy sources, distributed generation, and smart grid functions. Integration is made possible through the extensive use of power electronics[17].

It can clearly be seen that power electronics plays a vital role in energy-efficient energy transmission from the generation of energy, especially using time-variant energy sources, such as renewables (solar and wind) to the consumption in industrial as well as consumer electrical systems.
In the following, the materials for power electronic devices as well as the common device structures are being discussed.

Fig. 3 shows the typical power rating and the typical operating frequency for selected applications[18]. From this overview, one may deduct both certain types of devices as well as material of choice. The type of power device used in an application is furthermore dependent on the component of current and voltage from which the power is resulting. This important aspect is depicted in Fig. 4, also from Ref. 18.

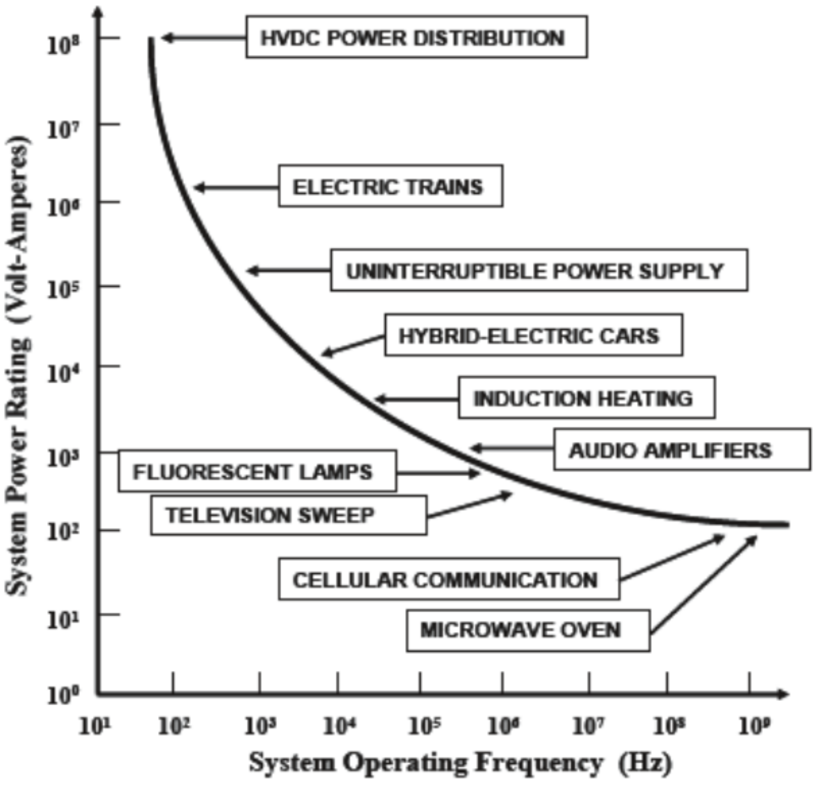

Fig. 3 Power electronics applications as a function of operating frequency[18].

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[18] B.J. Baliga, Fundamentals of Power Semiconductor Devices, p. 2, doi: 10.1007/978-0-387-47314-7_1, © Springer Science + Business Media, LLC 2008.

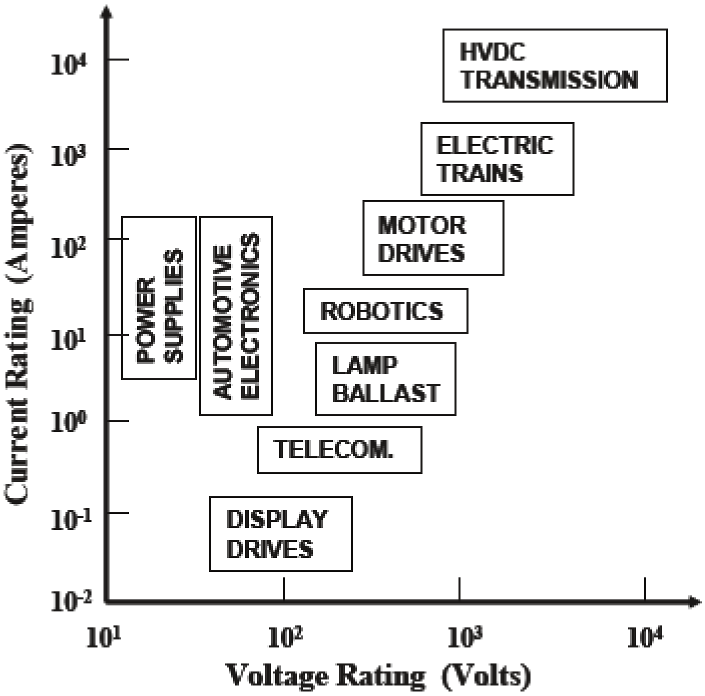


Fig. 4 System ratings for power devices[18].

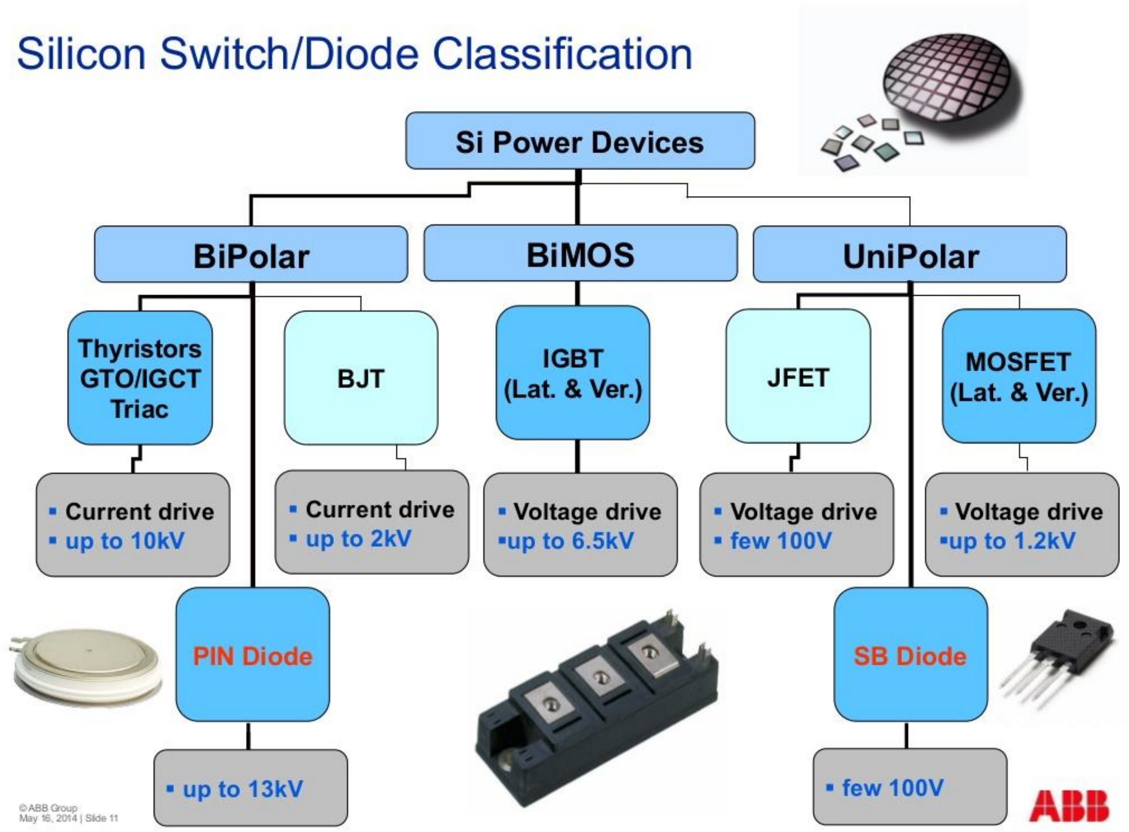
High voltages and low currents typically are provided by unipolar devices (one type of charge carrier only, most often electrons as they usually possess a higher mobility), whereas high current ratings are often demanding so-called bipolar devices (the current is constituted of both types of charge carriers, electrons and holes).

1.2 Power Semiconductor Devices and Materials

As discussed above, power devices are characterized by a voltage and a current rating. Typically, they are grouped in so-called voltage classes. In general, devices can be distinguished in bipolar and unipolar devices, where bipolar devices provide high currents and unipolar devices good switching characteristics. For vertical devices, i.e. the top of the devices serves as one terminal (for unipolar devices called source), the bottom as the other (also called drain), the voltage scales with thickness of the semiconductor die, the current scales with the area of the device. A so-called gate, providing control over operation is typically placed on the top side.

The devices types typically discussed for power electronics are the thyristors (also called Gate Turn Off thyristor –GTO or Integrated Gate Commutated Thyristor – IGCT), Bipolar Junction Transistor (BJT), Integrated Gate Bipolar Transistor (IGBT), Junction Field Effect Transistor (JFET), and Metal Oxide Semiconductor Field Effect Transistor (MOSFET). All of these serve as switches, they are controllable – either by current or by voltage. The power electronic circuit is typically also containing diodes, non-controllable components providing blocking behavior into one direction and current flow into the other direction of applied voltage. As switches, diodes maybe either uni-polar (utilizing a metal to provide a barrier – Schottky barrier diode - SB), bi-polar (PiN diode) or of mixed type (Junction Barrier Schottky – JBS, or Merged PiN Schottky (MPS).

Fig. 5 shows power semiconductor devices based on silicon (Si) classified in terms of their charge carrier type and their control (current driven or voltage driven)[19]. For each device a maximum voltage rating is indicated.



Silicon Switch/Diode Classification

Si Power Devices

BiPolar

BiMOS

UniPolar

Thyristors GTO/IGCT Triac
- Current drive
- up to 10kV

BJT
- Current drive
- up to 2kV

IGBT (Lat. & Ver.)
- Voltage drive
- up to 6.5kV

JFET
- Voltage drive
- few 100V

MOSFET (Lat. & Ver.)
- Voltage drive
- up to 1.2kV

PIN Diode
- up to 13kV

SB Diode
- few 100V

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Fig. 5 Power devices based on silicon with the respective voltage ratings[19].

For applications that require low voltage and current ratings, but high switching speeds, MOSFETs are the best choice. Due to their unipolar character, their switching speed is very high. In order to reach higher voltage ranges with MOSFETs, either advanced technologies as the super-junction design or wide bandgap materials such as silicon carbide (SiC) or gallium nitride (GaN) have to be used. When a lower switching frequency but a higher current is required, IGBTs are the device of choice. Since they provide both, electrons and holes, as charge carriers, they are able to conduct a large current even at high voltage ratings. Thyristors, which are often designed as single wafer devices, are used in applications where several kA and kV are needed. Due to their very low switching speed, they are typically applied in AC circuits operated at line frequency (f = 50…60 Hz). In Fig. 6, different device types are shown and their main applications depending on their capacity and operating frequency are indicated[20].

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[19] M. Rahimo, CAS-PSI Special Course Power Converters, Baden, Switzerland, 2014. https://www.slideshare.net/huy1983/rahimo

[20] J. M. Park, Novel Power Devices for Smart Power Applications, Ph.D. thesis, TU Wien, 2004.

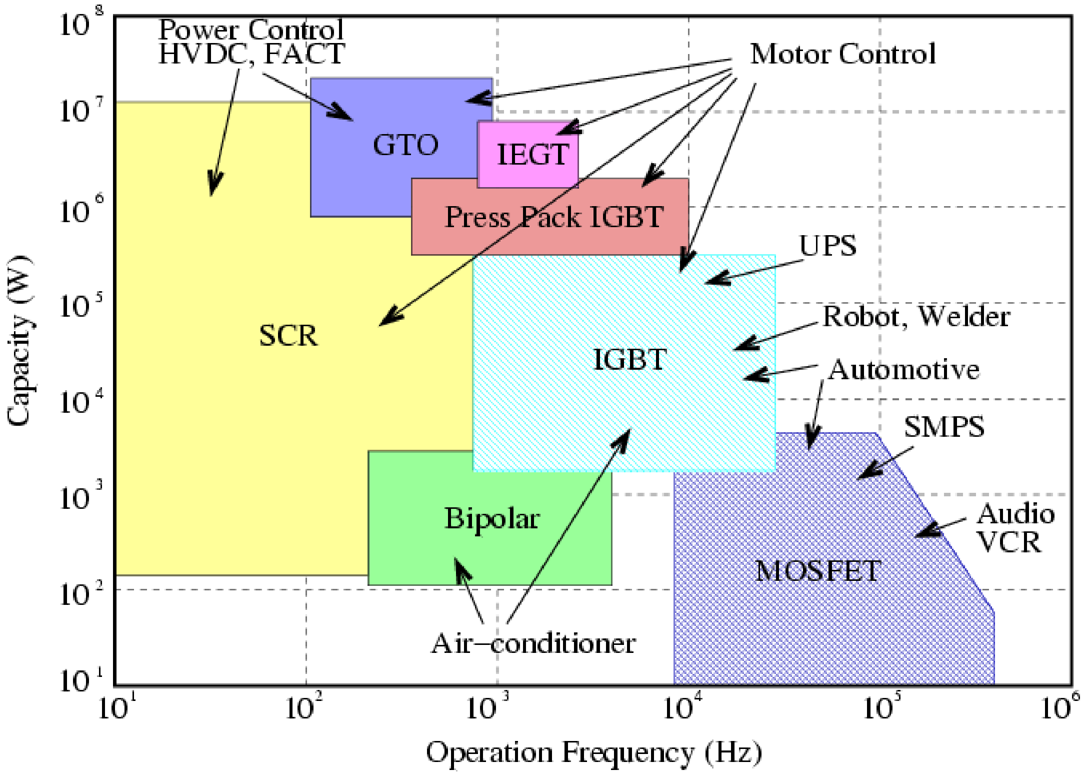
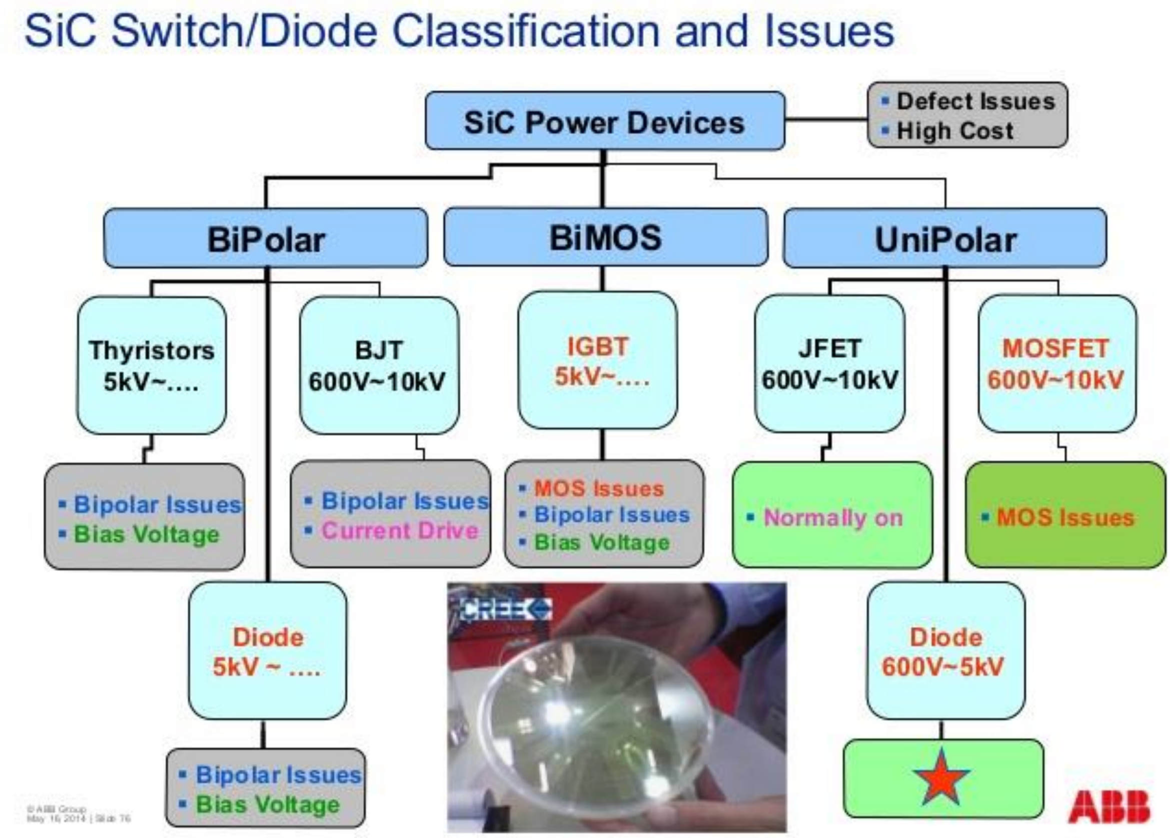


Fig. 6 Power devices and their applications in different areas[20].

In order to reach higher voltage ratings, and thus to enter new application areas, the use of wide bandgap semiconductors was suggested[18]. Due to their large bandgap they offer high critical electric fields. SiC is one of the most investigated and promising wide bandgap semiconductors. Already several commercial devices as Schottky diodes and MOSFETs exists. Fig. 7 shows the classification of different power devices based on SiC[19]. In addition to the control type, the remaining challenges are stated. For example, in PiN-diodes bipolar degradation (voltage drift under forward bias due to formation of stacking faults) is not entirely overcome yet.



SiC Switch/Diode Classification and Issues

SiC Power Devices
- Defect Issues
- High Cost

BiPolar
- Thyristors 5kV~....
  - Bipolar Issues
  - Bias Voltage
- BJT 600V~10kV
  - Bipolar Issues
  - Current Drive
- Diode 5kV ~ ....
  - Bipolar Issues
  - Bias Voltage

BiMOS
- IGBT 5kV~....
  - MOS Issues
  - Bipolar Issues
  - Bias Voltage

UniPolar
- JFET 600V~10kV
  - Normally on
- MOSFET 600V~10kV
  - MOS Issues
- Diode 600V~5kV
  - ★

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Fig. 7 Power devices based on SiC, indicating typical voltage ranges and current areas of development[19].

Based on the example for SiC, the path from the wafer material to the finalized power device or module is depicted in Fig. 8[21]. Based on a specific crystal growth method, a boule of material is manufactured, which is then separated into single wafers. The wafers are polished and the active device layer, also called drift layer, is deposited using an epitaxial process. The finalized material is then brought into semiconductor device manufacturing, the so-called front end. Her, different processed are used for providing specific layers and structures in order to optimize performance. The final processed wafer is separated into single dies, which are then packaged in the "back end".

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[21] http://www.semiconductortoday.com/news_items/2009/SEPT/YOLE_240909.htm

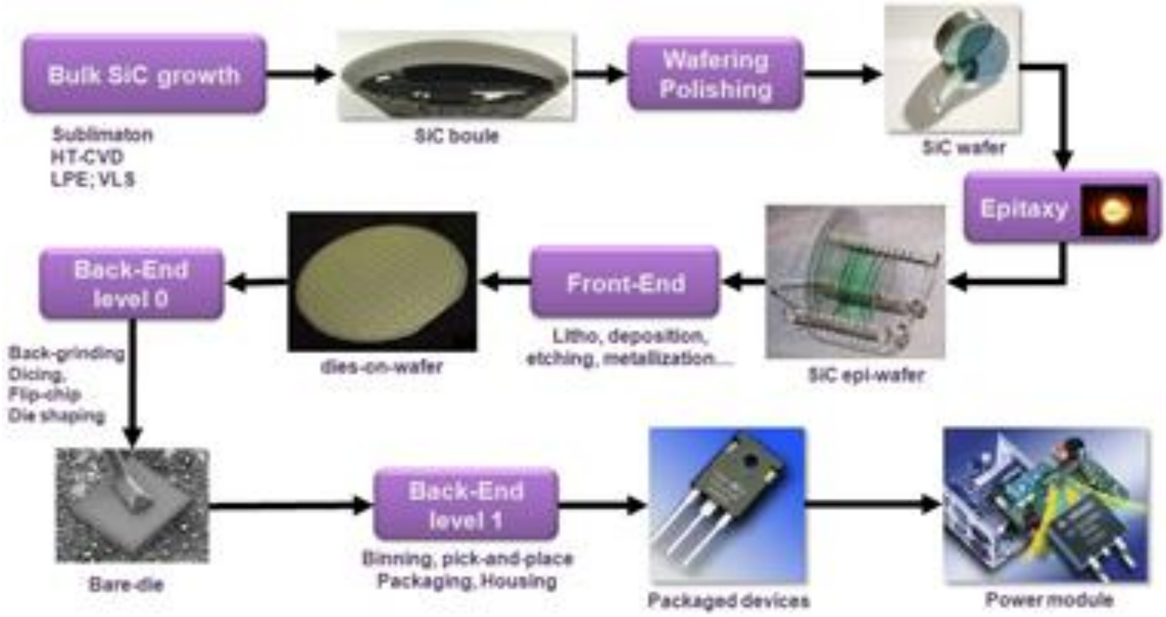

Fig. 8 Manufacturing of power devices, from material to final packaged device, for the example of SiC[21].

The package has several functions: it provides electrical contacts, dissipates the generated heat during chip operation, protects the semiconductor chip from harmful influences and also identifies the component type and the terminals.

This path is more or less typical for all power devices. However, the specific processing steps and actual technologies being used vary based on the material of choice, and – more importantly – the maturity of the technology. Silicon is by far the most mature material with wafers of up to 300 mm diameter (power devices are currently mainly manufactured on 200 mm wafers). SiC follows, as most processing steps are similar to the ones used for Si, and wafer material is commercially available in excellent quality up to 150 mm. For GaN, so far only lateral devices from GaN on Si wafers of 150 and 200 mm are commercially available. This significantly limits the blocking voltage capability and has caused significant reliability issues in the past.

Silicon is – by far – the most widely used semiconductor material at present, and will most likely remain that in the foreseeable future. The currently commercially used power electronic systems all are built upon the usage of one or the other silicon device. The current market revenue of power electronic devices is estimated to be around US$ 30 billion in 2018, with an increase to around 22 billion in 2022[22] Thereof, Si IGBTs account for approximately US $ 4 billion in 2018, with an increase to 5.5 billion in 2022[22].

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[22] Yole Development, IGBT market and technology trends 2017 report, 2017.

Compared to Si, both SiC and GaN possess a wider bandgap (WBG), a property which is proportional to the critical electric field (see Fig. 9). The critical electric field is the field required to break through the material, i.e. enabling a current path. It is the major contribution to the device property called blocking voltage, the parameter typically used for classification or power devices. Essentially, a semiconductor with a higher bandgap can block a higher field (applied voltage), for the same thickness. As the critical field is approximately 10 times higher for SiC compared to Si, it requires only one tenth of the material in thickness. In turn, SiC is expected to enable commercial devices with blocking voltages above 10 kV.

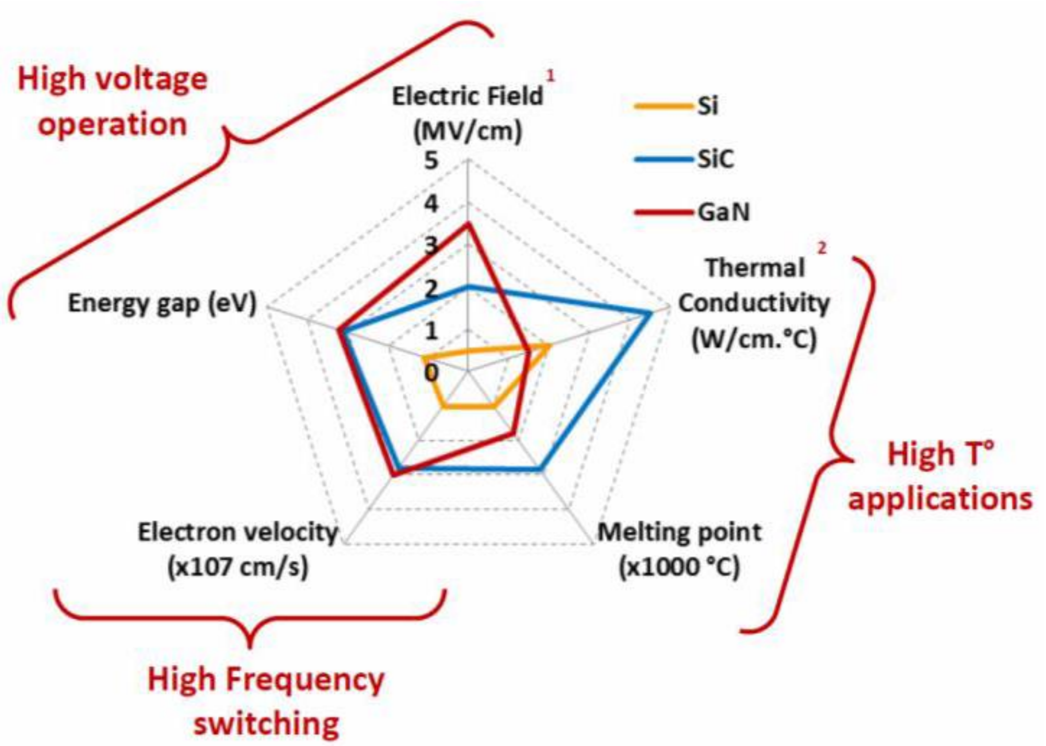

Fig. 9 Major properties of Si, SiC, and GaN and their impact on applications[16].

Contrary to SiC, GaN devices are commercially available only as lateral devices. This means that the blocking voltage needs to be supported in parallel to the device surface. This significantly impacts the device design: On the one hand, there is a need for field passivation at the surface, on the other, it enable the utilization of a distinct feature of GaN and AlGaN – a high polarization in the material. Modern GaN devices are designed such that a two-dimensional electron gas is formed, so that the electrons in the device serving as the charge carriers enabling a current flow are comparable fast. Fig. 10 shows a sketch of the cross section of a GaN High Electron Mobility Transistor (HEMT), the current state-of-the-art device type for GaN[23]. This property is unique for that particular layering of the semiconductor material stack, and cannot be easily achieved for other directions of the material. Therefore, there will be strict design constraints or limited benefits over SiC for future vertical GaN devices, an area which is currently under intense research efforts.

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[23] E. Bahat-Treidel, GaN-Based HEMTs for High Voltage Operation, PhD thesis, TU Berlin, 2012.

Apart from SiC and GaN, there are more materials under consideration for future replacement of Si. Typically, research is directed to materials with even higher critical electric field, such as diamond or gallium oxide (Ga_2O_3). However, so far these materials have not reached the threshold for significant commercial activity and are, therefore, not considered further in this report.

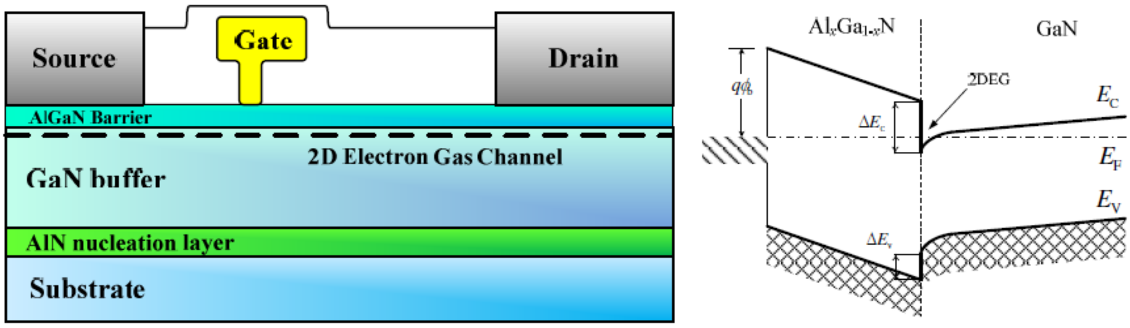

Fig. 10 A planar gate AlGaN/GaN based HEMT structure and the energy band-diagram under the gate electrode[23].

As an intermediate summary one may state the following:

- Power electronics allows the energy-efficient use of electrical power in a wide range of applications.
- The applications differ in required power and the respective switching frequency.
- The basic building block of a power electronic system are semiconductor-based devices.
- These devices are typically grouped according to voltage classes. The more material is used between the two terminals source and drain, the higher the respective blocking voltage.
- Higher switching speeds are typically served with unipolar devices, high current applications typically require bipolar devices.
- Three major semiconductor materials are the basis of the currently commercially available power devices: silicon, silicon carbide, and gallium nitride.

1.3 The Promise of Wide Bandgap Semiconductors in PE Applications

In Fig. 11, the impact of the different material properties on the device, system, and end use is depicted for SiC and GaN (adapted from Ref.[24]). Essentially, a combination of material properties themselves and the respective impact on design opportunities lead to a great impact on reduced losses in the power electronic system or for the application itself. This impact can either be indirect (high electron mobility of GaN HEMTs leading to faster switching, hence an increased operating switching frequency in the application leading to less required filters and lower weight) or direct (higher energy efficiency due to decreased losses based on a different type of device – unipolar instead of bipolar).

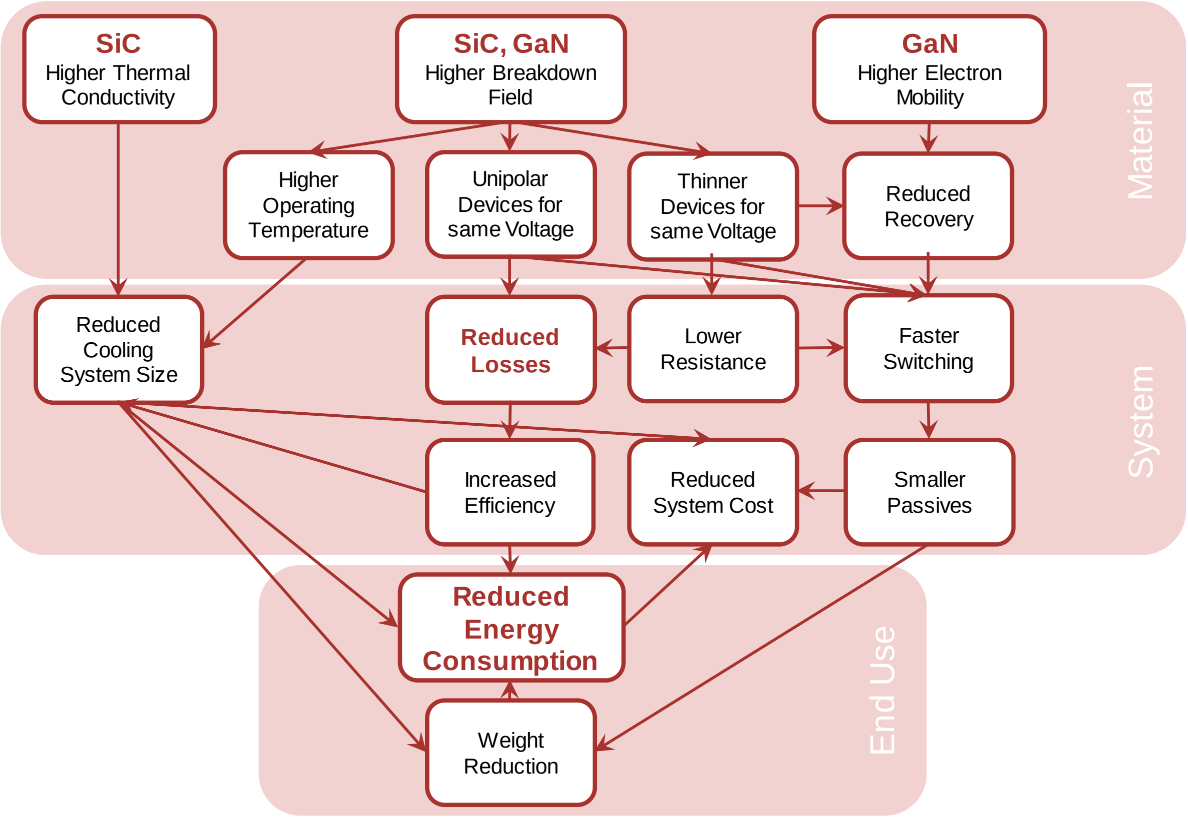

Fig. 11 Impact of basic material properties on device, system, and application[24].

An overview of the projected energy savings based on a replacement of Si-based devices with WBG components is shown in Fig. 12[25]. Here, a potential energy saving of 7,670 GWh/year is projected in case of a replacement of all Si-based components by WBG-based components in laptop, cell phone and tablet chargers alone. Such projections are being assembled for a series of applications, as also shown in Fig. 13[24].

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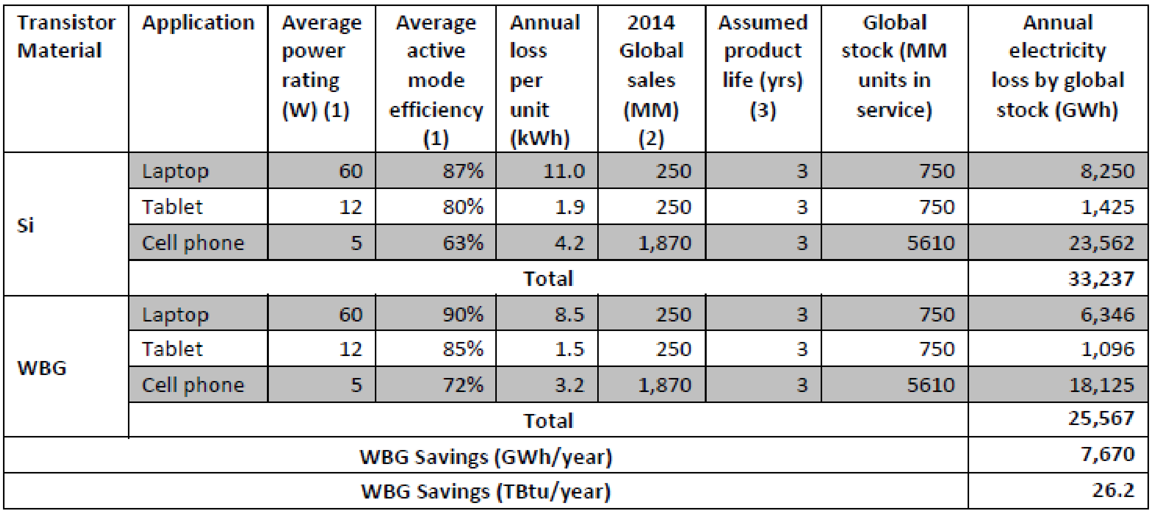
[24] K. Armstrong, S. Das, L. Marlino, ORNL/TM-2017/702, Nov. 2017.

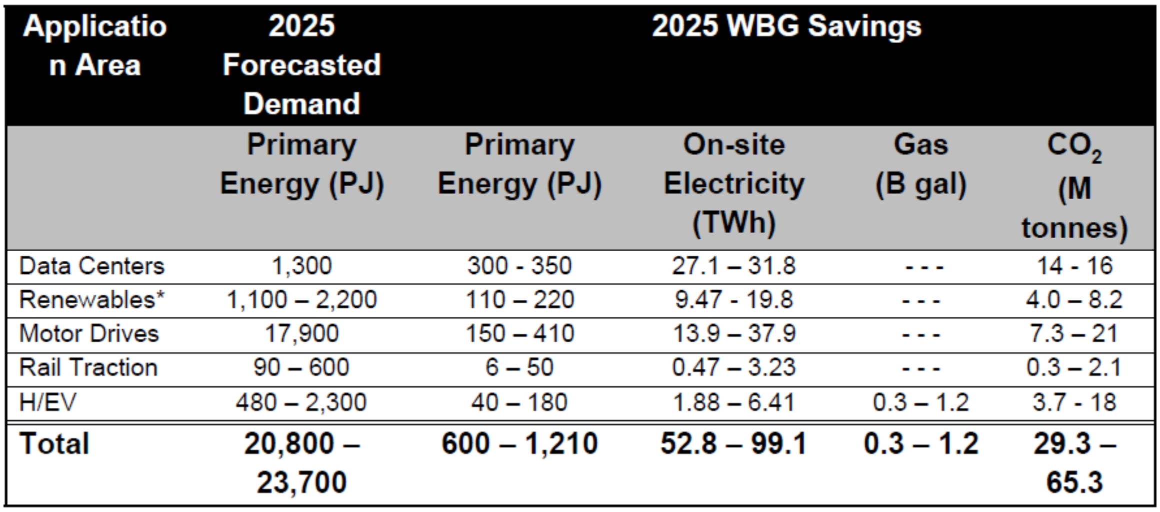
[25] DoE, Wide Bandgap Power Electronics Technology Assessment, draft version 2015.



Transistor Material	Application	Average power rating (W) (1)	Average active mode efficiency (1)	Annual loss per unit (kWh)	2014 Global sales (MM) (2)	Assumed product life (yrs) (3)	Global stock (MM units in service)	Annual electricity loss by global stock (GWh)
Si	Laptop	60	87%	11.0	250	3	750	8,250
	Tablet	12	80%	1.9	250	3	750	1,425
	Cell phone	5	63%	4.2	1,870	3	5610	23,562
	Total							33,237
WBG	Laptop	60	90%	8.5	250	3	750	6,346
	Tablet	12	85%	1.5	250	3	750	1,096
	Cell phone	5	72%	3.2	1,870	3	5610	18,125
	Total							25,567
WBG Savings (GWh/year)								7,670
WBG Savings (TBtu/year)								26.2

Sources: 1 (Navigant Consulting Inc. et al., 2012), 2 (Eykyn, 2013; Gartner, 2014), 3 (Boyd et al., 2009)

Fig. 12 Potential impact of WBG components on global energy use[25].



Application Area	2025 Forecasted Demand	2025 WBG Savings			
	Primary Energy (PJ)	Primary Energy (PJ)	On-site Electricity (TWh)	Gas (B gal)	CO_2 (M tonnes)
Data Centers	1,300	300 - 350	27.1 – 31.8	- - -	14 - 16
Renewables*	1,100 – 2,200	110 – 220	9.47 - 19.8	- - -	4.0 – 8.2
Motor Drives	17,900	150 – 410	13.9 – 37.9	- - -	7.3 – 21
Rail Traction	90 – 600	6 – 50	0.47 – 3.23	- - -	0.3 – 2.1
H/EV	480 – 2,300	40 – 180	1.88 – 6.41	0.3 – 1.2	3.7 - 18
Total	**20,800 – 23,700**	**600 – 1,210**	**52.8 – 99.1**	**0.3 – 1.2**	**29.3 – 65.3**

Fig. 13 WBG potential energy savings for various applications in 2025[24].

With all benefits assigned to WBG semiconductors, it should clearly be stated that the current assessment is based on projections established through record, not typical device performance. As these materials still lack a certain maturity, both in material quality as well as design approaches, a huge research and development effort is still required to enable a true success story for WBG enabled energy savings.

These efforts will have to be made on all levels of the manufacturing chain as depicted in Fig. 8. Hence, a variety of competences has to be available both in academia and industry. Furthermore, with the new WBG devices and modules, the power electronics system engineers are challenged in order to unlock the full potential of the WBG devices. As already stated in the beginning, the power electronics system consists not only of the semiconductor devices (although it enables the entire operation), but also other components which have to be adjusted toward the needs of the WBG device.

It can also be clearly seen and it should be kept in mind that the push for better technology somewhere in the manufacturing path is often equally applicable to Si devices and that the challenge by the new, emerging materials is well accepted by the Si technology community.

One interesting example is the change in packaging for Si superjunction MOSFETs from Through Hole Device (THD, for example TO-247) to a Surface Mount Device (SMD) package[26]. Here, a mature and improved Si technology is marketed as a clear competitor for GaN: “By driving down on-state resistance while providing ‘GaN-like’ switching losses, the latest super junction (SJ) MOSFET technologies hold the key to addressing these challenges in modern hard- and soft-switching applications.” Here, the cost and scalability of Si will have an impact on the competitiveness. In a later section, the Key Performance Indicators (KPI) for power devices and systems are discussed.

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[26] Infineon, CoolMOS™ C7 Gold + TOLL = A Perfect Combination, Application Note, AN_201605_PL52_019, 2016.

2 Global Activities

2.1 Academic Institutions and independent Research Labs

Departments of Electrical Engineering are well established in all technical and most general universities in the world. Most of them cover electrical engineering in the sense of traditional electrical systems as well as information technology. In the past two decades, globally acknowledged competence centers have established itself, either through the works of some distinct experts or in close collaboration with industrial partners. The following list is by no means complete; however, it aims to list the most highly acclaimed research groups in Europe, USA and Japan, dedicated to power electronics, based on research output and student education.

Europe

- ETH Zurich, CH, Department of Information Technology and Electrical Engineering: http://www.ee.ethz.ch/;
- EPF Lausanne, CH, School of Engineering, Electrical Engineering: https://sti.epfl.ch/research/institutes/iel/
- RWTH Aachen, D, E.ON Energy Research Center and Institute Power Generation and Storage Systems; Power Electronics and Electrical Drives:http://www.isea.rwth-aachen.de
- University of Aalborg, DK, Center of Reliable Power Electronics: https://www.corpe.et.aau.dk
- TU Delft, NL, Electrical Sustainable Energy: https://www.tudelft.nl/ewi/over-de-faculteit/afdelingen/electrical-sustainable-energy/
- University of Madrid, ESP, Centro de Electronica Industrial: http://www.cei.upm.es/research/research-lines-2/power/
- University of Nottingham, Power Electronics, Machines and Control: https://www.nottingham.ac.uk/research/groups/power-electronics-machines-and-control-group/index.aspx
- KTH Stockholm, S, Department of Electric Power and Energy Systems: https://www.kth.se/epe
- Austrian Institute of Technology AIT, Wien: https://www.ait.ac.at/en/

USA

- Virginia Tech, Center for Power Electronic Systems: https://cpes.vt.edu/
- University of Wisconsin, Wisconsin Electric Machines and Power Electronics Consortium: https://wempec.wisc.edu/
- Caltech, Department of Electrical Engineering: http://ee.caltech.edu/
- North Carolina State University, Electrical and Computer Engineering: https://www.ece.ncsu.edu
- University of Arkansas, Electrical Engineering Department: https://electrical-engineering.uark.edu/index.php
- University of Illinois, Power and energy systems: https://ece.illinois.edu/research/power.asp

Japan

- Tokyo Institute of Technology, Department of Electrical and Electronic Engineering: https://educ.titech.ac.jp/ee/eng/
- Kyoto University, Department of Electrical Engineering and Department of Electronic Science and Engineering: https://www.ee.t.kyoto-u.ac.jp/en
- University of Tokyo, Department of Electrical Engineering and Information Systems: www.eeis.t.u-tokyo.ac.jp/en/
- Osaka University, Department of Electrical Engineering: www.eei.eng.osaka-u.ac.jp/english/
- Tohoku University, Department of Electrical Engineering and Department of Electronic Engineering: https://www.eng.tohoku.ac.jp/english/

2.2 Industrial Activity

Industrial activities are much more closely observed and analyzed than academic activities due to the existing business case. Numerous market development and business analyst companies provide in-depth market data and analysis thereof. For WBG semiconductors, one of the most prominent and experienced ones is Yole Development, based in France. Yole has made itself a name in collecting and analyzing market and technology information from a series of companies, especially for SiC. An example is given in Fig. 14. Here, the different business models of the investigated companies were analyzed and they were grouped in different models consisting of different components in the overall value chain.

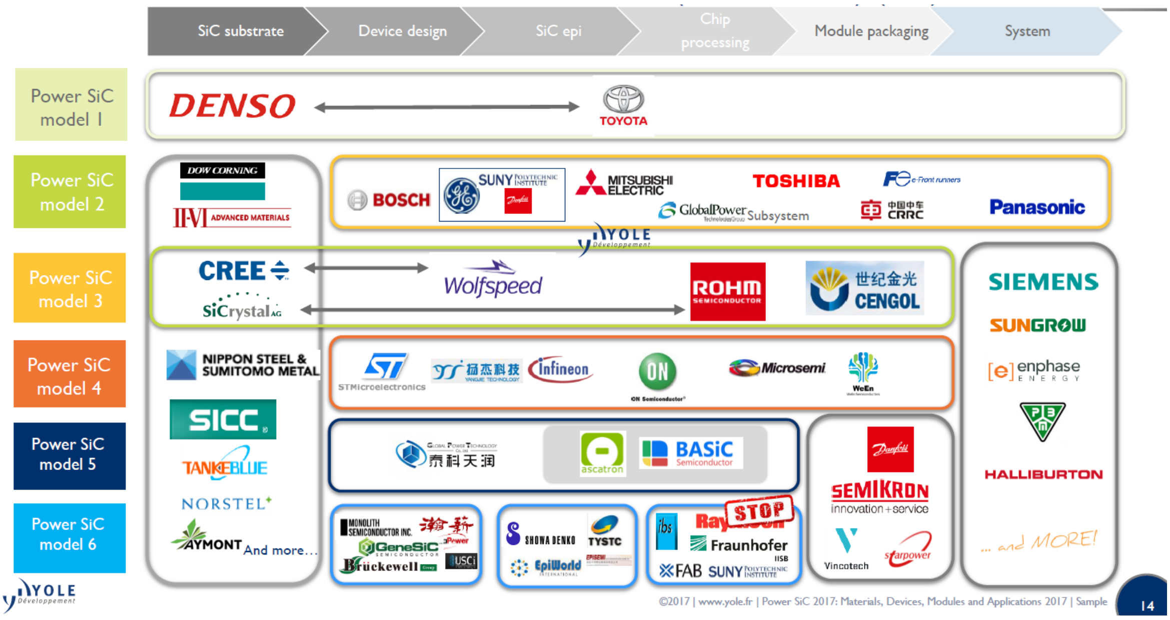

Fig. 14 SiC Power industry business model as typically compiled by Yole[28].

In the following, the leading companies in SiC and GaN (devices) are listed for Europe, the USA and Japan. Here, special emphasis is given to the ones active in R&D, but first and foremost also supplying commercial products beyond prototypes or research samples. There is some sort of a trend observable: Whereas European companies often focus on providing the best semiconductor and module solution for a given application (which is then typically developed and manufactured by another system company), the American companies more often focus on foundry models, i.e. the development of the devices, but outsourcing their manufacturing. In contrast to this, most Japanese companies are fully vertically integrated, meaning that although they do have in-house (or sub-unit) development and manufacturing of material and devices, they do only offer complete systems. This has a huge impact on the specific knowledge within these companies – the most successful European players accumulated a large system knowledge through close collaboration with their customers, allowing them to have knowledge in and being able to target a wide range of applications. The American companies tend to have a less pronounced system and application knowledge, and focus mainly on performance of the devices, which often shows in good results, but may be impractical for actual implementation or reliability. Japanese companies often have identified a key strategic application and subordinate the entire semiconductor values chain towards a success of that application.

Europe

- Infineon: https://www.infineon.com/ - focusing on semiconductor and system solutions. Manufacturing from epitaxial layers to power modules, strong research and development. The only company clearly stating that it manufactures Si, SiC and GaN devices in one-and-the-same facility, using wafers of 150 mm and above.
- STMicroelectronics: https://www.st.com/content/st_com/en.html - a global semiconductor company with internal SiC product development.
- Bosch: https://www.bosch.com/ - global supplier of technology and services with internal SiC product development.

USA/Canada

- Wolfspeed/Cree: https://www.wolfspeed.com/ - “fully commercialized broad portfolio of the most field-tested SiC Power and GaN RF solutions on the market”. Wolfspeed is a Cree company; whereas Cree focuses on GaN LEDs, it developed the SiC substrates. Wolfspeed provides epitaxial layers and SiC and GaN devices and modules.
- ON Semi: https://www.onsemi.com/ - supplier of semiconductor-based solutions. R&D and products in SiC and GaN, historically through purchase of the former Fairchild.
- X-FAB: https://www.xfab.com/technology/sic/ - untypical example, but interesting for its business model. While initially focusing on mixed-signal Si technology, it now tries to establish itself as a foundry service for fab-less SiC development companies. 6-inch Silicon Carbide foundry line fully integrated within our 30,000 wafers/month silicon wafer fab located in Lubbock, Texas.
- EPC: http://epc-co.com/epc - GaN-focused: “leading provider of gallium nitride (GaN)-based power management technology”
- GaN Systems: https://gansystems.com/ - “the leader in Gallium Nitride (GaN) based power management devices, specializing in power conversion, semiconductors and transistors.” Devices are mainly manufactured in Taiwan.

Japan

- Toshiba: https://www.toshiba.co.jp/worldwide/index.html - microwave and power products in SiC and GaN.
- Hitachi: http://www.hitachi.com/ - rail solutions.
- Mitsubishi Electric: https://www.mitsubishielectric.com/en/index.html - record 3.3kV SiC module for air conditioning in commuter trains.
- Panasonic: https://www.panasonic.com/global/home.html - unique GaN solutions for consumer electronics.
- Rohm: https://www.rohm.com/ - mainly semiconductor (SiC) material.
- Denso/Toyota: https://www.denso.com/global/en/, https://www.toyota.com/ - focusing on SiC for automitive applications.
- Fuji Electric: https://www.fujielectric.com/ - “contribute to the resolution of energy management problems”, provides SiC power modules.
- Sumitomo Electric: https://global-sei.com/ - manufacturing tools and material for SiC material and power devices; applications.

As stated above, the list is focusing on the most active players in the SiC and GaN community with the highest visibility. Clearly, there is a lot of dynamics in the market, both through start-up activities globally and also supported through state and private funds in China and Korea, as well as due to and ongoing consolidation phase in the semiconductor industry with mergers every year.

2.3 Organisations and Platforms for Information Exchange

Organizations

The largest and most widely spread organization focusing on power electronics and power devices is most likely the IEEE and its different sub-organizations and chapters.

- Power Electronics Society: https://www.ieee-pels.org/about - focusing on power electronics and its applications, in science and education.

- Electron Devices Society: https://eds.ieee.org/about.html - focusing at semiconductor devices (also employing holes, not just electrons).

- Electronics Packaging Society: https://eps.ieee.org/ - addresses the scientific, engineering, packaging, and production aspects of materials and component part for all electronics applications.

IEEE also runs an interactive community platform, which is currently also used for roadmap development see below.

Another more academic organization is the Materials Research Society (https://www.mrs.org/), providing a platform for WBG semiconductors on their spring and fall meetings.

On the industrial and collaborative side, the most important organization in Europe is the ECPE (European Center for Power Electronics, https://www.ecpe.org/), “founded in 2003 on the initiative of leading power electronics industries as an industry-driven Research Network to promote education, innovation, science, research and technology transfer in the area of Power Electronics in Europe.” It should be mentioned, that most globally active companies are also member of the ECPE through their European branches. Therefore, it provides by far the best platform for collaborative as well as pre-competitive research and exchange of information. Furthermore, due to the broad set of members, a wide range of applications and technologies is represented. ECPE provides excellent network-open trainings and workshops and regularly organizes a WBG user meeting for network members.

A somewhat smaller and more focused, but similar concept is followed by the more U.S.-centered Power Supply Manufacturers Association, PSMA (https://www.psma.com/). It is open to industry, but also academic associates and offers a good series of analysis reports on focus topics.

In the U.S., there is also another platform, primarily funded by the DoE[27]. “Lead by NC State University, PowerAmerica will work to make wide bandgap (WBG) semiconductor technologies cost-competitive with the silicon-based power electronics that are currently used.” Established in 2014, it brings together companies and universities focusing on SiC and GaN development. It is the primary of such efforts in the US.

Conferences and Workshops

In the following, major, more traditional meetings of the active part of the power electronics and power semiconductor community are listed. Again, this list is far from complete. New events are being established on a yearly basis and some newer meetings maybe marketed slightly misleading in terms of importance and track record. The following meetings have the most significant track record and are established as the major conferences in the respective field.

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[27] https://www.energy.gov/eere/amo/poweramerica

- PCIM: https://pcim.mesago.com/events/en.html - “the world's leading exhibition and conference for power electronics, intelligent motion, renewable energy, and energy management.
- APEC: www.apec-conf.org/ - “the premier global event in applied power electronics.”
- EPE/ECCE: www.epe2018.com/ - conference of the European Power Electronics and Drives Association.
- IPEC: https://www.ipec2018.org/ - International Power Electronics Conference.
- ISPSD: www.ispsd2019.com/ - “the premier forum for technical discussions in all areas of power semiconductor devices and power integrated circuits”.
- IEDM: https://ieee-iedm.org/ - “the world's pre-eminent forum for breakthroughs in semiconductor and electronic device technology.”
- ICSCRM/ECSCRM: https://www.icscrm2019.org/ - International/European Conference on Silicon Carbide and Related Materials, biennial, alternating.
- IWN: www.iwn2018.jp/ - International Workshop on Nitride Semiconductors
- MRS/EMRS Meetings: https://www.mrs.org/fall2018 - biannual, spring and fall with slightly different focus topics.

Newer meetings as created by IEEE include the WiPDA (wipda.org/) and IWiPP (iwipp.org/), focusing on WBG device applications and power packaging, respectively. It remains to be seen how these workshops develop also with respect to the more established conferences.

In any case, it is strongly suggested to attend one of the above-mentioned platforms when attempting to understand the current status of R&D in the WBG community. A cross-comparison of members of technical program and organizing committees and their affiliations is also very revealing when compared to research or product output in order to identify key personnel and industrial players in the field.

2.4 Funding Situation

The current funding situation is fairly diverse and should, most likely, be the subject of a separate report.

In general, the situation in Japan has been the most stable in the last few years, with programs on R&D as well as industrial development. However, the largest of the SiC related programs will end in March 2019 and it remains to be seen how funding in Japan will be distributed in the future.

In Europe, there are numerous more local initiatives on country[28],[29],[30], and even regional level[31]. The EU provides funding through the typical instruments[32], such as Innovative Training Networks (ITN[33]), Electronic Components and Systems for European Leadership Joint Undertakings (ECSEL EU[34]) and the Horizon 2020 Program (H2020[35]). Clearly, very often European funding is already earmarked for a

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[28] Germany, BMBF: https://www.foerderinfo.bund.de/en/index.php

[29] Switzerland, SFOE: http://www.bfe.admin.ch/themen/00519/00636/index.html?lang=en

[30] Sweden: www.energimyndigheten.se

[31] Bavaria, Germany: Cluster Leistungselektronik: http://www.clusterle.de/

[32] http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/index.html, new: https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/home

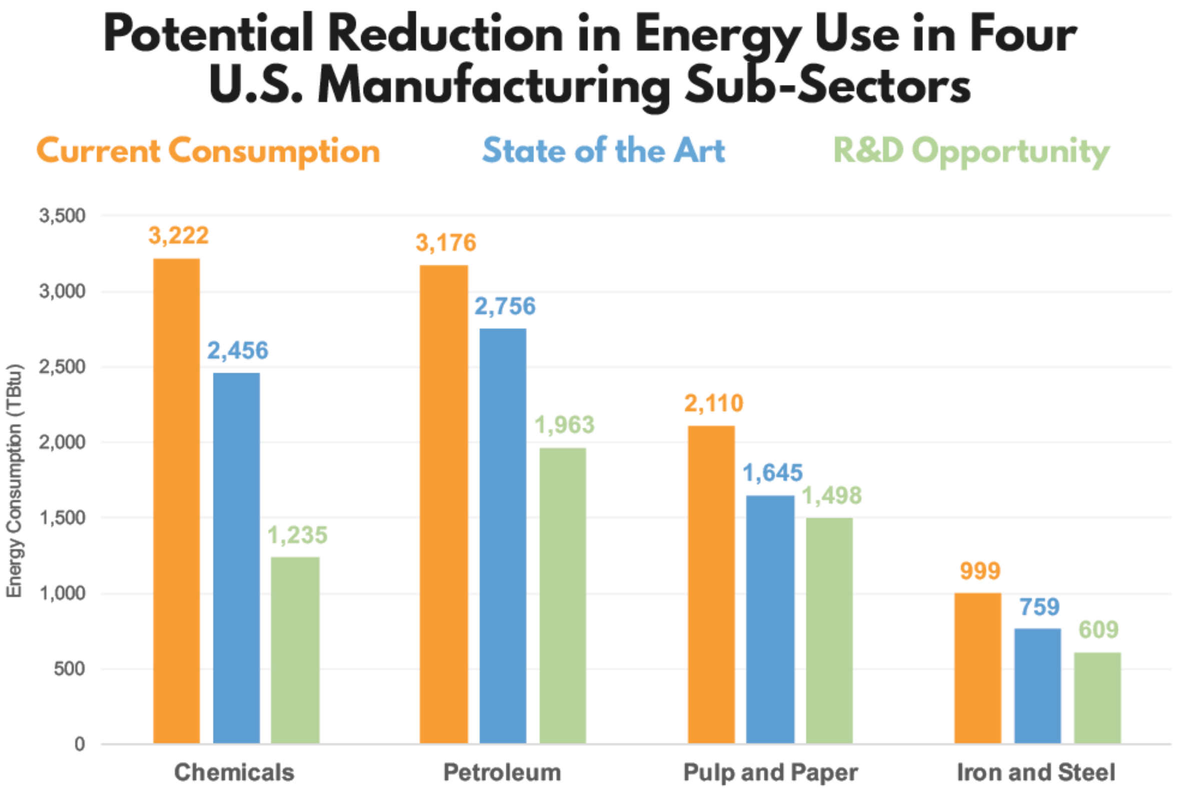
[33] https://ec.europa.eu/research/mariecurieactions/actions/get-funding/innovative-training-networks_en

[34] https://www.ecsel.eu/

[35] https://ec.europa.eu/programmes/horizon2020/

specific type of project or topic. Hence, the community has observed a fairly irregular pattern in funding opportunities and it remains to be seen how the situation develops.

In the U.S., albeit the current situation concerning the discussion on energy sources, it is widely accepted that energy efficiency on the one hand and prime research and development on the other are a key economic factor of a nation. Therefore, the funding opportunities seem constant if not even increasing when aiming for establishing a stable research and, first and foremost, manufacturing base for WBG semiconductors in the U.S.. Traditionally, funding for SiC and GaN has often been sponsored by DoD and alike, such as DARPA. However, funding in recent years has focused on more civil applications and was sponsored by DoE and ARPA-E. Most likely, the situation of lowered costs for batteries is beneficial also for funding of WBG-based power electronics for hybrid electrical and electrical vehicles. Clearly, WBG are now understood as a path towards a more “economic” use of energy [36 and references cited therein] (see also Fig. 15).



Note: Current energy consumption refers to the typical energy consumption of each manufacturing subsector as of 2010.
State of the Art refers to energy consumption that could be achieved if the most energy efficient technologies and practices existing today were widely adopted.
R&D Opportunity refers to energy consumption that could be achieved if energy-saving technologies and practices currently under development are successfully deployed
Source: U.S. Department of Energy, 2015.

Fig. 15 Technology-based estimates of potential energy savings opportunities in four energy-intensive manufacturers (EIM) sub-sectors[36].

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[36] Third Way, Industry Matters: Smarter Energy Use is Key for US Competitiveness, Jobs, and Climate Efforts, https://www.thirdway.org/report/industry-matters-smarter-energy-use-is-key-for-us-competitiveness-jobs-and-climate-effort

2.5 Technology Roadmaps

Technology Roadmaps are regularly developed in all sorts of organizations; however, they will only deliver meaningful value if also external parameters are considered. From the numerous roadmap initiatives, the following ones seem the most important, as they are publically discussed and discussion partners from all domains are involved.

Based on a White Paper called “Next Generation Power Electronics based on Wide Bandgap Devices - Challenges and Opportunities for Europe”16, the ECPE has now developed a WBG roadmap. It is available to involved network members as a draft version and will most likely be made more widely accessible by end of 2018. As ECPE has a very broad member base, this roadmap is fairly comprehensive.

In the U.S., the Oak Ridge National Laboratory has taken the role of investigating the current and future opportunities for WBG technology24.

The PowerAmerica Institute is leading the initiative “PowerAmerica Strategic Roadmap for Next Generation Wide Bandgap Power Electronics” [37]. However, its data is only accessible for members of PowerAmerica.

The 2018 GaN power electronics roadmap, on the other hand, is a researcher-driven, publically available documents published in a renowned journal[38].

Led by IEEE, a unification similar to the CMOS transistor technology roadmap is attempted: The International Technology Roadmap for Wide Bandgap Power Semiconductors (ITRW[39]). It is discussed internally in person at least twice a year (at APEC and WiPDA), and uses a IEEE platform for online discussion[40]. The ITRW stands out, as the efforts are more openly discussed and actively involve also Chinese and Korean partners.

2.6 Standardization

Standardization of testing procedures for WBG devices is clearly still in its infancy compared to Si technology.

As the standardization body for industry, JEDEC has established a Committee to Set Standards for Wide Bandgap Power Semiconductors in 2017[41]. It is “led by committee and subcommittee chairs from Infineon Technologies, Texas Instruments, Transphorm, and Wolfspeed, a Cree Company. Committee members include industry leaders in power GaN and SiC semiconductors as well as prospective users of WBG power semiconductors and T&M equipment manufacturers. Global multinational corporations and technology startups from the US, Europe, and Asia are working together to bring to the industry a set of standards for reliability, testing, and parametrics of WBG power semiconductors.” Access to the

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[37] https://poweramericainstitute.org/about-poweramerica/technology-roadmap/

[38] H. Amano et al., The 2018 GaN power electronics roadmap, J. Phys. D: Appl. Phys. 51 163001, 2018.

[39] https://www.ieee-pels.org/standards/about-itrw

[40] https://ieee-collabratec.ieee.org/

[41] https://www.jedec.org/news/pressreleases/new-jedec-committee-set-standards-wide-bandgap-power-semiconductors

discussions and results is strictly limited to JEDEC members (yearly fee required), and there is little input from academic partners.

In Japan, standards are commonly developed by the Japan Electronics and Information Technology Industries Association (JEITA)[42]. Here, the first standards specifically used for SIC have been established.

Overall, it is concluded that standardization is currently only driven by industry, and that little influence of public and research organizations is observed.

3 Challenges towards Implementation of WBG-Technology

3.1 Figures of Merit (FOM)

Very often, the FOM for WBG devices is the on-state resistance Ron and its relation to the achieved breakdown voltage Vbr (see also Ref. 18). This is a classical FOM, but it depends heavily on device design and maturity of manufacturing processes. Therefore, very often the optimization towards a low Ron has led to reliability issues. The main reason (a detailed description is beyond the scope of this report) is the design and manufacturing of the gate region in MOSFETs, of the lateral dimensions in HEMTs and of the drift layer thickness in diodes.

Therefore, more and more research is now targeted towards understanding the reliability and ruggedness of power devices, i.e. the performance under constant application and specific stress conditions. Here, FOMs are, for example, the time a device can withstand a certain voltage under short circuit conditions.

3.2 Key Performance Indicators (KPI)

Semiconductor industry in general is largely driven by cost. A series of Si devices is often compared by comparing the cost for 1 A, i.e. $/A. This is a clear sign of two things: i) The maturity of the technology, being it material, processing, or even design. The cost for a single Si die is composed of the cost for the amount of material (thickness and area), the manufacturing and assembly costs. As the wafer fabrication lines are typically fully optimized, there is a processing cost per wafer. Consequently, a larger wafer allowing the processing of more single dies is more cost efficient. Also, tools processing several hundred wafers at once are available. This economy of scale makes Si power device manufacturing cost rather than performance or even innovation controlled. ii) The cost of $/A being the most important KPI leads to the situation, that the achievable efficiency of power conversion is secondary. The power electronic system designers will budget for a power device, but the main system cost is accumulated in secondary functions. The KPI here is the Bill of Materials (BOM).

Here, the main problem of the implementation of WBG devices is caused. As long as only the device cost is considered, WBG devices will rarely have a chance for implementation. Therefore, there is a trend in marketing WBG power devices away from the mere BOM towards a true performance indicator, such as $/W saved over the lifetime of the system. Here, the benefits of WBG technology can be more effectively assessed, as the entire system (and the potential saving due to smaller filters, for example) is investigated.

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[42] https://www.jeita.or.jp/cgi-bin/standard_e/list.cgi?cateid=5&subcateid=34

3.3 Technology Gaps and Current Implementation Barriers

Depending on the position of the person asked in the value chain of WBG technology, the identified technology gaps will be significantly different. Clearly, there are commercially successful devices on the market, and more and more applications are both emerging and are pushing their performance boundaries by employing WBG devices.

The technology gaps as identified by industry are also reflected in its activities: As long as there is no consensus on testing procedures, for example, second sourcing for system companies will be difficult. Therefore, industry strongly supports standardization efforts. Roadmaps are another sign for a maturing technology – key strategic applications shall be identified and effort towards them are focused.

From a technological point of view, the key technology developments in SiC technology should be focused on i) the oxide-semiconductor interface, ii) technologies for charge-compensated devices (superjunction) and ii) bipolar technology. This still requires basic research in bulk and epitaxial material, and actual processing of devices.

For GaN, a large field is still the reliability at high currents and voltages. The lateral GaN devices are typically aiming at Vbr ≤ 600V. Vertical GaN devices for higher voltage classes appear not fit into the KPI criteria of the industry at the moment.

As briefly discussed in the previous section, one current implementation barrier is the choice of KPI. As long as the overall energy efficiency of a power electronic system in operation does not have cost assigned to it for the system designer or the supplier of the overall system, WBG implementation will be limited. Changing this, requires R&D and other efforts throughout the entire value chain and across domain. Applications where WBG devices will have an actual positive impact need to be identified and the type of impact needs to be classified. Such applications most likely require re-design or completely new concepts.